Sh0CK!
Sharing of Computable Knowledge!

eCAADe 35
20 - 22 September 2017 Rome
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ShoCK! – Sharing of Computable Knowledge!

The theme of the 35th eCAADe Conference is Sharing of Computable Knowledge! – ShoCK! so, we have invited eCAADe community, members of Sibling Organizations and CAADFuture friends to face this exciting theme. Why such a strong theme? Mainly for three reasons.
The first one, is that we live in a city that has been witness of several revolutions of the conceptions of architectural space: most turning points of space perception are present here by means of architectural masterpieces as Bruno Zevi stated. I like to quote Rem Koolhaas: “It is a platitude that the presence of history in Rome is detriment to the development and display of modern art. But if that were true, Rome – a city of successive modernities – would never happened.”
Secondly, as my DaaD research group states “Rome is an open-air museum of architectural avant-garde masterpieces of an uninterrupted history where styles are juxtaposed, intertwined and stratified other than culturally also physically…” This concept is very close to the modern concept of cognitive sciences: to think by means of several abstraction levels of intelligence. And the third reason is that we live in a Faculty founded in 1817 – right two centuries ago - has always had a multidisciplinary approach to understand and solve problems: from the outset Architecture, Civil engineering, Bridge construction, Topography, Geometry and Mathematics subjects were present. As a matter of facts this approach it is not limited to technical aspects as – most importantly – the Faculty, now Civil and Industrial Engineering, lives in Sapienza University of Rome – established in 1303 – a university that pursues the “universal” approach where each discipline enhances the others.

Going back to the theme, it involves in turn several subjects: Internet of Things, pervasive nets, Knowledge ‘on tap’, Big Data, Wearable devices and the ‘Third wave’ of AI, ... All of these disruptive technologies are upsetting our globalised world as far as it can be predicted henceforth.
So, academicians, professionals, researchers, students and innovation factories… are warmly invited to further shake up and boost our innovative and beloved CAAD world – we already are in the post-digital era – with new ideas, paradigms and points of view.
I said “CAAD world” as I think that it contains and involves several disciplines but it is a new subject it its own that overcomes the former ones.

The underlain idea of this International Conference is that as a catalyst of creative energy it pursues with determination founders’ purposes and to be a shocking vanguard, a melting
pot of novelties, in words: to become an “incubator” of innovative and seminal ideas, to generate enthusiasm, to be an occasion for new friendships and to facilitate the establishment of effective researches’ networks. The title of the conference reflects well these intentions:

Sh o CK! – Sharing of Computable Knowledge!

So the aim of the Conference was to knock our habitual design activities out, to compare the various methodological and technological trends and to disseminate the latest research advances in our community. Will our fine buildings and design traditions survive? Or, will they ‘simply’ be hybridized and enhanced by methods, techniques and CAAD tools? Obviously, computation is needed to match the ever-growing performance requirements, but this is not enough to answer all these questions we have to deal with the essence of problems: improve design solutions for a better life!

Obviously, computation is needed to match the ever-growing performance requirements, but this is not enough... As life is not a matter of single individuals, we need to increase collaboration and to improve knowledge and sharing. This means going back to focusing on human beings, and involves the humanistic approach, and the long history of architecture... from handicrafts to thinking to technology... to handicrafts again.

A large spiral of the architectura as eternal as our city.

A.

Antonio Fioravanti

eCAADe 2017 Conference Chair

* This second volume of the conference proceedings of the 35th eCAADe conference contains 81 papers grouped under 14 sub-themes; both volumes contain altogether 155 accepted papers. The Conference was held at the Faculty of Civil and Industrial Engineering, Sapienza University of Rome, Rome, Italy, in via Eudossiana 18, Rome, on 20th – 22nd September 2017.

In addition to the accepted papers, the first volume contains Keynote speakers’ contributions concerning the themes of their keynote lectures and the Workshop Contributions including the contents of workshops given; the second volume furthermore includes the Poster Session contents.

All the papers of these proceedings will be accessible via CuminCAD - Cumulative Index of Computer Aided Architectural Design, http://cumincad.scix.net
Acknowledgements

Authorities, colleagues, researchers, professors, students, professionals all of you are welcomed to the 35th eCAADe conference, in Rome the *eternal city*.

It has been a long time ago – 31 years – since the previous eCAADe conference was held in this Faculty, hosted by our University - “La Sapienza”. That time, Gianfranco Carrara, one of the eCAADe founders, chaired the 4th eCAADe conference in 1986. That time on, there was only one eCAADe conference in Italy precisely in Palermo in 1995 chaired by Benedetto Colajanni and Giuseppe Pellitteri. This Faculty – now Faculty of Civil and Industrial Engineering – inspired by Parisian and Austrian models, is quite old as it was funded by Pope Pius VII in 1817, so now it celebrates its Bicentennial!

But it is quite young compared to our mother University “La Sapienza” that was established by the Pope Bonifacius VIII in 1303.

The original idea of bringing the eCAADe conference back to Rome goes rather back in times, I remember it was in 2009 at eCAADe conference in Istanbul. You know things take their time in Italy, so only in 2013 my Faculty approved and on 21st March 2015 eCAADe Council granted us the permission to organize the 35th conference. Over the last years several people have helped us to make this conference happen. We thank the former Dean of Civil and Industrial Engineering Faculty, Prof. Fabrizio Vestrioni and especially the present Dean, Prof. Antonio D’Andrea for their supports.

During the process of organizing the eCAADe 2017 we have had the privilege to experience the supportive, collaborative and frank atmosphere of eCAADe Council, whose members, no one excluded, have helped us with all organizational aspects.

Let us be touched in remembering for his humanity the former eCAADe President, Johan Verbeke, who recently passed away. We all are sad in this moment thinking is no more physically with us now, but at the same time we are grateful to have met him and exchanged ideas on equal terms as his habit. In spirit, he is present so we can tell him: Johan, special thanks for your open-minded support, we warmly thank you! We miss you, and we do not forget you!

How cannot we mention Joachim Kieferle a friend, who is also the eCAADe President, for his encouragement and unswerving support during the last years and his ability to cut up dead-
locks into pieces. A special thanks to the great Bob Martens for his ability in organizing complex tasks and simplifying processes – Dutch origin helps – his daily support was precious and helped us relentlessly. And a “suuppper” thanks to a “super” friend as Gabriel Wurzer for his optimism and silent help in difficult issues.

Also, we wish to thank all the other previous conference organizers, Henri Achten, Rudi Stouffs and Emine Mine Thompson, for sharing their experience and knowledge. A special thanks to more recent conference organisers Bob Martens, Gabriel Wurzer, Thomas Grasl, Wolfgang E. Lorenz and Richard Schaffranek together with Aulikki Herneoja, Toni Österlund and Piia Markkanen!

Quality is the vital issue concerning conference proceedings.

To improve it we used different means: OpenConf conference management system that easily ensured that none of the reviewers came from the same institution as the authors; through special relationships between Liverpool University and eCAADe thank to Martin Winchester’s support we were able to overcome program bugs; a second and handcraft check of interest conflicts among authors and reviewers was made during the reviewing phase; a double-blind peer review process; and an accurate reviewers’ selection. The selection was fair, and only extended abstracts with high grades were admitted to full paper phase.

Quality means also typographic quality control in two ways: for printing results and for respecting author’s layout; so, thanks to the well-known ProceeDings formatting management system eCAADe could fulfil these two needs.

Authors uploaded their extended abstracts (length of 1000 to 1500 words, two optional images, 5 to 10 references) by 1st of February 2017; each abstract was evaluated anonymously.

Altogether, we received 309 extended abstracts from 46 different authors’ countries, shortly after 5 were withdrawn. Each extended abstract had three blinded peer reviews so 912 reviews were accomplished in a short time and 165 papers were accepted for full paper submission, 21 of these were withdrawn and eventually 154 papers were published in eCAADe 2017 Proceedings.

Let us express our very grateful appreciations for all the 132 reviewers from all over the world for their constructive and thorough comments for each author. A special thanks to reviewers who spent their time to review more than 8 extended abstracts – Joachim Kieferle and Anand Bhatt - not to mention members of “Joker Reviewers’ Team”: Stefano Cursi, Salma Elahmar,
Paolo Fiamma, Silvia Gargaro, Gianluigi Loffreda, Wolfgang E. Lorenz, Davide Simeone, Gabriel Wurzer and me that were able to review abstracts during the last days to accomplish missing reviews on time.

We thank and congratulate all authors for their hard work and support on using the ProceeDings tool and finalizing their full papers carefully in time. In this last phase of editing full papers we want to thank for his “extra-ordinary” work Gabriel Wurzer, the Master of the ProceeDings and Wolfgang E. Lorenz and Ugo Maria Coraglia, who with high sense of responsibility worked with us and to successfully produce high quality proceedings.

We also continued the practice started in eCAADe 2015 conference in Vienna of having all the session chairs to give prospective comments of the papers and to evoke the discourse at early stage between the author and session chair for the 27 sessions of the conference. All the session chairs also participated the peer review process of the extended abstracts.

We owe great gratitude to the session chairs for their commitment and their long-term contribution to the process until the final paper presentations.

We thank the keynote speakers and their contribution of writing the keynote papers concerning their lecture themes: Gianluca Peluffo, Chair in Exhibition Design and Art & Architecture, IULM - International University of Language and Media; John Gero, Research Prof. in Computer Science and Architecture, University of North Carolina at Charlotte and Krasnow Institute for Advanced Study George Mason University; and Gernot Riether, Director of School of Architecture, NJIT – New Jersey Institute of Technology, Editor of DCA Journal.

Workshops are part of eCAADe conferences, so we thank all the organizers for their workshop and for their contribution of short papers (non-peer reviewed) about the contents of their own workshop.

We are also grateful to Wolfgang Dokonal and the eCAADe Council for organizing the traditional PhD workshop for young researchers and supporting the grant winners with a subsidy for traveling to Rome.

We recovered an old tradition of previous eCAADe Conferences bringing poster session to life again, so during the conference we had 4 free lectures on interesting themes.

This year for the first time we launch an international competition linked to the Conference, the “eCAADe2017 Logo Contest” that helped in disseminate the spirit and values of eCAADe in new areas. We thank the International Jury that was made up by Antonino Saggio (President, Chair in Information Technology applied to Architecture and Urban and Architectural design), Eleonora Fiorani (Vice president, Chair in Cultural Anthropology and Sociology of Innovation),
Henri Achten (former eCAADe President, Chair in *Computer Aided Architectural Design*), Maria Argenti (Chair in *Architectural Composition* and Editor in chief of *Rassegna di Architettura e Urbanistica*), and Antonio Fioravanti (Chair in *Architectural Engineering*). Two Winners and three Honourable mentions were awarded (see on website https://www.daadgroup.org/result/).

We would like to express our gratitude for the administrative help in organizing this conference to eCAADe council and especially Nele De Meyere that has provided us valuable input and lessons learned from past conferences.

We have also had support from DaaDgroup for managing the conference services, ranging from the registration process to the actual on-site registration services. A big thank you goes to PhD students Ugo Maria Coraglia and Francesco Rossini for their extra-work in critical situations.

Thanks to the sponsors we were enabled to organize an international conference as eCAADe is. Financial supports, apart Sapienza University of Rome, was generously provided by A-Sapiens, AT Advanced Technologies, Autodesk; 3TI Progetti and Bentley Systems International Ltd. Technical support was provided by Epson Italia, Gangemi Editore, Geores, it solution, Noumena and ProceeDings.

We wish to also thank Gangemi Editore in person of Giuseppe and Fabio Gangemi for their very fast and accurate printing process and the high quality of both volumes.

As a special form of sponsorship, all members of the Organizing Team and students of Architecture-Building Engineering M. Course that donated their time to help prepare and organize this conference. Thank you all !!!

Rome, 1\textsuperscript{st} September 2017

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\textit{Angelo L.C. Ciribini, Gabriele Novembri and Armando Trento}

Conference Vice-chairs
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Gaudíean Flowers over Barcelona / Architecture for Meetings in VR
Marketa Gebrian, Czech Technical University in Prague / MOLAB / FLO\|W, Czech Republic

The virtual environment has a growing potential for an emergence of a new public space. We think that space should be designed by architects.

Virtual space and architecture can provide endless design possibilities and they are not limited by statics or structural and gravity conditions. We were testing the virtual architectural structures growing from 3D models of cities that we have generated, but we also used the model of Barcelona city blocks. Barcelona utopian urban blocks designed by Ildefons Cerdà provide many green courtyards, where our virtual structures are growing. We developed the idea even further, we would attach our structures to all green areas in the city, like parks, trees on the streets, etc.

We suggested simulation of the environments that have public chat rooms, which exist only when they are used. Together they form the new intangible layer of the city.

Size Matters: New possibilities for architectural design through large-scale 3D printing
Heike Matcha, Ante Ljubas and Andreas Scholl, Aachen School of Architecture, Germany

As the size of 3D-printable objects has been ever increasing, we investigate new possibilities for architectural design such obtained in experimental student design projects, conducted with a BigRep ONE v3 printer with a construction space of 1 cubic meter.

We see 5 implications of 3D printing with construction spaces of 1 cubic meter or more: (i) Rapid 1:1 prototype loops, (ii) Integration of different functions into one building element, (iii) the possibility to fabricate buildings or parts of buildings from one piece, (iv) Custom materials, and (v) increased On-site-Production.

So far, we have been focusing on aspects (i) - (iii) with 2 design projects where we develop: - Wall elements that are optimized for structural support while integrating additional functionalities like various ductwork internally and furniture-like possibilities externally. - A café bar counter prototype consisting of packed tubes with complex, hyperbolical geometries optimizing stability while providing storage space.

Our course is set up as a series of iterative loops, each consisting of brief study and then quick - digital - design in parametrized 3D (Rhino/Grasshopper) and production of 3D prototypes, be they 1:1 prototypes or scale models.
Spectral Geometries
Jose Algeciras Rodriguez, Burckhardt+Partner AG, Germany

Spectral Geometries explores design processes laying on the use of nonlinear procedures, through the use of Artificial Neural Network (ANN). Specifically Self-Organizing Maps (SOMs) are used in this project to produce geometry.

The SOM may be described formally as a nonlinear, ordered, smooth mapping of high-dimensional input data manifolds onto the elements of a regular, low-dimensional array (Kohonen 1982). The mapping process consists of a transfer of information from an input set of vectors to an output set of neurons. The input set is comprised of models of known art and architectural pieces, that are designed according to certain rules, proportions, ratios or any other form generator. In traditional (human) learning, knowing the details of the generative process would allow craftsmen to produce or reproduce a specific design, becoming crucial for the generation of form. The stochastic functioning of SOMs, based on random functions, will produce as a result an object that will perform, at a certain extent, as the original input object and source of information, regardless any fundamental generative procedure.

Topology and neighborhood between neurons, allow for sharing information between them. Hybrid objects emerge after neuron adaptation, generating a spectrum of geometries with mixed characteristics from the models.

JOIN IT: 3D Print in Design
Kateřina Nováková and Šimon Prokop, Czech Technical University in Prague, Czech Republic

The poster is focused on implementation of 3D printing techniques in the context of the architectural design process. It describes a case study of architectural design studio having 3D printed objects/joints as a semestral theme. The task was to design a “big” statue that celebrates additive manufacturing in architecture.
DIGITAL HERITAGE
Causes and effects

Methodologies used in digitalization of architectural-urban heritage

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Since some time already, digital reconstructions in architecture, urbanism and archaeology are gradually switching from describing built heritage as a collection of static and unchangeable entities towards more compound and explicit presentation and knowledge management techniques. This includes for instance data management and multimedia systems, immersive environments or semantic information modelling such as GIS (Geospatial Information Systems), BIM (Building Information Modeling) or HBIM (Historic Building Information Modeling). Graphical user interfaces, interaction and usability have become an essential part of produced reconstructions. This shift in terms of dissemination of an architectural and urban heritage that is supposed to increase the social awareness and participation should be structured in a way that enables recipients originating from different backgrounds to grasp information pertaining to almost any knowledge domain, allowing for self-exploration and interpretation of presented knowledge. This paper discusses important nodes of the reconstruction process in the spirit of informative modelling that are characteristic for any possible approach towards conscious heritage representations.

Keywords: Informative modelling, Spatio-temporal modelling, Cultural heritage

CONTEXT

In the field of architectural heritage the objects that researchers are striving to reconstruct are never fully known. The incontestable fact is that they do have a rich and usually complex history, abundant with evolutions and changes. These changes are usually understood only in terms of their topology and morphology as the physical appearance stresses the process. Yet the alteration does not affect only the artefacts materiality. Immaterial aspects of the site are affected by time passage and events not less. Elusive cause and effect factors that were influencing the entities determining their shape, condition, location or characteristics should be taken into consideration as well. There is a strong need to preserve space for uncertainty as well, as hardly any heritage unit is free of doubts emerging from, for instance, heterogeneous, dubious, incomplete or even contradictory historical documentation - if any in the first place. Furthermore urban, as well as architectural entities are never constant in time as they tend to undergo constant and unavoidable transformations of different types.
throughout their lifespan. These events in combination with plurality of factors that may seem divergent or even unrelated at the first glimpse, shape and form the buildings or whole urban complexes through their lifecycles. Moreover, the typological difference between architectural and urban entities, which results from the fact that the urban environment can be perceived as a container for multiple architectural components, awakens the awareness of different granularities - or scales - of aforementioned causative factors and events. Better or worse preserved remnants of architectural past encountered nowadays are therefore resultants of all these processes that had occurred. Amalgam of these factors can be eventually perceived as the construct of what could be called the meaning of the built artefact.

INFORMATIVE MODELLING
Complex, multi-layered network of intersecting elements and types characterizing architectural artefact requires adaptive representation model. In the domain of architectural heritage gathering, analysing, structuring and understanding various types of source documentation is the fundamental part of the process, whereas visualizing and retrieving information is the paramount aim of each. Therefore information visualization - where the 3D representation of an architectural entity serves only as a perceptive tool and does not constitute the final result of the reconstruction process - seems to more accurately fit in the general idea. This was summed up precisely by E. R. Tufte and J. Bertin who said respectively that: “We envision information in order to reason about, communicate, document and preserve that knowledge” (E.R. Tufte 1997) and “…a graphic is never an end in itself: it is a moment in, a process of decision making…” (J. Bertin 1967). This is already the basis of the interdisciplinary methodological approach - or concept - of an informative modelling in which the representation of artefacts does not claim veracity, but supports dynamic information retrieval and visualisation, reasoning and cognition. Abstraction (the information visualisation legacy) and figuration (the architectural representation legacy) are integrated as alternative/mixable types of representation, allowing partial knowledge to be communicated and important notions in historic sciences such as data uncertainty to be conveyed graphically. Though artefacts’ accurate and precise representation is not determined, present advancing data-processing technologies allow for more comprehensive and massive data acquisition from heritage sites. These become necessary in order to describe, understand and support built heritage. Moreover developing software technology allows to combine models acquired during high definition surveys with the informative layers, as well as to adopt them for logical re-use in various, process depending scenarios. Nevertheless the veracity of the model remains still in question as the dense point clouds need to be discretised into more efficient and reuse-ready meshes or polygons. This in turn demands simplification of the acquired data set, which results in some level of divergence from the original. (Figure 1) Authenticity of the model is however, out of the question when we discuss models constructed solely on the basis of existing historic documentation, which fundamentally must be treated with caution and cannot be taken for granted.
**BI-DIRECTIONALITY**

With progressive advancement of information technology more and more options to store, manage and present acquired datasets are available for the researchers. Nevertheless it occurs to the author that it is currently possible to determine two particular directions in which the process of digitizing built heritage is heading. The foundation for this specific bi-directionality lays on the one hand in the development of BIM theory into practice which results - from a CAD (Computer Aided Design) point of view - in the release of dedicated specific software such as Autodesk Revit or Graphisoft Archicad, as well as proliferation of its assumptions through diverse groups of interests such as architects, archaeologists, historians - to name a few; and on the other hand in the need to search for and create custom solutions dedicated to particular problems or issues, which is strongly encouraged and motivated with the spread and popularisation of programming languages and highly advanced frameworks such as Unity 5 or Unreal 4 engines which from some time already are no longer reserved only for a top-end professionals or AAA development studios. While both approaches are conceptually different they try to serve the same purpose: to gather, manage and disseminate the knowledge about built heritage.

**OUTSET**

Regardless of which approach is to be chosen finally, there are still some strategic decisions to be made and steps to be fulfilled initially. This article aims to describe them in more detail. It highlights three factors that are fundamental for the reliable organization of such a complex multidimensional reconstruction model: addressing temporal issues, spatio-temporal representation of uncertainty in data, hypotheses and a spatial organization of the model to allow diverse usability. Source data handling is not going to be included in this paper as this particular matter rather depends on their quality, quantity, type and specific purpose of undertaken reconstruction process. Therefore its management and treatment may vary and be performed in too many different ways using multiple approaches exclusively or in parallel.

**THE OCCURRENCE OF CHANGE**

As it was already mentioned, every built entity changes during its lifespan. Number of possible transformations it could go through are vast, though it is possible to distinguish most relevant: buildings are built, destroyed, rebuilt, they may be extended, attached to another entity or divided into several parts. Eventually they can peacefully degrade through the whole life-cycle. Last but not least it can occur that the building would be totally or partially erased and rebuild in the same or different location (e.g. city of Warsaw after II World War). This statement makes apparent that whenever there is a change in space (spatial alteration) it never happens instantly but instead implies that some time passed from the beginning of transformation to its end. Undeniably time plays an important role in the description of change. Even more when we take into consideration that not only spatial form of the building is changing but also its relationship with surrounding entities or its particular attributes. Reassuming, the change can affect objects morphology, topology or attribute definition and it never lacks a temporal dimension. (Figure 2) The time of each alter-
ation is, as a matter of fact, never constant. Each type of change lasts different amount of time. For example, the demolition of the building can take just a few days, while its construction could last for years or even decades. This implies that time of the event occurrence is therefore scalable, which means that temporal incidents have different granularities. Such complex spatio-temporal transformation system occurring on different - usually nested - levels with various scales need a proper and suitable data management system. Pelekis (Pelekis et al. 2004) described and compared eleven ready-to-adopt database models with various levels of complexity, each accurate for certain tasks and aims. The question of which model to choose relies mostly on the defined goal of the undertaken reconstruction, its intricacy, query structure and operations it should be capable to perform simultaneously. Whereas some models are simple and operate on the snapshot or time-stamping based structure (Figure 3), others reflect quite elaborated mechanisms derived from graph theory (Figure 4) or Object Oriented Programming (Figure 5).

**UNCERTAINTY IS WHAT REALLY MATTERS**

In the domain of digital heritage a lot of effort is put to create accurate and precise digital reconstruction models from available spatial data, preferably using Terrestrial Laser Scanning or photogrammetry techniques supported by historic documentation. Simultaneously it limits the scope of the reconstruction to the digitalisation of only what is left or, perchance, to particular states of the building to which available documentation does not arouse any level of uncertainty or suspicion. However, in the field of architectural heritage, more than anywhere else, due to its unstable and long-term character, not only spatial, but temporal aspects need to be taken into consideration. Traces in form of historic documentation stored in archives (if there are any in the first place!) are rarely satisfying the researchers. Heterogeneous, dubious, incomplete or even contradictory documentation leaves many question marks and door open for hypothesis and introduces the possibility of uncertainty concerning spatial, as well as temporal or even attributable aspects.

Spatial uncertainty results usually from lack of material on which the researcher could base the reconstruction. Historic sites were rarely, or never, surveyed in the past when no one would expect them to be historic one day. Most of the archived material consists usually of crude designs and drawings, but almost never of post-construction surveys. This
makes researchers working with almost hypothetic source documentation, as the changes made on-site during construction of the building were, with the high level of probability, never marked or described. Researchers are usually left with pieces of information on which they are supposed to build their proverbial church. As it is impossible to find just one ideal solution that would describe changing building morphology it is crucial to refer to the hypothesis based on reliable sources not necessarily concerning particular entity but at least similar from the same time period. Temporal uncertainty, on the other hand, is even more complex and can be described with several factors. First, and probably one of the most important, is the problem of dating exactness, which reminds instantly about time scale and granularity. Events which took place in XIXth century, in year 1845, between the year 1897 - 1909 denote different temporal weights. If the scale is the century - is there a possibility to define the year precisely? Or if the scale is the year - is it possible to define the month? This imprecisions in dating description causes lack of cohesion and presents first important technical problem as well - which constitutes the timeline and event positioning. Another trouble arises with the interpretation of the heritage sites. The past is usually interpreted by different kinds of historians (the historians, art or architecture historians, etc.) on the basis of available historic sources. This can undoubtedly lead to a formulation of various and divergent interpretations - or rather - hypotheses concerning particular entity, site, event or period of occurrence. As a result each formulated opinion is laden with some level of uncertainty, even despite the purest intentions of the interpreters, which in turn affects the entity and possibly distorts its spatio-temporal change pattern deviating it from unfortunately unknown reality. Realising the potential of the stratified uncertainty could leave us with the thought that the only real and certain element of spatio-temporal reconstruction chain is the existing residue of an object and that every attempt to model its past state is resulting in creating just a hypothesis.

**STRUCTURAL SYSTEMATICS**

To entirely utilize the potential of building entities for the sake of performed reconstruction it is necessary to classify them in order to withdraw maximum spatial information from general data. It is possible to distinguish three phases of such ordination. First one assumes classification according to the adopted point of view - which means distinguishing elements according to their e.g. function or material they are composed of, as well as to other criteria such as a time of erection or style they were built in, etc. Second differentiates elements according to their morphological decomposition in the life-cycle process. Eventually, in the third phase associations among concepts are created and visualized. Working with historic structures requires constant reasoning about temporal changes. This in turn necessitates proper model structuring and reorganization which leads to the question of its morphology as well as its attributes and spatial relationships with surrounding entities. Recalled earlier, the concept of granularity, has a strong influence not only in case of temporal dimension but spatial and structural as well. Each building undergoes changes, but each one is a composition of parts which, as a matter of fact, also undergo change. Accordingly, this works in opposite direction: a building is just an element of a larger group of buildings which in turn constructs a neighbourhood, district or town. Therefore it is possible to introduce various levels of spatial granularity as well. Defining this hierarchy is important, as every element or entity would have its own specific attributes, sometimes utterly unique, sometimes shared with others. In general it is possible to organize objects in three nested levels: groups - agglomerating building complexes, single buildings and their major components; entities - corresponding to the functional and temporal model divisions; references - representing some specific aspects of extracted entities. This peculiar morphological inception could be than limited by setting the minimum and maximum level of detail that seems sufficient for the purpose of performed reconstruction.
CONCLUSION
The society of information we are currently experiencing, demands an informative, scientific approach to each and every aspect of life. This is particularly valid and important in the domain of architectural heritage, which is built on the knowledge of the past. Therefore the number of methodologies or approaches to the matter of architectural-urban reconstruction processes seems fairly limited, as no matter what, any of them would revolve around the idea of creating a knowledge management system concerning the heritage entity. Research performed for this paper revealed that all analysed case studies did encounter particular problems while conceptualizing systematic workflow. Spatio-temporal data management, insufficient sources that provoke and fuel uncertainties related to spatial, temporal, as well as attribute layers, handling of existing hypotheses are mostly reported. Therefore the gravity centre of this article was moved a bit from depicting methodologies towards describing these specific challenging nodes that in the same time determine the structure of informative reconstruction model. Description and potential guidelines for handling such cases were formed on the basis of available literature. Application of these nodes in the process of reconstructing architectural or urban entities of different scales seem valid and critical for implementation either in BIM driven reconstruction models or custom-made solutions.

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Raising Awareness for Digital Heritage through Serious Game

The Teos of Dionysos

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In this study, the serious game is conceptualized as a digital medium to convert archaeological knowledge into playable interactions via a case study in the ancient city of Teos. The Teos of Dionysos Game is a digital platform that allows players without specialist computer skills to explore the archaeological knowledge and experience an ancient urban setup. A mythological story about the God Dionysos has been verbally and visually transcribed and adapted for four distinctive settings of this ancient site. The familiar realm of an interactive space, navigated by intuitive behaviours in a game setting, conveys archaeological data, allowing players to build an empathic understanding of ancient architecture. Diverse stakeholders have already tested a mobile game prototype in a workshop, which explored whether those without a prior historical background can advance their existing knowledge through activities that aim at providing entertainment.

Keywords: digital heritage, serious game, puzzle, mobile game, public awareness

INTRODUCTION
Heritage is defined as something of value that is, or should be, passed from generation to generation. Digital heritage is “created digitally, or converted into digital form, from existing analogue resources (National Library of Australia 2003, p.13). Today, the terms “virtual heritage”, “digital cultural heritage” or “new heritage” are used interchangeably across fields, and represent a common theme in different research fields, academic programs, conferences and workshops. A similar converging trend can be seen in traditional arts, design, humanities and social sciences, which are all increasingly moving towards large-scale digitization. A growing reservoir of data is accumulating in the digital field via new digital tools. New concepts of digital preservation have
progressively emerged from a need to acquire, store, research, communicate and exhibit cultural heritage data. Although the new possibilities provided by digital technologies are nurturing heritage studies, it is also important to make effective use of these technologies to convey this data in a comprehensible way to the various population profiles.

Video games have a twofold relation with digital cultural heritage. First, video games are cultural forms of digital culture, and thus themselves are a part of digital heritage to be preserved (Barbier, 2014; Barwick et al., 2011). Second, videogames are an emerging medium for disseminating cultural heritage. Videogames provide novel possibilities for the presentation of archaeological research to alternative audiences, allowing gamers to interact with a designed set up that immerses them in a digitally modelled environment. An archaeological research-based game environment immerses the user in an architectural environment, providing a virtual sensory experience that enables the processing and comprehension of the architectural and archaeological information. In our case, video games enhance the expressive abilities of archaeologist, making their research comprehensible and incorporating multiple perspectives and alternative narratives. 3D representation of heritage has been widely used since the videogame technology was introduced into the field of archaeology. Although historical references have been widely used in various games (i.e. Apotheon, Assassin's Creed, etc...), ‘disneyfication’ has been strongly criticised in the field of archaeology. Thus, it is very important to ensure correct representation of the archaeological and architectural information, as well as the historical accuracy of the props used in game design when attempting to utilize video games as an alternative narrative medium for disseminating archaeological information at a popular level. However, as well as maintaining accuracy, it is also important to build a game that can engage people, and encourages them to learn through experiencing ancient problems and their solutions, and empathizing with those that faced them (Gee, 2009).

In this respect, this serious game represents a pedagogical tool for testing learning outcomes related to archaeological and historical knowledge for interested non-professionals. This paper shows the potential of utilising video game research in the preservation of cultural heritage through the design, implementation and testing of the game the Teos of Dionysos. This effort also reveals a community of practice deeply involved in digital-making.

PROBLEM DEFINITION
The Digital revolution allowed access to unlimited information, with boundless availability, and yet much of this information seems to have questionable coherence when compared to traditional sources. The new generation, namely the millennials and post-millennials, are accustomed to building a separate virtual existence in the digital world. Therefore, their attention and interests have been changed by mutual global interactions as an alternative to books and other written sources of information, which nevertheless remain as a conventional and reliable reservoir of knowledge. This pedagogical challenge is also an opportunity for new methods of creating and distributing accumulated/novel knowledge. We believe that game-based learning (GBL) can significantly enhance learning for a multitude of users from varied educational backgrounds in diverse application domains (Aydin et al., 2016, Holland et al., 2016; Mortara et al., 2014). In the heritage domain, an effective serious game is often characterised as having three different forms: the static setup in a public space such as a museum, the augmented visit at the actual heritage site, and the standalone application for mobile devices.

In this study, the serious game is conceptualized as a digital medium to convert archaeological knowledge into playable interactions via a case study set in the ancient city of Teos, one of the most important cities of Ionia, at various stages of occupation. This paper presents and discusses the initial stage of the Digital Teos Project, an interdisciplinary research project which investigates and digitally an-
imates the excavation area, through a static public setup at the excavation site, an augmented immersive revisit through AR/VR devices, and a mobile game application (Figure 1). Within the scope of this paper, our focus is on a mobile platform puzzle game entitled the Teos of Dionysos. The project begins with the translation of existing excavation data into virtual environments, whereby the archaeological area and buildings are modelled and presented through digital techniques. This is a preparation for the design of a serious gaming environment, as well as a digital support for ongoing archaeological work. Concurrent to the storyline of the proposed game, level design follows a series of parametric and modular layers, in the form of challenging puzzles, exploring architectural construction techniques in a detailed and historically accurate way. These elements are designed and abstracted following the language of ancient architecture, highlighting a shape grammar as a coherent and holistic form generation tool (Coutinho, 2011). As well as providing enjoyment, the game arouses curiosity with educational and instructive aspects, i.e. a multidimensional objective of raising awareness of the features of an archaeological site, its historical background and associated mythological stories.

LITERATURE REVIEW

This is a collaborative approach involving historical scholarship and video games; the former provides material for the games, while the latter provides a new representation medium for the heritage.

Regarding the former, it is quite common for games to attempt to reconstruct buildings and cities of the past, corresponding to the walkthrough of the game. Apart from a few notable exceptions, such as Civilization Series (1991), The Age of Empires Series (1998) or The Assassin's Creed Series (2007), most widely-known games based on historical events are designed with only limited or selective contributions from archaeologists and historians (Wainwright, 2014). The resulting lack of historical and structural coherence tends to lead to chronological errors, inaccurate representations or inaccurate perceptions of the societies.

As an example, Apotheon, a platform game in 2015 by AlienTrap, has a setting in mythological ancient Greece. The design language of the game is inspired by the black figure pottery style of classical Greece. By doing so, the player becomes a character as portrayed on an ancient Greek vase while moving through different mythological scenarios. While it is important to acknowledge a number of chronological and mythological inaccuracies, the developers have nevertheless created a setting based on ancient material culture, bringing the sensorial experience of this landscape to wider audience in a unique way [3].

Even though formal historical scholarship provides the core material source for the games, these games can become the digital source of reference for a wide and non-specialist audience. The practice of using games to increase consumer engagement in Museums or experimental archaeology is a contemporary global trend. For instance, Tate Gallery has launched TATE Worlds in 2015. The application facilitates the “Minecraft” gaming platform to create a series of 3D maps based on a number of key artworks. Players can enter the galleries and step into the paintings and works of art to explore the worlds behind the paintings [2]. As another example, Morgan (2009) has rebuilt Catalhoyuk in digital environment to investigate a number of topics. One of these concerned the reconstruction of ovens found extensively on the site. Morgan was able to experiment with these ovens and buildings in “Second Life” in order to test the effects of smoke on living conditions (Morgan, 2009). Similarly, “The Rome Reborn Project” employs hypothetical reconstructions of Rome to test the validity of the virtual ancient city. The serious game “Roma Nova” investigates the feasibility of using this technology to support archaeological exploration, leading to historically accurate descriptions/understandings of societal aspects of an Ancient Roman life (Anderson et al., 2010). Besides discussing the serious game platform, which has non-entertainment
purposes, Anderson et al. (2010) present 3D content creation pipelines which demonstrate how information technology can play a key role in archaeological analysis. However, expanding heritage awareness among the general public remains an issue for exploration, as it is not adequately addressed or demonstrated in the above mentioned examples.

**METHODOLOGY**

In the effort of developing the Teos of Dionysos Game, an interdisciplinary team of designers, architectural historians and engineers has combined resources to design and implement a mobile platform game based on a historical site (Figure 2). Using virtual reconstructions of the buildings and sites and archaeological data, the game focuses on allowing the user to play by solving puzzles based on ancient mechanics in a historical setup. Exploiting the mythological story of the God Dionysos, it combines an atmosphere mystery with the enjoyment of the game. In this paper, the theoretical discussion is supported by an actual case study, a description of a workshop in which diverse stakeholders tested a mobile game prototype. The workshop explored whether people without a prior historical background could advance their existing knowl-
edge through activities aimed at enjoyment. The game is an initial step of the multi-layered Digital Teos project, aiming to utilize digital technologies to convert specialist archaeological knowledge into a form that can be experienced and comprehended by the non-expert.

The game provides tools and methods for creating an accurate reconstruction of a historical site, enabling the re-enactment of the spatial experience of the original dwellers’ daily life. This execution followed four concurrent steps.

First, the architectural setup was reconstructed based on orthographic drawings of the archaeological remains, restitution drawings, rules and grammar of the building elements. The historical buildings were translated into a shape grammar to create a modular system of sprite sheets to be used in all layers of the game. To achieve a more holistic approach in reconstructing this historical era, further research was conducted to gather data on clothing, lifestyles, tool mechanics, material details and landscape.

Second, the game was given a mythological narrative in order to develop a gameplay. A mythological story of the God Dionysos was verbally and visually transcribed and adapted on four distinctive settings of the ancient site: The temple of Dionysos, the theatre, the cistern and the south harbour. Gameplay enables the player to visit the city as an ancient citizen. The familiar realm of an interactive space navigated by intuitive behaviours of a game setting allows the player to build an empathic understanding of ancient architectural information through the directly interacting with the archaeological data. In this way, unfamiliar archaeological knowledge and the inevitable steep learning curve it requires is transformed, making the information more attractive and easier to digest.

Third, a distinctive visual language was designed and produced by a team of graphic designers. The team created sprite sheets of the built and natural environment, furniture, ornaments and artefacts, as well as typefaces for the visual language components of the game.

Finally, two senior software engineering students organized the programming phase with concurrent feedbacks and revisions. They guided the designers on the particular requirements for game assets, i.e. avatar and game setup, and then compiled these assets in the Unity Game Engine. The programmed scripts gave life to the game assets, determined the game mechanics and created the overall user experience.

The development team used the Super Tilemap Editor [1] tool to create the level designs. This tool enables a dialogue between the level designer with no prior programming knowledge and the developers. First, the non-programmer level designer in the team drew the levels by hand, then, guided by the development team, this tool was utilized to decide the locations of platforms, props, pickable items, mechanical structures and other game elements to create the levels. The development team created custom scripts to develop the Dionysos character as the game avatar controlled by user. In addition to standard actions, such as walking and jumping, the avatar can also shapeshift and become a leopard, a bull or a dolphin, all of which have different abilities to solve the puzzles presented in the game (Figure 3).

PLAYTESTING AND SURVEY
We conducted playtest sessions in May 2017 at the Faculty of Fine Arts and Design, at Izmir University of Economics with 14 (10 female) undergraduate students. Participants played the whole game on tablets and mobile devices. We interviewed participants about their experience and asked them to complete a survey with nine questions about their gaming backgrounds, seven about their background related to archaeology and games, and 14 general questions about the archaeological information delivered in the game.

The majority of the respondents (92%) stated that they play video games. Surprisingly, female participants were more interested in playing the game and filling the questionnaire, with 71% female. Participants had a fairly uniform distribution in terms
of the year of their undergraduate studies, and time spent on video games, which ranged from zero to over 14 hours per week. Overall, the respondents covered a wide spectrum from hard-core gamers to more casual players, some having several pieces of dedicated gaming equipment (dedicated PCs or laptops, consoles, etc.), while others mainly played browser or smartphone games. Participants reported playing a variety of games, i.e., roleplay games, action adventure, simulation, racing, etc., with puzzle games being the most common genre. They stated that they found the most enjoyable aspects of games to be the character, the story and the graphics.

When asked about archaeology and games, around one fifth (21.4%) reported playing archaeology-related game. When it comes to the inclusion of archaeological aspects in a game, the majority indicated that they did not find archaeology very enjoyable, and they did not regard games as representative of actual archaeology. One even described archaeology as being as “boring as all science”. One comment was that archaeology, based on facts, is at odds with games, usually based on fiction. It appears that many gamers seek to play games for fun, and regard the gamification of archaeology as unnecessary. One of the participants even complained that archaeology was already overused in games. These responses suggested that serious games related to archaeology may face resistance and lack of interest from gamers, unless the game is generally appealing and enjoyable.

Despite their general lack of interest in the area, participants reported enjoying our game due to its appealing graphics, gameplay and puzzles. Furthermore, their survey responses show evidence of learning archaeological information in the process. The third part of our survey had general knowledge questions related to concepts that the game aimed to teach. The game delivered such information through inscriptions that popped up an information panel when the player walked near, and through visual references such as level elements and backgrounds. A high percentage of correct answers were provided to these questions. For 12 out of the 14 questions, there were a choice of four answers. For all except one, the rate of correct answers was over 50%. This may indicate that while participants did not have a strong interest in archaeology, they learned a certain amount of archaeological information. This validates the idea that serious games may be a viable platform for teaching archaeological knowledge and raising awareness about archaeology.
CONCLUSION
This paper discusses the serious game as a pedagogical tool for preserving, distributing and sharing knowledge on heritage through an alternative digital medium for non-familiar users. It provides a description of an experimental phase of the Teos of Dionysos Game, in which historical information acquired from archaeologists, and from mythological stories, was converted into game graphics using a scenario developed by game-designers. The overall design pipeline was converted into a mobile platform game by developers. There are three significant outcomes of this project, yet to be explored. Firstly, the serious game, we believe, is an exciting medium for the location of and the exploration of original historical and archaeological sites and associated stories. Second, it is a valuable digital tool for preservation and representation, which, by nature, brings the opportunity to reach a mass global audience. Finally, as a future research direction for designers and programmers interested in human-digital interaction, it would be valuable to test the experience with various user groups from diverse cultural backgrounds.

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From TSL survey to HBIM, issues on survey and information modeling implementation for the built heritage

The case study of the Temple di Bacco Ravello

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The research presents an application of HBIM to the recovery process and design, which allows to highlight some potentialities and criticalities of what has become an important instrument in the documentation and conservation of architectural heritage. The object of the research is the Temple di Bacco, built by Lord Girmthorpe as his final resting place and located within the gardens of Villa Cimbrone, Ravello (SA). The survey has presented several difficulties due to the particular configuration of the site, very steep, with very limited space around the object. If on the one hand the TLS obvious to the lack of edges of cylindrical objects, on the other hand it poses problems for the tangency of the scan points. The Scan to BIM methodology has proven to be effective and has allowed to overcome the difficulties associated with the conformation of the artefact and of the site, in the study of the analyzed object. In conclusion, some assessments and results are reported, aimed at sharing and defining strategies and methodologies of scientific validity regarding the application of the HBIM model to a process of recovery and consolidation of an existing building object.

Keywords: BIM, HBIM, Built Heritage, TLS, Scan to BIM

INTRODUCTION

The digital storage technologies, analysis and management of information have found in the three-dimensional models the substrate on which to develop their potential (Centofanti et al., 2016) and HBIM (Heritage Building Information Modeling) is now an important tool in the documentation and conservation of architectural heritage (Murphy 2009, Chiarabrando, 2016). The evolution of the BIM process, applied to the built heritage, has brought with it a wide spectrum of issues ranging from the development of the selection and reception capacity of the large data sets provided by the digital surveys, to be based on model building, to the reaction of family libraries of objects for the existing (based, for example, on historical manuals) (Murphy 2011, Logothesis et al 2015), to the inclusion of information in the parametric model related to the characteristics of an already built object (such as materials, age of construction, state of conservation, state of progress of degradation) (Apollonio, Gaiani & Zheng, 2012). The research presented is placed in this field of investigation and
was divided into several phases: historical and documentary study; a first campaign for the planning and the scheduling of direct and instrumental survey; an integrated survey campaign (TLS, direct surveys, other instrumental surveys); a non-destructive testing campaign for the mechanical characterization of materials and finally the implementation of the BIM model for the project of recovery and consolidation.

The object of the research is the Temple di Bacco, built by Lord Girmthorpe as his final resting place and located within the gardens of Villa Cimbrone, Ravello (SA) - Italy (Fig.1).

**STATE OF ART**

**AD BIM, AS BIM, HBIM**

The basic difference in the use of BIM between new design and recovery of the existing buildings is well synthesized by Pătrăucean et al. 2015, which define the two categories of AD BIM (as-designed BIM) and AB BIM (as-built BIM): while the creation of an AD BIM (ie BIMs generated in the design of a building) is a simple process that becomes increasingly common, the generation of an AB BIM (ie BIM models that reflect a structure in its conditions at a given historical moment) is a challenge, but also a process required for building constructions not originally equipped with a BIM project, in which as-built conditions differ from those initially designed. The affinities between AB BIM and HBIM are therefore evident and numerous. Creating an AB BIM requires two main steps: collecting data and capturing current conditions in the first place, and then modeling the acquired data. The field of 3D reconstruction, related to laser scanning techniques, has filled the technological gap between the capabilities of AD BIM and AB BIM, which also includes the specificity of HBIM, providing tools for generating three-

![Figure 1](image_url)

Location of the Temple of Bacco, inside Villa Cimbrone, Ravello (SA).
dimensional models compliant with existing condition of buildings (Pâtrăucean et al. 2015). While on the one hand, BIM helps coordinate the various figures of the building process by introducing its expertise in models (distinct in architectural, structural and plant engineering) to plan their construction and to calculate the quantities for the construction site, on the other hand instead, the specificity of HBIM focuses on the importance of defining the state of conservation of sites and materials to better plan conscious recovery interventions (Garagnani 2015).

**Scan to BIM**

The innovative feature of the process chain attributes a central role to the Scan to BIM methodology (Catugno et al., 2016): namely the integration of survey data using methods that include the use of terrestrial laser scanner (TLS) and digital photogrammetry in an exportable model in a BIM software. These elements are becoming a standard in the construction practice in heritage conservation and management of structures within a wide range of different sectors (Laing et al., 2015). The laser scanning technology (TLS) has thus emerged as a useful tool to document the existing conditions of the existing buildings, and one of the main applications concerns those belonging to cultural heritage (Shanbari et al. 2016). The use of TLS allows the development of point cloud models built in one stage of the life cycle of a building, with great precision and speed. The mass of potentially acquirable data with the laser scanner technology is such as to make complex the editing, making it necessary for this a selection of the elements of the point cloud, which presents itself as uncritical, targeted to the purposes defined a priori. In addition to laser scanning, there are emerging technologies that aim to integrate, and in some cases replace, laser scanning techniques with TLS. The techniques most widely used today include the use of photogrammetry (Shanbari et al. 2016), through the detection of 3D measurements from 2D images. Through the combination of thousands of these measures it is possible to generate a 3D model and constitute a standard output of photogrammetry operations. In recent years, many companies have developed methods and software that convert 2D images to 3D point clouds or mesh models. Golparvar-Fard et al. (2012), for example, used daily state-of-the-art construction photos as part of an automated monitoring system, demonstrating the ability to use site images to develop an as-built model that can then be implemented in the BIM process. Obviously, this particular technique does not have a direct impact on the HBIM scope, but it may have some interesting implications, alongside a first complete survey with LTS, a sequence of images, shot at defined time intervals, for monitoring the building. However, the models and point clouds developed by using traditional photogrammetric methods are linked to the available image quality and can not match the pinpoint accuracy of the 3D scanning. Barber et al. (2007), in their guide to laser scanning for archaeological and architectural applications, highlight how the process related to the use of TLS technology may be difficult due to occlusions and obstacles in scanning the product, which may limit available data if incorrectly addressed. Laser scanners can not obviously see through solid objects that can cause problems in sites with excessive amounts of mobile objects that block the planned capture areas or in places with elevations, obstacles and vegetation that prevent optimal display of the analyzed building, as in the case exposed here.

The next step to the relief is the processing of the digital BIM model. To date, current BIM software is still quite deficient in managing the dot data data mass. However, there are interesting research developments, such as the “GreenSpider” plugin, (Garagnani, 2013) that is able to make the points of the cloud imported in the BIM environment selectable, for modeling as faithful to reality. Other interesting tools are those related to the automated recognition of building elements (Pâtrăucean et al. 2015), for their conversion into parametric families. However, this application still has many difficulties, especially when the object under analysis is part of the cultural
heritage or has complex and non-regular geometries that require a thorough and punctual study, especially from a constructive point of view.

**THE CASE STUDY: THE TEMPLE OF BACCO**

The case study, Temple of Bacco temple in Villa Cimbrone, Ravello, has allowed to explore some methodological elements related to the identification of speditive and effective ways for the processing of point clouds and consequently for the construction of a parametric model in BIM environment, to associate with more information concerning the object of study. The Villa is located in Ravello on a rocky promontory that had already hosted a Roman villa in antiquity. In 1904 Ernest William Beckett, 2nd Lord Grimthorpe, bought the western side of the villa from the Amici family, the last owners. The wealthy banker came to Ravello to fight the depression following the disappearance of his wife Lucy Lee, just 28 years old. When arrived in Ravello, he recovered and completely devoted himself to the creation of the Villa, where he introduced innumerable and valuable decorative elements such as fountains, nymphs, temples, pavilions, stone and bronze statues into a clear reinterpretation of the “Roman villa”: the cypress avenue little Temple, the Coffee House, the Mercury Palace and the Temple of Bacco. In particular, the Temple was built as part of the collaboration with Nicola Mansi, an eclectic citizen of Ravello known in England, who was able to give image and shape to the demands of Lord Grimthorpe, and its reading fully revealed the use of local workers (Fig. 2).

The circular temple is characterized by a dome covered in tiles, supported by eight columns in a rude Composite style. The survey campaign has presented several difficulties due to the configuration of the site, very steep, with very limited space around the object, and due the elements confor-

![Figure 2](image-url)
tion, all with circular section, whereby with obvious difficulty in highlighting significant points for surveying. In order to obtain an executive survey of the geometry and constructive characteristics of the temple we proceeded with the integrated digital survey methodology (Paris, 2015). The generated 3D model was derived from a TLS scan sequence. In detail, the scan survey have been associated with direct measurements on the individual constructive elements and ornamentation, and non-destructive testing campaigns (NDT) for the determination of materials and construction equipment in order to associate the material data to the model. The survey through TLS has solved some critical issues in data acquisition: Has allowed to easily access distant parts of the architectural object, to define precisely the points of surfaces that are not geometrically attributable to exact constructions, given the circular object of the object and the all circular section elements. 3D laser scanning was performed with a Faro Focus3D X 330 tool, with 7 shooting points to generate an overall cloud of points. The cloud was subsequently decimated with Faro SCENE software (Fig. 3), eliminating inaccuracies and “noise” of the survey, then imported into RECAP software for the management of the clouds itself and for the interoperability with Autodesk REVIT, within the BIM model was created.

The parametric model of the surveyed artifact was achieved by keeping the pointcloud and the photogrammetric data as a sort of ‘scaffold’ for BIM objects. The Scan to BIM procedure, implemented in the Revit environment, allowed the identification of the point cloud surfaces coinciding with the components of the temple and refine the location of the same, by transposing and properly representing the out of plumb of the columns, the inclinations and the translations of the drum and the dome. The dome is particularly interesting from the construction point of view, internally with an umbrella vault according to consolidated Amalfitans models, it has also been one of the elements more difficult to implement within HBIM model, both for its complex geometry that for correspondence with the point cloud. In the construction of the model we opted for the gen-

Figure 3
Point cloud processing resulting from the survey with Faro Focus3D X330 TLS, within the FARO Scene software.
Figure 4
Views of the BIM model:
Correspondence between the model and the point cloud, Axonometric split and Elevation views of a column
eration of parametric objects and families consisting of masses, rather than a mere detailed reconstruction of the ornamental apparatus of columns and capitals with the consolidated technique of transposition of the point cloud to polygonal meshes. This choice has been determined by the will to achieve an effective BIM model and by the need to interface with the structural calculation softwares in the next steps of the research. The textural properties, weight and substance of the modeled objects were therefore absolutely important in the implementation of the model (Oreni et al., 2014). The strong interdisciplinary nature of the presented research, developed between the Architecture and building design, the Structural Engineering, the Representation and Survey and the History of Architecture, has found an equally decisive response in an integrated approach such as the HBIM one. In particular, the model made for the construction and architectural analysis has reached a Level of Detail equal to the LOD 300, then simplified to the LOD 200 for interoperability with the structural calculation software, removing and simplifying part of the ornaments of the analysed object (Fig. 4).

RESULTS AND CONCLUSIONS
The application on the present case study allows to highlight, alongside the achieved results, some critical features regarding the application of HBIM in the process of recovering an existing building object:

- Geometric survey and degradation
- Widespread error and concentrated error
- Grey areas
- Edge Effects: tangent points on curved surfaces

Figure 5
Photo of the existing conditions of the constructive elements of the Temple where the states deformation and the existing cracking pattern are visible.


**Geometric survey and degradation**

The survey performed has allowed to characterize all the component parts of the temple from the geometrical point of view, including the deformation states (Fig. 5). Therefore, it was possible to metrically quantify the drum translational evidenced by the inclination of the columns with respect to the vertical axis and locate the planes within such inclinations occurred and the angles of the slope of each column. In addition, the model embodies the cracking pattern affecting all the columns of the Temple of Bacco, generally at the base and at the top, confirming its size and documenting its status for monitoring as long as the consolidation intervention is expected. These cracking phenomena have already been partially consolidated by the insertion of summit metal hoops of some columns, but these interventions, made of ductile iron, have not interrupted the manifestation of new lesions and the advancement of existing ones, as they continued the collapse towards the valley.

**Widespread error and concentrated error**

The technology of the laser scanner, which has allowed to define metrically with great precision the inclinations of the axes of the columns as a result of their rotation in the plane, it creates from another point of view known issues of accuracy: the cloud is a-critical and intercepts a density of points in a given desired surface without being able to operate the identification of significant intersections between the planes. In the unmanaged cloud there is a lack of significant points of definition for the main shapes of the architectural draw of the object. The probability that a point falls on a significant edge is low and it is therefore necessary to intervene with the well-known integrative actions represented generally by the association of raster images. In addition, as already mentioned above, it does not provide any details on a thorough construction study (Bonora and Sparò, 2004). This was precisely the case of the Temple dome which required a detailed study of the geometry and the constructive technique of the internal umbrella vault to be properly molded (Fig. 6).
**Grey areas and Edge Effects: tangent points on curved surfaces**

Finally, the case study analyzed has made it possible to deal with the problem of the effect called “mixed pixels”, mainly related to the resolution and the spot size of the TLS used, as well as the occlusions present during the detection (Hebert and Krotkov, 1991), and with the results of scans on curved surfaces. It is useful to remember that the points detected with each scan are equidistant with respect to a spherical surface concentric to the instrument. It is therefore obvious that by scanning objects at different distances and covering each other, there is a lack of gaps (Fig. 7), namely the absence of measured data, which determine, with respect to the instrumental center, the “grey areas”. As the object of study consisted of circular section elements, there were numerous grey areas present in the scans carried out and the point cloud was especially affected by this criticality. This is combined with the “mixed pixels” effect obtained in the detection of the elements, which led to a particularly dense cloud of “noises” around the constructive elements. An automatic recognition of surfaces (Tang et al., 2010), also by means of modeling plugin, is found to be totally ineffective, and so it was of paramount importance the critical evaluation processed by the operator assigned to the survey, processing and modeling.

The problem associated with grey areas was partially solved by the number of scans carried out at different points, despite the small size of the object being analyzed: 7 scans, of which 5 are at temple level and 2 are from upper terraces. The mixed pixel phenomenon, however, was solved by critical analysis.

In conclusion, the applicative process of transition from cloud point to HBIM model, in support of research, has allowed us to verify the effectiveness of a workflow useful to the analisys of the built cultural heritage, optimizing the design process, improving data management, effectively supporting decisions and increasing the accuracy of the recovery and consolidation design. However, it should be noted that the existing modeling process is limited by several objective factors and therefore it is difficult to think of obtaining an AB BIM that reaches the same level of maximum detail of an AD BIM. This is because the AD BIMs contain semantic information about the designer’s thorough knowledge of the product, but cannot be deduced from a digital model, such as some specific technical details, costs or times of realization (Simeone et al., 2014). The level of detail gained by an AB BIM is therefore limited by practical aspects of data collection. Although presumably the technology used for data collection can capture particularly meticulous details, the added value of modeling these small elements does not justify the time and cost of gathering and modeling meticulous the data. Taking into account these limits, we must define the desired output of the integrated modeling process as a functioning BIM model, which will reasonably represent a smaller version of the complete BIM, but that can appropriately encode the constructive elements and the visible spatial elements with their relationships of nesting and connectivity, based on the a priori defined objectives and goals.
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Post-Digital Design

The Hyperheritage project

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The cultural heritage domain, as many other domains, is invited to experience new "designs" in harmony with new development and consuming approaches. It should accept to deal with under continuous design objects & information on the first hand and the fact that every information consumer could become, somewhere and/or sometime, information broadcaster, on the other hand. In this paper we present some exploratory projects newly realized within the workshop "HyperHeritage" (Augmented Cultural Heritage) of the Master Program Net. This workshop, which is animated by three staff members of the department of digital humanities, invites 15 master program students to rethink the cultural heritage objects and information by considering the potential uses of information and communication technologies and their socio-cultural impacts. By the following, we intend to present four projects on "HyperHeritage" resulting from this collaborative approach. The suggested prototypes have considered advanced digital technologies, mainly the Internet of Things and the Contact-Less Communication, to experience new form and strategies of mediation and communication of the cultural heritage.

Keywords: Augmented Cultural Heritage, Collaborative Design, Connected Objects, Contact-Less Communication, HyperHeritage, Internet of Things

INTRODUCTION

In the Post-Digital era, at least three major technological trends and one fundamental social shifting, have influenced the activities of curators, mediators and communication managers in the domain of cultural heritage. The first trend is the ongoing developments in the fields of connected objects (Internet of Things) that integrate contact-less communication devices such as NFC (Near Field Communication), Flashcode (QR code), ... The second is the social network technology which is based on sharing experiences and discoveries through communities. The third one is related to pervasive and mobile computing. Thus, things of cultural heritage (object or information) ought to be intelligent, sustainable and geolocated. Those things, that embed technology, have allowed to explore and to imagine new ways of perceiving and practicing times and spaces.
of the cultural heritage. One of the most fundamental impacts of those technological advances would be “Social”. We can observe that the new user (consumer) skill doesn’t require, nor expect, an achieved and perfect cultural heritage object or information. This new consumer calls for usable objects (or information) that can evolve in time and space and can be considered in establishing and sharing new personalized object or piece of information. This fact brings new debates on the notions of author-rights, intimacy, privacy, publicity, individuality and sociability in every cultural heritage space, time, object and information design.

To learn more about this phenomenon, we have introduced, since 2015, within the framework of the Master program NET (Digital Challenges and Technology), a new design workshop, entitled HyperHeritage. This workshop is focused on designing enriched Cultural Heritage Applications based on Augmented and Virtual Realities Technologies.

**POST-DIGITAL DESIGN**
Designing in the Post-Digital era invites various actors to rethink their approaches to create, innovate, perceive and explore the Human Smart-Things Communication universe. Nowadays, the evolving of this universe (as an open set of connected “Things”) is very closed to information design, to information development and to information practicing. In the Post-Digital era every “Thing”-Design encapsulates explicitly Information Design. Obviously, every Information Design still has to consider 3 components: the “Transmitter”, the “Channel” (material or immaterial mediator) and the Receiver (Shannon, 1948). More obvious, every living envelope remains a set of “Things” and information (ex. Cultural Heritage).

In this paper we present our research problemmatic on the evolving of Cultural Heritage Information perceiving and processing, in a context of PostDigital design. This research project is based on three main hypotheses:

- The first one observes that Information & Communication Technology (ICT), mainly Smart “Things”, has strongly promoted and preferred mediated communication protocols (Human-to-Human) over Human Computer Interactions protocols.
- The second hypothesis is focused on the fact, that Human Capabilities and Human Capacities to deal with various kinds of information still to be explored.
- The third and last hypothesis considers the importance of Social dimensions that every smart-Thing must embed.

Those hypothesis are based on three main observations:

- “Thing”-Design is more than ever Information Design;
- ICT allow new way of living information and « Things »;
- “Thing”-Design has become, and has been accepted as, sustainable non-ended activity

Our research and teaching program is interested in hybrid cultural heritage environment, i.e. enriched with digital technology by embedding smart-“Things” that allow exploring various facets of information perceiving and practicing (by Human: user, designer, researcher). Massive development, and impressive uses, of Information and Communication Technology (ICT) as well as immersive devices (Augmented and Virtual Realities) have allowed to discover new forms of Human- « Things» Communication. ICT has established new ways, often independent of space and time, to access, process and to deal with interconnected Cultural-Heritage Information and Objects. We observe as well, that new Human-to-Human “Mediatised” Communication, are inviting designers to consider the non-stop evolving of the Cultural-Heritage Information (devices, protocols and data). However, it is important to notice, that our research and teaching project (entitled Hyperheritage) doesn’t question the Traditional Cultural Institution itself, it suggests other ways of dealing with Cultural-Heritage Information growing, consuming and producing in an interconnected unlim-
ited spaces. Consequently, this leads to consider a double exploratory adventure: on the first hand, to replay / rediscover some of Human Perceptual and Operational Capabilities (in handling cultural information) and on the other hand, as consequence, to re-design (re-engineer) the Cultural-Heritage Information itself.

“Things”-Design achieving is no more a requirement or a constraint, however continues object design has become part of user culture that increases seriously the complexity of « traditional » design process and methodology.

**HYPERHERITAGE WORKSHOP**

The cultural heritage domain, as many other domains, is invited to experience new “designs” in harmony with new development and consuming approaches. It should accept, on the first hand, to deal with under continuous design objects & information and on the other hand the fact that every information consumer could become, somewhere and/or sometime, information broadcaster.

In this context, most of enriched cultural applications undergo these shifting through new strategies of information, communication and mediation. In fact they have mainly considered the “traditional” curator point of view with the collaboration (optional) of a group of user. Otherwise, design approaches have been curator oriented. In this paper we avoid discussing the notion of Curator skill. We believe that curetting practices are also shifting. This can explain the use of the expression “traditional” curator.

Thus, the Hyperheritage workshop has been a place to handle this question in a very different way, where the consumer (master students) has become curator and where the “traditional” curator could become, a day, a user of those new visions. Targets of this workshop are both pedagogical and research. Students have to perform the use of new technology in the Cultural Heritage Information Design and on the other hand to free their visions of it, i.e. try to perceive and practice them in different times (synchrony, asynchrony) and places (hybrid spaces).

This year, as result of the collaboration between students (about 15) of tow master programs of the Digital Humanities Department, University Paris 8, the master NET (Digital Challenges & Technology) and the master THYP (Hypermedia Technology), four projects were developed, in the framework of this multidisciplinary workshop which was held at the university Paris 8 with the support of Idéfi-Creatic (Initiative of Excellence for Innovative Training). The workshop duration was about three months, once a week (time estimated to 50 hours / student). Most of the suggested prototypes have used advanced digital technologies as new mediations experiences in the field of cultural heritage.

By the following, we intend to present briefly four projects on Hyperheritage resulting from this collaborative approach. The first and the fourth consider museums as starting and continuous points. They are focused on visual information appropriating and sharing facilities, the idea is also to share benefit between museum administrators (initiating a network of potential interested consumers) and the visitors-collectors (archiving driven project). The second and the third project are completely outside the institution. They suggest visits on the city that are guided and enriched by social network (cultural & social driven project). Using personal mobile devices, offering more personalized content (Celestine 2012, Bariberi et al 2011), hybridization of space and multiplication of visit temporalities have been the priorities of most projects suggested by the student.
We have chosen those relevant projects because we have been surprised by the way the student thought the problematic, the needs, the scope, ... of their designs and applications. This fact will be pointed out after every presentation of those projects.

**Collect’Art: Connectivity as a museum experience!**

Given the growing popularity of cultural heritage objects and information, the evolution of cultural practices and the increasing use of digital devices and tools by the cultural heritage institutions have become more than obvious. The Collect’Art project is part of this perspective, whose aim is on the first hand to supply visitors of cultural heritage place with tools that enable them to restore the role of explorer and on the second hand to free them from certain constraints inherent to the visit of “traditional” museum, such like: the crowd stress, the inadequacy of places and contents for all audiences, etc. Moreover, this device has to satisfy the appropriation desire that new visitor (collector) requires to tag the art work with his/her own sentimental or memorial comments and key-words (htag). Collect’Art provides visitors with an easy-to-use tool for collecting good quality and well-framed images of the selected art works (Figure 1). The application captures (by using NFC technology) the art work and save it in a gallery that the visitor can reorganize at his/her will before sharing them via social networks (Facebook, Twitter, Instagram). Collect’Art should reduce the capture in burst of photos and enhance the fluidity in front of the art works.

This application fingers out new spatiotemporal relationships between the consumer and the cultural heritage place. Those relations show some paradoxes. It is not really necessary to come to the place to get the photos and to share them. Nevertheless, it still looks important to locate and live such social experience before sharing it. What is more, the use of NFC was to avoid the crowd and the use of social network was to connect with people outside the place. However, those are just observations.

**Cultural Walking**

This second application “Cultural Walking” is based on the principle of geolocation (Figure 2). Its users can predefine itineraries that allowing them to discover artistic places in Paris. This project is not meant to be a health application stricto-sensu, but rather a playful application, aimed at promoting the cultural heritage through physical activities. It highlights the principle of journey, enhanced with fitness trick as the steps progress. Thus, the appreciation and promotion of the cultural heritage are highlighted by visual indications throughout the different programmed paths. The project emphasizes the community dimension and encourages human contact and mutual support for the practice of physical activity and the promotion of cultural heritage.

This application puts forward 2 vitals issues that have very often omitted or forgotten until now by the vast majority of cultural heritage promoting devices. The first considers the role of the human body and its involvement in the cultural heritage information exploring. The second issue is strictly social; it is the matter of using cultural heritage as an alibi to develop, in new ways, the social life.

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Figure 2
Cultural Walking
(designed by Paula-Maria Santucci & Giulia Zecchini)
Paris Insolit

The Paris Insolit project is a mobile application designed for smartphones and tablets, whose aim is to discover Paris through its most unusual places and its lost monuments (Figure 3). It offers users access to emblematic places (available in the form of a database), guided by geolocated features. It allows its user to discover facets of Paris that are unknown to the general public, it proposes to them to visit places that are invisible for the profane or the “uninitiated”. It also suggests an enriched visiting experience in a space-time, thanks to augmented reality.

In this third experience, the designers (the students) have put forward, very strongly and on all levels, the explorer side of the users. They must explore places that are unusual, unknown and very weakly documented by the cultural heritage institutions. These explorers (users) are also invited to enrich the information and the realities related to these places. They can make use of augmented reality products to learn more or to say more about them.

FlashMU

FlashMU is also a mobile / tablet application designed for visitors of a cultural heritage establishment (Figure 4). This application is turning completely to the visitor experience. FlashMU is a platform that allows its users to directly comment on works of art from the collections of any museum (for example the National Center for Modern and Contemporary Art in Paris). This is to foster the museum experience of visitors by allowing them to share visitor comments that include valuable information expressed in the form of reflections, opinions, feelings, criticisms or impressions about the observed art works or the institution itself. FlashMU promotes the museum experience of visitors by posting comments that are shareable and accessible to all others users of the application.

This last project on the augmented cultural heritage applications, is to promote the connectivity between the visitors of the institution, between them and their friends (who would be new visitors) and finally and above all to bridge the institution to its visitors and their friends (potential visitors). Like the first project (Collect’Art), the comments posted en FlashMU offers to the institution a great open data to enhance its exhibitions policies and marketing strategies.

CONCLUSIONS

Observations on the developments of these projects (especially Projects 1 and 4) can not leave us indifferent. To our great and pleasant surprise, the approaches and visions of all the students, which are harmonious and very convergent, do not correspond at all to what we have been waiting for. No team asked about the spatial organization of the institu-
tion, nor the layout, nor the documentations, nor the communications strategies, etc. Everything was centered on the human, the visitor and the consumer who is outside of the institution, and on its new communication and information universes (mainly his mobile devices and his social networks). Thus, cultural heritage and arts institutions have become a kind of repositories (data warehouses) of information and points of intersection and sociability.

These experiences have challenged us on another surprising point concerning the cultural heritage itself (case of projects 2 and 3). The available, documented and accessible cultural heritage information has not seemed to attract enough the explorer-visitors. They would have preferred to seek what is not yet on the digital space, may be in order to make it exist and to sign it (to leave traces) before sharing it.

In sum, those experiences in addition to others experiences that we have developed in the area of Hyperurban (Bursztyn et al, 2015, Zreik, 2008) confirm that human perceiving and practicing of information, objects, spaces and times have been liberated and they are in continuous evolving. On the other hand the quantitative and qualitative requirements in terms of space and time are also moving by the integration and the appropriation of mini, micro and nanotechnology by every objects (IoT). Every architectural or urban design project is deeply concerned by those facts and those open debates.

N.B. The HyperUrban approach considers the concept of “city” as a complex and hybrid urban space that produces, maintains, exchanges, transfers and transacts information related to services and products. HyperUrban presents also reflections about the concept of “social city”, where the ways of communication, socialization, learning, sharing, work, etc. pass through different states of self-regulation, and where a large number is based on information and communication technologies

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Interiority & Perception in Cinema

Digitally Reconstructing Space, Light, and Motion

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Cinematic space is ephemeral and fleeting. After capture on film, the physical space of cinema is erased as lights are dimmed, props are dismantled, old sets torn down and new ones erected. For the understanding and research of historic cinematic space this is inherently limiting. Can computational tools aid this research and allow for digital reconstruction of film sets and scenes? This paper initiates a line of study into restitution methods of cinematic space. Assessment of software-based photogrammetry methods to cinematic sequences leads to the development of a bespoke parametric linear perspective reconstruction tool.

Keywords: Linear Perspective, Photogrammetry, Perspective Reconstruction, Cinema, Parametric Modeling, CATIA

INTRODUCTION

The goal of this paper is to evaluate and expand on existing tools for the digital three dimensional reconstruction of film scenes for the study of cinema. The ability to digitally reconstruct the geometry of set layout, camera position, camera movement, and lighting positions offers potential for significant insight into historic film practices. A rich complexity of spatial manipulation occurs in mid-twentieth century film: sets were purposefully misproportioned, lighting was distorted for affect, perspective was manipulated by lens effects, and actors manipulated movement through space. (Bruno: 2003) This paper proposes novel applications of digital tools tailored to reconstructing and exploring manipulations of space in cinema. Permanent archives of constructed set documentation are sparse and film as an archival medium is limited to what is visible on screen. In some films, multiple angles of a set are provided, in others partial angles, others only a single locked camera point. Constructing and computing analytical set documentation from within this wide range requires multiple tools. The intent of this paper is to explore methods specific to scene reconstruction, with emphasis on methodologies and approaches that are accessible, flexible, and adaptable.

A key challenge in film scene reconstruction is the limited spatial information provided by cinema.

The first of the two methods explored involves the adoption and application of commercially available photogrammetry software for digital film set reconstruction. Computational photogrammetry is the subject of extensive research and development, in a range of disciplines from mathematics to computer science. While photogrammetry is commonplace in a range of industries, its application to the study of
space and history in a humanities context is understudied.

The second method involves the application of geometric linear perspective reconstruction. Linear perspective has also been the subject of extensive research and development, dating back to the renaissance era. Until the widespread adoption of computer-aided design linear perspective was the primary method of architects and artists for constructing hand drawn renderings. The method proposed here involves a hybrid between computational and traditional manually drawn geometric methods. This method remains geometry-based, requiring minimal scripting and mathematical computation, while allowing for automated reconstruction by applying constraint-based digital modeling and parametric templates. This offers high flexibility in use and applications, and can be applied quickly to a reconstruct a wide range of conditions.

Together, these two methods provide a robust and flexible toolkit for digital reconstruction of film scenes.

PHOTOGRAMMETRY & CINEMA
The digital capture of architectural and landscape space through photogrammetry methods is a well established technique (Ogleby, Rivett 1985) (Mikhail et al 2001). Multiple still images captured within or surrounding a space are utilized to reconstruct a calibrated 3d model. Recent advances in algorithms and processing technology have created the ability to use large numbers of sequential images in the photogrammetry process (Sabina et al 2015) for extremely high resolution output. This technique is commonly applied in the architectural, archeological, animation and gaming industries. Input data in these cases are high resolution DSLR image sequences from local site surveys or from object turntable documentation. High numbers of sequential images can be captured for site surveys from aerial drones. The output data from these techniques is a point cloud dataset, a three dimensional mesh model built upon the interpolation of the point cloud, and textures sampled and projected from the original photographic imagery by way of the point cloud. (Chevrier 2009).

While Photogrammetry and Camera matchmoving are commonplace in the aforementioned specific industries, their application to the study of space and history in a humanities context is understudied. We propose the implementation of these technologies in the study of historic cinematic set and camera space.

Select cinematic camera moves and scenes are converted into still image sequences to be processed in photogrammetry software. The resulting photogrammetry output will generate an architectural model of the original film location and set. Having this dataset will free us to analyze and study the set freed from the confines of the original camera move. Applying common architectural representational tools such as orthogonal projections, perspectival views and formal analysis to the resultant 3d model can be manifested once free from the original cinematic camera movement. This technique will allow us to gather insights into the architectural and perspectival distortions present in the design.

APPLICATION OF PHOTOGRAMMETRY SOFTWARE TO FILM SCENE RECONSTRUCTION
The film “High Noon” (1952), directed by Fred Zinnemann is considered a classic case study of mid-century Hollywood filmmaking. A single camera move, or “crane shot” is heavily referenced and agreed to be an iconic storytelling device, the large scale crane shot at the tail end of the feature. (Figure 1). This shot, composed by cinematographer Floyd Crosby transitions the camera view from a close up of the lead character to pull back, lift and reveal the immediate town context.

The large scale scene definition, camera movement and iconic status led us to select this shot as a case study for applied photogrammetry reconstruction. The large scale scene transition provides multiple images (frames, exposures) depicting building scale set pieces. The camera movement provided
what initially appeared to be a large divergence in camera viewpoints. The iconic status self selected this clip as an intriguing opportunity to reoccupy a lost location in physical cinema space.

The shot was subdivided into a series of still images that populated the photogrammetry scene. Identifying the camera movement on a per frame basis was easily achieved based on the interpolation of multiple software identified key points. These key points are identified by a texture and pattern based algorithm within the software. By identifying similar patterns from multiple vantage points the photogrammetry process can identify relative locations and dimensions of these key points. In order to assist the photogrammetry process manually located markers at important geometric references were added early in the process. These markers were added at the corners of window frames, the edges of projecting roofs, and the base and crown of vertical wall surfaces. These markers are additionally useful in registering the photogrammetry solution in a specific cartesian orientation.

As this case study was conducted we encountered a limitation derivative of the camera movement. Although the camera moves significantly higher in elevation over the course of the shot, there is relatively little lateral movement. The lack of lateral movement creates a challenge for the photogrammetry reconstruction algorithm. Accurate reconstruction is aided when there is a large relative parallax difference between the same detail in multiple views. Larger camera orientation differences provide a more significant spatial deviation to process. In the case of the High Noon crane shot the software had difficulty properly interpreting the depth of elements further from the camera (Figure 2). This created a spatial accuracy that lessened as the distance from the camera increased. While other challenges arose in this case study related to image sequence resolution and the moving character demanding a masking solution for computation, the lack of significant lateral camera movement was the most pronounced issue.
BENEFITS AND LIMITATIONS OF SOFTWARE-BASED PHOTOGRAMMETRY SOLUTIONS

Photogrammetry offers a robust solution for spatial computation. When supplied with accurate and appropriate input imagery the algorithms can solve for highly complex spatial reconstructions. Both the dense point clouds and the interpolated 3D mesh geometry can be used for computational analysis and to create high detail spatial and visual simulations. The simultaneous ability to project textures from the point cloud onto the 3D mesh geometry amplifies the utility of this output in visual simulations. As an alternative to creating a traditionally modeled spatial reconstruction this process is relatively automated and efficient.

The limitations of photogrammetry can be divided into two subsets. If the input data images do not provide enough deviation of viewpoint the algorithm will struggle to identify enough similar key points to properly identify geometric features. Likewise if the input imagery is optically loose with a lack of consistent deep focus, low resolution or blurriness/shaky the software will be unable to identify consistent key points.

The second subset of challenges are tied to scalability. The spatial resolution of the reconstruction is directly related to the scale of input data. The more detail needed in a solution, the more imagery input. The larger the geographic area to be reconstructed, the larger the number of input images. As the number of input images scales the computational demands of this process dictate the speed and efficiency of the resulting spatial reconstruction dataset.

LINEAR PERSPECTIVE RECONSTRUCTION

Software-based photogrammetry produces a large amount of data for a given scene. As demonstrated the method has two manifest limitations. First, scenes require a significant amount of orbital motion by the camera to generate geometry and the method fails entirely for single still images. Second, a high degree of noise exists in the generated data set.

For irregular geometries such as landscape and trees, noise is less impactful than for built objects for which rectilinear geometry is predominant. In evaluating alternative methods for scene reconstruction to address these criteria, methods of linear perspective offer a counterpart solution. Linear perspective methods prioritise precision rectilinear geometry, and are well-suited to architectural applications. The principles of linear perspective, which were first developed in the renaissance era, have been well-established since the 19th century, both geometrical and mathematically. (Kemp 1990)

The technique for reconstructing geometry from still images is called linear perspective reconstruction, also referred to as perspective restitution, and works by inverting the traditional process of perspective construction. The method allows for the extraction of geometry from a single image, along with scene variables such as the horizon line, camera location, focal length, and rotation angles of azimuth, tilt, and swing. (Williamson and Brill 1987) Given a single known dimension in the image, the sizes and positions of scene objects and geometry can be measured precisely.

The principles of perspective reconstruction were first developed by the mathematician Johann Heinrich Lambert in the 16th century, and perspective reconstruction methods remain useful and insightful as a strategy for evaluating images of the built environment and the manipulations therein. (Rapp 2008). Applications include the study of art, architecture, site surveying, forensics, and more. An additional benefit of geometric perspective reconstruction over software-based photogrammetry is...
the method's high level of flexibility by allowing direct interaction with both image and process.

**PARAMETRIC CONSTRAINT-DRIVEN TWO POINT PERSPECTIVE RECONSTRUCTION**

A primary drawback to perspective reconstruction is complexity of the process, as many construction lines and curves are involved in the mapping of a single line from a two dimensional image to three dimensional geometry. Additionally, steps in the procedure may require solving for angles mathematically, requiring trigonometry, or additional complex steps. (Dzwierzynska) Fully computational solutions, which typically involve matrix multiplication, are highly effective for specific use scenarios but do not to lend themselves to interactive and adaptable approaches. The applicability of traditional geometric perspective reconstruction however, can be extended by computer-aided design and parametric software, partly automating the process and allowing real-time interaction with results. The benefit of applying computer-aided and parametric solutions to the process of perspective reconstruction has been demonstrated in disciplines such as historical preservation site mapping and painting analysis. (Crankshaw 1990; Lordick 2012) Applications to film may generally assume correct physical principles, unlike painting, and anticipate manipulation of these principles for affect. This paper proposes an automated parametric constraint-based methodology for two point perspective reconstruction. The method applied here reconstructs camera location, camera lens, focus, camera angle, and planimetric geometry. Variations and adaptations of this methods can allow for additional applications, such as three point perspective reconstruction, elevation and three-dimensional reconstruction, lighting source reconstruction, and non-linear lens reconstruction, and more. (Richardson 1993; Brill and Williamson 1987)

The approach allows for automation of the perspective reconstruction process through the use of parametric templates and constraint-based modeling. The resulting method is highly customizable, flexible system for creating detailed perspective reconstruction. Parametric templates encoding of geometric construction without scripting. A single a parametric template constructed of the geometrical process may then be iterated in a loop that remains parametric. Inputs allow for very large amounts of input geometry to reproduce high-fidelity perspective reconstructions. Flexibility of system also allows for varying degrees of manual input versus automation, and maintains real-time interactivity with the resultant model throughout.

There are multiple methods for two point perspective reconstruction. The system used here involves identifying a planimetric square the image and solving for the “parallel asymptotic condition” of that same image for which only a single solution exists for the camera point CP. Identifying a square in the picture plane of the “typical condition” provides a reference point for mapping all angles of the geometry. (Figure 4) A triangle of known angles will also allow mapping geometry to a single solution, but in architectural the built environment squares are typically readily avail-
able (often in the form of a circle, from which a square can be derived). Without a reference square or triangle, there are infinite geometric solutions possible for a given image.

Once a square is identified, the parallel asymptotic condition can be derived. The parallel asymptotic condition serves as a key to derive the camera point CP. In the typical condition, orthogonal projections in plan and elevation contain too many variables to geometrically solve simultaneously. In the parallel asymptotic condition, the coincidence of points D and D', combined with the perpendicular alignment of line CP D in plan, and the alignment of the heights of points CP and B reduce the number of variables in each projection and allow a straightforward geometric solution for identifying the camera point location CP, and therefore the projected geometry in plan.

In the method developed, the horizon line (HL) between the two vanishing points VP1 and VP2 is drawn manually from the image. (Figure 5) While the geometry may be derived parametrically, the graphical construction of the horizon line allows for evaluation of the image, and helps identify in the trace of the im-
age edge lines which lines follow proper perspective. It is also a simple exercise that requires only extending lines traced from the image to their intersecting points.

Figure 9
Orthographic projection composite view of both elevation and plan mapped to a single plane.

Once the vanishing points and horizon line are derived for quadrilateral ABCD, the elevation of the parallel asymptotic condition square MNOP can be driven using constraint-based parametric software. (Figure 6) The simplest method is using software that allows for constraint solving, such as the Sketch tool in Dassault Systems CATIA. Multiple approaches for inputting solvable geometry are possible, so long as a solvable number of the constraints identified in Figure 6 are input into the parametric model. Once the parallel asymptotic condition is solved for the elevation, the camera point CP can be derived, and the plan of the square A'B'C'D' projected to the ground plane. For most instances, either the height of the camera point CP or a single dimension in the image must be known, otherwise the reconstructed geometry will be scaleless, and the vertical location of the ground plane arbitrary. The entire system can be developed in a single orthogonal projection by rotating the picture plane 90 degrees counterclockwise and aligning with the ground plane. (Figure 7) For solutions that require only planimetric geometry, this case suffices and reduces complexity.

APPLICATION AND AUTOMATION OF PARAMETRIC TEMPLATES

The parametric perspective reconstruction system was modeled in Dassault Systemes 3DEXPERIENCE platform, using CATIA. (Figure 9) The software platform allows the encapsulation of parametric geometry into templates for instantiation on variable geometry. There are several templates available in CATIA, including “Engineering Templates,” “PowerCopies,” and “User Defined Features.” In this scenario, PowerCopies were used to instantiate the parallel asymptotic condition onto the traced geometry, and solve for the camera point and planimetric reconstruction. The inputs to the PowerCopy consist of only the horizon line and a four lines of a square in the picture plane, and output the camera point and resultant planimetric geometry. Adjusting points controlling the corners of the quadrilateral in the picture plane produces variations in real time. An additional PowerCopy can then be made to instantiate any geometry in the picture plane, so long as it is known to lie on the same plane as the original quadrilateral ABCD. Scripting using CATIA’s “Knowledgeware Engineering Language,” the instantiation of PowerCopies can be automated and looped over any number of inputs using a script of fewer than 20 lines of code. This allows for the entire reconstruction of complex scenes to be executed within seconds, producing parametric model of perspective reconstruction driving by equilateral ABCD that can be dynamically adjusted in real time to evaluate of results.

TWO POINT PERSPECTIVE PLANIMETRIC RECONSTRUCTION, CASE STUDY

A case study of the system is presented reconstructing the plan of an image of an interior courtyard walkway in the Newark Public Library. (Figure 10) The photograph and scene provides a good case study, as the results can be verified against measurements of the physical space. Additionally, the reconstruction regular, repetitive, orthonormal geometry of the space, while a simple layout, allows for easy verification of errors or inconsistencies in the output. The
image of the courtyard walkway is first traced manually. Identification of the vanishing points VP1 and VP2 determine the horizon line, which helps identify the camera and resulting image rotation. Identifying the horizon line improves accuracy with regular, orthonormal geometry in the image and solve for assumed locations beyond the perimeter of the image itself. The resulting vector trace is then input into a single “Geometrical Set” in CATIA for instantiation of the reverse perspective Power Copy, which is run over each line segment individually. The output of the system is a convincing and verifiable plan of the space, including the location of the camera point matching the location at which the photograph was taken. (Figure 11)

CONCLUSION
The two techniques of computational photogrammetry and parametric reverse perspective reconstruction provide a robust and flexible toolkit for film scene digital reconstruction. Computational photogrammetry solves well for irregular geometries, outputs raster texture maps, and produces a large amount of geometric data. Linear perspective reconstruction solves well rectilinear geometries and single image cases. Further steps involve pairing both techniques together towards reconstructing the same cinematic scene, and solving for additional variables such as scene lighting and camera path.

Our larger goal is to develop a tool set to better analyze and understand set design and manipulation in mid-twentieth century film, and explore the use of a new medium to deconstruct manipulations of space, light, and motion.
Figure 11
Perspectival reconstruction of a portion of the Newark Public Library from a single photograph. Overlaid construction geometry reveals process of automated template instantiation.
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FABRICATION - MANUFACTURING
An Italian BIM-based portal to support collaborative design and construction

A case study on an enhanced use of information relying on a classification system and computational technical datasheets

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A great amount of information needs to be managed along the building life cycle in order to fulfil building codes, standards and regulations, client and user requirements. However, a lack of transparency in the information management and a lack of communication between stakeholders often bring to the adoption of solutions in the design process that do not meet the original requirements. Therefore, an ordered structure for information improves its storage, enhancing its visibility, traceability, usability and re-usability. In addition, for public works contracts and design contests, the use of specific electronic tools, such as building information electronic modelling tools, is often required for the information management. The paper presents the efforts devoted within the Italian building sector for proposing a standardized structure and developing tools for collecting, sharing and exchanging information between stakeholders involved in different stages of the building process. An enhanced use of information relying on the adoption of the standardized structure of information is presented, proposing dedicated applications for automating the process of information fruition.

Keywords: BIM-based portal, Standardized information, Computational technical datasheets

INTRODUCTION
The fulfilment of building codes, of standards and regulations, of clients’ and users’ requirements also depends on an improved management of the great amount of information produced along the building life cycle. Therefore, an ordered structure for information is needed to store and use all the required data. This is even truer nowadays, when data and information tend to dissolve in a digital ecosystem more and more volatile.
In fact, for enhancing visibility and traceability of information, it is essential to adequately manage requirements from the Strategic Definition stage to the In Use stage [1]. A lack of transparency in the information management and a lack of communication between stakeholders often bring to the adoption of solutions in the design process that do not meet the original requirements (Jallow et al. 2008; Kiviniemi 2005). Therefore, the process results in design iterations, rework, and, consequently, low efficiency (Jansson et al. 2013). Furthermore, the operational islands between different disciplines cause ineffective coordination (Schade et al. 2011). All those barriers affect the fulfilment of the multiple requirements, impacting in turn on the performance of buildings.

In addition, for public works contracts and design contests, there is an increasing demand in the use of specific electronic tools, such as building information electronic modelling tools [2, 3]. Therefore, great efforts have been devoted by corporations, organizations, and working groups at different levels, dealing with BIM-related issues. That highlights another dimension of the information management, that is the usability and re-usability of data and information in order to create value in the process.

The paper focuses on some preliminary efforts within the Italian building sector for proposing a standardized structure and developing tools for collecting, sharing and exchanging information between stakeholders involved in different stages of the building process.

The paper presents the main aspects emerged during the development of: a) a standardized structure for collecting, sharing and exchanging information concerning technological solutions; and b) a national database for the fruition of information from different stakeholders through a web-portal. Furthermore, usability of the information is explored and compared to what is provided by the existing market through digital-based applications. In fact, an enhanced use of information, relying on the adoption of the standardized data structure, is presented for the assessment of environmental sustainability. Dedicated applications are presented in the paper for automating the process of information fruition, especially establishing a link between information in the structured database and information provided by BIM-Models. Information is then adopted within algorithms for the estimation of selected indicators.

**APPROACH**

An analysis of the Italian building sector has been performed for identifying main criticalities to be solved and essential information to be collected, shared and exchanged. Therefore, several stakeholders (e.g., universities, research centres, construction companies, designers, associations and federations of product manufacturers, software houses) have been involved during the research for identifying informational requirements and information technologies to be adopted for the definition of a standardized structure and for the fruition of information through a web-portal. The points of view of different actors have been analysed through the establishment of working groups (Figure 1) at the Italian standardization organization (UNI) and through the participation at a national research project (INNOVance project).

After the definition of the information content and structure, different applications have been explored in order to demonstrate how the developed structure affects the current use of information in the construction sector, using information for the assessment of environmental impacts applying a LCA approach.

**AN ITALIAN BIM-BASED PORTAL TO SUPPORT COLLABORATIVE DESIGN AND CONSTRUCTION**

The collaboration between several stakeholders through the Italian standardization organization and the involvement of different teams in INNOVance project result in the definition of criteria for the unification of terminology, organization, collection and exchange of information for the construction sector.
Two main results have been achieved:

- an unambiguous classification system;
- models for performance-based computational digital technical datasheets.

Both the classification system and the models for technical datasheets have been proposed for different technical solutions adopted in building processes.

The criteria identified for the definition of an unambiguous classification system allow to identify families of objects considering different aspects. Namely, those aspects are: category, typology, reference standard or function, main performance, geometry, dimensions and physical-chemical characteristics (Pavan et al. 2014). By selecting a specific choice for each field, a unique code is created for each object.

Furthermore, models have been defined for collecting, organizing and archiving technical information about construction products and technological solutions. Particularly, standard criteria have been identified to describe construction products, in indicative, qualitative and quantitative terms. The structure has been defined in accordance with harmonized standards for CE marked products or in agreement with other relevant reference standards (if available and/or applicable) for non-CE marked products. Once defined the models for construction products, a comparable structure has been developed also for technological solutions and technological systems. As demonstrated through the exploration of uses proposed in the paper, such structure is essential to provide an easily accessible source of data, directly usable from machines.

The models for the collection of technical information have been organized into informative blocks of homogeneous data. The structure collects information into classes and provides guidance on how to fill datasheets, standardizing the process of description and characterization of those ones. The informative blocks, differentiated for CE and non-CE marked products, are related to: identifying manufacturer information; identifying product information; technical information; information about packaging, movement, storage in factory and transport; commercial information; additional technical information; information about laying/installation, maintenance and disposal of products, description of the main components of products; attachments; information on data reliability.

Beyond the definition and development of the classification system and computational technical datasheets, a web-portal has been created for the
fruition of information. The web-portal is composed of four main sections for:

- the collection of information related to technological systems, MEP objects and construction works;
- the fruition of information related to technological systems, MEP objects and construction works;
- the collection of BIModels linked to the standardized structure of the database;
- the collaboration among several stakeholders through a BIM Server.

Particularly, a link among information collected within the standardized structure and BIModels have been established, considering the approach adopted in the development of the BIM library, as presented in (Pasini et al. 2017).

Moreover, interoperability has been guaranteed thanks to the development of scripts for enriching the IFC schema with information stored in an external database. In fact, an automated process can be developed in a Python-encoded environment for reading the information of all the objects both in the native BIModel and in the IFC model, detecting the missing information and writing those ones in a structured database, as described in (Mirarchi et al. 2017).

PRACTICAL IMPLICATIONS

Background

The whole supply chain can take advantages from the availability of a standardized information structure and from its implementation in a BIM-based portal to support web-based collaborative design and construction. Particularly, for what concerns the section of the portal for the collection of information related to technological systems, different manufacturers have the possibility to upload complete information of their products, designers can easily compare characteristics and performances of similar products, construction companies have access to information concerning the installation and the maintenance of selected products. Moreover, such structure can promote the development of dedicated applications for using and re-using information through automated processes. Those applications can be developed because data collected following the proposed structure and stored in the portal are accessible in an electronic way, in line with the growing demands in that direction [2].

The development of automated processes is often bounded to the rules defined for a specific project. Generally, if information is not orderly collected, a specific application cannot be reused in different projects and by different subjects (Held et al. 2016). Instead, thanks to the standardized structure of the database behind the portal, applications can be developed following defined rules that are applied to each project supported by the portal itself. That means that a defined application can be developed by a third subject and then used directly in each project.

Authors present specific applications focusing on the usability of information concerning environmental sustainability. Particularly, environmental issues are gaining attention within the building sector, so that standardized methods have been developed for the assessment of environmental impacts [4]. Consequently, stakeholders as manufacturers are putting great efforts in the collection of information describing those aspects concerning their products. However, that information is often not collected in a standardized way and in open and query-able formats. As an example, several Environmental Product Declarations (EPDs) can be retrieved from different web-
sites. However, information is often stored within a PDF and, consequently, information of different products cannot be directly compared or queried. Within that context, the research presents an improved use of that information, when orderly collected in a database, as that developed within INNOVance project. Indeed, information stored in the database can be easily compared and queried. Moreover, linking information in the database and information provided by BIModels, environmental impacts of technological solutions and buildings can be easily assessed through automated processes.

**Logical definition**

The paper reports a case study related to the assessment of global warming potential (GWP). The GWP impact information is commonly related to a specific material referred to a functional unit. In a BIModel, objects represent construction elements (technological solutions and/or technological systems) that usually are constructed using one or more materials. The database can store all the information related to the specific material; then, materials can be used for virtually construct each technological solution that can be assembled in technological systems (Figure 2).

Technological solutions and technological systems are characterized by specific geometrical information (e.g., the thickness of the wall) that are reported both in the database and in the geometrical model. That could lead to the generation of discrepancies and inconsistencies between the model and the information related to the objects contained in the database. Thus, the coherence between the database and the geometrical model must be verified. The geometrical model contains all the information related to the geometrical characteristics of the elements (e.g., area, volume, thickness), while the database collects all the size features (e.g., thickness for walls, height and width for windows) and the non-geometric information. By coupling those kinds of information and by applying specific algorithms, the environmental impact of a technological solution and/or a technological system can be evaluated in an automated way. Consequently, obtaining the quantities of each technological solution and/or technological system within a project and coupling them with information stored in the database, the environmental impacts of a whole building can be assessed.
The definition of the link between the geometrical model and the database is allowed through the unique code associated to the classification systems and defined within the portal, as previously presented. Thus, including that code as informative content of the objects in the BIModel, it is possible to directly retrieve the related information from the database. Using a standardized structure allows to define stable rules, specific for each element class. In a BIM environment, a class can be defined as a set of relations and rules to control the parameters by which singular specific element of the class (called element instances) can be generated (Eastman et al., 2011). Thus, for each element class, different rules must be defined also in the algorithm for the assessment of environmental indicators for several reasons, as:

- the extraction of information from the database: in fact, different information has to be accessed in relation to the considered element class. For example, the number of leaves is required for windows but not for walls;
- the calculation rules to be applied to that information. As an example, when evaluating the environmental impact of windows, the weight (in kg) of a profile needs to be considered using its linear dimensions; whilst, evaluating the environmental impact of walls, the volume (m3) and the density (in kg/m3) of an insulation panel needs to be considered.

Therefore, after defining the information required for the environmental assessment of each technological system, a set of rules has been created for matching the information in the database to the right object in the BIModel. For reaching that purpose, a specific application has been developed through Dynamo, a visual programming environment, integrated with customized Python scripts (Figure 3).

Therefore, a workflow (Figure 4) has been proposed for enhancing an automated process for the evaluation of environmental indicators, coupling information in BIModels and in the database on the web-portal (structured within INNOVance project) and creating customized rules for different element classes.

**Case study application**

The workflow has been validated on a test model that contains basic objects (doors, windows, walls) defined through the portal. Each element is characterized by its fundamental information (the set of information that are provided by the BIM authoring tool, i.e. Autodesk Revit in the presented case) enriched by the code that links each element type to the correct information stored in the database. A type can be defined as a subset of a specific class which groups elements with the same characteristic features (e.g., thickness and number of layers for a wall). As shown in Figure 5, elements in the BIModel are described through:

- a specific name, that is defined at the project level and can be used in the project environment;
- a code, that remains the same for every project that uses the same element type.
For example, in different projects the name C.V.01 can be associated to element types that are different to each other, whilst the code (C003.5OJ89.JFGHV.O0.8R74J.W6.8RE92) is unique for each element type, as it is the result of the choices made in the classification system (those choices are always the same, even when the same element type is used in different projects).

The objects used in the test model are defined with a Level of Development (LOD) that is reasonably high because the evaluation of the GWP needs the definition of the specific materials and layers that compose each element. In accordance with the Italian standard UNI 11337:2017 [5], the reached LOD for all the objects (doors, windows and walls) is LOD E. The informative content required for reaching LOD E is intended combining the information provided by the geometrical model and by the database.

The proposed application has been developed through the following steps:

- considering that different algorithms and calculation rules need to be applied and associated to different elements, the first step of the workflow analyzes the element classes defined in the geometrical model and directs the data in the correct data flow, through rules (as shown in Figure 3);
- in a second step, geometrical information and the code are extracted from the BIModel and stored in a temporary list (Figure 6). Using the code, the dataset related to the specific object is isolated and the useful data are extracted (selecting the data accordingly to the specific element class). The extraction of the only data related to the specific application on which the script is focused is possible because the data field is every time in the same position and is called with the same name in the database;
- the final step combines geometrical data extracted from the model and GWP information referred to the component materials provided by the database, calculating the GWP of the selected element.

Extending that process to each element of the model, it is possible to evaluate the global GWP impact referred to technological solutions and systems and, thus, to the whole building (Figure 7).

The automated system includes also a verification process for validating the information extracted from the geometrical model and the ones provided by the database. In particular, geometrical information of the same element is compared between the two sources (geometrical model and database) and
an error message is shown if some discrepancies or inconsistencies are revealed (Figure 8).

The development of the case study highlights an important aspect characterizing the data structure proposed by the portal. In a BIModel, usually, there are several kinds of information that are represented using the geometrical representation without any relation with the informative content. For example, in the proposed model, doors have a graphical representation of their open direction but no information related to it. Therefore, an automated process cannot use that information in order to perform calculation or other activities on the specific object. In the specific case study, the number of leaves of windows is a fundamental information for the calculation of the GWP of the specific element type. That information is well represented in a geometrical way in the BIModel but no informative fields are commonly defined. In a traditional process, that lack of informative fields could hinder the definition of automated scripts. Instead, in the proposed structure, the number of leaves are identified in the database. Consequently, that information can be used in the automated process allowing a correct calculation of the required data fields.

**DISCUSSION**

The proposed solution aims to overcome barriers and difficulties derived from the fragmentation of information among actors and along building stages.

The application presented in the paper concerns environmental aspects. However, the same considerations can be extended to other sectors, characterized by the same issues, as:

- each stakeholder (especially manufacturers) collects their information (not only environmental information) and promotes their use through personal webpages; instead, having a standardized structure adopted at national level enhances their visibility and competition;
- information stored in PDF cannot be reused in an automatic way, e.g. applying algorithms; instead, the research demonstrates how information can be re-used if orderly stored in a database;
- generally, there is not a direct link among information provided by manufacturers and objects (especially, BIM objects) in a project; instead, the code proposed in INNOVance project allows to create that link and enhances
the fruition of information stored in different databases, also through applications that are not related to one single project:

- it is often difficult to compare objects belonging to the same element class, but described by different manufacturers (e.g., information is provided with different units of measure); instead, collecting information in a standardized structure enhances comparisons because information is always expressed in the same way and stored in the same section of the database.

A direct and easy fruition of information is possible through a BIM-based portal. The presented portal has been developed for enhancing the collection, sharing and exchanging of information, according to the standardized structure. However, nowadays, the portal has been released only as a prototype. Additional resources are required for optimizing and in-
creasing the diffusion of the tool. However, the background data structure implemented in the portal represents a challenging point in the project and allows the further development of automated procedures for the use of stored information.

CONCLUSION

The development of a classification system and computational technical datasheets accessible through the BIM-based portal aims to improve actual building processes through a standardized structure for collecting building-related information, that is still lacking in the Italian construction sector.

The standardized structure applies to the information flow of the construction process and affects all subjects and phases related to it (such as planning, procurement, production, purchasing/supplying, construction, usage, maintenance and disposal).

Therefore, the results of the project support collaborative design and construction, providing a shared database and promoting the usability of data and information through dedicated applications.

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From digital design to physical model

Origami techniques applied to dynamic paneling shapes for acoustic performance control

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The recent trend toward non-standard and free form architecture has generated a lot of debate among the Scientific Community. The reasons can be found in the renewed interest in organic shapes, in addition to recent and powerful capabilities of parametric platforms. In this regard, the Visual Programming Language (VPL) interface gives a high level of freedom and control for conceiving complex shapes. The geometric problems in identifying a suitable shape have been addressed by relying on the study of Origami. The control of variable geometry has required the use of algorithmic models that ensure fast changes and free control of the model, besides a physical one made of rigid cardboard to simulate its rigid-foldability. The aim is to present a prototype of an adaptive structure, with an acoustic application, to control sound quality and perception in spaces where this has a central role, such as theatres or concert halls.

Keywords: parametric modeling, generative design, shape and form studies, acoustics conditions, digital Representation

INTRODUCTION (MLT UZ)
Over the last several decades, the recent trend toward non-standard and free form architecture has been deeply discussed by the Scientific Community. The reasons can be found in the renewed interest in organic shapes, in addition to recent and powerful capabilities of parametric platforms. In this regard, the Visual Programming Language (VPL) interface gives a high level of freedom and control for conceiving complex shapes. The geometric problems in identifying a suitable shape have been addressed by relying on the study of Origami: the terms derive from the Japanese “ori” (fold) and “kami” (paper), which has already been used for engineering applications. The control of variable geometry has required the use of algorithmic models to ensure fast changes and free control of the model, by defining the rules that control folding geometries and the succession of folds found in nature: it is possible to apply these principles to the architecture and engineering
sectors to obtain an analogous mechanism for similar functionalities. The mix of different variables can generate a wide variety of possibilities that can be used to study possible applications and efficient adaptive structures. The project analyzes a proposal for an adaptive structure able to change its spatial conformation and to address changing external acoustic conditions. The aim of this research is to present a prototype of an adaptive structure related to acoustic models, to control sound quality and perception in spaces where this has a central role, such as a theatre or concert hall.

STATE-OF-THE-ART AND REFERENCES (MLT MBP)

One of the main recurrent issues related to the architecture field is the international debate on Smart Cities: this topic encloses the vision of experts about how the city will be in the next future considering the effects of the massive diffusion of the digital technologies. At the regard, experts previsions suggest that both the cities and the single buildings (Smart Buildings) will be more and more populated by sensors able to optimize consumptions and to improve the life quality of the inhabitants. According to the diffusion of these systems, different experiments have been performed to understand how parametric shapes and structures can react to some external variable conditions (Smart Structures). A lot of focus has been put into the Adaptive Structures able to change their shape or to change their own geometrical or material (Smart Materials) features to answer to the environmental changes. The whole surface of the Deployable Structures (Pellegrino, 2001) undergoes a unique movement generated by the application of an actuating force in a single point, whereas transformable structures limit their movement to single elements located inside fixed supporting frames and so this requires a distributed actuation systems. Such adaptive capability is often realized by folding mechanisms of a certain surface performed by a precise distribution of elements and forces. The theme of adaptiveness has been faced at first with a biomimetic analysis, studying the geometries and mechanisms of deployable structure that are present in nature. The dynamism of an origami model, intended as the result of rules that control folding geometries and the succession of folds, is recognizable in some dynamics of recent architectural projects. We propose some issues: 1. This building designed by H. Larsen Architects presents a peculiar shading system made by a composition of movable triangular panels, mounted through supporting hinges that allow them to move by changing their degree of openness. The panels are moved by different small electric motors controlled by a network of sensors which measures the external lighting conditions and the air temperature (Figure 1.1).

Al Bahr Towers is an office tower designed by Aedas Architects in Abu Dhabi. The double skin system has been designed by taking into consideration the sun path and the inclination of the solar rays on the façade in the different periods. The layout of the skin is inspired by a hexagonal origami pattern. Triangular panels are hinged on fix frames that allow them to perform their rotational movement (Figure 1.2).

The pavilion EXPO Yeosu has been realized for the 2012 Expo in Korea by SOMA. The theme is “The living Ocean and Coast”: in fact it is characterized by a dynamic façade, composed by vertical strips, whose changes reproduce the waves’ movement, favoring the maintenance of optimal internal conditions and reducing the energy consumption of the building (Figure 1.3).

Resonant Chamber has been built using digital modeling and manufacturing tools, acoustic performance simulation, material tests. The first prototype has been developed by the studio RVTR, and installed at the University of Michigan Taubman in 2012. It is an indoor interactive system able to modify the acoustic surroundings throughout the transformation of the geometry and the use of electro-acoustic technologies and materials. This system allows to modify the degree of acoustic exposure of the surfaces. The software simulates the physical behavior of the structure, giving the possibility to study both the acoustic response related to different posi-
Figure 1
(1) The façade is composed by 1600 elements of perforated sheet metal. Al Bahr Towers (2) presents a shading system to control the solar rays, as for the structure of the EXPO pavilion (3): (4) the kinetic system of the Resonant Chamber governs the sound level and the reverberation time.

THEORETICAL BASES
Origami (UZ)
In traditional origami, folds determine the shape and constitute the essence also through its transformation over time, by linking together 2D and 3D. Each bend, its repeatability and its possible reversibility, becomes part of the structure of the form that has been defined during the transformation process. Born to be a paper and/or tissue modeling tool, origami has rapidly evolved into rigid material management in accordance with Huzita-Hatori’s axioms (Tachi, 2010). As said, in a rigid origami the rotation axis between flat surfaces, and hence a hinge is recognizable in its folds: at the regard, the choice of material used further defines the constraints. Working with paper means taking into account a sequence of steps bound by trying not to tear the material. Working with rigid materials - having a defined thickness that results in an increase in the section on each layer overlap - can lead to work with modular elements to reduce the number of folds and to simplify the shape. In this case, the modularity of the components explored in several modifications, offers further flexibility to the project. The starting point is a flat surface constituted by a sheet of paper, so performing the deployment movement by distributing the forces applied in one point thanks to the folding patterns. The category of the rigid foldable ensures the possibility to realize them with rigid material. Different pattern of tessellation - all the points are moving approaching or departing on non-linear paths and the surface extension changes along the movement - were taken into consideration: their deployment movement were controlled through the Rigid Origami Simulator by Tachi. Doing that, the Miura-Ori pattern, considered as one of the simplest and most diffuse rigid origami pattern, has been analyzed. It has already been used in engineer application which creates a periodical corrugation with increasing depth during the folding procedure, till reaching the flat folded condition.

Computational, Parametric and Algorithmic Design (MLT)
New design and representation options, better known as parametric and algorithmic procedures, are characterized by two computational design methods: computation means mathematical, so it implies a method related to logic and calculus. Computerization instead is related to the power of a computer system, used to enter and process data. Computation
Parameter design has introduced new opportunities in several fields, from design to fabrication, from construction to management. Parametric design can be defined as the capability to control and develop a project through parameters (De Kestelier et al. 2013), set since the beginning of the design process, then controlled and managed at any stage of the design development. This implies a rigorous mental process useful to correctly set both the parameters and the constraints (Kolarevic et al. 2013). The resulting design solution therefore is not unique, but there is a whole list of variations generated by several combinations of the parameters. One of the main advantages relies on the possibility to perform variations: the resulting geometry can be obtained in real-time, allowing a dynamic and interactive optimization process. It is possible to identify two categories of parametric models that are commonly used in practice: the first one (parametric variation - PV) provides the generation of different design instances by the variation of parameters that control the shape. A previous design phase has been required to set correctly the parameters and to obtain the desired variations; the result is called parameterized modeling schema: the same geometry in fact could be ruled by different schemas. The second category is known as parametric combinations (PC) or associative geometry models. It works with the composition of different geometrical entities according to set rules; the design options are the result of several combinations of the defined starting shapes. Finally, the merging of these two methods creates hybrid parametric models where the combination of parametrized base entities allows shape variations, useful for the geometrical exploration and the definition of the final design solution. Regarding to the Algorithmic Design, the final model is defined by a succession of operational steps that can be expressed through an algorithmic language. An algorithm is a procedure to obtain a certain result following a defined process composed by a finite list of basic and simple actions. The results is a well-defined list of successive instructions and a graphic representation of the resulting geometry. These operations can be manually written or performed by a computer: in the latter case the algorithm has to be written in a specific language, with the support of a scripting editor, linked to a 3D modeler or graphic software able to display the result (Figure 2). Some visual programming editor can be used to write an algorithm through nodes (the operations) and links (dataflow between the nodes). Another possibility, enabled by the parametric and computational tools, is to modify the design by integrating the results of different analysis, realized aiming to evaluate the performance of the building. The flexibility of the model, in fact, guarantees its easy manipulation at different design stages; the optimization process for the building efficiency thus becomes faster, resulting in an easier way to produce different design solutions. These are called evolutionary algorithms and they calculate the geometrical solution that best fits to the set variables defined in the first phases (Mendez et al. 2014). In this case the designer does not draw directly the shape, but he designs the process and the rules necessary to generate it (form-finding process).

**DESIGN DEVELOPMENT (MLT MBP UZ)**

The 3D geometry traditionally conceived had to be considered in a new dynamic dimension (4D) that...
best satisfies the environmental requirements. One of the more unexplored aspects of architecture design is the acoustic component; the research around sound and all the related aspects is still ongoing and a lack of tools, both for design and tests, complicates acoustic designer life, reducing the quality of the product; so, the aim of this work is the design of a prototypical adaptive structure, able to be critically evaluated by an acoustic application, to control sound quality and perception in spaces where this has a central role, such as theatre or concert hall. The topic is the control of reflections by creating surfaces with variable conformation: flat conditions generate specular reflections, while rough states generate scattering effects. The structure requirements that drove the design process have been developed through the following steps: 1. Flat starting condition and rough final condition; 2. Rigid deployment movement and simple actuation system; 3. Need to cover a large surface; 4. Application suitable for different orientations; 5. Aesthetic features.

**Geometry selection, tests and assessments**

As said, the geometry definition was based on the study of the Origami. Different patterns were taken into consideration. According to the Miura-Ori pattern, it is quite interesting to notice that the resulting support structure would have been too complex and visible in some condition, revealing moreover a background surface. A sort of second acoustic skin that with an air gap behind with a low reflection capacity would be necessary. The problems emerged from the analysis of a tessellation pattern drove the research to simpler pattern relevant for matrix configurations that can be used as bases for more complex origami. Different patterns have been tested through digital simulation and paper folding. The first pattern analyzed shows an intermediate state between the open and flat fold condition, with a geometric configuration that could determine scattering effect. Its displayed a critical issue: the volume included in the intermediate state has not a closed profile that can be lied on a surface; this aspect could cause a great sound absorption, which should be avoided in scattering objects. A new form has been found out by simplifying a larger one, keeping the central scheme that still constitutes a flat and rigidly foldable pattern. The new simulation points out that the external edges of the surface constitute a profile able to generate a closed volume with no gap. The resulting shape has a cross conformation with the points on the external edges move on linear trajectories while the central point that moves vertically and it can be considered the actuation point for the whole movement of the geometry. Similar features have been conceived in the third pattern which has a central square instead of a single point and a greater amount of folding lines and vertices with high degree value so with more lines converging in (Figure 3). The digital simulation with Grasshopper has revealed a slight deformation on the quadratic faces during the deployment movement; this has led to add two folding lines to split them in triangular faces ensuring more flexibility to the whole geometry. The selected pattern has a squared shape composed by 16 triangular faces of two types; the faces of the same type are coupled and one is specular to another. The starting input of the algorithmic model used for movement simulation and geometric analysis is a mesh composed by faces equivalent to the faces of the pattern; the folding lines are divided into mountain and valley folds. The physic engine of the plug-in Kangaroo, through a dedicated tool for the Origami, reproduces the folding movement. Within the digital environment it is possible to set other acting forces or to indicate constraints that limit or guide the movement; they have been applied to ensure that the external points can move on rectilinear trajectories and to reproduce the actuating force on the central point. Adding constraints it is possible to observe the behavior of the structure by simulating the real installation with anchor points and obliged movements. The use of an algorithmic ensured the mathematical management applied to each point of the movement, beside the graphic representation of the geometrical entity and its animation. Doing that, it is possible to measure
the folding angles between every face, a very crucial data useful for modeling thick panels of the structure. The planarity of the faces during the deployment can be tested to evaluate if the rigidity is kept. The algorithmic model moreover allows to scale the geometry, a precise dimension of the base panel therefore can be defined after acoustic considerations; the reflecting surface thus would be composed by the repetition of this base module, each of them will require a distinct actuation system that permits to control the amount of scattering surface in the space, answering to the changing needs. The squared shape ensures a complete cover factor of a flat surface without leaving empty space between close modules in the flat condition. Then, the coating of several components defines the aesthetic aspect of the wall and its acoustic behavior.

**Digital model**
The algorithm virtually folds the mesh according to the folding angle applying rigidity and stiffness to the side of the faces. Other forces can be added to the model creating anchor points or obliged movements. The output is calculated per each frame of the deployment movement and it is constituted by the folded mesh and the points positions from which it is possible to extract their coordinates and trajectories. It allows several operations related to the output geometries in order to perform the necessary tests and obtain the desired information. A planarity test for the faces of the panel has been applied as the display of the side’s lengths, to check their deformation along the deployment. The same model has been used to calculate the folding angles between each face at the final condition to draw the faces and to realize a functioning prototype of the module using real dimensions, avoiding the issues related with the thickness of the material by following the tapered panel method by Tachi.

**Physical prototypes for acoustic tests (LS AA)**
The test samples have to guarantee a low value of absorption factor (α) to produce good results, thus they should be realized both with rigid material and with a specific thickness that avoids dispersion for resonance effect. Different material and techniques have been tested for the acoustic tests, aiming to find the best mix of material and production effort. The first attempt has been realized gluing wood panels on a cardboard engraved on the two side to reproduce the different folding lines. It has been used a 3D print to obtain a precise model. The physical model presents (l = 7 cm) some printing defects, thought these could be corrected, the time necessary to realize one piece took about 2 hours with a very low thickness of the external surface, that could cause a bad acoustic performance: for these limits...
the 3D printing have been discarded. The wood has very good acoustic properties for its rigidity and density, furthermore it is largely appreciated by architects for its visual aspect. Each of the 45 panels necessary for the acoustic measurement is composed by 16 faces for a total amount of 720 single pieces that needed to be cut and then joint together in the correct position with a good precision. Laser-cut machines provide very sharp cuts of different material, guaranteeing a fast production. The geometries have been exported directly from the algorithmic model by sectioning the surface, in its open state to obtain the profiles of the surface that constitute the supporting element for the faces (Figure 4). Then, the samples have been assembled for the acoustic measurement. To ensure sharp edges and no gap between the panels, the internal edges of the mountain folds have been smoothed. The faces in fact have been mounted considering from the ideal surface an internal extrusion to generate the thickness of the panels. In this way the inner side of the faces in correspondence of mountain valley would have collided without any smooth operation. All the panels have been varnished with a transparent finishing to enhance the reflectiveness of the surface. The design process of the surface studied in this work has been mainly focused on its sound diffusion characteristics, i.e. scattering properties. Contrary to the acoustic absorp-
tion properties, the diffusive characterization of different surfaces is less pursued and very often leads to inaccurate objective evaluations of the acoustic parameters for different environments. However, these surfaces have been extensively studied subjectively and objectively in concert halls where their effects influence the reduction of echoes and sound concentration, and help in improving the uniformity of the sound quality distribution among the audience area (Beranek, 1996). Beside the tangible effects on the perceptual aspects of the sound field within a space (Torres et al. 2000; Ruy et al. 2008; Shtrepi et al., 2015), the assessment of the diffusive properties result crucial for the accuracy in acoustic simulations based on the geometrical acoustic principles (Vorländ er, 1995). This evidence has led to the standard (ISO 17497, 2004) for acoustic measurements of the diffusive properties. ISO 17497 defines the scattering and the diffusion coefficients, which are related to a quantitative and a qualitative description of the diffusive properties, respectively. In this work the scattering coefficient properties, which represent the energy ratio between the diffusively reflected and the total reflected energy, have been considered since they are used in acoustic simulation software as input data. Thus, by using this standard, valid databases can be generated and used in the preliminary phases of the design process to make evidence based choices that could guide a performance-based design and become helpful to a multidisciplinary panel of practitioners.

Variable acoustic properties have been used extensively for performance spaces in order to recreate different conditions based on the purpose of the performance. One of the well-known examples is the ESPRO hall at IRCAM (Peutz, 1978; Shtrepi et al., 2016), where the variable acoustics is obtained by rotating triangular prisms with different acoustic properties as well as diffusive conditions. Since the spectral properties of the sound sources, i.e. musical instruments and voices, in concert halls cover almost the entire range of audible frequencies, it is suggested to maximize the sound diffusion at all frequencies. Therefore, the design of diffusive surfaces should aim to increase the scattering properties at a broad range of frequencies. This objective has guided the design of the diffusive surfaces configurations in this paper based on geometrical design rules, i.e. the scattering phenomenon is more likely to be generated when corrugations are of the order of magnitude of the wavelength.

ACOUSTIC MEASUREMENTS (LS AA)

The acoustic analysis consisted of both acoustic measurements and simulations. The measurements, which aimed to characterize the absorptive and scattering properties, have been performed for three different samples based on the recommendations of ISO 17497-1. The simulations have been performed for a small multipurpose hall (“Aula Magna Giovanni Agnelli” at Politecnico di Torino) by applying the acoustic properties of the measured samples in the model of a hybrid acoustic software named Odeon.

Scattering properties

The measurements have been performed in the 1:5 scale reverberation room (Figure 5, a, b, c) at the Applied Acoustics Lab at Politecnico di Torino. Three square samples (0.54x0.54 m) have been built using the same scale factor. The samples differ from each other with regard to the dimensions of the diffusing elements, i.e. with regard to the lowest scattering frequency limit (Figure 5, f). The first panel is made of the largest elements (Figure 5, a), the second is made of the smallest elements (Figure 5, b), and the third is a random combination of the largest and the smallest elements (Figure 5, c). The results of the scattering coefficients measurements (Figure 5, d) showed that the use of randomized irregularities (sample 3) could improve its properties at lower frequencies similarly to the sample made of the largest elements (sample 1). However, the diffusive properties of these samples have been largely influenced by the properties of the fiberboard used in their production. It could be expected that more reflective materials (e.g. plastic) could lead to higher values of scattering coefficients.
Odeon Simulations

In order to have a more complete understanding of the behavior of the adaptive panel, it has been applied in the lateral walls of the Odeon model of “Aula Magna Giovanni Agnelli” at Politecnico di Torino. The room has a fan-shaped plan and a tilted audience area. Its length is 31 m and its width varies from 17 m at the front to 21.5 m at the rear. The hall has been formerly characterized acoustically through in-situ measurements which resulted in a reverberation time of 1.58 s at mid frequencies. Odeon is a hybrid simulation model that takes into account the diffusive properties of the surfaces by applying the scattering coefficient values to flat modeled surfaces or by directly modelling the diffusive patterns (Christensen, 2013). Both these modelling methods (Figure 6, a and b) have been used in this study in order to investigate the accuracy of the simulations based on the modelling method and availability of the scattering input data. The results (Figure 6, c) showed that both methods lead to similar results. Therefore, an accurate evaluation of the acoustic properties of the diffusive surfaces could be helpful to diminish the efforts regarding modelling details and consequently reduce the evaluation time in the design workflow.

CONCLUSION

The work started with an analysis of the state-of-the-art and related professional applications on the theme of adaptive structures. Then, some principles were analyzed: foldable geometries, modeling and prototyping process as well as the capability to manage the development of the project considering all the issues involved. The project took into consideration the acoustic theme, aiming to produce a proposal of an adaptive structure able to increase the efficiency and versatility of close environment, with a specific regard to conference and music halls. To solve specific issues, the reading and the understanding of important scientific publications (i.e. thick rigid origami) was crucial. In addition, the laboratory measurement was essential to determine the scattering coefficient of a surface covered with the selected geometry necessary to answer to this need. The deep study of the specific application contributes to enhance the completeness of the work, giving a description of its behavior that often lacks in the presentation of similar solutions. In order to provide a more complete and wide work, after having measure the scattering coefficient of the panels, an installation inside an existing space has been simulated; this study was crucial to understand their real effect on a sound field, by comparing the obtained results with the reference case. The analysis shows an evident change in the distribution of the energy which ensures a real impact of the scattering diffusion on the environment perception. Music and speech require different reverberation times to provide suitable clarity and definition levels. A static space will always provide the same conditions; the choice of adaptive panels ensures the possibility to modify the space and the acoustic response of the surfaces. Such versatility opens up new ways to conceive structures including the dimension of time. The traditionally conceived three-dimensional geometry had to change in the fourth dimension: in fact, the proposed solution
is an adaptive panel able to modify its spatial configuration by provoking a change in sound reflection which rebound on the acoustic of the room. The research and the examples are still in their preliminary phase, the effects of a massive introduction of adaptive products in all the aspect of human life are difficult to predict, but of course they will generate a significant innovation affecting our society, our habits and our cities. At this days, we are seeing the evolution of the relationship between thinking and making, which originally was attended in the action of the hand of the craft-person artist and then was expressed by the design; Drawing plays its role from making to thinking and the coming back to its early conception as technical language no more simply considered as an active tool of the creative process (Lo Turco et al. 2016).

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The rise in robotics is not only changing fabrication research in architecture but increasingly providing opportunities for animating the materiality of architecture, offering responsive, performative and adaptive design possibilities for the built environment. A fundamental challenge with robotics is its suitability to safe, and comfortable use in proximity to the human body. Here we present the preliminary results of the Roamniture Project, a hybrid approach to developing kinetic architecture based on a combination of rigid and soft body dynamics.

Keywords: Kinetic Architecture, Soft Robotics, Soft Architecture, Furniture

INTRODUCTION

Robotics are not just changing fabrication in architecture but increasingly providing opportunities for animating the materiality of architecture offering responsive, performative and adaptive design possibilities for the built environment. A fundamental challenge with robotics is their suitability to safe, and comfortable use in proximity to the human body. Industrial mechanical principles with rigid-body dynamics characterised early exploration of Kinetic Architecture such as Frederick Kiesler’s Raumbühne (space stage, 1924), or Vladimir Tatlin’s Monument to the Third International (1919-20). Later Archigram imagined Walking Cities (Cook 2009) and Cedric Price the Fun Palace (Price 1968) and today we are seeing the realisation of some of these ideas in Diller Scofidio + Renfro The Shed [5] project opening in 2019. The approach to the transformability of The Shed, borrows from industrial rigid-body dynamics and the traditions of theatre rigging being able to expand and contract by rolling the telescoping shell on rails. Transformations occur out of reach of the public. Similarly, Chuck Hoberman’s Iris Dome (Kassabian et al 1999) elevates his expanding mechanisms up out of reach as a transforming roof. Furthermore, a variety of projects in recent years have investigated building envelope surface transformations e.g. Bloom by DO|SU Studio Architecture (2012) (Orhon 2016), Ned Khan’s kinetic wind responsive facades (Ryu et al. 2015) or Al Bahar Towers responsive facade (Elghazi et al. 2014) in Abu Dhabi which feature actuated solar system attached to the rigid structure. What these examples point to is that many popular examples of kinetic architecture are characterised by rigid-body principles, and do not address an architectures direct material relationship to inhabitants bodies and their movement.

Soft Architecture

Looking towards softer kinetics we were drawn first to architectures pneumatic experimentation of the 1960s were inflatables critiqued the hardness and
inflexible forms of modernism. Architects such as J.P. Jungmann and his Dyodon (1968) (Pauletti, et al. 2005) project for pneumatic dwelling environment, or Jose Miguel de Prada Poole and project La Casa Jonás (1968) [2] developed proposals for dwellings principally reliant on complex inter-connect inflatable cushions. Meanwhile Austria architects Haus-Rucker-Co and Coop Himmelblau through provocative installations begun to test the feasibility of a radically soft architecture. Coop Himmelblau’s motto was ‘an architecture that is as variable as a cloud’ (Noever 2007) and appropriately so they have built many installations that expressed this idea in early 70s and 80s. Projects such as Villa Rosa (1968), Wolke- The Cloud (1968), Herz Stadt - der weisse Anzug - Heart City - the white suit (1969), exploring transformable, volume changing pneumatic structures and ‘the possibilities of technology as a “natural” extension of the body’ (Vidler 2000).

In the UK, Mark Fisher, studying under Peter Cook at AA introduced a series of pneumatic experiments as a way of real time space response to user’s requirements, by expansion and contraction of its pneumatic structure. Projects like Automat (1968), Dynamat (1969-72) (Mullen 2014) and Responsive Dwelling Project (1973-75) demonstrate Fisher’s fascination with dynamically changeable pneumatic structures. Similar ideas are found in Sean R. Wellesley-Miller projects done at MIT - Prototype of ‘air-coil-system’ (1971) and Prototype of ‘binary cell system’ (1971). Ant Farm, a radical architecture collective based in Berkeley, California, issued the Inflatocookbook (1971), a guide to the construction and realization of inflatable architecture, and presented many projects such as Clean Air Pod (1970) and Pillow (1970) (Lewallen et al. 2004). Frei Otto who demonstrated his research explorations in the 1970s, later came to be the inspiration to pneumatic motion and soft systems of contemporary architects to follow. He presented ‘Motion sequence of pneumatic studies with tension bands’ in 1979, where he discussed hydro-skeleton of caterpillars, worms and other animals.

Negroponte’s seminal publication Soft Architecture Machine (1975) (Negroponte 1975), stated that soft materials, such as inflatable plastics, were at the moment the most natural material for responsive architecture. His notion of softness however extended into thinking about the softness of systems as well as materials and lay the intellectual basis for responsive architecture research such as that produced at the Hyperbody group at TU Delft led by Kas Oosterhuis. Hyperbody has shown projects such as Emotive House (2002), NSA Muscle (2003) and Muscle-Body (2005) (Oosterhuis et al. 2004). In 2006 Michael Fox et al, built Bubbles (Fox 2009), an interactive spatially adaptable pneumatic environment, which consisted of large air-bags or “bubbles” that inflate and deflate in reaction to visitors. Commercial use of inflatable architecture has remained limited to deployable but unresponsive systems. Some of the explanations for this limited adoption of softer approaches to responsive architecture lie in material reliability, challenges to control systems, and the relatively small number of research groups exploring this space. In recent years there has been a revival in interest in softer architecture that parallels developments in the state of the art of robotics, and material research.

**Soft Robotics**

The development of Industrial robotics have been historically based on rigid-body dynamics. The focus of control has been on the relationship between motors, loads, and minimising elasticity in linkages to track and position “end effectors” within working spaces. These work spaces are rarely occupied by human presence and up till today, the vast majority of industrial robotics function within highly controlled, humanless environments.

New requirements for robots to work in proximity to human beings and to manipulate more complex objects has encouraged the development of compliant actuation systems that cause no or less damage during inadvertent contact, have superior good shock tolerance, are lighter, exhibit lower inertia, use less power and more accurate and stable in
a variety of tasks. Compliant actuators can be found in walking and running robots for example exploiting the natural dynamics such as Denise (Wisse 2004), Flame (Hobbelen et al. 2008), Lucy (Vanderborght et al. 2008), Mowgli (Niiyama et al. 2008), BiMasc (Hurst et al. 2007), Handle etc. Developments in compliant robotics are associated with combination of expertise from very diverse disciplines such as innovative 3D printing, mechanical engineering, microfluidics, biorobotics etc. Numerous new trends and applications have emerged such as Exoskeletons resulting in various launched prototypes - suitX MAX, The Active Pelvis Orthosis, Ekso GT Exoskeleton (Chen and al. 2016), suitX Phoenix Exoskeleton (Leibowitz 2016) and many others. These advances prove promising potential for application as well in architecture and product design related to Human Robot Interaction (HRI), which require close physical contact, and robotic integration into our environments.

Material elasticity is a common characteristic of compliant robotics. Silicone rubbers are being widely explored for the embodied behaviour that can be programmed by careful arrangement of internal air channels. Applications have included soft end effector grippers because of their ability to take the shape of the objects they encounter and their high friction contact. A wide variety of soft elastomeric materials has been tested, in order to optimize their design to achieve required operation space such as soft fluidic actuators consisting of elastomeric matrices with embedded flexible materials (e.g. cloth, paper, fiber, particles). Soft actuators are preferred over rigid actuators when it comes to robotic applications for physical human interaction and delicate object manipulation. Soft robotics utilise pneumatic actuation in combination with morphological design, sensing and control for ‘soft bodies composed of soft materials, soft actuators and sensors [that] will be capable of soft movements and soft and safe interaction with humans’ (Pfeifer et al. 2012). One of the examples is Cecilia Laschi et al. with their Soft robotic octopus arm (2012) (Laschi et al. 2012). It’s worth noting that Mark Fishers and Frei Otto’s experimentation resembles some of soft silicon robotics we are seeing appear today. The polymer rubber experiments of Architect Omar Khan installations such as Open Columns (2007), Homeostat (2007), employing the soft kinetics of silicone rubber. These were however passive elastic structures externally actuated by cables. More recently ETH researchers have looked at applications of silicone soft robots with Dino Rossi et al, Adaptive Solar Facade Project (2011) (Rossi et al. 2014). At Interactive Architecture Lab, we have explored a variety of kinetic projects using cast silicone soft robots however the scale issues have limited prototyping to small scale deformable components networked to produce larger surfaces (Glynn et al. 2013). We have moved our Silicone Soft Robotics towards wearable interfaces for haptic interaction such as the Sarotis project (2016) [4], which is an experimental prosthesis that was designed to study whether a person’s awareness of space could be amplified using live 3D scanning technologies controlling the inflation and deflation of soft robotic wearable. The applications of soft actuation around the body seem particularly promising but many questions remain about the feasibility of such systems to scale to architectural applications. We are looking to explore actuation of structures between the scale of the body and architecture and have chosen the architectural tradition of the furniture prototype to develop solutions that could lead to larger scale constructions.

**METHODODOLOGY**

Mies van der Rohe said: “A chair is a very difficult object. A skyscraper is almost easier. That is why Chippendale is famous” (Mies quote appeared in Time Magazine, Feb. 18, 1957). Many 20th-century architects like Mies - including Le Corbusier, Marcel Breuer, Alvar Aalto, and Eero Saarinen designed chairs and other furniture pieces that would not only occupy their own buildings but also act as a way of thinking about the intricate details, the formal and material choices that characterised their architecture. For example, comparison between Jürgen Mayer H.’s Lo Glo for Vitra Design Museum brings to mind the Lazika
Pier he realized in Georgia in 2012. The creation of new furniture is implicit in the development of a new architecture. In 2013 architect Rem Koolhaas unveiled a collection of rotating, sliding and motorised furniture for US furniture brand Knoll. Seeking kinetic solutions not characterised by the rigid dynamics of Koolhaas’s approach we initially studied examples of inflatable furniture. Long term durability of inflatable furniture which importantly must maintain air pressure to be stable is a very commonly cited problem leading us to look for structural systems that have stability when deflated and inflated providing a range of stable configurable opportunities. In the field of Meta-Material Research we encountered a fertile research space of rigid and soft material combinations which demonstrate a variety of promising stable configurations that can be actuated by air (Overvelde et al. 2017).

With the ability to reconfigure between several stable states, our interests have moved towards making furniture flexible in terms of several possible functions. We draw on methodologies in metamaterial research that are themselves partly inspired by origami design techniques which provide an ideal platform for the design of reconfigurable systems. In a variety of applications, researchers are looking at transformable molecular structures with embedded actuation potentially harnessing heat exchange, light or chemical energy sources for applications in nano-robotics and “smart” material engineering. Origami principles relating to specific geometries are of particular interest in Molecular Engineering research currently taking place at the Dutch Institute for Atomic and Molecular Physics (AMOLF). Our visit to their labs in April 2017 revealed that alongside the use of advanced mathematical models, paper based origami prototypes remain an essential method of research exploration helping to visualise potential problems and possibilities with geometric configurations. Reconfigurable prismatic structure materials were explored by AMOLF in collaboration with Chuck Hoberman, with the important difference that they are manually controlled and do not seek to solve issues of human proximity that our approach is looking towards nor use soft actuation approaches that would enable more compliant behaviour. We examined two soft actuation techniques.

**Pouch Motors**

Pouch Motors, were developed exploring printable actuators for enhancing mass-fabrication of robots from sheet materials using easily accessible tools and methods. The pouch motors consist of gas-tight bladders - pouches, fabricated by heat bond-
ing which is an essential part of the fabrication. The theoretical maximum contraction ratio of the linear pouch motor is 36%. Pouch motors tested in the Lab, were made out of 0.18mm PVC sheet and proved to have 10% contraction ratio, as compared to linear pouch motors made in Robotics Lab, MIT made of 0.102mm PVC sheet, where the measured maximum stroke and tension of the linear pouch motor were up to 28% and 100N. These pneumatic actuators perform better in case they are fabricated with custom stencils and a heat sealing head for 3-axis CNC machines in order to achieve needed precision for programmable transformations. Nonetheless, for quick experimentation and prototyping manual sealing is simple and does not require expensive hardware. This approach satisfied our aims for an easy and cheap fabrication, and actuation of lightweight structures provided some initially interesting results. However durability was low under loads and pouch motors were found to not scale sufficiently. (see Figures 1 and 2)

Air Muscles
Commonly referred to by a variety of terms, such as Pneumatic Artificial Muscles (PAMs), air muscles or McKibben muscles, soft actuators are often made up by an elastic internal bladder surrounded by a braided mesh shell. In case of complex structures which have more rigid states, thus never fold flat, we determined that air muscles are found to work better, being stronger and able to effectively move the structure from one stable state to another. Industrial air muscle actuators are resilient and relatively affordable but at the Interactive Architecture Lab we found in our earlier Golem Project [1] that air muscles sufficiently strong (200N of lift) could be self-fabricated. Our DIY muscles proved to have a contraction ratio of 25% compared to the commercial ones such as Festo's 33% [3].

Mobility: The Roamniture Project
The implicit opportunity of using a robotic technology is that it can become mobile. Our experiments presented below with pouch and air muscles would often appear to exhibit crawling behaviours when actuated so we have embraced this compelling feature for its interaction possibilities with its environment and human users. The first stage of experiments presented below focus on the fundamental mechanics and in doing so we share our design approach which is looking at hybrid soft-rigid dynamics enabled by meta-material principles of bistable and other multi-stable structures, which we see as advantageous over simply inflatable structures

RESULTS
Our preliminary research has revealed materials-structural compositions that offer promising transformable characteristics with a variety of states of structural stability. Below we share a selection of the most promising. Our prototype's combinations of rigid material and soft actuation provide performance characteristics of soft robotics in terms of compliancy, smooth movement and low inertia, while also demonstrating stability necessary to develop furniture prototypes in our next stage of research. We refrain from too much speculation at this point on the furniture applications but do want to point out some initial thoughts on their use.
**Hexagonal Prism**

5 stable states (2 primary), the hexagonal base has six rectangular sides. This polyhedron has 8 faces, 18 edges, and 12 vertices. All the edges are uniformly extruded and each extruded unit cell is modelled as a set of rigid faces connected by linear torsional springs, with periodic boundary conditions applied to the vertices located on the boundaries. Degree of freedom of a single unit is 5, while its space-filling tessellation or combination with other units such as triangular prisms, cubes, dodecagonal prisms and others has a lot fewer degrees of freedom, in most cases 2. Moreover, the results indicate that most of the reconfigurable structures are characterized by fewer degrees of freedom than the constituent individual polyhedral. It is found that the mobility of the unit cells is affected by two parameters: the average connectivity of the unit cell, and the average number of modes of the individual polyhedral (Figure 3).

**Truncated Octahedron**

5 Stable States (Figure 4). A truncated octahedron is constructed from a regular octahedron by the removal of six right square pyramids, one from each point. It has 14 faces (8 regular hexagonal and 6 square), 36 edges, and 24 vertices. In this example, all the edges are uniformly extruded in the direction normal to their faces to construct the extruded unit cell. This results in a 3D structure which has the faces that are rigid and the structure can only fold along the edges, creating a unit that has 5 degrees of freedom, when all 14 faces are extruded. Changing these 5 angles we deform the internal structure and reconfigure the unit into many specific shapes. However, when the space tessellation is done, and this unit is combined or multiplied, new space-filling structure becomes completely rigid having a degree of freedom 0.
hedron has more potential arrangements when it comes to furniture - working surface / sitting places / space divider / storage spaces. As a divider it can be set to provide more or less privacy, having closed or open cell faces. In terms of lighting it could offer several potential applications where translucency of differently materialized faces could play a significant role. However, materials characterized by higher number of degrees of freedom are characterized by more ‘soft’ deformation modes. As such, materials with ndof = 1 seem most promising for the design of reconfigurable materials, since they can be reconfigured along a specific direction, while still being able to carry loads in all other directions. This has to be taken into consideration when combining different materials onto a single unit.

Figure 5
Actuated Tripod (Truncated octahedra modification), air muscle actuation

Actuated Tripod: Truncated octahedra modification
Previously we established that space tessellation of truncated octahedra, when all 14 faces are extruded, becomes rigid having a degree of freedom ndof=0. Shown here, is the example of the individual unit of truncated octahedral, having only 6 extruded faces, while 8 remain rigid. With this principle, both individual unit and a new space tessellation have a degree of freedom ndof=1, in comparison to uniformly extruded previous one where the single unit had 5, but the space tessellation 0 ndof. Three out of six faces went through single extrusion, while the remaining three went through double extrusion. Pneumatic muscles (Figure 5) can raise the height of the structure while remaining perfectly stable, thus giving the idea of variable and adjustable furniture use. Contraction and relaxation of the air muscle (ratio of 25 %) can furthermore achieve certain types of crawling like motion. The movement we got with this test is rather smooth and can be compared to human breathing. In relation to people's proximity of the furniture, such degree of speed is desirable and perceived as pleasant. Possible applications of such a model could range from sitting places towards inclined and adjustable working surfaces with changeable heights (today often introduced for health purposes).

Modified truncated octahedra array
Aforementioned, to further explore the potential of bistability and possible transformation this is the spatial array of 8 tripod units (6 extruded faces / 8 rigid) - modified truncated octahedra, which enhances the reconfigurability of the whole structure having the same degree of freedom as its single unit, ndof=1. This means that apart from its initial state this structure has only one more stable state. By actuating it we discovered that air muscles (Figure 6) work well with these complex geometrical combinations, however acting different when applied to a single unit tripod than to an array of them, based on the limitations of freedom in their inter connections. Importantly, when it comes to an array, air muscles must be placed equally along the structure in each individual tripod’s “leg pockets” in order to uniformly affect the whole unit and remain stable. By placing air muscles, actuated and controlled separately in opposite legs of the tripods, we are able to achieve the movement which causes transformation between the initial to the second stable state.
DISCUSSION

The inherent behavioural features of soft metamaterial inspired systems provide a range of useful characteristics that lend themselves towards applications in furniture. In addition to compliance with the body, they include self-stabilisation. Our next steps will be to examine control systems that animate these and would allow automated, responsive and mobile behaviours.

Body motion planning for control of soft robotic furniture face significant challenges not faced in taking a rigid body approach. Body plans can not be computed with the classical mechanics of chains of rigid and rotational/sliding links. Instead the non-linear complexity of soft dynamic compositions demands alternative approaches. Whereas rigid robotic systems typically employ central control systems, our approach the Roamniture will in its next steps look to the inherent behavioural character of our material compositions and examine light-weight (both material and computationally speaking) systems for controlled motion and behaviour.

We intend to address this challenges when we incorporate distributed feedback control into our next prototypes.

As social scientists Herbert Simon pointed out in The Sciences of the Artificial (1969/1996 : 52) “An ant, viewed as a behaving system, is quite simple. The apparent complexity of its behaviour over time is largely a reflection of the complexity of the environment in which it finds itself.” This is an understanding all too often overlooked in robot design, and by extension robotic applications to architecture. As the Interactive Architecture Lab is interested in developing robust stimulus-response (behavioural robotics) strategies for system design we see it worth reflecting on even the most primitive of mobile robotic presidents. Grey Walter’s “tortoise” robots of the late 1940’s demonstrated elegantly that the environment itself is an essential driver of behaviour and that we might consider the modulation of the environment as a method of steering Roamniture rather than thinking only of the internal working states of the machine itself. The next steps of Roamniture will address not only the control systems within the dynamic structures themselves but also their sensitivity to their environment and the potential for the environment to modulate itself in order to control our behavioural furniture.

The remarkably animacy (lifelike quality) of Walter’s Tortoises came from their primitive yet continuous and purposeful stimulus-response interaction with their environment. We see this animacy as a positive quality to aspire to and our own air-muscle driven structures through not yet driven by purposeful systems, do exhibit animate qualities by the quality of their breathing motion. The potential for this gestures to exhibit a range of characters is in itself a fascinating unaddressed question latent in work like this. The Interactive Architecture Lab’s recent work with puppeteers has taught us that at the centre of communicating all emotional content is Breath. Soft Robotic Furniture has inherently emotive qualities that we intend to study further and take advantage of.

Whether our future steps of research will comprise out of large arrays of small units of geometries or scaling up of current geometries, will be guided by
experimentation with larger prototypes planned for the summer of 2017.

CONCLUSION
Our explorative experimentation with actuated metamaterial inspired structures presented in this paper demonstrate a range of encouraging possibilities for new design approaches to soft kinetic architecture. We have identified particular promising geometries that offer a range of shape changing forms and potential functions. By combination of hard and soft components, we imitate the morphology of both hard and soft nature of our own bodies. The next steps for use will be to look to the types of body-inspired stimulus-response control systems that can steer mobile behaviour. In the convergence of techniques from kinetic architecture and robotics our hybrid approach offers a new approach to developing a softer, more intimate, body responsive architecture.

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Articulate Objects

hard processes and soft effects

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If the design of environments and experiences has become a key concern for many contemporary designers and artists, then what is the medium that becomes most prevalent? Light. Although elusive (one might even say `withdrawn') and transitory, light can be seen as both objective and subjective content that is being explored by contemporary artists, designers, and architects. In addition, the very ephemeral quality of human experience means that light (although it is a condition which is made visible, objectified and transformed through its interactions with form and surface) is often, and strangely, disassociated from objective criteria. This paper uses two recently completed projects to outline an approach to overcoming tendency to separate the objective and subjective. It describes an approach which is positioned within contemporary theory and explored through processes, methods and outcomes. The work outlined explores how effects are theorized and instrumentalized through design processes not only as subjective or `soft', effective, atmospheric conditions, but as affective drivers of objective or `hard' processes.

INTRODUCTION

If the design of environments and experiences has become a key concern for many contemporary designers and artists, then what is the environmental medium that becomes most prevalent? Light. Although elusive (one might even say `withdrawn') and transitory, light can be seen as both objective and subjective content that is being explored by contemporary artists, designers, and architects (Author’s Note 1). The very notion of effects (re: the production of sensorial and subjective outcomes) could seem out of place when framed within the context of computational design and architecture. However, emerging from the critical speculative work of the 1970s and 80s on into the early digital explorations of the 1990s, the question of the effects has been critical if not core to contemporary spatial practices including architecture, interior design, and installation art. Bernard Tschumi (1997, p107), literally the Dean of Digital 1.0 (Author’s Note 2) said, “Sensuality has been known to overcome even the most rational of buildings...Carry it to excess and it will reveal both the traces of reason and the sensual experience of space. Simultaneously.” Tshumi’s statement rings true in that he is articulating complex, nuanced sets of relationships which emerge between effects and objects, or as he says “reason and the sensual experience of space”. Similarly, Antoine Picon (2010, p147) has described an interior/exterior relationship between “…phenomena and noumena; that is, between objects and events as we perceive them and objects and events as they truly are.”
Building upon this basic foundation, the primary assertion of this paper is that ephemeral and subjective visual effects (emerging primarily through relations between light and form) can either be the result of, or inform and drive the design, fabrication and installation of objects (Author’s Note 3). This assertion frames two recently realized projects: Waller Phantasm (WPh), installed in Austin, Texas in 2015 (see Figure 1), and Flowering Phantasm (FPh), installed in Amsterdam, The Netherlands in 2016 (see Figure 2), and Enghien les Bains, France in 2017. These particular works use existing, environmental conditions of light as well as numerically controlled artificial light in combination with material, surface and form which is organized, fabricated, and assembled parametrically to generate a range of visual and optical effects.

There are three basic premises which are important to consider relative to both the works’ underlying assertion and the eCAADe Conference. First, contemporary works of architecture and design, most likely sparked by the rise of digital computation and fabrication regimes, have moved beyond the smooth, un-articulated surfaces of the early digital into articulated surfaces and objects (Authors Note 4). Second, novel outcomes and approaches to design and fabrication can be generated from basic design operations and programming methods afforded by accessible software packages. And finally, observations of outcomes, processes and methods may be selected from individual projects and projected forward as basic codes for new project instantiations and iterations. Fundamentally, the paper uses the projects as examples which help to synthesize questions and outline novel approaches to the generation of effects.

In this process, effective conditions which are generated through the computational design, fabrication, assembly, and contextual installation of complex, or articulate, objects are foregrounded (see Figure 2).

**FOUNDATIONS OF EFFECTS**

As a primary effects generator, light is certainly a complex and extensive topic. It may be understood through many lenses including science, art, architec-
ture, interior design, art history, phenomenology and perception to name a few. Although the norm for many architects and designers, is to explore light primarily through digital rendering processes, yielding pixels or raster images or photos of the project after-the-fact, there are certainly contemporary examples of more complex entanglements of form, material and effects. A few projects and practitioners which have been foundational to the prioritization of effects include the ‘Blur Building’ by Diller Scofidio from the early 2000s, and more recent works by installation artists Anish Kappoor, Tomas Saraceno, and Olafur Eliasson. Although not necessarily associated explicitly with ‘the digital’ or ‘computational’, each of these works employ highly complex design and fabrication processes to realize works where effects and subjective experience are prioritized.

Building on these references, a set of projects were developed as investigations of this relationship between form, surface, materiality and effects. The projects used a combination of light-weight materials with reflective surfaces in combination with category forms and light projections to generate immersive atmospheres. The most important effect produced by this system was the caustic (see Figure 3). A caustic is a visual effect produced by the convergence of light rays which is generated by material and form. In short, “...the effect results from a discrete manipulation of phenomena that is facilitated by the material but not determined by it.” (Addington, p203) The intricate caustic effect is produced by rays of light reflecting off of a formally manipulated surface with reflective material properties. This does implicate questions surrounding embellishment and ornament within design. More importantly, interrogating the caustic effect yielded the realization that light can be understood as vectors which may become instances of geometry (see Figures 1 and 4). In addition, we can explore and visualize the interaction between this ‘geometric’ light and geometric form through thin membranes, or surfaces (see Figure 3). However, as a visual effect, light may also conceal or blur the surface or formal delimitation. Once a range of interactions between light and form is created, we have effectively developed parametric light and form. The interactions between these conditions generate effects which typically fall into the broad category of optics. (Authors Note 5)

**SCRIPTING PROCESSES**

Within WPh and FPh, light is understood as both an effective and affective condition, as both acting and being acted upon. This understanding buttresses the primary assertion of the work related to the relationship between objects and effects. In previous projects (see Figure 3). Light was observed to have two key characteristics. It consists of parametric and geometric relationships (associated with objective form and materiality) as well as sensorial and spatial properties (associated with atmosphere and subjective experience). Certainly behaviors prompted by material and form drive the emergence of effects within the projects, but formal considerations and processes of design had to be developed to maximize these qualities. For Waller Phantasm (WPh) and Flowering Phantasm (FPh), project specific requirements such as contextual durability and fabrication constraints (inflected by the desire to expand complex optical and visual effects) drive much of the technical development.
Each of the projects are developed as armatures that are located within contextual conditions and host numerically controlled LED lighting elements. The productions, or effects, in their deep relation to underlying armatures as well as form and surface, cannot be de-coupled from the development of the tools, and thus, the development of the tools and techniques are critical. (Authors Note 6) The projects are organized, developed and resolved primarily though parametric, node-based programming. In these cases I have used readily available software Rhino by McNeel with the visual programming plugin, Grasshopper. This program allows me to easily build programs which both allow for form and for the development of surface. Being parametric, the software affords the development of subtle variations which may be quickly tested through visualization methods. Ultimately, the information from this design process is captured, organized, and fed directly to computer controlled machines for fabrication. (Authors Note 7)

**Scripting Waller Phantasm**

For the project, Waller Phantasm (WPh), the technical development built first on the conceptual understanding of light as a form of vector based geometry. This geometry was developed into a material armature which was both structural and linked to a materialization of light by using LED Neon strips. The formal armature was made up of a networked set of linear elements which, as all networks, converged at points in space. Elements were laid-out initially as loose wire frame models which established overall formal character (see Figure 4). These linear elements would ultimately host linear LED Neon lights, and the 3d printed nodes also allowed for the attachment of nylon cabling which spanned the site to attach to other critical points in the existing context (Authors Note 8).

Ultimately, points of convergence within the network became defined as a series of nodes which, if designed properly, would become a jig which would maintain precise coordinate locations for the assembly of each linear element. These nodes were ultimately scripted to also allow for watertight, solid .stl format output which would facilitate fabrication using cloud-based 3d printing services (see Figure 5). Most importantly, the development of the programming focused on how to maintain unique geometric and contextual requirements and create a variable thickness of shell to meet structural and cost parameters. The use of Grasshopper allowed for the creation of a parametric definition which used standard components such as Pipe Variable and Surface Difference and Surface Union (see Figure 6). This definition afforded for the creation of nodes which not only provided for the connection of a network of linear aluminum tubes, but also created support. In addition, each node contained a point for connection a cable element which would span and link to larger contextual conditions.
Scripting Flowering Phantasm

Diverging from the previous project, Flowering Phantasm’s supporting armature emerged from the scripting process as the by-product of a set of formal/surface articulations. Where the previous work used a combination of modeling methods, here the totality of the work from the double curving proxy surface to the articulated surface units (petals) was generated using a set of Grasshopper definitions.

The use of scripts and parametric definitions developed in Grasshopper allowed for the development of an approach which explores the relationship between a parametrically defined form which becomes a proxy for a heterogeneous surface and structural system (see Figure 7). Further, the underlying surface is then re-used in later stages to generate areas for surface perforation and the development of additional layers of LED fiber.

With the desire to generate each part of the project through visual programming, the beginning script defined a proxy surface (see Figure 8) which becomes the basis for the development of the project which moves from smoothness to articulation. Working through a single script the project afforded both the generation of a parametric formal proxy which was smooth and double curving, and the generation of articulated heterogeneous assembly system where geometries were controlled by both fabrication and material qualities. (see Figure 7). This is at least tangentially related to contemporary questions of computational ‘excess’ where, as Mario Carpo (p81) suggests, “Subdivisions-based programs originally used to simulate continuous curves and surfaces, are now often tweaked to achieve the opposite effect, and segments or patches are left large enough for the surface to look rough or angular.”

To conserve computing power, once the form of the first surface reached desirability, it was baked and then referenced into the second part of the script which began to articulate the surface as flat panels (see Figures 7 and 9). Flat panels were desirable because, as described, the project was to be fabricated using flat sheet methods and tools. In this case, CNC Routing and CNC Water Jet Cutting were used to fabricate the pieces.

The beginning surface was panelized then each panel was given a tolerance relative to its neighbors. This tolerance was built up through successive steps with this 2mm offset being the first.

The panels, called ‘petals’ in the context of the project, were the given added tolerance by generating randomized radiused corners (see Figure 9). Creating radiused corners not only increased tolerance for assembly but also generated new figure/ground relationships which link to the conceptual approach. The petals were understood as individ-
ual entities which remained somewhat autonomous or withdrawn from their neighbors while simultaneously acting in aggregate rather than acting as discrete assemblies (Authors Note 9).

Once the base panels were generated, the proxy was superimposed into the panelized system (see Figure 10). This originally was an accidental condition which was created by turning on the proxy surface and panelized surface simultaneously. The resulting condition was clearly notable and through the development of a multi-scalar surface, the relationship was examined as a set of nested topographic lines generating a new figure on the flat panels themselves. Ultimately, these emergent geometric figures would host a set of surface perforations and would also be inflated digitally and become pneumatically controlled objects.

Once the basic petals were designed, the work had to focus on the structure and support of these elements (see Figure 11). With the goal of heterogeneous assemblage, the inner structure was developed as a three-fold set of layers which would ultimately be materialized using the same material. The outer part of this structural system had to support and locate each of the petals in space (similar to the nodal system developed for WPh). The scripts ultimately allowed for an ease of transition from digital modeling the fabrication.

**MATERIALITY, FABRICATION, AND INSTALLATION**

It is certain that materials must be considered relative to functional requirements such as stability, machinability and availability. However, materials are now also asked to retain the capacity for transformation of contextual information in the form of visual and optical effects. In discussing a transformation of our relationship to materiality, Michelle Addington (p201) goes further in her essay ‘Magic or Material’, stating that ‘...we should be asking about what behaviors we could manipulate...’ through design processes. She follows that ‘...the behaviors are what matter and we should recognized that we can produce our desired behaviors...’ For example, the outer material of Flowering Phantasm begins to resonate more deeply with its cultural and physical contexts. The gold finish of the petals resonates with the tradition of gold de-
tails on buildings which are found throughout Amsterdam. and the 'hairs' (in plants small hairs found on the surfaces are called trichomes) and systemic biological resonances fit with the context of the garden in which the project is set while also containing references to traditions of textile crafts.

CNC WaterJet cutting was used for the 3mm aluminum inner structure which was designed to host the computer controlled LED light fixtures (see Figure 13). Arduino controlled blower fans were also located within the structure and were programmed to expand and contract the soft, textile bags. The textile bags were also generated through the scripting process and fabricated using CNC knife cutting and sewn together by hand. Flowering Phantasm is at first a purely visual experience. People see the object, and are drawn through this visual provocation to experience an object that seems familiar without being referenced directly to anything in the world (see Figure 12). To generate this visual outcome, FPh used a range of numerically controlled fabrication techniques each with it’s particular material agenda.

CNC routing was used to fabricate the delicate, .02” gold, mirror anodized aluminum, exterior petal. Each of these units were unique and also highly perforated. The formal profile and perforations both provide for visual and functional conditions. The perforations allow light out, views in, reduce wind uplift in outdoor settings.

Rather than using materials which align with flat sheet processes, Waller Phantasm used 3d printing as its primary advanced fabrication mode. Each node was 3d Printed using the on-demand print service, Shapeways, which allowed for the use of different material from what was readily available locally. The suppleness of 3d printing allowed for a vast quantity of nodal pieces to be fabricated quickly and relatively cheaply using a material that also provided a good degree of structural capacity and robustness (see Figure 14). In addition, this material choice provided for additional joint strength without additional cost. The linear tubes were measured directly from model and cut using standard techniques. These tubes ultimately supported the linear led lighting units. Linear Units were dimensioned directly out of the digital file and cut using a standard chop saw. The LED lights were pre-fabricated by a third party and shipped to
Austin, Texas for installation onto the linear elements. The entire linear system was situated by a secondary armature which was designed and CNC routed out of plywood. This element fit snugly over an existing railing and support the primary linear, structural system which visually and structurally performs as a hybrid of rigid frame and para-textile.

**Observations on Outcomes**

Although each work described within this paper may be seen as singular project, Waller Phantasm and the subsequent work Flowering Phantasm are actually the evolutionary result of set of previous projects. Each project is a step of a process of honing and defining questions and generating new inflections. The possibilities for each novel condition are developed into new conditions as they are developed and re-instantiated. The processes, and by extension the produced outcomes, are constantly reconstituting and updating themselves. Their codes are passed forward, (a form of design-based genetic drive) and their logics and techniques are honed. It is a heuristic model for practice that is inherently speculative without being prescriptive. This mode of operation allows for accidental discoveries, such as the caustic effect described previously (see Figure 3), to become the core of future explorations. The projects as assemblages of theory, process, and outcomes present opportunities rather than didactic solutions. They ultimately provoke rather than tell.

The work does seek to use ephemeral conditions of light as ways of enabling the object to move beyond something that is conceptually and formally inert. Work such as Flowering Phantasm is at times is moving so slowly (either the lighting or the pneumatics) that it is difficult to discern that is doing anything. This aspect of the work engages the contemporary theory of Triple O (the OOO, or Object Oriented Ontology) which allows the work to conceptually engage and physically explore working with questions of elusiveness and natural and human engagements across multiple timescales which do not necessarily operate at the scale of human perception only. At other times, the work moves quickly with light color and speed changing through the use of algorithms which control and vary its timing. People are drawn to these displays much as we might be drawn into
natural situations with animals or plants who may only display certain behaviors or certain moments of flowering during very short time frames. The combination of heterogeneous components and effects is experienced sometimes as totality that people might describe as ‘atmosphere’ (see Figure 15). The type of atmospheric conditions produced by this variegated set of forms, materials, and effects become a pliable relational construct that engages people. It inflects our understanding of relationships between things in a more nuanced way while realizing that the invisible connects and orders as much as the material.

CONCLUSION

In synthesizing technical and conceptual approaches to effects-oriented design, the most critical effect produced is the work itself. In the conceptual and technical framework described, the object as both effect and affect is never a singular condition and therefore cannot be expressed as single, un-articulated form. Digital design and computational process provide the platforms for both the conceptual potential and the procedural development of this mode of contemporary practice. Articulate Objects are then defined as projects which engage in the generation of effects that are maximized through the development of overall form and the aggregation and excessive articulation of localized surface characteristics. These surface characteristics and by extension the visual and optical effects generated are informed by a move away from continuity and smoothness toward assemblages of surface parts and layering of surface and structural support. Within projects such as Flowering Phantasm, controlled processes which are focused on effects production yield outcomes where the function of parts works in and out of gestalt relationships. In other words, the parts and layers simultaneously work in together in contingent relationships and as autonomous units. They generate visual effects such as parallax views (which emerges subjectively through individual movement in combination with articulations of form and surface), and blur (which is generated by layered lighting, material and formal properties). The relationship between controlled geometry and materiality in relationship to the production of effects not only provides the frame for the work, but also represents a larger desire to transcend the modernist, dialectical opposition of subjective and objective within the spatial design fields of architecture and interior design.

The articulate object, because it is understood as a heterogeneous assemblage, is allowed to develop its own personality traits or characteristics. Characteristics include surface articulations such as perforations which host LED fibers, material properties such as color and reflectivity, and overall formal conditions. These characteristics then interact with people and other contextual surroundings by capturing light, projecting light, and transforming light through visual and surface conditions (see Figure 16). In this interaction, they generate both pre-figured and emergent qualities such as parallax or blur. The assemblage of parts that are articulated to operate individually and to interact together, react to generate productions as a set of visual, formal and material effects. For example, with Flowering Phantasm, the assemblage pieces, broadly structure, surface and ‘hair’, never fully join together. They operate in parallel, and by allowing them to remain somewhat independent the effects are amplified.

Finally, the work outlined within this paper seeks to explore notions of aggregated systems as contemporary design ecologies which generate effects
through their engagement with contextual environments and interactions with people. The pieces are motivated by a set of key questions regarding complex relationships which emerge between the soft (or subjective) and the hard (or objective). This motivation drives the works’ development not only from concept to installation but also to future works. Where “space’ and ‘environment’ are ways in which objects sensually relate to the other objects in their vicinity, including larger contexts in which they find themselves” (Morton, p43), atmospheres and effects of spatiality, visuality and experience are made manifest based on multi-directional relationships with the assemblage which is also affected in the process. Ultimately, explorations seeking to synthesize theoretical and technical approaches through an effects-driven methodology are important and timely to discuss within the context of conference dedicated to research and exploration of computation. The underlying observations and questions are open, yet critical to expanding the territories of architecture and interior design as being objective, procedural and computationally driven as well as subjective, and effects-driven, spatial and formal disciplines.

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Exhaustive Exploration of Modular Design Options to Inform Decision Making

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Europe is facing an increasing demand for new construction, which is pushing the industry away from traditional construction technology towards prefabrication and Mass-Customization. However, prefabrication-based construction requires a more efficient, better informed decision making process due to the increased difficulty of on-site variations. Furthermore, the lack of means to navigate the whole spectrum of solutions for a given design problem using traditional tools, and the absence of the manufacturer's input in the early phases of the project can present significant challenges for the efficiency of the design and construction process. As a way to face these challenges, this paper presents an approach, realized as an Autodesk Dynamo-for-Revit package called Box Module Generator (BMG), which enables the exhaustive generation of configurations for a given building based on a construction scheme that utilizes Box Prefabricates. The output can be sorted, dissected and explored by users in various ways and the building geometry can be generated automatically in a Building Information Modeling environment. This makes it possible for the projects' stakeholders to browse thousands of potential design alternatives, which would otherwise be very hard to explore manually, or using traditional parametric modelers.

Keywords: Prefabrication, Box Prefabricates, Design Tools, Design Automation, Building Information Modeling, Dynamo

INTRODUCTION
Attempts at prefabricating building modules to provide large amounts of well-constructed spaces date back at least to the Crimean war in 1854, when Isambard Kingdom Brunel designed and built a 1,000 patient hospital in Renkioi using prefabricated timber units that were shipped to be assembled on-site (Gibb, 1999). The trend of using prefabrication in construction to minimize time and waste continued to rise during the eighteenth and nineteenth centuries, especially after World War II, to cover the post-war housing needs in Europe (Huang et al., 2006). The need for high quality, speedy construction is still ubiquitous. Europe in general, and Germany with its very buoyant labor market in particular, are facing a fast growing need for new construction. For example, to accommodate the increase in inhabitants in Munich between 2011 and 2016 alone, 55,000 homes are needed simply to cover the gap in the supply of housing units (Möbert, 2017). This highly challeng-
ing environment demands more efficiency in design and construction, giving rise to the idea of Mass Customization.

Mass Customization corresponds to technologies and systems that are used to deliver goods and services in order to meet individual needs with enough variety and customization and with mass production efficiency (Piroozfar and Piller, 2013). One of the key strategies for Mass Customization is modularization, whereby building designs are based on modular components and subsystems that are prefabricated in parallel in a factory and afterwards assembled on the construction site to satisfy the individual requirements for each building design (Huang et al., 2006). Mass-Customization and prefabrication offer significant advantages to the construction industry including time saving in construction schedules, lower construction cost, tighter quality control, less material waste, better sustainability, enhanced occupational health and safety, lower manpower requirements, and a safer working environment (Tam et al., 2007) (Rathnapala, 2009) (McGraw Hill Construction, 2011).

One of the approaches to Mass Customization and prefabrication is “Box Prefabricates”. Building designs that can afford a high level of modularization are standardized into a group of box modules, which are large space prefabricates enclosing whole rooms or a group of rooms (Lewicki, 1966). These box modules are suitable for a lot of building types, can be repeated by stacking, and can be 95% decorated and fitted with the necessary equipment in factory, reducing the work on-site to the assembly of the units and connecting them to services (Knaack, 2012). This approach comes with a multitude of benefits: consistent quality because units are manufactured under factory conditions, Just-in-Time delivery to construction site to decrease waste and prevent material theft on-site, and time savings up to 50% in projects’ schedules (Gibb, 1999). An example of such an approach is shown in Figure 1, where 78 box modules acting as rooms for senior citizens were installed in a social center in Fieberbrunn, Austria, complete with flooring, windows, doors, bath equipment and furnishings. Box Prefabricates can be constructed from steel, wood, or concrete; they can also be self-supported or installed on a supporting structure (Staib et al., 2008). They can thus be mass-customized to meet the individual needs of each project with different sizes, finishes, fittings, and with closed or open sides to fit both open plan and closed rooms schemes (See Figure 2).

But the nature of design for prefabrication-based construction differs from that of the traditional construction because of the increased difficulty of on-site variations to the design when using prefabricated components (Maxwell, 2015). That means that programming and design phases have to be more robust and better informed than in traditional construction to minimize the possibility of last-minute design changes. Furthermore, designers do not think about spaces or modules only in a three-dimensional paradigm. In addition to the length, width, and height of a space or a module, designers may also
consider orientation, cost, number of floors, and natural lighting, among a group of parameters (n). Designers have to navigate the full extent of varieties of these n-dimensional spaces in order to make well-informed design decisions, a process that could be very daunting and labor intensive. Even in ordinary design problems, the architect may contemplate very few solutions like few needles in the haystack of all the configurations satisfying the boundary conditions of the design problem (Galle, 1981). While using geometric parametric modelers can help designers, explore multiple design parameters more quickly and efficiently, they do not possess the ability to explore the entire set of possible solutions, nor do they offer the rich data environment enabled by Building Information Modeling (BIM) platforms. The problem can be further complicated by the lack of interaction with prefabrication experts early on the design project, leading to significant flows in project planning, misinformed design decisions and unnecessary rework.

By providing a platform that can generate an exhaustive list of all possible design configurations and the outcomes of these configurations in a rich BIM environment, stakeholders can make more informed decisions with regard to prefabrication-based projects, and easily utilize the BIM models to any (n) number of analyses necessary for a given project. The intent of the research summarized here is to provide a platform that enables the production of this exhaustive list for a given project in a modular construction scheme, with the scope being limited to Box Prefabricates. The range of input parameters integrates the input from prefabricators, owners, and the architects. The visual and numerical output can be sorted, filtered, and viewed in different ways that serve as a basis for the decision making process in the early design stages and design brief. The aim of this process is not to automate the design of the entire building with all details. Instead it serves as a way for stakeholders to rapidly assess hundreds or thousands of alternatives and extend the generated BIM models to any analysis environment needed.

### BACKGROUND

**Related work**

Retik and Warszawski (1994) presented a knowledge-based system that encapsulates prefabrication expertise for the automated detailed design of prefabricated buildings. This system receives the preliminary architectural design and then produces solutions for partitioning the building into modular components. Huang and Krawczyk (2007) proposed a web-based design system that can generate design options for modular houses based on the client's needs, captured via an online questionnaire. Diez et al. (2007) presented an automatic modular construction software environment “AUTMOD3” that offers two methods of modular design; the architects can input architectural plans that can be processed to obtain the modules needed for a house design, or they can make the design from scratch using a catalogue of 3D parametric modules. El-Zanfaly (2009) built a user interface to produce alternatives for modular housing arrangements. Through the interface, the user can vary the design parameters and specify a number of alternatives. The system will then produce 3D alternatives based on stochastic search. Kwiecinski et al. (2016) proposed a design method based on shape grammars, focusing on light wood frame construction for the automatic generation of housing layouts according to the users' requirements.
While these research efforts tried to tackle the existing need for an automated design and communication tool for prefabrication in design and construction, none of them approached the field of Box prefabricates. Additionally, most of the research focused on a stage of the design process where the decision for a prefabricated building has already been taken with a very specific design outcome in mind. What is lacking is a platform that provides a comprehensive look on all the possible design scenarios, allowing the users to get feedback for the feasibility of these scenarios in earlier stages. While online services such as Autodesk Project Fractal (Autodesk, 2017) can fulfill this role partially, it operates on three-dimensional geometry only and cannot handle BIM models (at the date of writing).

**Problem statement and objective**

The traditional manual approach or even geometric parametric modelers may not present the whole spectrum of solutions for a given design problem. A building is not only judged by its appearance or architectural style; designing a building needs careful consideration to a number of parameters. The problem can be further complicated by the lack of proper communication between owners, architects and construction experts from the early design stages. This becomes of special importance in projects based on Mass Customization and prefabrication because of the increased difficulty of on-site variations. This paper presents a tool that generates all the possible configurations of a building’s design that is based on Box Prefabricates, given input from the user regarding the maximum and minimum bounds of a set of parameters and the number of variations allowed for each parameter. The outcome can be sorted and dissected in a multitude of ways to enable the user to navigate the solution set and generate preliminary BIM models (See Figure 3). The tool fulfils a necessary
communicative role in conveying the manufacturer’s requirements to the architect, who in turn can easily communicate the full spectrum of design possibilities to the owner during the programming and the early design phases in a rich BIM environment that can be extended to further types of analyses when needed.

“Custom Nodes”, which are tailored to help the designer generate, filter, sort, and visualize an exhaustive set of solutions for projects based on Box Prefabricates. “Custom nodes” refer to reusable blocks of code, which can be utilized repeatedly by users across multiple projects for various project scenarios (Das et al., 2016). Custom nodes can contain blocks of visual code as well as written IronPython code, which is an implementation of the Python programming language that is tightly integrated with Microsoft’s .NET Framework. This enabled the authors to use Windows Forms, a graphical class library that is a part of the .Net Framework, to design a Graphical user interface (GUI) for BMG. The authors also used a custom Dynamo package called “Mandrill” by Konrad K. Sobon (Sobon, 2016) for parts of the GUI. The following subsections explain the general workflow, the structure of the Dynamo library, user inputs, outputs, and the GUI of the tool.

**General workflow and user inputs**
The general process starts with the input from architects, owners and manufacturers with regard to project requirements, local building regulations and construction limitations. For example the architect may acknowledge that the distance from the furthest point in any room and the stair should not be more than 35 m, which could decrease to 25m in high-rises (according to the building regulations in Germany: Musterbauordnung) (Stiftung et al., 2010). The manufacturer could determine that the maximum number of floors is six, and the dimensions of the units could range from 3*5 to 6*20 m with heights ranging from 3.2 to 3.6 m (Staib et al., 2008), all depending on the material used and transportation and lifting limitations. The owner may also have specific requirements for natural lighting, total guest capacity or other considerations.

The input parameters are then passed to the exhaustive generator, which generates all the possible combinations of the input parameters, calculates the outputs, and presents them to the user where he would be able to slice or sort them and finally gen-
erate the solutions he chooses as BIM models inside Revit. Figure 4 outlines the operations inside BMG and the corresponding Dynamo nodes. The input parameters include variable parameters (where a range of values is considered), which are the dimensions of the box unit, number of floors, floor height, fenestration dimensions, and outer building dimensions. The input also includes fixed parameters, which are corridor’s width, maximum distance between cores, ground floor height, the ratio of the ground floor size to the typical floor area, and the cost per square meter. The result provides information about the areas (individual unit, circulation, footprint, and built-up area), total building capacity, cost, window to wall ratio and total number of individual box units.

**System components**

BMG is composed of a group of custom nodes comprising a package inside Dynamo. An overview of these nodes is shown in Figure 5. The nodes are classified into GUI nodes, which aid the user in giving inputs and displaying/sorting outputs, and core nodes, which generate the solutions and the Revit geometry. The user can either use both sets of nodes together or the core nodes separately just for generating different configurations directly in Revit.

**BMG GUI Nodes.** The first GUI node is the “Input parameters” node, which initiates an input form asking...
the users for a set of input parameters (See Figure 6). The input parameters are classified into fixed parameters, which will be constant throughout all the generated solutions, and variable parameters, where the user has to input maximum and minimum bounds and number of variations for each parameter.

Once the input parameters are given, the GUI transfers the user to the sorting and slicing view triggered by the “Sort and Slice” node (See Figure 7). This view enables the user to slice through the generated results using a parallel coordinates graph and then either input the final parameters to generate a BIM model directly, or sort the results in an ascending or descending order by any of the input or output parameters. If the user opts for the later, the tool will display the sorted results window (See Figure 8), triggered by the “Display Sorted results” node. In this window, the user can select any of the sorted set of parameters and generate the Revit geometry.

**BMG Core Nodes.** The first of the two core nodes is the “Exhaustive Solution Generator” node, which performs a Cartesian product operation on the user inputs, the inputs are then passed to a Dynamo “code block” which encapsulates the mathematical formulas needed to calculate the outputs. After the user decides on the parameters, the “Module Geometry in Revit” triggers Revit to render the desired BIM model. Both of the core nodes can be used separately from the other GUI nodes. Figure 9 shows a group of rendered views of the Revit models produced by BMG.

**CONCLUSION**

The importance of Mass Customization and prefabrication in the construction industry will continue to grow, making use of the efficiency of factory conditions to produce building elements in compact time schedules, with greater quality control and minimal waste. However, programming and design for prefabrication-based construction need a better informed decision making process due to the increased difficulty of on-site variations. Combined with the lack of means to navigate the full extent of the solution space for a given project using traditional tools, and with the lack of means to integrate the manufacturer's expertise in the early phases of the project, this can present significant challenges for the efficiency of the design and decision making process.
means to rapidly assess hundreds or even thousands of possibilities and validate decisions during feasibility studies, programming and early design stages. Furthermore, Box Prefabricates are arranged in rectilinear stacked configurations to achieve maximum efficiency, so the research focuses on the possibilities of these rectilinear configurations. This research is part of a wider investigation into the usage of computer systems based on BIM to devise a decision support system for project stakeholders in early design stages to optimize project designs for prefabrication requirements and to integrate the expertise of prefabricators. While the scope of the current paper was limited to Box Prefabricates in particular, the future direction of the research will focus on developing a BIM-based framework to help the architects optimize building designs in early design stages in other fields of prefabrication-based construction. The aim is to reduce misinterpretations and discrepancies between architects’ design intent and requirements for prefabrication to reduce rework and ultimately to speed up the process to face an ever increasing demand for faster, more informed, and more efficient design and construction operations.

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This paper explores the process of digital materialization through robotic fabrication techniques by presenting three wooden projects. The analysis of the case studies is oriented to underline the impact that computation had on architectural construction due to its methodological and instrumental innovations over the last decades. The absorption of computing and digital fabrication logics within the discipline is explored from either an architectural point of view and from the improvements related to automation of the constructive process. On the one hand the case studies are caught because of the desire to expand material complexity and, on the other hand because of the integration with other technological systems. The narrative allows gathering pros and cons in three different investigative macro areas: material culture, methodological oversights, and operative setbacks coming from digital machine and communicational constraints. This analytical investigation helps the definition of a new pathway for future researches, looking forward the assimilation of digital materiality learning in building construction.

**Keywords:** computational design, file-to-factory, large-scale robotic woodworking, new production methods
not as a marginal remedy to architectural design, but as a methodical vehicle. The teleological studies on gestalt (form) and bildung (formation) epitomise the founding factors of the theory of morphology: this discipline has a major impact on architecture inasmuch it regards the evolution of form. This pivotal but general concept that is mainly borrowed from exact sciences reveals its operational potential in architectural design when paired with cybernetics. On a theoretical standpoint, first designing episodes started to embed the theories of formation, transformation and of growth of form within the project path and resulted instrumental to promote cybernetics concepts in the architectural investigative agenda.

The word cybernetics stems from Greek kybernetike, meaning governance: although it is referred to conceptions that appear far apart from architecture - namely control systems, or logic modelling - the intellectual domain of cybernetics advances the research of the “goodness of fit” (Alexander, 1964) by augmenting its transdisciplinary value. Cybernetics, defined “as a field that illuminates the concepts of adaption and control by way of abstraction” (Riiber, 2011), specifies that systems are built on regulation, adjustment and purpose. The advent of computational design, thanks to its generic and flexible nature, constitutes a convenient platform in matching the growing body of available information. It steers the generation of mutual interactions among constituents while the computed agent (the object) is distinguished from the computational process (the method). Rather than implying cybernetics as the oversampled way to control an architectural system by using technology (i.e. hardware or software technology), the most effective value of computational design arises from the opportunity to arrange manifold focuses, which are decoded and conceptualized as iteration, generation and variation of geometric formation. As consequence, the attention of a common digital approach is focused on the shift from a “pre-emptive act” (Sheil, 2012) towards a procedural process that implements performances relying on shapes validating innovative spatial configuration.

The relentless digital enhancement in architectural design has progressively transformed the architect’s drafting board into a software ecosystem, and has made the sequential separation between modeling, optimization, analysis and fabrication processes more evident. While strengthening further the separation between design and making already theorized centuries earlier by L. B. Alberti, the “computational fallacy” stated by S. Kwinter (2003) demands the seamless correspondence between original ideas and material fabrication as a resolving answer to a jammed computational scenario. Architects have already realized that computing is not only a convenient gizmo for formal and aesthetic investigations, but it inaugurates an operative dialogue with the digital manufacturing lattice on which the project can be based. Therefore emerging frameworks and techniques in the fields of design and construction are contributing to a disciplinary revolution due to the progressive convergence of computation and materialization.

Thus the recent achievements demonstrate the impact of IT on both the ideation and the digital manufacturing of unconventional prototypical architectures. A profound upheaval has been put in place by avant-garde academic and professional practices since the introduction of tailored CNC and robotic fabrication systems, mainly borrowed from automotive. In particular, the narrative traces different ways through which digital fabrication technologies are simultaneously developing and expanding the role of computation as interface between the digitally computed design and the physical world.

COMPUTATIONAL AND MATERIAL COALESCENCE

The digital turn has definitely triggered a considerable symbolic and systemic revaluation in architectural design; by the same token the digital manufacturing of material space has been introduced as one of the computational parameters. Once the mindset about forms that “are no longer designed but calculated” (Cache and Speaks, 1995) has been en-
The focus of the research shifts from the computable abstraction to the tangible computing of its manufacturing process. The same transdisciplinary key concepts - such as automation, adaptation, emergence, convergence, communication, efficiency, efficacy, and connectivity -, that have been the foundational thoughts for the transfer of cybernetics’ logics within the architectural designing flow, are now becoming paradigms addressed towards fabrication. Thus, the project conceptualized as a computational system transfers its rule-based design in criteria involving both digital machineries and materials. The spread of digital fabrication facilities in architecture activates the “new digital continuum” (Kolarevic, 2003) inasmuch capabilities like standardization or automation don’t represent simply practical solutions, but they become design parameters in assuring architectural qualities.

Three wooden structures are showed as representative of full-scale implications; they outline part of the evolving array of interoperable tools and processes that allow the design-to-production chain of non-standard outcomes. As matter of fact architects have developed pioneering and innovative material fabrication setups, which purposefully allow the transfer in actual-size constructions of essentials from manifold branches of knowledge as well as from different craft expertise. Material, manufacturing constraints and assembly logics become designing parameters proving that file-to-factory is not a process as linear and reductive as some detractor may claim (Sheil & Glynn, 2011). As M. Burry suggests, the digital fabrication advent has taken the credit of blurring the model and prototype boundaries (Sheil, 2012), focusing on a discipline that intertwines design and production.

**CASE STUDIES**

Amidst the broad array of digital fabrication applications, the dissertation chooses wooden structure as case studies in order to investigate theoretical statements. Architects are honing robotic and CNC fabrication techniques for manufacturing purposes reconsidering wood and its derivatives as suitable building materials for the experimental design researches at an actual scale and no longer as an out-of-date material. Recent years have seen unprecedented innovation of new technologies for “advancing wood architecture” (Menges et al., 2016).

The selected case studies - the Landesgartenschau Exhibition Hall (University of Stuttgart, 2014), the Woodchip Barn (Architectural Association, Design&Make, 2015), and the Digital Urban Orchard (Institute for Advanced Architecture of Catalonia, OTF, 2016) - bring forward different achievements and perspectives on digital fabrication in architecture to illustrate the interplay between the virtual design and the virtue of material.
As a prime example, the Landesgartenschau Exhibition Hall (LaGa from here on) largely demonstrates the efficiency of the “machinic morphospace” (Menges, 2012) first applied at a building size. The applied morphogenetic process explores the multifarious advantages arising from the reciprocal influence between the rationalization of biological rules, the material fabrication requirements and from the multiple performative applications. The entire constructive principle of this exhibition hall is based on the large-scale application of the robotically fabricated finger joint system, developed in the previous biomimetic research of the Research Pavilion 2011 by ICD and ITKE.

The LaGa’s final morphology results in a permanent, fully enclosed, insulated and waterproof building (Figure 1), which uses beech plywood plates as the primary load bearing elements. The resulting three layers’ sandwich dome-shaped shell considers solutions to the programmatic requests (two functional zones were required: a reception and an exhibition area) while applying a form-finding strategy oriented to generate a lightweight structure. In fact the implemented Agent-Based Modelling (ABM) algorithm allows the discretization of the doubly curved surface through planar subdivision accordingly to the Tangent Plane Intersection (TPI) strategy. Each individual and unique polygonal plate interacts with its neighbours ensuring the structural stability through the distribution of in-plane shear forces along the plate edges. The computed plate outlines visually reflect the changing of Gaussian curvature between the two computed synclastic main areas. Besides the programmatic, geometric and structural focusing, the plate-structure and the relative three-dimensional finger joints have been generated following also other parameters. For example the robotic workspace, the angle variety achievable by the robot-arm equipped with the spindle and paired with the turntable, and even assembly-related functionalities or material conditions, such as the stock material size (Figure 2).

This comprehensive computational approach, in making every detail adaptable to local and global geometric parameters, represent a valuable proof of concept of the integration of innovative constructive process and technological system - e.g. load-bearing structure and insulated sealed shell - within a computational protocol. However the resource-efficient lightweight structure and its corresponding fabrication procedures reveal minor cons. They directly arise from the high level of specialization in the study, limiting the conception stage of the design process and consequently the spatial configuration of the final shape.

The large-spanning and unprecedented Vierendeel-style truss built by the Design&Make team (Figure 3), while been focused on the evolutionary metaheuristic optimization placement technique, considers the substantial material parameter
in robotic fabrication as strength of the applied research. The Woodchip Barn project is entirely built with non-engineered wood and thoroughly relies on a data-driven process coming from the survey of the tree forks’ digital catalogue.

An ambition of the project is achieving a structural diversity not only thanks to the differentiated robotic processing, but also directly from the natural conformation of the 25 selected forks (Figure 4). Each one of them is wholly unique by nature and the shape is optimized by itself: the capacity of carrying “significant cantilevers with minimal material” (Self and Vercruysse, 2017) is exploited by a customized robotic fabrication setup that augments its inherent structural and geometric qualities. A 6-axis robot arm equipped with a routing spindle has machined each tenon-mortise connections; they were defined between each root and branch of the forks as volumetric subtraction of geometric primitives - e.g. cuboid, cylinder, truncated cone - correctly aligned. The tolerances management was a key point in the whole computational process, highlighting the consistent system of geometric references developed to ultimately achieve the maximum construction precision with irregular natural round-wood. The connection strategy designated the use of “steel bolts and split rings to provide tension and shear capacity” (Mollica and Self, 2016) to the compression transfer through timber-to-timber joints.

Besides the uniqueness and the noteworthy of the truss, the final result totally relies on the algorithmic process of metaheuristic repositioning of the forks selected from the photographic campaign done in the forest of Hooke Park. Whenever this process would be applied in another place, the structure will be limited to the configuration and size of natural material available on that specific site.

The Digital Urban Orchard research project (DUO) involves the construction of a functional prototype to be implemented in urban public spaces within the self-sufficiency programme of the city of Barcelona. The OTF pavilion stems from the relation among form, function and application context for a new concept of socialization space and food production (Figure 5). As subsidiary section of the study, the built prototype hosts a hydroponic farming system and a opening silicone skin able to ensure the indoor comfort conditions for plants by natural ventilation. The simultaneous concerns on designing a stable yet iterative structure and on the solar gain have required
multiple design expedients in complying each one of the functional, structural and environmental performance criteria. In order to inform the genetic optimization of the shape (i.e. genotype), a data-driven strategy was set: the multiple phenotypes, among which the designer has found the final form, were generated through the progressive modification of environmental, geometric and manufacturing parameters.

The adopted hyper static structural system is generated from a pantograph-like pattern: the repetition of diagonals elements at differentiated angles ensures the structural rigidity. Despite the fact that at first sight the structure is an undifferentiated set of stick nailed to each other, each Redwood stick of Flanders, according to its position performs diversified tasks. Through the adaptable pattern of angled end-cuts, the stick-assembly alternately offers flat supporting areas for the hydroponic pipes, or it constitutes space-functional furniture or either some extended sticks are designed as holder of the silicone skin. The density of the structural pattern also responds to optimization logics for solar gain and considers almost total transparency at the top of the pavilion. The final shape has been discretized according to robotic fabrication constraints and manual assembly logics in 6 types of sections, for 12 components in total.

Three manufacturing strategies have been defined depending on the size of the sections. They involve the robotic processing of the entire section or of two halves or of three parts of the final arc section with 30 assembled parts in total. 2,524 shank nails were used in order to maximize the joints resistance. The collaborative fabrication process between robotic manufacturing and manual finishing was implemented starting from the achievements of the previous Fusta Robòtica Pavilion (exposed at the Setmana de la Fusta, Barcelona, 2015). Implementations concerned all stages in order to reduce material consumption and expand the range of achievable geometry within a non-industrial working setup. Furthermore the customization concerns also the hacking of standard woodworking tools placed on the rotary table, such as the miter saw which allows 3-dimensional angled cuts, or the pneumatic gripper fixed on the robot flange used as end effector, and also the sticks supplier which provides wooden profiles in three different lengths in order to reduce waste material (Figure 6). Realized with 1682 sticks, the pavilion is the result of a fast process of a design-to-production chain; 52 hours of production in the robotic room and 36 hours of unskilled manual assembly have ensured the custom digital design workflow completed in a rapid and automated production process, with only 2% of scraps from the material supply. While the OTF project involves different implications then the ones of the previous renowned design experiences, such as the environmental optimization of shape and the mass-customization advantages, its
working setup opens up the debate around the fabrication’s tolerance: the integration between technical/technological systems and low-engineered setup produces variances between the virtual design and the material actual size pavilion, due to high tolerance.

In different ways the three structures demonstrate the computational path, previously theoretically introduced, actuating the digital chain and materializing it through a collaborative robotic-human production process, customized from time to time. Within this design cycle forcefully emerges the need of taking in account of the material features, not as a final add-on of the architectural process, rather as part of the required informative loop. For the final implementation of complex design programs, the development of digital fabrication facilities constitutes the essential requirement allowing the production of individually differentiated geometries. In improving one single full-scale design-to-production workflow, critical points and advantages of the bi-directional digital and physical design process arise.

DELINEATING HORIZONS
The analytical interpretation of these case studies introduces different macro areas of intertwining limitations and potentialities arising directly from an experienced computational mindset and also facets linked to fabrication facilities, or to material properties involved in the digital fabrication. Indeed the material culture brings a projective capacity within the computational workflow, breaking the conceptual separation between the processes of design and the physical making of a built architecture. In stark contrast to precursors linear and mechanistic modes of digital making, the digital manufacturing implemented in the case studies assists the computational work progress, giving rise to an explorative “cyber-physical” (Menges, 2015) process. The material- and fabrication-aware design are reawakened not in the sense of the tenet “truth to materials” of modernist attempts, but rather as truly new design paradigms for vernacular materials by intertwining material computation, digital fabrication facilities, cybernetics and optimization. As counterpart the prediction of material behaviour, especially for natural materials and low-engineered components, is an entire field of research to be investigated in order to overturn material hurdles in material facilitations.

When architectural implementations are decidedly oriented to digital machineries they express a contrived mechanical commitment, which leads to “a lack of architectural taste”, as G. Scott states in his work The Architecture of Humanism: A Study in the History of Taste (1914). This definition, borrowed from a context far apart from the digital fabrication’s background, properly describes the risks that may occur when designers emphasize a proactive approach while embracing industrial technologies.
However, the actual change comes from adoption and adaptation of advanced production tools, complying choices for architectural space. In regards to architects, one of the most valuable features established is the management of the whole process from design-to-production, relying on a data-driven process that embed different kind of parameters and customised fabrication tools since the early design stages. Although the “new digital continuum” (Kolarevic, 2003) could be carried out within a single virtual environment, the high level of interoperability required between different programming languages can produce communicational constraints between different machine’s protocols. Given the fact that the high specificity of the case studies activates remarkable accomplishments, it means also that bespoke tools and fabrication equipment are not aimed to work for any other project and remain exclusive to only a particular design. In this sense, wider applications “related to the precise working of CNC-controlled machines [...] led to irreparable production errors” (Kloft, 2009). However some of these limitations become marginal in a trial-and-error approach; conversely their spread use in the building industry would amplify their relevance.

Another category of limitations and potentialities woven together can be described as a combination of methodological oversights and benefits. In fact, besides technical difficulties, which are inevitable during applied researches, this last group of failures is centered less on the characteristics of the machinery and more on the nature of the design process. Multifarious research projects demonstrate the sought changes in the fields of software, hardware, and mindset above all. However it is useful reinstate the difference between computerizing a design process and computing material spaces. Sometimes they can be defined as mistaken perspectives arising from emphasized fascination for computational and Computer Numerically Controlled capabilities exceeding architectural design interests. One of the most insidious attitudinal fallacies occurs when authors attribute more value to the enticing and streamlined virtual flow, rather than to the underlying opportunities of novel tangible formations to be transferred to the building industry by means of “digital materiality” (Gramazio et al., 2008).

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FABRICATION - ROBOTICS
Multi-objective design optimization and robotic fabrication towards sustainable construction

The example of a timber structure in actual scale

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This paper attempts to reconsider the role of advanced tools and their effective implementation in the field of Architecture, Engineering and Construction (AEC) through the concept of sustainable construction. In parallel, the paper aims to discuss and find common ground for communication between industrial and experimental processes guided by sustainable criteria, an area of investigation that is currently in the forefront of the research work conducted in our robotic construction laboratory. Within this frame, an ongoing work into the design, analysis and automated construction of a timber structure in actual scale is exemplified and used as a pilot study for further discussion. Specifically, the structure consists of superimposed layers of timber elements that are robotically cut and assembled together, formulating the overall structural system. In order to achieve a robust, reliable and economically feasible solution and to control the automated construction process, a multi-objective design optimization process using evolutionary principles is applied. Our purpose is to investigate possibilities for sustainable construction considering minimization of cost and material waste, and in parallel, discussing issues related to the environmental impact and the feasibility of solutions to be realized in actual scale.

Keywords: Multi-objective optimization, robotic fabrication, cost and material waste minimization, sustainable construction, timber structure

INTRODUCTION
Recently, efforts towards the establishment of alternative strategies and solutions that will lead to smarter, more sustainable and inclusive economy are coming to the fore (European Commission, 2010), directions that are intrinsically connected within the broader notion of circular economy (Hebel et al, 2014). Although, the concept of sustainable design and construction (Abeer, 2012) is currently gaining significant attention in other disciplines including Architecture, Engineering and Construction (AEC), when the discussion refers to the way such principles are applied within the area of computational design and robotic fabrication, less focused examples can be found. On the other hand, integrated computational design and robotic fabrication processes
are currently in the forefront of the research undertaken in architecture and engineering field, mostly in experimental level, with little impact in the broader field of AEC. This is due to various reasons including the expensive technology and the low expertise among constructors. As a sequence, their implementation is observed partially, preventing the establishment of robust and reliable methodologies in the wider construction industry. In the literature, the implementation of optimization techniques is mainly focused, either on the design investigation of conventional forms influenced by sustainable criteria or on experimental studies, where advanced computational design and robotic fabrication techniques are used in the development of complex morphologies, but with little consideration about the sustainability of solutions.

In the first direction, examples can be mostly found in the area of multi-objective analysis using genetic algorithms in order to optimize solutions by minimizing their environmental impact, for instance in example for minimizing the life carbon footprint and life cycle cost of residential complex (Schwartz et al, 2015), building envelope (Barg et al, 2015), etc. In the second direction, advanced computational design and robotic construction techniques are applied, in most of the cases, in experimental studies considering timber as a material with high sustainable potential. Examples like the work on robotic timber construction of non-standard forms (Willmann et al, 2016) or the work on robotic fabrication of wood plates morphologies (Schwinn et al, 2012) demonstrate the potential of timber to be used as an ecological material, followed by other studies where robotic construction of timber is combined with topology optimization techniques for design and robotic construction experimentation (Søndergaard et al, 2016).

This paper implements a multi-objective design optimization strategy towards an automated construction process in the case example of a timber structure driven by cost and material waste objectives. Moreover, issues related to the robot-human intervention within the workflow, the robotic constructability and the applicability of other mechanisms involved in the construction process are examined. Next chapter describes the research methodology that includes a multi-objective optimization strategy based on evolutionary principles. This is integrated with an automated construction process, which involves an industrial robot and a parallel intervention of manufacturers. Then, the case study example of a timber construction is described followed by discussion in regard to the effectiveness of the process to be implemented within the broader area of construction industry. Finally, general conclusions in regard to the role of computational design and multi-objective optimization, integrated with robotic fabrication and driven by sustainable criteria are drawn.

**RESEARCH METHODOLOGY**

This paper suggests the development of two equally important steps towards the construction of a timber structure in actual scale, the design optimization and the robotic construction process. This is done in an integrated and interrelated manner where the design
results derived from digital optimization inform the robotic construction stage and vice versa. The objectives related to the cost and material waste minimization lies within the broader aim of this research, which is the introduction of a sustainable construction process using advanced robotic technology and multi-objective design optimization (Dep, 2002).

In the design optimization stage, the parametric associative design tool Grasshopper [1] (plug-in for Rhino [2]) and the multi-objective analysis plug-in Octopus [3] based on evolutionary principles are introduced to evaluate design solutions against minimum cost and material waste performance but also against other design performance criteria including maximum area of openings and maximum dimensions of the interior space. In addition, the selected design of structural elements and the articulation of the overall structure considers robotic construction criteria, which among others include minimum and maximum length of shortest and longest timber members respectively, aiming to be effectively handled by the custom-made end-effector tool. Also, the investigation is influenced by other criteria related to the capacity of the robot to perform the given tasks and include reach length, payload and working area. In addition, the involvement of the manufacturers during the construction process is taken into consideration since it consists an indispensable part of the process, functioning as an assistive factor for the effective execution of the given structure. Overall, the suggested multi-objective optimization process achieves to generate a pool of solutions that can formulate the range of feasible candidate structural systems to be fabricated, attempting to be materialized in the next stage of experimentation.

Within the framework of this ongoing research work, the design optimization is followed by the robotic construction in 1:1 scale in order to evaluate the selected optimized results but also to validate the performance of current robotic construction scenarios. In order to achieve this, initially, a single structural component is selected to be robotically fabricated, aiming also to observe potential drawbacks or obstacles occurring during the process. These are particularly related to the robotic tool path that might cause singularity and possible collision with the structure.

Firstly, the structural component is robotically executed using foam material as an alternative and low budget choice and secondly, actual timber material is implemented in the construction process to test our hypothesis. In a future stage, the goal is to fabricate the overall structural system that consists of eighteen differentiated components based on the same geometrical configuration and construction logic. This paper demonstrates results derived during the first stage of experimentation that is the robotic construction of a single structural component using foam material.
CASE STUDY EXAMPLE

Construction system review

The suggested structure, which is functioning as a small size shelter for resting, is 9 m² in area and 2.50 m in height. In pre-design and pre-construction stage, its geometrical configuration is influenced by construction objectives but also by environmental and functional performance criteria that allow an efficient use of space by the visitors. In terms of environmental aspects involved, two openings in the western and eastern part of the shelter provide ventilation and allow the light to enter the interior space. In addition, two other openings in southern and northern part are functioning as the entrances-exits of the structure. The shelter creates a narrow interior consists of benches for resting but also a corridor, which allows visitors to move through the space (Figure 1).

The structural system consists of eighteen individual structural components that are joined in groups of three to create six larger segments that make up the entire structure (Figure 2). Each structural component consists of superimposed layers of timber elements that are robotically cut and assembled together in horizontal layers, formulating closed polygons. Specifically, each layer consists of two long and two short primary beams that create the outline of the closed polygon and the secondary transverse beams that are laid on top of the two opposite short members to support the primary systems but also to achieve larger gaps between layers of timber in the interior and exterior façade of the shelter. The timber elements are in square section of 44x44 mm². The separation of the overall construction system in individual components allows their manufacturing in the laboratory (Figure 3), their easy of transport and finally their effective assembly in the location.

The overall geometrical configuration together with the arrangement of timber structural elements are parametrically controlled, aiming to adapt their morphology according to the design performance criteria mentioned in previous paragraphs but also according to the robotic construction constrains. The restrictions related to the use of material and the assembly logic of timber elements, lead to the application of a multi-objective optimization strategy so that any changes occur in the entire structure to influence individual construction components and vice versa.

Multi-objective optimization process

As it has been already mentioned in the research methodology part of this paper, the complexity of design tasks as well as the construction process itself lead to the introduction and the implementation of a multi-objective optimization mechanism [3]. This methodology allows the production of a range of possible solutions through generations, aiming to achieve minimum values in the given objectives by
Figure 6
Three selected solutions with minimum values for cost and material waste objectives: case 1. 13.13% of material waste and 553.14 Euros cost of material, case 2. 12.85% of material waste and 557.53 Euros cost of material, and case 3. 12.78% of material waste and 561.92 Euros cost of material

displaying solutions with different combination of parametric variables. The running process is based on the reproduction of two population of solutions that generate a new offspring, leading to the generation of a new population of better solutions. Through the Pareto front, a series of best solutions are selected, mainly the desirable ones, aiming to achieve a feasible construction process.

Initially, the geometrical configuration of the small size shelter is parametrically defined [1] taking into consideration a number of variables that are either constant or flexible. The overall structural system is enclosed in an imaginary square box with dimensions of W=3m (width), L=3m (length) and H=2.5m (height). The overall structure consists of six large structural segments (SSi), each of them parametrically defined by four curves Ci that in turn, are controlled through lines Li and triads of point Pij shape controllers. Figure 4 shows the structural segment SS1 that contains triads of Pij shape controllers responsible for the parametric control of the northern entrance-exit and of the lower point AB, middle point B and upper point B of the eastern opening. Simultaneously, other shape controllers are responsible to control an extension of SS1 on its base, allowing the creation of a bench area. Analytically, in the case of northern entrance-exit, the height of point shape controller is defined as a flexible variable with values range from 1.5 to 2.25m. In the same way, the flexible variable for the height of the lower point AB range from 0.75 to 1.25m and the flexible variable for middle and upper point B is defined as distance from the middle point AB with range 0.2 to 0.65 and 0.2 to 1.1 respectively (the values control parametrically the eastern opening area). Subsequently, each of the four Ci in every SSi is divided in a number of segments to formulate the superimposed layers of timber members. The length of division is fixed and is defined as the height of timber component with value 44mm resulting in the creation of 56 segments that formulate the superimposed layers of the horizontal primary long and short elements as well as of the secondary beams.

Figure 7
Spatial organization of the working area: a. location of robot, b. containers positioning, c. cutting area, and d. assembling area

Apart from the variables controlling the overall geometrical configuration, the introduction of several objectives are tested during the multi-objective opti-
mization process. These objectives include minimum cost and material waste, minimum average length of the longest timber members, maximum average length of shortest timber members, maximum eastern opening area, maximum western opening area, and maximum average dimension of interior corridor.

Due to the highly differentiated and customized individual timber elements (size, cutting angle, etc.), the cost and material waste minimization are found to be the primary objectives necessary to be considered during the process. Toward this direction, the concept of bin-packing algorithm (Crainic et al, 2007) based on the PackRat platform [4] (plug-in for Grasshopper) is introduced. The specific plug-in offers the possibility for packing rectangular shapes in rectangular containers, an algorithmic procedure that achieves to minimize the used space and hence to achieve less material waste, leading to the reduction of cost and material.

Figure 8
Selected robotic simulation steps in a continue single toolpath that involves picking, cutting and placing

Figure 9
Robotic cutting using circular saw

Figure 10
Picking the appropriate rod for robotic cutting
The suggested process determines the material waste as the total volume of used timber members divided by the total volume of available timber members or containers (pieces of 4m length) that take part in bin-packing minimization process. This is described as the used/available ratio U/C with values in percentage (%). Also, the number of available timber members is calculated, providing the total cost in Euros (4.39 Euros/per piece of 4m length).

In addition, the process takes into account limitations occurring during the construction stage (Kontovourkis and Tryfonos, 2016), mainly based on the robotic construction capacity, which includes the dimensions of the end-effector tool for the effective handling of timber elements, and the size of working area that influence decisions in regard to the robotic construction scenario and hence the sequential production of structural components. Specifically, fitness values control the length of the average longest timber members to be less than L=1.2m and the average length of the shortest timber members to be larger than L=0.40m, values directly related with the capacity but also accuracy of the gripper tool (0.20m length) to handle and control different angles and size of structural elements during cutting and assembling process. Finally, objectives that determine the maximum percentage of opening areas in both eastern and western sides of the shelter are applied. Moreover, a fitness value related to the maximum average dimension of corridor in the interior space is incorporated in the optimization process, targeting on values larger than d=1.0m.

Hence, the multi-objective optimization provides the framework where several objectives are introduced and evaluated simultaneously in a continuously iterated feedback loop process, providing quantitative results related to the environmental impact, architectural qualities and limits of the manufacturing process. These objectives are evaluated against each other, influencing the selection of the best fitting results and therefore are directing the design decision-making. The results obtained during several runs of the multi-objective optimization process shows the variety of solutions over the generations (Figure 5). Figure 6 shows three selected solutions obtained from the optimization process based on minimum values for cost and material waste objectives.

Robotic behavior simulation

Due to the complexity of the tasks involved, which include picking the timber with the appropriate length, placing the timber with the right angle to the circular saw for cutting in both edges and finally assembling the appropriate shape of timber element in the overall structure, initially, a comprehensive installation of the workspace and offline simulation was necessary to be developed in order to capture the robotic behavior. In addition to this, due to the random distribution of the available timbers (containers) that were determined during bin-packing algorithm optimization stage, the appropriate sequence of robotic motion behavior in relation to the construction logic and the chronological placing of timber, were important issues to be investigated in advance.

Equally important factors that influenced robotic simulation process were the technical characteristics of robotic mechanism, particularly the robot reach
length as well as the available working area of the laboratory. Towards this direction, attention was given on the right positioning of available timber members (containers) to be inside the range of robot reach length and on the appropriate placing of circular saw in order to avoid collision with timber members but also to effectively cut the members in specific lengths and angles. Also, attention was given on the collision of timber members with the robot itself and with the structure under construction (Figure 7).

Towards this direction, a feasible design solution of a structural component derived from the multi-objective design optimization process was selected and further investigated, focusing on its capacity to be executed by the available industrial robot and within the working area in actual scale. This allows pre-control and pre-testing of construction sequence as well as enables drawbacks and limitations to be observed.

The simulation of robot is achieved by using the Taco ABB [5], a plug-in applied for offline programming simulation of ABB industrial robots for Grasshopper (plug-in in Rhino). Final output is the generation of a Rapid program, read by the ABB controller IRC5 that is used to execute the robotic movement in each case. In addition to this, custom commands controlling the opening and closing of the gripper are added to the algorithm. In total, the overall behavior of the robot includes pick the available material, cut using the saw and finally placing in the appropriate position on the structural component. This is done in continues single toolpath that includes 15-17 targets, depending on the construction sequence and type of timber member. Also, the algorithm involves waiting time period in order to give the necessary time to the manufacturers to assists the robot during the process or to allow enough time to the manufacturers to proceed more effectively with the assistive of working tasks like gluing and repositioning of the leftover timber/container for next robotic execution (Figure 8).

**Automated construction process**

The fabrication in actual scale is conducted in the robotic construction research laboratory (directed by the author), which is equipped with an industrial ABB robot, model IRB2600-20/1.65. The robotic arm is used for cutting and assembling each timber beam in the correct position. In this research a custom-made end-effector gripper tool mounted on the edge of the robotic arm is used for material handling. As it has been already stated, in the final phase of this ongoing research where the cutting of timber material will be executed, a circular saw will be used (Figure 9).

However, in this phase of experimentation where foam material is applied, the robotic demonstration involves the use of a vertical hot-wire cutter. All the other automated principles and set-up configurations that are involved in the construction process remain the same, including size and behavior of custom-made gripper, toolpath trajectory, position of available timbers (containers) and assembly.
logic. Hence, following paragraphs describe the process through the use of rods made of foam material and include three main steps: a. pick the rod with the appropriate length from the material container, b. place the rod in the right angle to the vertical hot-wire machine for cutting in both edges, and c. assemble the appropriate shape of rod in the structure.

Analytically, in the first step, the robot picks the appropriate rod from the material container. The choice of suitable rod is based on the dimensions of the existing leftover rods and the dimension of the next rod to be placed (Figure 10).

In the second step, the robot places the rod in the right angle for cutting in both edges of the structural component keeping the cutting machine in constant direction XZ (Figure 11). In this step, the manufacturer assists the robot in cases where very long beams are processed, by holding the remaining material after it is cut (Figure 12). In parallel, the manufacturer is responsible to replace the leftover material in the right position for next execution.

Then, the robotic arm locates and assembles precisely the rod in the appropriate position, a last robotic action that follows inspection and gluing by the manufacturer using fast curing adhesive (Figure 13). Figure 14 demonstrates selected layers of sequential construction and figure 15 shows the final prototype in 1:1 scale.

CONCLUSIONS
Preliminary results of the robotic construction of the timber structure in actual scale show the feasibility of the process especially in cases where the complexity of design demands the use of advanced tools and mechanisms that move beyond conventional design and construction processes. Particularly, the integration of multi-objective design optimization with the robotic construction as well as the assessment of solutions and the selection of the best fitting ones, attempt to established an active and close collaboration between experimental and conventional design and construction processes. Moreover, results of optimization and then the selection of the best possible design that can be physically realized, attempts to give an understanding and promote awareness in regard to the way solutions can be evaluated and then materialized, aiming at sustainable construction. Within this frame, the minimization of cost and material waste is taken into consideration aiming at low environmental impact solutions. Furthermore, the transferring of information derived from the digital investigation to the physical execution and then the realization of product in actual scale might open the discussion in regard to the role of integrated computational design and robotic fabrication as mechanisms introduced in the wider area of AEC industry.

Further work will be concentrated on the physical construction of the entire structure as a pilot
study that might open the ground for diversified and more complex implementations of advanced computational design and robotic fabrication tools in the construction industry. Nevertheless, the complexity of the tasks involved is integrally connected with the demand for more active collaboration between robots and manufacturers during the workflow procedure. This is also an area of investigation that requires further attention, especially towards a productive and close collaboration between those two agents that influence construction process.

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Case Specific Robotic Fabrication of Foam Shell Structures

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Most recent developments in the design of free form shells pursue new approaches in digital fabrication based on material properties and construction-aware design. In this research we proposed an alternative approach based on implementation of expanded polystyrene (EPS), a non-standard material for shells, in the process of industrial robot fabrication that enables fast and precise cutting of building elements. Main motivation for using EPS as a building material was driven by numerous advantages when compared to commonly used materials such as: recycleability, cost-efficiency, high earthquake resistance, durability and short assembly time. We describe case specific fabrication approach based on numerous production constraints (size of the panels, limited robot workspace, in situ conditions) that directly design the process.

Keywords: computational design, shell structures, robotic fabrication, hot-wire cutting, multi-robot control

INTRODUCTION

The concept of using curved surfaces in contemporary architectural practice has been increasing in the last decade. With this interest, the field of architectural geometry has been developing, including the geometry of shell structures as well. While thin pavilions, experimental structures and shells serve as vehicles for developing future concepts of architecture through the employment of new materials, fabrication techniques and design strategies, they also bring new solutions. The reason for using shell structures as pavilions is due to its self-supporting ability, low cost and material consumption, while the improving various research methods ease up the process. Research methods pertain to structural optimization, material application, various tessellation, fabrication, assembly approaches and in situ conditions. New advances in architectural geometry allow for adequate analysis and simulation of shell structures, thus generating a structurally informed model (Richardson et al, 2013). Such a model is used in an integrated approach to indulge all the requirements of above mentioned areas. Integrated design, in this research, refers to integration of various fields of expertise, including design, fabrication, material properties, assembly and transportation, in order to procure a precise and valid solution to a predefined set of parameters in the early stages of the design process. Referred to as "fabrication-aware design", it emphasizes the necessity of the design and fabrication connection (Wu & Kilian 2016). It is fundamentally about removing the fissure between the processes that bring
forth a design and the operations that will lead to its fabrication (Pigram & McGee, 2011).

For example, tessellating a surface can be done with regards to the size of the model and the panels (Wang et al, 2014) as well as the size and capabilities of the fabrication tools and machines (La Magna et al, 2016; Rippmann et al, 2016) and the material being used (Block Research Group, 2012; Rippmann & Block, 2011a). Furthermore, with inclusion of cost-effectiveness as a condition, the tessellation can be done with planar panels that have a major impact on the entire design (Eigensatz, 2010). Structural integrity is also used as a tessellation guideline, generating panels with connecting faces oriented perpendicular to the surface (Rippmann & Block, 2011b). Fabrication conditions, such as hotwire cutting, influence the panel generation by using ruled surfaces (Pottmann et al, 2008), and thus the path the machine needs to follow in order to fabricate the panel (Wang & Elber, 2014).

The assembly is the end of such a process, but still an inseparable part of the integrated approach. In order to grasp the magnitude and the complexity of the project and fabricate it, it is necessary to generate a proper workflow. The problem, which this paper focuses on, is when the conditions for the fabrication of the architectural structure are not ideal and hence it is necessary to find the way to satisfy the requirements of the project with the capabilities available. In this paper, fabricating a real-size shell structure out of expanded polystyrene (EPS A100) is presented and the goal of the research is to find a proper workflow that adjusts to in situ conditions and available equipment on one side, and project requirements on the other.

**PROJECT REQUIREMENTS**

The pavilion was made for the European Research Night, where the main topic was cool science. Therefore, for the topic of architecture, building a shell structure resembling an igloo was chosen, based on novel fabrication methods. The available space was set to as no more than 8x8m in floor plan area. The assembly process had to be finished in 12h or less, since the in situ conditions dictated that the Igloo may not be placed before the start of the manifestation, which implied prior partial assembly and transportation. Furthermore, the parts had to be light-weight, demountable and easily transportable to allow for multiple assemblies on different location. Taking into account the size of the building’s entrance, and the prior assembly area, the parts had to be no more than 2m in any direction. The necessity of the visitors to learn and acquaint themselves with the project, and be able to move through it, showed that a classical approach to generating an Igloo was inadequate. Therefore, the Igloo needed to be designed with at least two entrances, and 2m in height to serve as an unrestricted passageway. The funds for the material application were limited which influenced its choice. Using expanded polystyrene as a material of choice proved to be prudent, for its lightweight properties, color, low cost, easy cutting, shape and size manipulation. The equipment used for the hotwire cutting process were two ABB IRB 140 industrial robots and a hotwire cutting tool 40x40cm in size. After the project requirements were laid out, the integrated design approach and workflow followed.
THE WORKFLOW

The workflow needed to be generated with early integration of all viable areas of interest, necessary for the adequate completion of the structure. Important areas included the form generation, then tessellation with regards to the choice of material and the fabrication tool and process, the fabrication process itself, the assembly, transportation and (de)mounting on site. Project requirements influenced each of these interest zones and presented omnipresent conditions that limited and guided the solution to the end, accompanied with contemporary methods and techniques. The starting point was generating the form, since all other areas of interest depended on it.

Figure 2
The depiction of the structure as a NURBS model procured by means of converting polylines into NURBS curves and generating a surface

FORM GENERATION

Given the latter and following the conceptual appearance of shell structures, a Y floor-plan shape was taken as a starting point, offering 3 possible passages for the visitors with varying passage heights. A hole was placed on top of the shell, in order to show the potential that shell structures have when transferring load through narrow sections and to give people the sense of openness when going through it. In order to generate a self-supporting shell structure, RhinoVault plug-in for Rhinoceros software was used. Following the project requirements, the mesh model was obtained, which served to guide the rest of the process (Figure 1).

Since, a model with smoother surface continuity and curvature fairness was necessary in order to acquire a more precise tessellation procedure, the mesh model was sectioned into horizontal polylines for each prong, which were converted into degree 3 NURBS and used for generating a NURBS surface (Figure 2). That model was used for generating the tessellation procedure following the fabrication tool and process choice.

FABRICATION TOOL AND PROCESS

Implementing an integrated design approach demands that all processes be taken into consideration in reference to one another. The tessellation process had to be done with consideration to the material application and affordability, capability and size of the fabrication machines. In contemporary practice, hotwire cutting and CNC milling are the preferred fabrication approaches when using Polystyrene as a material of choice.

CNC milling is a time consuming process, it causes a large amount of residual waste in form of small unrecyclable particles and the panel size is determined by the machine’s work area. On the other side, by applying hotwire cutting, the residual waste material is in recyclable parts, and he process can cover a larger percent of the panel in reference to the time consumed. Hotwire cutting can be up to 126 times faster when compared to adequate milling processes (Brander et al, 2016a) and even faster than that (McGee et al, 2013). The level of details less when compared to milling. Hotwire cutting is used by CNC machines with 3 degrees of freedom in contemporary practice for cutting out desired parts from larger Polystyrene blocks. By implementing industrial robots with 6 degrees of freedom, the fabrication process can be upgraded. It is even used for changing the profile of the curve during the cutting process to achieve greater level of detail in surface generation (Brander et al, 2016b; Rust et al, 2016b). That is why robotic hotwire cutting was chosen as the fabrication process. However, there was a great inconsistency between the size of the Igloo, which was 2.2m high
and spanned for 8m and the size and working area of the available industrial robot (ABB IRB 140), which was around 1m.

This indicated that the tessellation procedure had to yield properly sized panels in order to accommodate for the size discrepancy. However, having a large number of small panels would complicate and prolong the assembly process, where minor fabrication errors would build up to larger ones during the assembly. Two options were possible:

- The first one was to enlarge the hotwire cutting tool (up to 60x70cm) for a single industrial robot (Figure 3a), thus enabling the enlargement of the panels, decreasing their number, but in the process limiting and decreasing the robot’s dexterity. Furthermore, the cutting error would exist due to the length of the fork holding the hotwire, which would vibrate due to the high speed rapid changes in the cutting path direction, meaning that the speed of the changes would need to be minimal.

- The second option was to use two robots of the same type in a conjoined fabrication approach, where one would hold the piece and rotate it, and the other would use a smaller hotwire cutting tool (40x40cm) to cut the outside ribbon (Figure 3b). This is an innovative way of overcoming the size discrepancy between the panel and the working area of the robot and the tool combined. In such a way, a larger panel could be produced more precisely without the error due to the tool. This approach demanded a proper calibration between the two robots, enough space to maneuver and the necessity to cut the Polystyrene block to size to fit onto the robot, which demanded more time than the first option.

In the end, a hybrid approach was chosen, where sufficiently large panels, spanning beyond the size of the larger hotwire cutting tool were fabricated by using the conjoined approach, while the rest was fabricated following the first approach, which was already tested in previous research (Jovanovic et al, 2017).

**THE TESSELLATION PROCEDURE**

Following the decision, the shape and the size of the panels had to be determined. Taking the refined digital model as a starting point and using the Evolute tessellation tools, a hexagonal shape was chosen and applied throughout the surface of the model, counting 267 panels with double-curved outer and inner shell faces (Figure 4a). The panels near the base were significantly larger than the ones near the top, given the larger cross section and the dimensions of the prongs near the supporting area, while keeping the same grid and disposition of the panels. This further confirmed the necessity for a hybrid approach to fabrication. Average size was around 55cm in both direc-
tions of the boundary box, due to the size of model and the desired number of panels. Due to the changing Gaussian curvature throughout the model, a planar hotwire with a constant curvature was not an option as a cutting tool. Using a wire with a changing curvature, as was done prior (Rust et al, 2016a; Brander et al, 2016a) was not an option due to lack of proper equipment.

In order to enable an easier fabrication process, a faceted panel appearance was chosen, making the front and back side of the hexagonal panels planar (Figure 4b). An add-on Kangaroo was chosen for aligning the six vertices of each panel into a single plane and generating a planar polyline, respectively. The structure still needed to have a certain thickness to overcome the load and forces acting on it. A custom script was generated offsetting the vertices of each hexagonal panel in reference to its surface normal vector. The offset vertices were joined into a planar polyline and lofted with the initial polyline to form the connecting faces of a panel, which are ruled surface. In such a manner, a planar straight hotwire could be applied. The load transfer would go perpendicular to the initial form, avoiding shearing. Once the initial and the offset polyline were used to form planar surfaces, they were joined with the ruled surface to form each panel respectively. Once the panels were generated, it was necessary to prepare them for the fabrication process.
THE FABRICATION, ASSEMBLY AND TRANSPORTATION PROCESS
The fabrication process was done following a workflow done prior (Jovanovic et al, 2017). The only difference was that each panel had to be oriented in a certain manner, so its cutting path can be used later in RobotStudio for positioning purposes in both approaches. The orientation was done in two steps. First, a source coordinate system that lays in the offset planar surface of each panel was generated, with its origin placed in the center (Figure 5a). Second, the panel was oriented from its source coordinate system to the targeted world XY coordinate system and its origin (Figure 5b). The path was generated as was done in prior research.

Regarding the conjoined approach for fabricating the larger panels, the following methods were used. First, the calibration process is done in order to define the relative position of the robots to one another. A robot station for two robots was generated inside RobotStudio, using the acquired data. One larger panel was oriented in the coordinate system of the 6th axis of the second robot along with its bounding box (Figure 6a). The path was acquired by using the multimove feature that the software offers, and referencing the points and the orientation (robtargets) of the hotwire tool. The starting robtarget was placed along the edge of the bounding box, in order to be able to position the block during the actual fabrication process. The following robtargets were
The finished structure on site during the manifestation b) the demounted and reassembled structure in the kindergarten backyard referenced in the middle of the panel's ruled surface edges. The software generated the code for the robot controller, which was used for the fabrication process of larger panels. The assembly and transportation had to be taken into consideration in this process. The shell was divided into 3 prongs and a crown, out of which, every prong was divided into 2 more (Figure 6b).

Each of the 7 sections had around 35 to 40 panels, and the numbering was done accordingly. Since the assembly had to be done parallel to the fabrication process, due to relatively short time, it was not possible to use nesting algorithms for packing all the panels at once and waiting until all are fabricated. The panels had to be packed inside individual sections so they would take up as little space as possible from the 40 blocks measuring 1m x 1.2m x 0.2m that were obtained. The problem was that the length of the hotwire fork was only 60cm and the fabrication process had to be stopped and reengaged to adjust the block and the fork to avoid collision (Figure 7a). The running time of the process was 130 hours done during the course of 2 weeks. During the panel fabrication, the assembly process was under way, in order to allow for the panels to stick together better and due to scheduling (Figure 7b).

Keeping in mind the project requirements about assembly, the parts were assembled and transported to the manifestation site the prior night for putting everything together.

The assembly lasted throughout the night and the finished structure remained during the manifestation(Figure 8a). Afterwards, the structure had to be demounted. It was done by making a cut along the seams where the prongs connect to the crown part. Afterwards it was transported and assembled in the same manner, in a different location, a kindergarten, proving its demountability and easy transportation (Figure 8b).

**CONCLUSION**

In this paper we presented a case specific approach to shell structure design and fabrication process adjusted to specific circumstances. The innovative approach to fabricating large scale panels was researched through conjoined parallel work of two industrial robots, where one robot was holding the piece, from which the other robot will cut out the desired shape using a hotwire tool. Following this workflow, similar structures can be fabricated, finding the best course of action when compromising between the general aesthetical appearance and desired design on one hand, project requirements and the available fabrication and digital tools. Compromising between the available resources and the optimal outcome, keeping in mind the integrated approach between all phases is necessary.

**ACKNOWLEDGEMENT**

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*Proceedings of the IABSE-IASS Symposium*
Robotic Spatial Printing

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There has been significant research into large-scale 3D printing processes with industrial robots. These were initially used to extrude in a layered manner. In recent years, research has aimed to make use of six degrees of freedom instead of three. These so called “spatial extrusion” methods are based on a toolhead, mounted on a robot arm, that extrudes a material along a non horizontal spatial vector. This method is more time efficient but up to now has suffered from a number of limiting geometrical and structural constraints. This limited the formal possibilities to highly repetitive truss-like patterns. This paper presents a generalised approach to spatial extrusion based on the notion of discreteness. It explores how discrete computational design methods offer increased control over the organisation of toolpaths, without compromising design intent while maintaining structural integrity. The research argues that, compared to continuous methods, discrete methods are easier to prototype, compute and manufacture. A discrete approach to spatial printing uses a single toolpath fragment as basic unit for computation. This paper will describe a method based on a voxel space. The voxel contains geometrical information, toolpath fragments, that is subsequently assembled into a continuous, kilometers long path. The path can be designed in response to different criteria, such as structural performance, material behaviour or aesthetics. This approach is similar to the design of meta-materials - synthetic composite materials with a programmed performance that is not found in natural materials. Formal differentiation and structural performance is achieved, not through continuous variation, but through the recombination of discrete toolpath fragments. Combining voxel-based modelling with notions of meta-materials and discrete design opens this domain to large-scale 3D printing. Please write your abstract here by clicking this paragraph.

Keywords: discrete, architecture, robotic fabrication, large scale printing, software, plastic extrusion
INTRODUCTION
The research presented in this paper is produced at the Design Computation Lab, University College of London (UCL), and led by Manuel Jimenez Garcia, Gilles Retsin and Vicente Soler. Since 2013, one of the labs research strands has been the development of design methods for additive manufacturing with robots. The term spatial extrusion (Mesh Mould, 2008) refers to a manufacturing technique in which plastic is mostly extruded in the air without any support, following a truss like pattern. The segments are only supported by their nodes. The research presented here has been initially developed through teaching in the context of M.Arch Architectural Design (AD) Research Cluster 4. Various research topics are developed by postgraduate students working in teams of three to four people. Previous projects, such as SpatialCurves by Curvoxels (Hyunchul Kwon, Amreen Kaleel, Xiaolin Li) (Figure 1-2) or Topopath by Voxatile (Efstratios Georgiou, Palak Jhunjhunwala, Juan Olaya, Yiheng Y) (Figure 3-4) explore similar discrete methods for robotic spatial extrusion. The last project that will be presented in this paper is developed as a non-teaching based research, and aims to develop a generalised approach to design methods for spatial printing.

In the methodology proposed in this paper, toolpath fragments are used as discrete elements that can be combined together in a limited number of ways. These combinations are informed by design and other criteria, and once assembled, they generate a continuous single path. This methodology is being implemented in a stand-alone software application and plugin for Grasshopper. To build this software as a generally available tool, in-depth technical research was required to establish an overview of the parameters and constraints.

A series of furniture scale prototypes have been developed in this research, aiming to test the efficiency of the design method, as well as the adaptability of the software to geometrical and material limitations.
This paper aims to give a wide and reproducible overview of the technical background of the software. It explains the relation between the plastic extruder, material, robotic manipulator and computational process. Based on this framework, a beta-version of the software has been developed, and a first prototype fabricated.

BACKGROUND

FDM (Fused Deposition Modelling) is one of the most common technologies available for affordable, small scale 3D printing. In 2009 the FDM patent expired. Since then, there has been active experimentation with this technology, implementing it in unusual ways.

With the aim of scaling up FDM technology, there has been significant research into large-scale 3D printing processes with industrial robots. These robots were initially used to deposit materials in a layered manner. For example, research at IAAC by Marta Male-Alemany looked into 3D-Printing with clay. It can be argued that the properties of the robot to move along six axis are not really capitalised on in these examples. In recent years, research has aimed to make use of some of the freedoms given by robots, that do not exist in 3-axis machines. These spatial extrusion methods are based on a plastic extruder, mounted on a robot arm, that extrudes a material along a spatial vector.

This method has been initially explored by IAAC, making use of a composite resin (Mataerial, 2013) and at the ETH, with the Mesh Mould project (Hack, Lauer, Gramazio, Kohler, 2014). In comparison to layered methods, spatial extrusion is more time efficient. However, the method has a number of limiting constraints, the most important one that the robot can never intersect previously deposited material.
There are also structural constraints: material can only be extruded in the air for a limited range - at some point support structures are needed. Therefore, most spatial extrusion projects make use of a highly repetitive toolpath organisation, based on parallel contours, connected by a triangular, truss-like toolpath. The formal possibilities are limited, and the toolpath organisation is not very complex. Complexity is usually a trade-off with speed. As Neil Gershenfeld points out, digital design based on mass-customisation of building elements is caught in a permanent conflict between speed and complexity, and is as well fundamentally analog. (Gershenfeld et al., 2015) To operate in a digital way, machines should operate on materials that are themselves digital - meaning that they are always the same discrete units with a limited connection possibility. (Gershenfeld et al, 2015)

This paper presents a generalised approach to spatial extrusion based on the notion of discreteness. The paper explores how discrete computational design methods offer increased control over the organisation of toolpaths, without compromising design intent and while maintaining structural integrity. The paper then gives an overview of the technical challenges in developing a discrete design software for spatial printing.

**DISCRETE APPROACH**

A discrete approach to spatial extrusion uses a single toolpath fragment as basic unit for computation. This approach to seriality and discreteness may initially seem antithetical to digital design - and particularly 3D printing (Sanchez, 2014). Digital Design has previously always been associated with continuous differentiation, rather than seriality (Carpo, 2014).

This method increases the efficiency of 3D printing processes by reducing the prototyping phase to a limited number of discrete elements, avoiding the need to compute and test the entire tool path against printing constraints. The possible errors throughout the printed object are not continuously differentiated, but limited and serialised. Printability for the entire object is guaranteed by testing the individual fragments in all possible orientations (Figure 5).

This method is based on a voxel space. Each voxel contains geometrical information: one or more toolpath fragments, which are then assembled into a single, kilometers long, continuous extrusion path. The assembly pattern can be designed and controlled in response to different criteria, such as structural performance, material behaviour or more aesthetic design concerns. All of these criteria can be embedded or assigned to the voxel space. This approach is similar to the design of so called meta-materials - synthetic composite materials with a programmed performance that is not found back in natural materials. Formal differentiation and structural performance is
achieved not through continuous variation of toolpath segments but through the recombination of discrete toolpath fragments.

The computational process begins by defining the volume that will shape the workpiece. This could be any imported mesh object. A voxel space is created that matches the object's shape. This allows for the independent control of the individual voxels, rather than requiring topological manipulations. In fact, once the voxel space is created, the object could be defined as non-topological.

Current developments in voxel-based softwares such as Monolith (Panagiotis and Payne) resonate well with the proposed method, which essentially allows to translate complex, multi-material voxel-data into information that can be fabricated on a macro scale using spatial extrusion with robots. Until now, these type of voxel-based, multi-material prints have only been realised on small scale. However, the proposed method, combining voxel-based modelling with notions of meta-materials and discrete design, opens this domain to large-scale printing.

To optimise the printed mass for large scale objects, a sensible understanding of the scale of the voxels (and its contained toolpath fragment) is needed. This is designed in relation to the limitations of the plastic extrusion, as well as the physical constraints required to create a stable structure. A range of material densities is achieved through the use of the octree subdivision of voxels. This division is defined by performing a structural finite element analysis. This analysis must be performed recursively since any changes will affect the distribution of structural forces. This process leads to the generation of smaller voxels when structural requirements are higher, and bigger ones in those areas where the object can be weaker (Figure 6). This creates a differentiated porosity throughout the entire printed object. There are three types of cells, void, support and filled (Figure 7). Void cells are not extruded. Support cells contain material to be removed afterwards. Filled cells form the actual final result.

TOOL PATH OPTIMISATION - COMBINATORIAL METHOD

An optimal rotation of each toolpath fragment is required to generate a continuous toolpath. This increases the efficiency of the extrusion process, by allowing a continuous extrusion of material, minimizing unproductive robot motions and fabrication errors that appear when the extrusion is interrupted and continued in a different location. (Figure 8) In order to achieve a continuous toolpath, a Hamiltonian path must be found in each of the voxel layers. That is, a path that will visit all cells only once. This is not guaranteed to exist on any arbitrary graph and has a computational complexity of NP-complete (Figure 9).
To guarantee this path to exist, voxels are first grouped into four, forming a larger voxel with four quadrants. These groups of voxels will be culled out or kept as a whole. A spanning tree is calculated from these group of voxels. This is a kind of graph that guarantees that all groups of voxels are connected to each other at least once, and no closed loops are generated. Offsetting this spanning tree to the voxel quadrants (the individual voxels) creates a closed continuous path (a Hamiltonian cycle).

To introduce differentiation in material density, each voxel can be subdivided, producing scaled down versions of the fragment paths. The voxel has to still be self-supporting, as the main four opposing corners of the parent voxel are still the only guaranteed supports. The scaled down sub-voxels can't rely on neighbor voxels being subdivided for supporting nodes. The maximum subdivision level depends on the extrusion thickness. The maximum horizontal subdivision level will limit the segments to be at least twice as long as the extrusion thickness. The vertical subdivision is limited to the extrusion thickness itself, creating in essence a conventional layered toolpath at maximum density.

These toolpath fragments are not physical entities, but rather digital units which will be materialised in a continuous printing method. This design method remains close to the notion of digital materials developed by Neil Gerschenfeld at The MIT Centre for Bits and Atoms, where parts that have a discrete set of relative positions and orientations are able to be assembled quickly into complex and structurally efficient forms. (Gershenfeld et al., 2015) However, this is only true for the design method, as the fabrication method is based on a continuous extrusion.

**ROBOTIC PLASTIC EXTRUSION**

After the path is computed, a robot program is generated that includes additional parameters, such as approach targets, speeds, and commands to control the extrusion flow.

As a test-case to demonstrate the efficiency of the software as a large scale 3d printing tool, a furniture scale physical prototype was developed. This piece, entitled Voxel Chair v1.0, is one of the possibilities abstracted from the 39 first outputs generated using the software. Based on the shape of a Panton chair, these prototypes explore different material distributions and porosities, responding to different structural criteria (Figure 10). Voxel Chair v1.0 was first exhibited at the “Imprimer Le Monde” exhibition at the Centre Pompidou in Paris.
The prototype was fabricated at Nagami, a small company in Avila, Spain, a company specialized in large scale 3D printing. Transparent PLA pellets mixed with cyan coloring (Figure 11) was used as the extrusion material. The equipment at Nagami consists of an ABB IRB4600 industrial robot with a mounted customized plastic pellet extruder. It uses a stepper motor with an independent controller (not driven by the robot controller) (Figure 12).

The main fabrication errors in the finished product were the deflection of the segments through the extrusion process. This was not consistent, since some deflected more than others and also curved in unpredictable giving the pattern an uneven look. The deflection was still within tolerance, still working properly as supports for the top segments. The chair is assembled out of thousands of smaller toolpath fragments, and then extruded as a continuous, 2.36 km long line (Figure 13).

The extrusion process begins by first having the extruded plastic adhere to the base. The extruder is then moved diagonally upwards creating a segment that is suspended in the air. The extruder nozzle holds the segment by the top end waiting for the material to cool down. After the plastic solidifies, the segment will stay in place only being attached by the bottom node, which is acting as a rigid joint. The extruder is now free to extrude an additional segment without having to support the previous one. The top ends of the segments will become support for additional segments extruded on top (Figure 14).

**SOFTWARE IMPLEMENTATION**

A programming library and application are produced that implement this methodology (Figure 6). The programming language used is C and the library targets .NET Standard 1.0. This library can be used on multiple platforms where the .NET framework is available, such as Windows, MacOS and Linux. For the application, Unity, a video game development platform was used as the front end for its built in graphics engine, interface creation and cross platform publishing. A secondary library is created to mediate between the Unity C scripts used as the front end and the programming library containing the core logic. This application is available in MacOS, Windows and Linux.

**CONCLUSION AND FUTURE WORK**

The computational process assumes the extrusion equipment is reliable enough to produce a constant and predictable result. This was not always the case, changes in temperature and other exogenous factors cause the extruded segments to behave unpredictably. Extruding the same pattern multiple times caused non repeatable mistakes. We believe the computation process is valid and the main factor to improve is the use of better engineered equipment. Tolerance parameters can be further tweaked to avoid critical failures, like a collapsing structure, but this will have an effect on the cleanliness of the final object and speed. The volume of the supporting structures can be minimized. We plan to implement a branching structure for this. Currently there’s no feedback checking for deviations and deflections of the extruded structures compared to the digital model. We plan to investigate this in a closed loop systems using different types of sensors, including force torque sensor, depth sensors and camera systems that make use of advanced vision algorithms. In addition to the software application, we plan on developing a plug-in for Rhinoceros 3D / Grasshopper.
We can use the core library without any changes as Rhino 3D is extended through plugins using the same .NET framework. Through this plugin, users will be able to design directly the shape of the toolpath, without the need of importing a mesh object. Users will have finer control on how structural and other properties have an effect on the toolpath. They will be able to transverse through the design space quickly, exploring how changes in parameters can influence the aesthetics of the different toolpaths, giving them more control over the final output. Our approach of variable voxel density, using a single material to void ratio, allows for multi-material data to be 3D printed in large scale through the process of robotic spatial extrusion.

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Adaptive Industrial Robot Control for Designers

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In this research, we present a system to allow designers to adaptively control an industrial robot from within a 3D modeling environment, for the purpose of real time feedback with respect to visual imagery of the object as well as robot pose during the fabrication process. Our work uses the Kuka industrial robots due to their capability in fabrication and programmability, and the Rhino 3D modeling software with the Grasshopper plugin which allows for visual programming for designers. A Microsoft Kinect sensor is used to provide visual feedback of the part during the fabrication process. We present the methodology used to develop the system, explaining various design and architecture choices made to allow for easy use of our system, while ensuring our system is open to further extension. We also show qualitative results of the fabrication process performed using our system in order to validate that our proposed system improves the interaction and collaboration between designer and robot when performing the task, in contrast to the iterative process that is generally followed.

Keywords: Human-robot collaboration, Robotic fabrication, Adaptive control, Feedback

INTRODUCTION
This research proposes a framework to enhance the collaboration process between human designers and industrial robots. Recent technological advancements have led to the development of the new generation of industrial robots. Compared to earlier generations, these robots are much more affordable, accurate, and highly flexible multi-purpose manipulators. All these aspects have made these robots optimal tools for creative and mass-customized architectural fabrication processes. Over the last decade, architects have adopted industrial robots for additive, subtractive and deformative fabrication processes.

However, the robot control and motion programming software tools for these robots are all originally developed for industrial mass production of components in factories. Robot path planning and programming is completely engineered for a specific production process with predictable outcomes. The main criteria for these industrial robot systems is functional accuracy and repeatability over an extended operation time period. The developed and confirmed robot tool-path with these software systems runs for several months on a robot for the mass-production of a unique product. On the other hand, the creative design and fabrication processes in architecture are highly exploratory, meaning that architects need to solve complexities of new forms, materials, fabrication processes, and unpredictable construction environment. The solution for these cre-
ative endeavors relies on a reciprocal investigation between conceptual, digital and materials forms in order to find the best possible solution for the design and fabrication problem in hand. Consequently, for the processes that use digital design and fabrication tools, it is essential that tools of these processes facilitate the reciprocal design and fabrication development process.

However, using the existing industrial robot control system for architectural fabrication processes requires that the designer have a comprehensive view of the fabrication and machining process, and embed all the required considerations in the digital model, before the start of the fabrication phase (Sharif and Gentry 2015). This is a one-directional workflow (Figure 1), in which the designer has to predict material state, tool selection, fixture positioning and robot motion planning based on prior experience (Figure 2). This established workflow of robotic technology that performs adequately and effectively in production manufacturing does not provide much room for any interactive creative design/fabrication activity. There is a high cost and time penalty for re-work in this process.

As the conventional methods of robot control and motion programming were not developed based on the needs and skills of designers, researchers in these field have focused on the development of more flexible and intuitive robot control and programming tools. These new software tools have acquired graphical programming editors such as Grasshopper. Different plug-ins such as Kuka|prc (Braumann and Brell-Cokcan 2011), HAL (Schwartz 2013), and Scorpion (Elashry and Glynn 2014) for programming and kinematic simulation of industrial robots such as KUKA, ABB, and Universal Robots have been developed for Grasshopper and Dynamo. The plug-ins for graphical robot programming provide the option for architectural designers to program and simulate industrial robots directly out of the parametric modelling environment based on the geometric parameters of their designs. These tools provide interactive design and robot programming/simulation in the initial stages of the process. However, most of these tools result in a static robot control data file that has to be transferred from the personal PC equipped with the robot programming tool to the robot computer. After the robot path generation and export of the file, the con-
nection between the design model and the robot movement path is completely disconnected. By the start of the robotic fabrication process, the designer would have no control over the process of fabrication in real-time. In this process, the final physical prototype outcomes are still highly dependent on the architect’s predictive capability of design, fabrication, analytical and process models.

Consequently, this research proposes an integrated framework that transforms the current one-directional workflow of design-to-fabrication process into a comprehensive closed-loop workflow. By using the proposed system, designers can monitor the fabrication process and control the robot in real-time. The developed system provides the functionality for the users to modify the programmed robot tool-path in real-time, due to material tolerances or dynamic or unstructured environment conditions that vary from the expected state. The robot tool-path may also be required based on the designer’s decision for a different course of action during the fabrication process to achieve the desired design and fabrication outcome.

BACKGROUND

Robot manufactures produce robots for two major target users, manufacturing industries, and research applications and developments. While the mechanical and hardware requirements of robots for both these applications is similar, the software and control requirements are quite different. While the manufacturing industry requires higher safety features and easy to use operational interfaces, researchers, including design researcher, prefer higher control over the robot. In the last few years, robot manufacturers are investing more on the development of research robots, also known as collaborative robots.

Collaborative robotics is a new research and development approach in robotic industry. By design, collaborative robots are equipped with communication interfaces that provide accessible external control to these robots. These robots are provided with new interfaces and internal sensor (motor torques and joint torque sensors) and access to external sensor systems (camera, and 3D or laser scanner) that enable the accessible programming for defining robotic tool-paths. Robots such as LBR iiwa from Kuka, Yumi from ABB, UR10 and UR5 from Universal Robots, and Baxter and Saywer from Rethink Robotics are developed based on the principals of human-robot interaction. These robots are usually lightweight and desktop size robots compared to their industrial counterparts. And their major feature is that these robots can perform in close proximity to, and collaboration with human workers (Shepherd and Buchstab 2014).

The controller kernels of these robots is by design modular and open interface that enables object-oriented programming of complex robot kinematics. In addition, these interfaces make external control of the robots and integration of sensors systems relatively straightforward. Taking advantage of these integrated features, researchers have developed interactive robotic fabrication application using interactive robots. Research by Elshary and Glynn presents a developed robot control plug-in for Universal Robots in the Grasshopper environment. Scorpion takes advantage of Java and Python object oriented programming languages and their existing libraries for programming and real-time visualization of the robot tool-path and configuration (Elashry and Glynn 2014). In another research project, researchers have developed a system for on-site robot programming that takes advantage of the embedded force torque sensors of Kuka LBR iiwa robot to facilitate human-robot collaboration and manage material tolerances during the fabrication process (Stumm et al. 2016).

While the collaborative robots provide great features for researchers, these robots have lower pay-loads. Robot payload is the maximum weight that a robot can pick up or manipulate. Robot payload is specifically important for architectural fabrication processes, as the robots needs to handle heavy construction materials such as concrete, metal or stone, and apply high force for processes such as milling or lifting and assembly. While collaborative robots
have about 5-10 Kg payloads, industrial robots - with medium payloads from 50 to 150 Kg and high payloads from 250 to 600 Kg - are more suitable for architectural construction processes. However, as discussed above these robots are not equipped with flexible programming and control interfaces. In order to make high payload industrial robots suitable for research or design fabrication applications, it is necessary to develop custom communication interfaces to provide required flexibility for the control of robots in such applications.

**ADAPTIVE CONTROL INTERFACES FOR INDUSTRIAL ROBOTS**

Focusing on Kuka industrial robots, these robots are programmed with Kuka’s own programming language, KRL (Kuka Robot Language) (2003). KRL is a text-based language that contains tool and machine movement commands as well as data type declarations, conditional clauses and interaction with tools and sensors via digital or analog Input/Output (I/O) operations. KRL programming is usually performed offline via an external computer with software tools such as KUKA.Sim Pro, or Kuka|PRC with a visual programming interface. While KRL features are adequate for industrial applications, it has limited capabilities for adaptive control: no support for advanced mathematical operations or including third party libraries to extend KRL with user defined methods or object (Sanfilippo et al. 2015). In addition, in order to use external input devices such as sensors, it is necessary to install supplementary software packages such as Kuka.RobotSensorInterface (RSI) or Kuka.Ethernet KRL XML.

Various research groups have investigated creating custom communication interfaces to act as middleware between user programs (such as CAD software tools in architecture) and robot controllers to make the interface of industrial robots suitable for research or design fabrication applications. An open-source communication interface for Kuka industrial robots, JOpenShowVar, is a custom designed program which connects to the Kuka controller from a remote computer via TCP/IP, without using Kuka software packages, such RSI (Robot Sensor Interface) or Ethernet.XML. This system uses KUKAVARPROXY, a server developed in Visual Basic to implement the Kuka CrossComm interface which allows for the interaction with the real-time control process of the robot. JOpenShowVar which is written in Java runs as a client on a remote computer connected with the Kuka controller via TCP/IP. The Java based platform allows for high-level programming and use of third party libraries. However, as discussed by the authors, when accessed with TCP/IP communication to the KUKAVARPROXY server, it creates unavoidable delays in the real-time access to the robot’s data, thus it can only be used for soft real-time applications. In addition, as this system is based on Java, it makes difficult to work with C#.NET components in Grasshopper and Rhino .NET SDK (Software Developers Kit) that is the target application for creative industry.

Another interface that is currently available for Kuka robots is mxAutomation which allows for real-time communication with Kuka industrial robots (Munz, Braumann, and Brell-Cokcan 2016, Braumann and Brell-Cokcan 2015). The mxAutomation software package, which has been created in collaboration with Siemens, has two main parts, a server program that runs on Kuka robot controller (KRC), and a robot control program with a client library that runs on a remote computer. These two parts of the system are connected via either field buses EtherCAT or UDP-Ethernet. The authors have developed a custom client software that connects the mxAutomation library with Robots in Architecture’s KUKA|prc framework which runs in the Rhino/Grasshopper environment. This would allow for the exchange of data between the remote computer with KUKA|prc and the robot. While the system offers a high-level programming interface for the user with promising applications, it requires the use of the mxAutomation software package.
METHOD
This research proposes a framework for human-robot interaction that has two main elements: 1) An adaptive robot control system based on sensor feedback, and 2) a design-fabrication library. The main advantage of our proposed framework compared to other discussed research efforts on the development of adaptive robot controls is the use of real-time feedback from a scanning system, as well as the read/write of data from/to the design-fabrication library.

This paper discusses the first element of the framework, the adaptive robot control system. The system architecture diagram in Figure 3 illustrates the high-level view of our developed system and its major components. The adaptive control system uses the following hardware and software elements as the testbed for the framework, hardware: Industrial Kuka robotic arms with either KRC2 or KRC4 operating system, and Microsoft Kinect as the 3D scanner, Software: Rhino 3D, Grasshopper, KUKA|prc robot programming plug-in for Grasshopper, Kuka RSI (Robot Sensor Interface), and Kinect Fusion Library. The only prerequisite is that the user has a solid understanding of computer networking and the KRL programming language.

Figure 3
The proposed real-time control system architecture for Kuka industrial robots. The server runs as client on a remote computer. The server interacts locally with Rhino/Grasshopper and communicates with Kuka KRC remotely via TCi/IP. Feedback data from Kinect 3D scanner is received by the Grasshopper.

The design of our system is based on the following choices:
- Target user: This system is intended for use in design and fabrication processes, where architects and designers are the target users. As a result, it is important for the system to sync and run on CAD applications such as Rhino/Grasshopper or Autodesk Dynamo for visual programming purposes.
- Speed: Although Microsoft Windows computers do not provide hard real-time communication, it is desired to minimize the lag in the communication between the robot control system and remote controlling computer as much as possible. Industrial robots also have real-time constraints, hence maintaining the speed of the application is imperative.
- Native packages: This system employs Kuka’s own developed software package, Kuka RSI (Real-time Sensor Interface), for real-time communication to ensure system compatibility.
- Flexibility: This is accomplished by providing a structure and system architecture that can offer the future possibility of including third party libraries.
Our overall architecture consists of three high level modules - a RSI-Grasshopper module, a Kinect-Grasshopper module and the KUKA Robot Sensor Interface (RSI) server (Figure 4). We outline the design of each module below.

**KUKA RSI Server**

KUKA robots allow their real-time control via the KUKA.RobotSensorInterface or RSI from an external PC over an Ethernet connection. To enable this, the user needs to write a UDP (User Datagram Protocol) based network server on an external PC, in a programming language of their choice, and provide the Internet Protocol address of the server to the robot via the RSI configuration XML. This allows for bidirectional communication between the robot and the server, allowing for the robot motion to be corrected via XML-based instructions. We developed the RSI Server in the Python programming language due to its ease of experimentation and abundance of libraries for network operations. Our implementation supports both the KUKA KRC2 and KRC4 robots.

Our RSI Server spawns three sub-servers - a Robot Server, a Read Server, and a Write Server. These are essentially sub-processes that communicate between each other. The Robot server is the server that connects to the KUKA robot over UDP and always responds to the robot in the 12-millisecond time limit in order to maintain the hard real-time constraint and keep the connection active. This also allows the Read and Write servers to perform long running operations independently and not violate the response time constraint. The Robot server checks for any new input at each cycle before transferring the input or a standard response without corrections to the robot while always updating the new robot configuration in its internal data structures. The Read Server reads the RSI data from the Robot Server’s internal structures and provides it to the user in JSON format for display or logging. The Write Server accepts input from the user in the form of a JSON of per-axis corrections and transforms this input to a JSON format which is then sent to the Robot Server to encode into valid XML and then send to the robot. We use JSON to communicate between the three sub-servers due to its ease of use with Python and many other high-level languages (such as Matlab or C#) and relatively lower memory requirements compared to XML. All communication between the 3 sub-servers is done using inter-process messaging queues.
To ensure safety of the robot and to not violate its torque correction limits while performing the robot corrections via the RSI, we chunk all the corrections into smaller corrections of 2 millimeters or less, and generate the appropriate number of UDP packets which are sent in a batch. This also provides smoother path corrections for the robot allowing for better feedback to the user. The chunk size is a configurable variable in our program, thus allowing for either very slow and small motions or large rapid motions as may be desired.

From the KRL programming end, we create the RSI object and set the correction limits to the approximate boundaries of the workspace in which the robot will operate. This ensures the KRL program does not give an error due to limit violations. The RSI object is enabled when the program is run, allowing it to communicate to the RSI server.

**RSI-Grasshopper Module**

To allow for Rhino 3D to transfer user updates to the robot, we developed a RSI-Grasshopper module using the Grasshopper plugin (Figure 5). This module allows the integration of Rhino 3D with the RSI Server by linking the Rhino 3D UI elements with the data in the RSI Server via TCP connections over Ethernet. The Read and Write sub-servers in the RSI server provide the external interface to our RSI server and allows us to send the robot corrections and receive the RSI data. In this module, we create the TCP requests to transfer the data to the Write Server and to read the robot pose from the Read Server and update the Rhino 3D user interface, thus allowing for real time control and updates for the user. Using the developed server and added module in Grasshopper together, we can receive and see the robot’s actual position in real time, and send corrections for the robot tool path in real time.

**Kinect-Grasshopper Module**

To allow for visual feedback of the object we are fabricating, we integrated a Kinect sensor feedback into Rhino 3D by developing a Kinect-Grasshopper plugin module (Figure 6). The Kinect acts as a 3D scanner to generate a real time point cloud of the object as feedback to the user. Using the Kinect Fusion Library in the C# programming language, we developed the plugin for Grasshopper that can bring the Fusion depth stream into Grasshopper, thus providing a 3D point cloud of the actual physical environment of the part under fabrication inside the Grasshopper environment. Using this 3D view, the user would be able to move the robot Tool Center Point (TCP) to an actual point in the physical space, via the RSI-Grasshopper module, and see the visual feedback from the Kinect window to guide the robot.

As future steps for the completion of this system, we intend to develop a structure that by overlapping the generated mesh from the Kinect point cloud data on top of the existing CAD model, it would be possible to measure the deviations between the expected 3D and actual physical forms.
CONCLUSIONS AND FUTURE STEPS

In this research, we have elaborated upon the first part of a real-time framework for robotic fabrication, particularly the integration between Rhino/Grasshopper CAD modeling and visual programming environment, and an industrial robot to allow for instant feedback during the fabrication process. We have described the architecture of our system that allows for maintaining the real-time constraints required by the robot as well as providing efficiency for the end user to complete their task without damaging the robot or its surroundings. Visual feedback both in terms of robot data as well as 3D depth data from a Microsoft Kinect with the KinectFusion library provides more comprehensive information during the whole process.

As the next step of this project for the development of a comprehensive human-robot interaction framework, we will focus on the development of a design-fabrication library that would utilize the developed adaptive robot control system for storing various design and fabrication information in its database. In the conceptual design stage, this library will assist the designers with the decision making process on the adequacy of the design choices, detailing, material selection for the selected robotic production techniques, and end-effectors. This design library will be instantiated incrementally based on both experimentation and human expert knowledge. The database will grow over time with data from continued experimentation by multiple users, which will be enabled by the system described here. In addition, a user study on Human-Robot Interaction aspects of the system will be performed. This study will compare scenarios for an identical fabrication process with the assistance of the adoptive robot control system or without it, by measuring aspects such as time, success rate, number of successful attempts, and quality of the final product.

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MoleMOD

On Design specification and applications of a self-reconfigurable constructional robotic system

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The paper explores the use of in-house developed self-reconfigurable modular robotic system in civil construction activities and investigates a concept where an arbitrary Civil Engineering structure or a daily use industrial product are self-assembled from a number of self-reconfigurable composite blocks. The system extends current range of modular robot systems (mDrs) where autonomous modules self-assemble into a wide variety of forms. However, contrary to conventional mDrs, MoleMOD has not mechatronic actuating parts permanently fixed to each individual module. The MoleMOD actuators are separable and operate inside the modules, tight them together or relocate them to required configuration. It significantly reduces number of expensive mechatronics parts and the environment the actuators operate. Although MoleMOD focuses on architecture, it can take over other mDrs tasks as research and rescue. This paper describes properties, advantages, foreseen applications, and basic design specifications of the second generation prototype.

Keywords: Modular robotic systems, Mobile robotic systems, Adaptive architecture, MoleMOD, Smart materials and structures, Multi-robot systems

1. LIVING COLONY-LIKE ARCHITECTURE

Architecture has, for many years, remained basically unchanged. It still uses the same principles and archetypes as walls, roofs, windows or doors which have been known for thousands of years. Architecture is very slowly adapting to current material research, information technologies and user behaviour. Nonetheless, several architectural studios and academic groups have already started to react to these facts. Principal question stems from how can we predict the building we designed today will serve societal needs in ten, twenty or fifty years? For reasons of using “new spaces” (social networks or virtual and augmented reality) and technologies (robots, smartphones, nanotechnology, etc.), it can be very difficult to predict what form of physical space will be needed in a very near future. For instance, do we really need physical space as an office? Most likely
yes, but what size, where, how often? This question evokes that the buildings of the future should be able to adapt to emerging purposes, aggregate and segregate, self-heal, self-diagnose, possibly relocate, in similar ways the living colonies of termites, ants, or bees do, i.e. constantly adapt to surrounding environment and local conditions (Miller 2011). Colony-inspired Agent based models as Ant Colony or Boids are currently used mostly for prediction models, design of complex shapes or to control multi-robot systems. The control of collective behaviour alone can be the inspiration for the adaptive architecture. Contemporary architecture is no longer only about the form, material, function, colour etc., but the life-cycle of the building is becoming more important. It is not only about recyclable materials or so, but more about effective use of building during its hardly predictable lifetime (Spyropoulos 2016). For new self-assembly architecture as it is focused here, it is necessary to develop materials and systems with completely new features as self-healing and self-diagnostics capabilities as well as and self-reconfiguration ability, and others.

2. MULTI-ROBOT SYSTEMS IN ARCHITECTURAL CONTEXT

MoleMod extends existing multi-robot systems (MRS) towards applications in Architecture and Civil Engineering. MRS cooperate usually as an organic intelligent swarm system (ants, termites, bees etc.) so that they allow for versatile interactions with the internal and external environment. (Ahmadzadeh et al. 2015). In the sequel, MRS are splitted to Modular robot systems (mDrs) and Mobile robot systems (mBrs).
2.1 mDrs

Consist of many modules that can move relative to each other, thereby changing the overall shape of a target assembly to suit different tasks. MoleMOD differs substantially from state-of-art mDrs except some similarities with ROOMBOT developed on École polytechnique fédérale de Lausanne, which may combine active and passive components (Spröwitz et al. 2014). Nonetheless, not every passive part of ROOMBOT may become active, as it is allowed in the case of MoleMOD concept. Another excellent example is project HyperCell by AADRL Spyropoulos Design Lab, which focuses directly on architecture. HyperCell is able to create structures without predefined instructions with cells represented by small scale cooperating robots. Contrary to MoleMOD the cells have a common design and each is fully mechanized (Spyropoulos 2016).

2.2 mBrs

Contrary to mDrs, mBrs do not have to consist of a large number of robots. These systems usually consists of a robot (manipulator) and an object to be manipulated. MBrs should be significantly cheaper, but it is not as versatile as in mDrs. A representative example is project Termes (Petersen et al. 2011) developed at Harvard University. Termes is based on the behaviour of termites. It splits into active and pas-
sive parts. The Active part is represented by a special robotic climbing vehicle which is able to pick up and carry the passive parts, represented by modular blocks with lines the vehicle follows. This is appealing namely from the fact the robot is operates in a predefined environment created by rigid blocks, making it easier for orientation than in a real world environment (RWE).

Without any relation to a particular size of robots, their hardware components, forms or applications, there is a significant gap between research and industrial applications. MRS development is expensive, due to a vast number of hardware components needed to create a reasonable large community of robots. Thus MRS are tested only with few components in-vitro or only in-silico without a real application. Another difficulty is sensing and operating in RWE. MoleMOD reacts at least on the letter as it brings a novel insight in the self-assembly problem demonstrated though applications in Architecture

3. MOLEMOD CONCEPT IN CONTEXT OF CURRENT APPROACHES

MoleMOD in fact has material features, but contrary to traditional understanding it is designed to fulfil the above requirements. On the other hand, internally reassembles mDRs. The split of the system to passive and active parts gave a name to the whole system, Mole (animal) + MOD (module). Furthermore, Mole is used for the active part (detachable soft robot) and MOD for the passive part (modular building block). The site-specific construction of MoleMOD is the assembly of Moles and MODs. Each MOD has a minimum one tunnel, which usually leads through it. In the tunnels the Moles operate and fix and move with Mods, which become active as in existing mDRs. The system offers extensive possibilities of reconfiguration and adaptation as well as material design. The material can vary, because MODs are rigid and they do not have any special mechatronic parts embedded, what makes it also significantly cheaper. However, the weight of MODs is very important, so the lighter material is better after all. Thanks to design of MODs the final building is a big maze of tunnels where Moles can operate. An advantage of this is that these tunnels can be used for piping, wiring or reinforcement as well as fixing to the ground by pile. Although pilot design respects rectangular grid module (30 x 30 x 30cm), dimensions, grid shape, robot actuators, robot design, connections can vary.

3.1 Moles (active part)

Moles consist of two primary components: a soft body and revolving heads attached to both soft body ends. The head is responsible for screwing ring coupling to interconnect two neighbouring Mods, the casing of the head help to fix the robot to ring coupling as well as to provide a peristaltic movement (Seok et al. 2013), the secondary function is to ride, because the head works also as a wheel. The soft body (Bishop-Moser & Kota 2015) allows the peristaltic movement of the whole robot, and the manipulation with the blocks similarly to elephant trunk (see Figures 2, 3, 4, 5 and 6).

Revolving heads are located on both ends of the soft body. The main part of the head is the revolving casing, which by protrusion of flexible elements on the perimeter, screws with ring coupling inside MODs and tightens them together. Also by

![Figure 5](image-url)

Testing of the active part (Mole) on the part of passive part (MOD).
revolving this component it is possible to transport MODs. Electronic parts like a DC motor, compressor, valves, microcontroller and pneumatic silicon pillow are placed inside the head.

The soft body connects both heads and allows to control the head’s direction. The body consists of pneumatic silicone pillows and a skeleton structure from 3D printed flexi material, which stabilizes Mole (Figure 4). By controlled inflation or deflation the pillows are able to inflect, stretch or contract the whole body according to our needs (Figure 5).

3.2 MODs (Passive part)
Desired structure consists of MODs and very limited number of Moles assumed to be present for longer than the reassembly building time. The current cubic shape of passive blocks was chosen since it is mostly used in modular robotics (Ahmadzadeh et al. 2016). However, the system is not restricted only to cubic block shape alone. It can consist of arbitrary polytopes. It means that it is possible to build conglomerates without extensive limitation. The principle task was to develop joints. Usually in mDrs joints are magnetic or mechanical (Ahmadzadeh et al. 2016), but MoleMOD cannot work like that, because architecture and civil engineering require passive joints. For this reason, special coupling rings were developed which allow robots go through it, as well as tighten them (see Figures 5 and 6). The advantage is also, that the connection not uses male and female joints but unisex joints. It offers many variations of connectivity.

4. ADVANTAGES, APPLICATION, INNOVATIONS
Though the MoleMOD focuses on future architecture which should be adaptive and movable, several applications exist where this system can be very helpful.

4.1 Socio-economic point of view
Hard to reach places and disasters. Use of MoleMOD gives a sense of security in places where there may be low safety of workers. Robots will be easily transported close to the building site, check the location, and start to automatically build it. MoleMOD should underpin human ambitions towards exploration and occupation of places like deserts, Polar...
Regions or hospitable planets, as well as fix problems after disasters without human labor.

Example of Scenario: For Mars’ first buildings it would be very risky to use a human sources as well as transport a large amount of building material. With MoleMOD and 3D printing technologies it could be easier. From earth the only active part (Mole) of MoleMOD will be transported, while the MODs will be printed on site using local sources. Due to the fact that Moles operate inside MODs (passive part), there is a lower risk that will be damaged by the unpredictable Mars environment.

Example of Scenario: After a nuclear disaster there is a need to prevent the release of radioactivity. There is no possibility to fix it by human hands because it is life threatening. One of the possibilities could be to build a sarcophagus from MoleMOD blocks. Another way is to build temporary dwellings for people affected by disaster.

4.2 Mechanical point of view

From the mechanical point of view, the synergy of described features, together with a built-in communication system, would allow for self-diagnostic and self-healing capability going in line with excellent Life-cycle management of the resulting assemblies.

Example of Scenario 1: A local failure occurred, i.e. a subscale element in a critical location is damaged, yielding a decrease in load bearing capacity. The self-diagnostic feedback is instant, followed by a new assembly plan that takes into account changed conditions. Other undamaged members of the community follow the plan and reconfigure in a way to entirely or partly recover the load-bearing capacity until the bridge is fully fixed. This is what we understand as self-healing ability in the MoleMOD context.

Example of Scenario 2: A bridge has to withstand peak loads. It has not been designed for, or it was, but their extremes can harm the structure in terms of service-life longitude. During such a load moving over the bridge, the modular blocks or bar elements may be reconfigured to withstand the load, or to reinforce critically strained regions in order to decrease the risk of local damage, yielding more serious failures in a long term perspective.

4.3 Life-cycle management

MoleMOD properties allow for a very good life-cycle of the product. Thanks to separated parts it is possible to recycle the passive part as well as use en-
environmentally friendly materials for its manufacture. The whole system is based on permanent adaptation and should provide conglomerates which are open to reuse after their lifetime, with minimum impact to the environment during the transformation to next use (Figure 7).

5. FUTURE WORK
MoleMOD is at the start of development and will need to go through several challenges due to the complexity of a developed system before it can be fully commercialized. In this first stage the design of active part is mostly solved, because it is necessary to first develop the robot (Mole) on which the following will be tested: sensing of an environment, self-configuration algorithms, possibilities of blocks (material, connections, etc.), and static and dynamics simulations of resulting conglomerates. Future work will especially test different types of soft actuators for Moles because silicone is a very soft material for this application. Considered materials are pneumatic bellows, pistons or shape memory alloys. Also will be optimize the joint system and develop another shapes
for different types of grids. Finally is needed to find ideal materials for required applications.

Future work will especially test different types of soft actuators because silicone is a very soft material for this application. Considered materials are pneumatic bellows, pistons or shape memory alloys. Flexinol wire was already tested (Seok et al. 2013). This wire is able to contract and stretch and when electricity goes through the wire it is heated, which allows contraction, making it possible to use as an actuator. Unfortunately the result was not ideal for this application due to slow reaction when the wire is cooling down (figure 8).

5.1 Planning and sensing
It is needed to develop fast and robust planning algorithms providing good quality solutions like collision-free trajectories for providing generated plans of the reconfiguration process which will respect the static and dynamics models as well as human requirements, ideally collecting from Big Data. The developed algorithms will allow efficient life-cycle management consisting of self-reconfiguration, self-diagnostic and self-healing without the need for human intervention. Even though a final conglomerate thus formed a maze that reduce the RealWorld Environment (RWE) complexity (Kulich et al. 2014) where robots normally operate, sensing equipment is necessary (cameras, distance sensors, pressure sensors, RFID tags, etc.). Early future MoleMOD will be equipped with these.

CONCLUSION
MoleMOD is designed so that it shouldn’t limit architectural visions. This is not new architecture, it is a new system of material distribution. It is good to know that it is still basically mDrs, which has some specifications and limitations. The Main goal of this design is trying to minimalize costs by splitting the system into active parts (Moles) and passive parts (MODs) and reduce RWE complexity.

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Low-Cost Housing

Testing snap-fit joints in agricultural residue panels

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Within the field of digitally fabricated housing, the paper outlines a theoretical model for a housing system that combines complete off-site prefabrication with parametric assemblies. The paper then presents some insights on the application of snap-fit joints to the wall assemblies entirely fabricated using agricultural residue panels. Mechanical characterization of the material was performed through axial tension, compression and 4-point bending tests. Guidelines of plastics snap-fit design were applied to the joint design within the elastic limits of the material. Three different full scale wall typology prototypes were built using this jointing technique. The results show that while snap-fits can be a promising solution encouraging self-build in low-cost housing, the brittle nature of the specific agricultural residue panel material necessitates further joint enhancements.

Keywords: Digital fabrication, Low-cost housing, Agricultural residues, Structural testing

RESEARCH MOTIVATION AND BACKGROUND

In a world with diminishing resources and changing climatic conditions, the concepts of sustainability are becoming a critical broad background to research and practice. The world population is increasing at a rate that is shockingly rapid. The livelihood and safe housing environments are becoming increasingly difficult to obtain in developing countries. Motivated by this rising demand for affordable housing especially in poor and developing countries, the authors had previously performed an investigation that examined built prototypes of digitally fabricated houses within twenty years (1995 - 2015). It was an attempt to understand the limitations and potentials of using digital fabrication in the affordable housing sector in developing countries (Elsayed & Fioravanti, 2015).

Among the most important limitations was the almost exclusive usage of plywood and timber in general as the core building material for this approach of housing as it is easily machined using relatively affordable digital fabrication tools. This becomes an evident limitation when working in countries that have no tradition of building construction using timber, or mainly depend on imported timber. On the potentials side though, digital fabrica-
tion still promises to provide a process that is efficient and rapid while maintaining the possibility of mass-customization through coupling fabrication tools with parametric design.

Moreover, from an environmental point of view, many developing countries with long tradition of agricultural activities face a yearly challenge in the harvest season. The process of harvest produces large amounts of residue that must be disposed of. Unfortunately, the current practice is largely burning these residues forming huge black clouds of smoke above surrounding villages and cities. The environmental impacts of such practice are utterly harmful causing multiple lung diseases, needless to mention other negative effects. There has been on-going research exploring the use of condensed, treated rice straw as a building block (Mansour, et al., 2007, Akmal, et al., 2011). Few researchers started exploring potential use of rice or wheat straw residues in flat sheets. This particular application is of great potential to the field of digital fabrication in which the authors are involved.

PRECEDENTS IN DIGITALLY FABRICATED HOUSING

Wikihouse (1); Instant House (Botha and Sass, 2006); Shotgun House (2); ECOnnect Haiti emergency shelter (Stoutjesdijk, 2013) are all examples that demonstrate the potentials of using digital fabrication coupled with Do-It-Yourself approach in housing construction where the end-user is seen as an active contributor to the assembly/construction process. These prototypes skillfully represented quick yet temporary responses to emergency housing situations however little attention was given to analytical structural aspects and long term living space requirements. For instance, the Instant Cabin and ECOnnect emergency shelter have an area that is less than 20 square meters with no wet spaces which is understandable in emergency situations but not for long term living.

From this starting point and with the aim of finding solutions to the pressuring problem of housing in developing countries, we explored alternative materials that can be utilized for housing construction while having minimal environmental impact. With the criteria of environmental and financial sustainability, low cost, simplicity of construction, customizability and ease of transport; the authors scanned the construction market for stock sheets made of compressed agricultural residues.

AIM AND OBJECTIVES

The paper attempts to address and understand the structural performance of agricultural residue based sheets in the construction process utilizing digital fabrication tools and snap fit joints. ECOboard (3) is a wheat straw resin-bonded fiber panel product produced by a Chinese company and introduced to the European market under the commercial name ECOboard. The commercial data sheet gives high mechanical resistance values which tend to be overestimated for marketing reasons. The data sheets also mention values related to moisture content, thermal performance and fire resistance. The author at this point is solely interested in verifying the mechanical material values to understand the possibility of using these panels as principal load bearing structural elements within wall, floor and ceiling assemblies designed with snap-fit and friction-fit joints with no adhesives or bolts. Within the scope of this paper, a set of 3 mechanical tests were performed as will be demonstrated. Three different wall typologies were built but due to time limitations, their structural testing is not shown within this paper.

PROPOSITIONS OF A LOW-COST HOUSING SYSTEM

Within these premises, the author proposes a housing system (Figure 1) that is mainly comprised of: Firstly, modular parametric wall, ceiling and floor assemblies. By parametric we intend going beyond being modularly and dimensionally fixed. The wall assembly overall internal and external dimensions can be changed based on layout design decisions of the client and the architect. Secondly, a factory built prefabricated core that contains wet spaces of bath-
room, kitchen and mechanical equipment with the aim of reducing on-site construction complexity.

There are certain time and budget benefits for combining these two systems together. The construction of a new site-built home in the US for instance, typically consists of 80% labour and 20% material cost (Larson, et al., 2004). While using modular panelised approach saves time for on-site construction, the utility services and mechanical system connections consume large amounts of time for onsite installation. Hence the housing system proposed by the authors promotes off-site fabrication for the more complex part of the housing system in search for cost savings associated with controlled environments that factories can offer. Better working conditions, automation of some tasks, fewer scheduling and weather-related problems, and simplified inspection processes are all seen to be strong players for the reduction of costs associated with on-site construction.

The parametric assemblies are meant to be built entirely of flat sheet material (agricultural residue panels) using snap-fit and friction fit joints. The constructive logic is based on stand-alone hollow cassettes that are assembled within themselves and to the neighbouring ones using snap-fit easy-to-assemble and disassemble joints (Figure 2). This choice was made to ease fabrication and encourage self-build by unskilled home owners.

**CHARACTERIZING THE MATERIAL**

The ability to define reliable mechanical values of the material to be used as safe design values is an indispensible step in dimensioning the cantilever snap-fit joints and structural elements of the modular system. The material comes in different flat panel thicknesses such as 9, 12, 15, 16, 18, 19 and 25 mm. The Modulus of Elasticity (MOE) and bending strength provided by the manufacturer for the 18mm thick standard panels were 3810 MPa and 38 MPa respectively. These values cannot be regarded as safe design values as they were taken from a commercial data sheet which generally tends to be over-estimated for marketing reasons. The reports received from the company did not mention which norm was followed for testing the mechanical properties. Hence, it was important to perform basic mechanical tests which can give a better indication of the material behavior of 18mm thick stock sheets.

The tests included: axial tension, axial compression and 4-point bending. The European norm EN789 (Timber structures - Test methods - Determination of mechanical properties of wood based panels) was used loosely as a general guideline for the test pieces’ preparation, loading arrangement and procedure. The norm was not fully met due to several limitations such as availability of specific testing machinery, relatively large test-piece dimensions required by the norm. The results of lab experimentation on the 18mm sheets shall be seen merely as indicative as the tests were only performed twice in different panel orientations while the norm states performing each test 4 times in a given panel orientation.

The material showed overall good resistance values, however, the obtained Modulus of Elasticity in bending was 2100 MPa which is 44% less than the commercial values provided by the manufacturers while the bending strength was found to be 14 MPa which is almost 60% lower than the commercial
value. The material showed elevated levels of resistance in pure compression (9.2 and 11.1 MPa for two tests) and lower resistance in pure tension (7.2 and 8.5 MPa for two tests). It was observed that the material has a brittle behavior in tension (Figure 3). This can be largely attributed to the very fine fibres that the material is composed of.

In compression, it was observed that failure was consistent with natural wood failure modes. The first test piece failed with shearing while the second test piece failed with a combined mode consistent with crushing and splitting. The material showed consistent behaviour for the two test pieces with no observable difference between panel orientations. Given the artificial nature of the material being a composite with its characteristics depending primarily on the bonding material (resin) therefore, a coherent result was expected with no major deviations. These values
are considered very important inputs for the design of an efficient snap-fit and friction fit jointing system.

Figure 3
Failure of test piece under axial tension.

SNAP-FIT AND FRICTION-FIT JOINTS
Any Snap-fit joint consists mainly of one male part and one female part. The temporary bending of the cantilever part allows for the fit of the two pieces using the material elastic behaviour. After the joining operation, the two parts return to a stress-free state. (Robeller, et al., 2014).

Although snap-fits can be designed with many materials, the design manual developed by BASF (2007) and BAYER (2012) deal exclusively with different thermoplastics because of their high flexibility and their ability to be easily and inexpensively moulded into complex geometries. Within the scope of this research and with the aim of simplifying the process of fabrication, only straight cantilever joints will be used. Other more complex joints like “U” and “L” shape cantilever snaps with the presence of under-cuts necessitate the use of complex fabrication -such as subtractive multi axes robotic fabrication- which would significantly raise fabrication time, cost and complexity. Snap fits were studied previously by Robeller et al. (2014), using cross-laminated veneer lumber (LVL) as the base material in the context of shell structures. LVL material composition and stratification implies a certain behavior to local stresses that was simulated by Robeller et al. using Finite Element Analysis (FEA) tools and verified later by physical testing. It is therefore expected that with a material that has a different internal composition, bonding and overall mechanical performance; to have different response to stresses and thus different structural performance.

BASF (2007) design guide explains that snap-fit joint dimensioning can be approached in two different ways. Material first: were a material has been already chosen with known allowable strain and then dimensions are designed to fit it. Dimensions first: were primary dimensions are fixed and then a material research is performed to select an appropriate material that allows using those dimensions. In this case, a material selection has been already done, so the design activity becomes defining the proper dimensions for the joint. When designing a cantilever snap, it is not unusual for the designer to go through several iterations (changing length, thickness, deflection dimensions, etc.) to design a snap-fit with a lower allowable strain for a given material (BASF, 2007).

One of the usual approaches for snap-fit design is to start from a group of design approximations or assumptions. In the case in hand, we started from an initial rough geometry for both part and mating part (Figure 4). The cantilever beam length (l) is assumed to be 90 mm, and the height at base (hbase) to be 19 mm. A tapered cantilever was also used in order to minimize the uneven distribution of strains on the material. For all the calculations, it was assumed that the mating part of the snap-fit remains rigid while all the flexural stresses happen in the cantilever beam (BAYER, 2012). This assumption represents an additional precaution against material failure. The cantilever base connects to the wall using a root radius of 4 mm. While the guidelines propose a ratio of 0.6 between radius of fillet and height of beam (R/hbase), it however acknowledges that this would result in a large base at the cantilever connection with the supporting wall. It calls upon the designer to reach a compromise between a large radius to reduce stress concentration or a smaller radius to avoid residual stresses due to the creation of a thick section adjac-
The initial assumptions used for the design of the snap-fit joint, taking into consideration milling machine limitations, required geometry and some best practice assumptions.

The entrance angle was assumed at 20° while the retraction angle is kept at 90° to ensure that the disassembly is not too easy under circumstantial pulling forces.

Short and long cantilever arms were tested in assembly and disassembly.

**PHYSICAL PROTOTYPING**

Various trials were performed to test the integrity of the cantilever beam arm. While keeping the cantilever base height at 19 mm, two different trials were made changing only the length (l min) of the cantilever beam. One trial at a length of 90 mm, the second at a length of 76 mm. While the longer beam length allowed for easier deflection and accordingly easier assembly, it was easily broken under hand-applied force. The shorter beam however, showed better overall resistance given that sufficient tolerance is considered for the mating parts.

Given the accuracy with which the dimensioning calculations are made, fabrication tolerances also had a considerable effect on the overall performance of the cantilever beam. The fabricator was provided with a CAD file for the first joint trial in which 1 mm tolerance was designed to accommodate for the accumulated tolerance effect that might arise with the assembly of a big number of pieces. This tolerance also accounted for imperfections in material sheet thickness and any eventual expansion due to moisture or heat. However, on an individual scale, this tolerance was found to affect the overall integrity of the joint making it considerably loose. The subsequent fabrication trials were designed at zero toler-
ance while assumed a machining tolerance of 0.3 mm (set from CAM software) for the tab holes and this value proved satisfactory for the individual and accumulative tolerance requirements. Three wall typologies were modeled then fabricated using an open source CNC milling machine (Figure 6).

Figure 6  
Three CNC milled wall typology full scale prototypes.

OBSERVATIONS AND CONCLUSIONS
While the process of assembly was smooth and quick in which the author by himself assembled the three wall typologies with very little help in less than an hour, some challenges were faced during assembly that require further enhancement and optimization. This section provides some insights on these issues and the prospective steps that might be taken to address them.

It can be concluded that this material with its characteristic fine fibers is not best suited for delicate joining. Although the joint was designed within the elastic limits of the material, some of the snap-fit cantilevers were broken during assembly, specifically 4 out of 58 cantilever arms which is around 7%. The brittle nature of the material was a very noticeable aspect during assembly. These failures might be attributed to local material weak zones or to applying high strains -beyond the material’s allowable strain- during assembly of more than one cantilever arm in the same time. However, it is evident that the dimensions of the snap fit cantilever in brittle materials is a critical issue that needs further analysis and design optimizations.

It was observed that the overall rigidity of the assemblies increase with the increase of number of components and their bi-directionality. For instance, the L wall was more rigid than the straight wall and the T wall was more rigid than the L wall and so on. This is quite logic as the contact surfaces between different components increase and thus increase the system’s global rigidity. The straight wall was more prone to skewing in the horizontal plane while the two other assemblies where much better on that front. This necessitates adding horizontal bracing profiles within the straight wall and between different assemblies.

The integrity of the edges in direct contact with snap-fit were prone to fiber crushing due to high friction during assembly. The bonding strength of the exposed edges in this material is questionable. It is critical to find good tolerance balance that would account for this edge weakness while not compromising the retaining force of the snap fit.

SIGNIFICANCE OF THE RESEARCH
Based on availability in local markets, the selection of wheat straw as the base material promised to address more than one issue concurrently; First, fits the available relatively cheap digital fabrication technologies available through Fablabs and hacker spaces. The standard equipment that are provided by these labs is considered a defining factor to the development of this housing technology as the intention is democratizing the process of construction by providing access to means of production and making it available for low-income populations. Second, adds economic value to materials that previously had little value. Third, lower the initial cost for the construction of the house if used in a structural manner. Fourth, minimize the environmental impact of abundant un-used agricultural residues.

OUTLOOK
The paper gave some insights to the design and fabrication of snap-fit joints in brittle materials through better understating of structural performance and assembly behaviour using agricultural residue panels.
The designed joint will be optimized and revisited in the light of this specific material behavior implying rethinking issues of tolerance, edge clearances and friction fitness.

On the contrary to snap fits, the half-lap joint insert which was used the L wall and T wall assemblies showed high resistance and strong fit during the construction of the prototype. This type of jointing can be further explored as a substitute to cantilever snap-fits in brittle materials. These enhancements or possible joint concept trials are part of the future work.

The wall assemblies -rather than only the stock material- are scheduled for structural testing but due to the busy time schedule of the testing laboratory it was not possible to finish them within the time frame for this paper. They will however be part of a subsequent publication.

The results of the structural testing are not intended to be seen as the ultimate result of the paper but as an initiator of a broader discussion within the architecture audience interested in architectural materials, sustainability and affordable housing about the viability of using this material and this jointing technique for low-cost construction.

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FABRICATION - VIRTUAL AND PHYSICAL PROTOTYPING
Simulating Self Supporting Structures

A Comparison study of Interlocking Wave Jointed Geometry using Finite Element and Physical Modelling Methods

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Self-supporting modular block systems of stone or masonry architecture are amongst ancient building techniques that survived unchanged for centuries. The control over geometry and structural performance of arches, domes and vaults continues to be exemplary and structural integrity is analysed through analogue and virtual simulation methods. With the advancement of computational tools and software development, finite and discrete element modeling have become efficient practices for analysing aspects for economy, tolerances and safety of stone masonry structures. This paper compares methods of structural simulation and analysis of an arch based on an interlocking wave joint assembly. As an extension of standard planar brick or stone modules, two specific geometry variations of catenary and sinusoidal curvature are investigated and simulated in a comparison of physical compression tests and finite element analysis methods. This is in order to test the stress performance and resilience provided by three-dimensional joints respectively through their capacity to resist vertical compression, as well as torsion and shear forces. The research reports on the threshold for maximum sinusoidal curvature evidenced by structural failure in physical modelling methods and finite element analysis.

Keywords: Mortar-less, Interlocking, Structures, Finite Element Modelling, Models

INTRODUCTION / CONTEXT OF RESEARCH

Self-supporting stone or masonry architecture is the arrangement of modular elements that are structurally performative and hold together through vertical force, without the need for mortar or connectors. This method of construction has potential to be used in areas where efficient assembly and disassembly are required. As no secondary construction is used, consideration of relative position of each block within the overall geometry, and joints of a block assembly become the driving factor that determine the architecture.

In mortar-less structures based on topological interlocking blocks, the mortar and connectors make the structure stiffer, which reduces its resilience to vibrations and seismicity (Dyskin et al. 2012). In
most dry stone structures, the self-weight and friction hold modules in place. In addition, cantilevering structures with planar joint typologies can be supplemented by use of steel-reinforcement (Fallacara et al 2013).

The increased ability to analyse the line of thrust in a masonry arch or vault is contributing to the renewed interest in simulating stereotomic structures.

Traditional methods of thrust line analysis performed by hand are often tedious and inaccurate. As has been argued, “historic masonry buildings fail due to instability rather than a lack of material strength because stresses in historical masonry are typically an order of magnitude lower than the crushing capacity of the stone” (Heymen 1995). In order to overcome these problems, current practices apply structural analysis tools, such as Finite Element Modelling (FEM) techniques, and Finite Element Analysis (FEA) where an initial model is developed based on a designer’s concept, then analysing the model providing a feedback loop informing what design decisions are to be made. The method of FEA has direct associations with predicting the behavior and performance of masonry structures in relation to factors such as instability. Other modeling and analysis tools have been customized, such as RhinoVault (Rippmann 2016). As a solution to this, Block at al (2006) developed an equilibrium approach used for analysing the structural behaviour of masonry buildings, using thrust lines to visualize forces and predict potential collapse modes. The interactive and parametric nature of the models allow for the exploration of possible equilibrium conditions in real time. This was applied to recent self-supporting sandstone modules acting in compression: the Armadillo vault by Block Research Group (Rippmann 2016), however, the prototype was based on planar joint typologies, with limited capacity to integrate forces beyond compression.

Consequently, this paper focuses on the further development of customised modules, in testing different three-dimensional joint typologies for the ability to perform under various load scenarios, self-weight, cantilevering, and resulting shear forces. It is part of an ongoing research into six-axis robotic fabrication of multi-dimensional customised face joints in form and force fitting connections (Jung, Reinhardt, Watt 2016), and an increased formal and structural complexity by robotic wave joints (Weir, Moul, Fernando 2016). Hence, the focus of this paper is on the structural integrity of complex three-dimensional joints and their capacity to interlock, and withstand forces of shear and rotation, based on the amplitude of their curvature. Specifically, the amplitude of variations in sinusoidal and catenary curvature is investigated here. This is significant because the higher the amplitude of the curvature, the greater the interlocking capacity of the blocks (Figure 1). While the structural performance may vary based on the rotation of the blocks, boundary conditions, supports and location of loads, the foundational investigation of structural performance for a singular joint, and its threshold in maximum curvature is essential for understanding the performance in macro geometries. As can be seen in figure 1, variations were tested from a generic planar block (A) to a sinusoidal 30 and 45 degree curve (B) and (C), then towards an equivalent 30 and 45 degree catenary curve (D) and (E) respectively.

Figure 1
Interlocking base block geometry with variations in sinusoidal and catenary curvature

Figure 2
Left: FEA visualizations of a catenary arch structure modelled in ABAQUS/Standard and Right: twisted catenary arch structure in ABAQUS/Explicit (Fernando 2017)

Figure 3
Rotational axis on twisted catenary arch structure with FEA mesh
Analyzing the structural action of complex domes and vaults as a series of two-dimensional arches enables the additional structural integrity resulting from the three-dimensional aspect of vaults and domes which in turn provides a further margin of safety (Ochsendorf et al 2012).

Structural analysis and modelling undertaken as ‘finite element modelling’ (FEM) and ‘finite element analysis’ (FEA), are methods of numerical analysis. Here, a process of ‘discretization’ is used with sets of simultaneous equations (Ip 1999). These equations are utilized to connect the internal forces with the external applied loads. Different standard software sets are available for this, such as Simulia ABAQUS (Dassault Systèmes), ANSYS LS-DYNA and Karamba3D. FEM can be applied to macro-modelling and micro-modelling of complex geometries. The first FEM application, macro-modelling, does not consider the use of joints or details between units and connections of the model. The second FEM application, micro-modelling, is used to simulate more detailed aspects of masonry units including mortar gaps and contact surfaces. It requires intensive computational effort and is suitable for small structural elements with strong heterogeneous states and direct consideration of stress and strain.

However, the accuracy of the set of equations is reliant on the linear matrixes. Masonry or stone blocks typically behave in a non-linear manner, therefore FEA programs such as ABAQUS adopt a ‘Newton-Raphson procedure’, whereby a convergence criterion is established and so simulation errors are minimized, because “if the simulation were to be non-linear, this simple matrix solution will give rise to incorrect accumulation of computational errors” (Ip, 1999). In particular, this is important in the context of non-Cartesian geometries, such as catenary structures, arches and domes, as it helps to forecast structural behavior. To illustrate this, Figure 2 shows a generic catenary arch, and variations of structural complexity with a 90 degree twist at both footings. The use of structural FEA software ABAQUS/Explicit is used to solve and visualize the compressive forces in the more complex twisted arch system, due to increased complexity in geometry and mesh resolution. This is an example of a macro-modelled catenary arched structure acting as one continuous part. Benefits of this type of modelling include simpler mesh structures, which contribute to overall efficiency of the analysis. In contrast Figure 3 starts to reveal the arch structure combined with detailed wave joints. Micro-modelling is used to simulate the interactions between contact surfaces.

The assessment of the ‘reliability of numerical non-linear analysis as a versatile tool’ for the simulation of masonry structures are often compared to physical experimental tests (Tahmasebinia & Remennikov 2008). Relationship between digital modeling in FEA programs such as ABAQUS, and physical modeling analysis for different structures such as for example reinforced concrete and masonry have been discussed in a comparison study (Yong 2011, Tahmasebinia 2008), where ABAQUS was chosen as basis for comparison studies, due to its versatility and level of control in all aspects of modeling and analysis using both Standard and Explicit solvers. This allows a
better understanding of how modules form a structure, and how that structural unity then behaves under force influence from relative rotation to collapse.

The structural performance of catenary structures and the concept of equilibrium have a long history. Robert Hooke stated in 1676 “as hangs a flexible cable, so inverted, stand the touching pieces of an arch”, with consecutively the first general theory on the stability of arches published by Coulomb in 1773 (Roca et al. 2010). This followed on from an understanding of the arch as a modular structure; a “conjunction of rigid bodies which could experience relative displacements” (Roca et al. 2010). Whereas these catenary arches remain stable while experiencing singular direction of force impacts, a collapse occurs when sections are experiencing relative rotation, so as to ‘become a mechanism’ (Heymen 1995). This is particularly significant in systems where more complex geometries (such as shown in Figure 3) with varied sections would weaken the overall structure. Yet Coulomb’s theory further provides a mathematical base offering different possible modes of collapse considering both relative rotations and sliding between parts. This has a direct correlation with the plastic theory or limit analysis as described by Heymen (1995) with the following conditions; that the compression strength of the material is infinite; that sliding between parts is impossible; and that the tensile strength of masonry is null (Heymen 1995). Further developments in limit analysis utilizes Coulomb’s law characterised by friction angles and contact interfaces. This leads to the factor of plasticity range defined by a Mohr-Coulomb law characterised by friction angle and cohesion of contact surfaces. This becomes useful as the material between the joints (stone or brick masonry) is described as either linear elastic or non-linear plastic homogeneous material.

In addition to the aforementioned FEA and FEM methods, another method should be mentioned here; the discrete element method (DEM). Here, material is modelled as an assemblage of distinct blocks with interactions along boundaries. This particular methodology combines FEM with multi-body dynamics, with capacity to analyse fractures, crack patterns and deformed parts of a model and reveal them...
in real time. For this paper DEM is not utilized due to this comparison study being focused on finite element and physical methods only. In the following, the paper discusses physical test studies for a series of modular joint prototypes from planar joints to varying sinusoidal and catenary curvatures. Then, it explains the micro-modeling of these geometries in FEA by using ABAQUS software to provide stress and strain analysis and data of each set of block variations. Then, the paper concludes with results and research trajectories.

**Figure 8**
a) Base blocks b) Geometry developed for load testing, c) Initial FEM and FEA simulations (ABAQUS Standard) based on applied top and bottom loads of 50kN

**PHYSICAL COMPRESSION TESTS FOR INTERLOCKING WAVE JOINTS**

This section presents a comparison study into two specific methods of structural analysis. One based on a finite element method and the other based on physical compression testing. Osteomorphic blocks based on pure sinusoidal geometry has been discussed in detail (Yong 2011) with a similar method to be adopted for this process. Yong (2011) utilizes ABAQUS FEA to both model and analyse the compression test mechanism and the individual blocks.

The initial ruled surface geometry (modelled in Rhinoceros 5 with Grasshopper plugin) is based on both sinusoidal and catenary curvature with a step or linear section to assist in assembly of contact surfaces. Sinusoidal curvature is based on a sine wave or sinusoid describing smooth repetitive oscillation. Catenary curvature is based on a hyperbolic cosine or catenoid. This particular study pursued the question of how the geometry behaves under compression and shear forces.

These geometries were then 3D printed in PLA plastic so that a silicon mould was cast for each geometry variation to accommodate for plaster and hydro-stone casting. In total 6 sets of the Hydro-stone simulation specimens were prepared (Figure 4). It will test the material behaviour and points of deflection in the overall joint assembly. The failure criteria include reasonable cracking and fractures which are sometimes only visible in the deflection graph output by the compression machine (MTS Criterion) and software analysis program named TestWorks.

Hydro-stone gypsum cement has a dry compressive strength of 10000 psi or 69MPa. This is comparable to sandstone with a compressive strength of 59MPa (ASTM C170-87 test method). The specimens were 60x60x180mm blocks to the Australian Standard test method ASTM C170 which specifies the testing of equidimensional specimens with a minimum 50mm specimen size.

The machines used for the experiment include MTS Criterion load testing machines (Figure 5) with both compression disk attachments and a specially configured tensile stress testing machine with attached steel plate to simulate a linear load.

**Figure 9**
FEA micro-models with distributed load applied to middle block with constrained ends comparing block C (sinusoidal) and block E (catenary).

The reason for the rotation is in order for the joint typology to aggregate over larger structural assemblies such as arched structures as shown in Figure
3. The test method suggests three test variations I, II and III for three specific angles explained in figure 5. Test methods (II) and (III) utilizes a linear distributed load only applied to the middle block to test shear strength and failure points of the joints.

**Vertical Compression Testing**

For the vertical compression tests as shown in Figure 5 test method (I), the MTS Criterion 50kN machine with fixed lower compression disk is used. Two sets of the 5 geometry variations were tested under this method of compression. The test settings for all vertical compression specimens include pre-load speed and test speed of 1mm/min, a platen separation of 50.8mm and a pre-load of 44.48 kN. The resultant data gathered included the load (kN), time (s), extension/deflection (mm), stress (MPa) and strain (mm/mm). The results are shown in Figure 6 with accompanying graphs in figure 7.

Whilst planar block A showed the optimum response, block D (low amplitude catenary curve) responded best out of the series closely followed by block B (lower amplitude sinusoidal curve). This is shown in figure 7 where the lighter blue line representing the planar block A for both test experiments are much higher in comparison to the catenary and sinusoidal wave blocks shown by the green and blue lines. The point of failure of the planar block occurs approximately 417 seconds with a load of 34kN in experiment 1, while experiment 2 yields the failure point at 313 seconds with a load of 45 kN. The planar block in this case is the control or base case block. The actual test subjects block B,C,D and E all have sinusoidal or catenary curvature. The physical test specimens after they are compressed are shown in Figures 6 and 7. Block D (low amplitude catenary curve) takes the highest load (green line in Figure 7) of 19 kN before it fails at approximately 500 seconds.

The same geometry (Figure 1) is imported into the Finite Element Analysis program ABAQUS/Standard. A consistent workflow is set up involving defining parts of an assembly and material properties. In this case the density of 2000kg/m$^3$ is utilised to simulate stone with a Youngs Modulus of 118MPa and Poisson’s ratio of 0.15. These parameters can vary as more tests are undertaken with various materials. Defining boundary conditions, constraints and loads are kept as close as possible to the physical load testing method.
tion can affect the overall outcome of the simulation. The specific ABAQUS/Standard solver was not sufficient to analyse the 45 degree high amplitude blocks as there were mesh convergence issues. In order to resolve this, ABAQUS/Explicit was used after some partitioning and refinement of the generated mesh. With the current settings as described above the failure points or most amount of deflection occurs where the blocks experience sharp changes in geometry. In vertical compression for both the physical and FEM methods the successful block is the planar block which can take the highest load. However when the block is rotated 90 degrees, the amplitude of the wave enables the block to extend its structural capacity (Figure 9).

The results of the FEA and physical testing reveal variations and inconsistencies. An accurate method of verifying whether the physical results match the FEA is overlaying the graph output from the physical compression blocks with the FEA resultant graph. However the resultant deflection visualisation as shown figures 8 and 9 reveal points of stress and strain which have a tendency to be located at the at the joints, especially where there are sharp changes in geometry. The linear ‘step’ elements seem to fail first in the physical compression tests and are also shown in red colour in the FEA results.

Figure 10 shows the shear failure points of the joints under compression. Here the middle block is loaded with a linear distributed load. It is important to note that the graphs do not show the location of failure in relation to the physical specimen. Therefore it is integral to have both the FEA and physical test specimens. The graphs do however reveal the points of failure in relation to load and time. The red and purple lines indicates high amplitude 45 degree sinusoidal (C) and catenary (E) curve respectively. The blue and green lines represent the low amplitude 30 degree sinusoidal (B) and catenary (D) curved blocks.

When the load is applied to the front face of the middle block, the sinusoidal joint 45 degrees block C takes the highest load (Figure 10). However when rotated and the load is applied to the top (Figure 12), the catenary joint 45 degrees block E takes the highest load before it fails. The overall results of the physical test experiments reveal that whilst the high amplitude catenary and sinusoidal interlocking blocks do not perform well in relation to failure under vertical compression, they take the highest loads before failure when rotated laterally. The FEA results indicate the points of stress visualised both externally and internally within the structure.

As these results were only based on 2 sets of test experiments, the accuracy varies due a number of errors. These include material inconsistencies due to hand made blocks; machine faults and errors with the test method. For example the clamps caused the high amplitude blocks to lift off their fixed position on the steel side bars. This will have created more axial forces due to rotation of the blocks. However these material errors and inconsistencies reveal the nature of construction and how material performs
under various loading conditions. For example the inconsistency in loads during a storm or earthquake scenario will cause the failure of a structure based on its behavior and flexibility to external conditions. This can potentially open up possible research trajectories for seismic analysis of masonry structures.

CONCLUSION / FUTURE TRAJECTORIES
Mortar-less structures based on interlocking blocks provide a level of structural stability due to its flexibility and movement allowed in the joints compared to traditional mortar structures which are more brittle. The ease of assembly and disassembly make using these mortar-less interlocking blocks for the construction of arched and vaulted spaces more viable. The process of utilizing FEA and physical testing methods contribute to an effective feedback loop between the initial design, method, material, machine and outcome. Through the analysis of two specific methods we were able to make initial assumptions on both the validity of the results and the most efficient joint geometry using interlocking assemblies.

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Integration of environmental criteria in early stages of digital fabrication

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The construction sector is responsible for a big share of the global energy, resource demand and greenhouse gas emissions. As such, buildings and their designers are key players for carbon mitigation actions. Current research in digital fabrication is beginning to reveal its potential to improve the sustainability of the construction sector. To evaluate the environmental performance of buildings, life cycle assessment (LCA) is commonly employed. Recent research developments have successfully linked LCA to CAD and BIM tools for a faster evaluation of environmental impacts. However, these are only partially applicable to digital fabrication, because of differences in the design process. In contrast to conventional construction, in digital fabrication the geometry is the consequence of the definition of functional, structural and fabrication parameters during design. Therefore, this paper presents an LCA-based method for design-integrated environmental assessment of digitally fabricated building elements. The method is divided into four levels of detail following the degree of available information during the design process. Finally, the method is applied to the case study “Mesh Mould”, a digitally fabricated complex concrete wall that does not require any formwork. The results prove the applicability of the method and highlight the environmental benefits digital fabrication can provide.

Keywords: Digital fabrication, Parametric LCA, Early design, Sustainability

INTRODUCTION
The construction sector is responsible for a significant amount of environmental impacts, such as 38% of greenhouse gas emissions and one third of global resource consumption. Nevertheless, these large impacts represent an opportunity for improvement, and buildings are seen as a key player for carbon mitigation actions (UNEP, 2012). The evaluation of sustainability aspects in the construction sector is generally based on the optimization of the energy demand in buildings over their life cycle, which is divided in embodied (production, construction and end-of-life) and operational energy (use phase). As Passer et al. (2012) pointed out, European energy regulations focus principally on the optimization of the energy performance in buildings during operation. Consequently, the use of energy efficient materials and building operation technologies has increased the contribution of embodied energy in buildings. Figure 1 shows the shift in the ratio of embodied and
operational energy demand, reaching nearly 100% of embodied energy in nearly zero-energy buildings (NZEB) buildings. This clearly shows the need for optimizing the embodied energy of buildings during design. Specifically, the Life cycle assessment (LCA) framework (ISO 14040:2006) has become a widely used decision support tool for the selection of appropriate materials and technical solutions to reduce environmental impacts (Ingrao et al., 2016).

Several computer-aided tools based on the LCA framework are available for the environmental evaluation of construction materials and buildings (e.g. SimaPro, Gabi and OpenLCA). Currently, LCA is not integrated into the design process but typically used as post-design evaluation, for example for building certification schemes. To environmentally improve building designs, LCA must be applied during early design stages, when decisions have high influence on the project and changes can be realized with minimum additional costs (see Figure 2).

Several recent studies focus on the development of methods and tools for the environmental assessment of buildings during early design stages (Soust-Verdaguer et al., 2017). The introduction of Building Information Modelling (BIM) in the planning process has increased the demand for BIM-based LCA approaches. Different BIM-integrated tools and methods, such as Tally (Bates et al., 2013), aim to quantify the environmental impacts during design. However, a common problem of these approaches is the representation of results, which are not easy to understand by designers without LCA knowledge. As a response, a recent BIM-integrated method proposes a visual feedback of the environmental performance directly on the building model (Röck et al., 2016).

BIM-integrated tools for the environmental assessment of projects are becoming more user-friendly and design-integrated. However, they still have limitations regarding real-time assessment, visualization and optimization of building performance. Due to the complexity of the models, application of BIM is limited for quick comparison of design variants in very early design phases. Furthermore, the evolution of modern architecture towards complex forms and shapes has promoted the use of parametric design tools. These tools, for example Grasshopper, allow changing the parameters that define the geometry and make instantaneous modifications of the model during design. Parametric design approaches present high formal flexibility and data uncertainty during early design; consequently, they require alternative LCA approaches. First design-integrated LCA parametric tools, have been developed by Hollberg and Ruth (2016) or Tortuga, which aims to improve the visualization of results through a simple Global Warming Potential (GWP) overview of the building model.

The combination of parametric design and robotic construction processes in digital fabrication provides potential to create innovative architecture. In digital fabrication, architecture is planned, assessed, and optimized during the design phase, and understanding construction as an integral part of design (Gramazio and Kohler, 2008). Consequently, environmental criteria must be integrated during early design stages. However, there is a lack of tools to quantify the environmental performance of digitally
fabricated architecture. The goal of this paper is to present a simplified method integrated in a parametric design tool (Grasshopper) for environmental assessment of digital fabrication in early stages of design. Finally, the method is applied to a case study of a digitally fabricated project to evaluate it.

DIGITAL FABRICATION IN ARCHITECTURE
Digital fabrication processes at the architectural scale are generally based on computational design methods and robotic construction processes, which are typically categorized as subtractive or additive fabrication. Additive fabrication processes consist of material aggregation (assembly, lamination, extrusion, and other forms of 3D printing), usually carried out by an industrial robot to enable large-scale implementation. Recent developments in digital fabrication in architecture demonstrate strong potential to construct customized complex structures (Gramazio et al., 2014). But most importantly, recent studies such as Agustí-Juan and Habert (2017) and Agustí-Juan et al. (2017) demonstrate the potential of digital technologies and processes to improve the sustainability of the construction sector. Projects such as Smart Dynamic Casting (Wangler et al., 2016), Mesh Mould (Hack et al., 2017) or The Sequential Roof (Willmann et al., 2016) save material compared to conventional construction through the use of innovative construction processes. One of the main conclusions drawn from the analysis of digitally fabricated architecture was that the impact of digital processes is negligible compared to the material manufacturing process. This means that any project saving material compared to a conventional construction will allow for reduction of environmental impacts. Furthermore, the study of different case studies highlighted the following environmental opportunities allowed by digital fabrication techniques:

- Material hybridization: production of structures with material efficiency and improved performance through using composite and hybrid materials (e.g. binder-jet 3D printing).
- Structural optimization: reduction of highly industrialized materials (high environmental impact) through computational structural optimization to only use material where it is structurally needed.
- Complexity: environmental benefits increase proportionally to the level of complexity of the structure due to the avoidance of additional environmental costs attributed to conventional construction techniques (e.g. formworks).

METHOD
Tools for environmental assessment of digital fabrication must be parametric and present results in a visual and simple way to support designers during real-time project optimization. Specifically, the evaluation method must consider characteristic aspects of digitally fabricated architecture, such as an increased structural complexity, the integration of additional functions in the structure and the optimization of material use, facilitated by digital fabrication techniques (Agustí-Juan and Habert, 2017). The complexity of the design and fabrication process usually implies
that digitally fabricated elements are planned individually. Therefore, the method focuses on the environmental evaluation of a single building element, considering the geometry and parameters attributed to digital fabrication, such as complexity and functional hybridization.

In a conventional design process, the architect begins with the creation of geometric variants of a building model. In contrast, in digital fabrication the geometry is a result of the design process and interaction with digital technologies. The design process in digital fabrication begins with the definition of functional and structural parameters, without a clear geometry. Consequently, the first step for the elaboration of the methodology is the definition of four design stages following the digital fabrication design process. The levels of development (LOD) for conventional building elements from BIMForum [1] are considered as a reference. Each design stage is formed by four categories of information about the model:

- **Geometry**: refers to the building element that is designed. The geometry evolves from a generic surface in level 1 to a detailed geometry in level 4.
- **Element function**: refers to the information related to the main function of the element. It considers the type of building element, type of material and structural function.
- **Additional function**: refers to the information related to additional functions integrated in the element, such as acoustic or thermal insulation.
- **Complexity**: refers to the information related to the shape of the element and conventional construction elements such as formworks.

Table 1 shows the design levels established for digital fabrication and the geometry and parameters defined in each level:

The environmental assessment of each design stage is performed through applying LCA. The evaluation provides an overview of embodied impacts expressed in Global Warming Potential (GWP) per 1 m² of building element (kg CO₂ eq/m²). For the evaluation, environmental data from Swiss production of materials and building elements are collected from KBOB and Bauteilkatalog and organized in three different databases: building materials, building elements and additional functions/complexity.
cradle-to-gate analysis focuses on the production stage of building elements, including data from raw material extraction, transport and building materials production (EN 15978 modules: A1-A3). The impact of the robotic construction is omitted from the analysis due to its low impact compared to materials production as showed in Agustí-Juan and Habert (2017). Each database is divided in different levels of detail to evaluate the four successive design stages. This simplified LCA method differs from usual environmental analysis of traditional construction elements, which only use a database of materials (e.g. ecoinvent). In this case, each database allows the evaluation of one characteristic of digital fabrication (functional hybridization, complexity, etc.) and the comparison with conventional construction.

The evaluation is performed according to the information available in each design stage. In level 1, when the geometry is not yet defined, the selection of parameters related to the building element’s functionality allows the estimation of a reference value based on the environmental impact of conventional construction. In the second design level, when a basic geometry is available, the user defines further parameters such as type of material to estimate the GWP impact of the digital fabrication element based on the GWP that a conventional element would have. In levels 3 and 4, when a more accurate geometry is available, the quantities are taken-off automatically to calculate the GWP impacts with the specific material selection. The impact of digital fabrication is compared to the environmental impact of conventional construction with the same functionality. This impact is simultaneously calculated through the definition of parameters: element function, structural capacity, type of material, hybridized functions and complexity.

CASE STUDY
One case study of a building element is evaluated to prove the effectiveness of the method and the usability of the tool.

Mesh Mould
Contemporary architecture has evolved towards a new culture based on the integration of design, structure and materiality to create complex non-standard surfaces (Rippmann et al., 2012). However, non-standard concrete structures require the planning and fabrication of complex and labour-intensive rebar geometries and formworks that are not easy to fabricate with current construction techniques. The research project Mesh Mould from Gramazio Kohler Research at ETH Zürich is a novel construction system based on the combination of formwork and reinforcement into one single element fabricated on-site. This element is a three-dimensional mesh robotically fabricated through bending, cutting and welding steel wires. The mesh acts as the formwork during concrete pouring and as structural reinforcement after the concrete is cured. The structure is no longer limited by the formwork and can be geometrically complex and individually adapted to the forces that act on the mesh (Hack et al., 2015). This case study is selected for the following evaluation to facilitate the identification of functional parameters and comparison with conventional construction as reinforced concrete walls are commonly used in building construction. Figure 3 shows one of the recent prototypes of the Mesh Mould project.

Evaluation tool
To apply the developed method it is integrated in the design process using Grasshopper, a visual scripting interface that allows the manipulation of parametrized geometry and the extraction of data from the 3D model designed in Rhinoceros. Both are common tools used in digital fabrication that allow design flexibility and real-time optimization of the model during design.

In level one, the user selects the element function and the additional function, if available. Here, this is an exterior wall with no additional function, see Table 2. Based on the median of typical conventional exterior wall solutions, the GWP is output as result. In level two, the main material of the element is defined,
which is concrete in this case. The median of the conventional concrete wall solutions is calculated from the database providing a more accurate result than in level 2.

In levels 3 and 4, when a more accurate geometry is available, the tool automatically extracts the geometrical information from Rhinoceros to calculate the GWP impacts with the specific material selection. The impact of digital fabrication is compared to the environmental impact of conventional construction with the same functionality. This impact is simultaneously calculated through the definition of parameters: element function, structural capacity, type of material, hybridized functions and complexity. Furthermore, the tool displays a real-time visualization of the environmental comparison directly on the 3D model using a color scale from green to red depending on positive or negative performance of digital fabrication, see Table 3. This information can be used as quantitative basis to successively optimize the environmental impact of the building element using the input parameters and the geometry.

**RESULTS**

The results for the individual design levels are shown in Figure 4. Since the geometry is not yet defined in level 1 and 2, only the results for the conventional construction are displayed. These serve as benchmarks or target value for the digitally fabricated element. The range of the possible results is visualized through the whiskers in the graph. The variability is greatest in level 1 because all database solutions for exterior wall are considered. The uncertainty decreases in successive levels due to the definition of parameters defined for the evaluation of design levels 1 and 2 from the case study.
parameters, such as type of material, until a single conventional construction is chosen as reference in level 4. We observe that the reference value from conventional construction increases from level 1 to level 4 due to choice of a reinforced concrete wall, which CO2 emissions are higher than other exterior wall solutions. Finally, the results clearly indicate the environmental benefits of the digitally fabricated element compared to the conventional one. In level 4, the digital fabrication performs better and causes 46% less GWP. In level 3, the uncertainty for both elements is still high, which results in the assumption that 65% of GWP can be saved through digital fabrication.

CONCLUSION & OUTLOOK
Digital fabrication will gain more and more importance for the manufacturing of building elements. In contrast to the conventional design process, digital fabrication begins with the definition of functional and structural parameters, without a clear geometry. The geometry is a consequence of the interaction with digital technologies. Therefore, design-integrated analysis methods have to be adapted. This paper presents a method to assess the environmental impact through simplified LCA at different levels throughout the design process. The method adapts to the level of information available and the detail of the geometry. By defining element function and additional functions, the digitally fabricated project can be compared to a conventional one. In level 1 and 2, the method provides a target value for the designer, while in level 3 and 4 a direct quantitative comparison is provided. As such, it grants continuous feedback for the designer and provides a basis for decision-making. The case study proved the applicability. By incorporating a simplified LCA into the design process, the effort for designers is considerably reduced compared to a conventional LCA. Moreover, the method allows the estimation of environmental

Figure 4
GWP results of each design stage of digital fabrication.
impacts in initial digital fabrication stages that are typically not assessed because the final geometry is not available or the project data is uncertain.

The case study presented here focuses on the aspect of complexity. The results indicate the environmental benefits that digital fabrication can provide. However, the method could provide more benefits when assessing functional hybridization such as an acoustic performance through the complex surface of a digitally fabricated element. Therefore, further case studies should be carried out in the future to further validate the proposed method. In addition, the method could be extended through integrating further performance analysis, such as the analysis of operational energy or the possibility to choose the environmental indicator to be displayed.

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Fabricating Stereotomy

Variable moulds for cast voussoirs

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Recent developments in digital design and fabrication tools have led architects and researchers to renew the interest in stereotomy. This interest converges with a growing ecological and economical conscience that matches classic stereotomy raw material needs: compression resistance materials. However, material resources or prefabrication time are still major counterparts for the adoption of this construction system. This paper focuses in exploring techniques that profit from the interdependency between built form and fabrication technique, foraging methodologies that allow for stereotomic block creation with simpler resources. The premise is to explore faster, cheaper, more accessible ways to build stereotomic structures. The technique developed in this research explores alternatives to the traditional cutting of stone by expanding techniques for variable moulds to form solid voussoirs.

Keywords: stereotomy, voussoir, mould, variable production, robotic fabrication

INTRODUCTION

Stereotomy, as a construction technique, is only successful if a relatively accurate control of the voussoir’s (i.e. stereotomy construction block) physical geometry is attained. Traditionally this is dependent on very skilled craftsmen or multiple axis CNC machines. If pre-digital stereotomy mainly resorted to planar, spherical and conical sections, post-digital stereotomy encompasses a wide array of free-form surfaces made possible by the digital tools (Fallacara, 2009). Stereotomic voussoir geometric complexity is directly characterized by the technical possibilities available to produce them.

Carving a voussoir from a block of stone can be considered an act of beauty compared to that of classic sculpture. Just as its classic sibling hand labour method, digitally carving through milling is also a fabrication method very prone to material waste, as much as it is time consuming. Additive fabrication lends itself to minimal material waste; casting into an existing mould is the most direct additive fabrication method. The technique developed in this research expands on moulding techniques to form voussoirs in an attempt to tackle these problems.

Forming is typically dependent on one-off moulds, which generates mass production (lack of variability); on the other hand, mass customization of moulds currently results in heavy expenditure (lack of economic feasibility). Digitally customized mould technology has been applied for concrete moulding. One of these techniques relies in a technically complex apparatus based in a matrix of pin actua-
tors which interpolate a free form surface that acts as mould surface (Pedersen and Lenau, 2010; Schipper and Janssen, 2011; Gramazio and Kohler, 2011); another approach is having a digitally controlled end effector to smooth a clay or sand box until the desired shape is attained so that wax can be poured and consequently concrete can be cast (Heikkilä, Vähä e Seppälä, 2015). Although both these systems are successful in shaping double curvatures, only one continuous surface is controlled; in stereotomy application, one can imagine this surface to represent either the intrados (inner face) and extrados (outer face).

Stereotomic construction efficiency is dependent on the geometric accuracy of the contact face; the intrados or extrados should follow the normals to the thrust surface (Rippmann, 2016), although most of the times are subject to aesthetics. This specificity of stereotomy allows us to shift the focus of design and fabrication from the visible surfaces (intrados and extrados) to the contact edges, taking advantage of the fact that many materials are easily available or produced in slabs, with their largest area opposite faces parallel to each other (Kaczynski, McGee and Pigram 2011; de Azambuja Varela and Merritt 2016; Rippmann 2016). The technique developed in this research draws on a balance between constraints and possibilities, expanding on the swiftness of construction while keeping a high degree of formal freedom.

PREVIOUS WORK

Digital fabrication of voussoirs

The success of the stability of a stereotomic structure lies in the correct structural design, in using appropriate materials and in the geometric accuracy of the contact faces of each block. This geometric information was classically transferred from paper to stone by hand tools operated by masons. The machine automation of this carving process was first attained with milling tools. Other subtractive approaches have been experimented such as circular saw, cutting diamond wire, or water jet cutting. While the milling process is the most free in terms of resulting geometry, it is also the slowest. A circular saw is much faster, but much more restrictive to planes of two dimensional curves. The cutting wire allows for spatial ruled surface cutting but is highly resource intensive; water jet cutting is bound to short (<150mm) ruled surfaces cutting but is quick and practical. All these processes share the subtractive approach as means to the final fabricated block; applied to a freeform vault composed of varying geometry voussoirs, this is synonym to a large quantity of wasted material.

By using an additive fabrication method, the wasting of raw material is reduced to a minimum. Creating three-dimensional free form blocks with 3D printing would be the ideal additive approach, but current technology constraints still set this concept apart from feasible construction approaches. Another additive method is that of casting, such as precast concrete, adobe or plaster elements, where raw material waste is also barely quantifiable. This technique relies in a bilateral relationship between the mould (negative) and the cast element (positive). Fabricating disposable moulds is currently the industry standard for casting variable geometry elements, with few advancements from the seminal Neuer Zollhof project by Frank Gehry. To address this problem, a few research projects have relied in pin type tooling, effectively creating reusable free form double curvature surfaces for casting material. However, this approach does not fully address the stereotomy problem as the edge faces are not considered and usually fall within a box, failing to meet the geometric unique angles that allow for the correct transfer of compression forces.

Flat panel voussoirs

Taking cues from previous works using flat panels as raw material for stereotomic constructions, two prerogatives for a variable moulding system of stereotomic block fabrication are established as hypothesis: planar intrados and ruled edge contact surfaces (see figure 1). Typical casting is made into a box of some sort, and this idea is transported to our prerogatives: the bottom of the box shall be the intra-
dos surface, and the walls should reproduce the contact surfaces geometry. A clear advantage of having a solid mould is that its geometry is quite stable, resulting in a very accurate cast. By using a variable geometry system, instability is an added negative factor and should be minimized to the maximum extent possible. A strategy for avoiding geometric inaccuracies is by using the shortest path method for creating a line; by defining a large set of lines connecting consecutive points of two skew lines we get a unique doubly ruled surface. This geometric principle drives the physical experiment described below.

EXPERIMENT DESCRIPTION

Fabrication apparatus

For creating the casting container, the voussoir faces to be replicated shall be the intrados and contact surfaces. The intrados is created with a planar material, and the contact surfaces with a stretched material between two skew lines, materialized by straight edge pins (see figure 2). Materialization of this concept should follow some guidelines:

- The stretchable material band should be flexible enough to always contain straight lines connecting the pins; on the other hand, it should avoid bulging in the normal direction;
- The pins should be allowed to exist along any vector with any origin in the base plate; this vector is bounded to less than pi/4 amplitude from the base plate (intrados) normal due to stereotomic constraints;
- The pin should be fixed in position with enough strength as not to give under the stretched material, but easily relocated as to generate a new stretched band geometry.

From an ideal point of view, each pin should be controlled individually to swiftly follow a specific spatial vector, changing position (coordinates) and direction (polar and azimuth angle); a clear possibility for this would be to electronically control each pin, or assign an articulated robot for each pin. As this kind and quantity of equipment is not widely available, an alternative was devised: use one robot to drill a hole for each pin that should tightly fit into the hole so that it won’t move sideways, but may be put into place and taken out without destroying the base plate. This plate should be thick enough to allow for a solid grip and soft enough to drill; 40mm plywood was chosen by fixing two 20mm boards together. During the experiment, it was found that a large number of groups of holes could be made in the same base plate, minimizing the waste of this material.

The rubber band should bridge every two consecutive pins; for simplification purposes it was found that one single band around all the perimeter of the block would need less fixations and hardware, contributing to a cleaner surface. Similarly to the digital description of a closed curve, this band has its start and end points in the same pin. The start of the band is always fixed to the pin, and the end of the band slides under the metal tab and fixed when it is stretched enough.

Besides the board, pins and band, an extra element was added to the apparatus: a ratchet strap. This was a remedy solution to the bulging effect in the band caused by the horizontal forces exerted by the casting material. This bulging would not be so evident in the stretching of the band would be carried out by machines instead of pulling by hand.

Digital work

Bottom up principles. The fabrication strategy is key to define the design constraints of each of the voussoirs and, consequently, the morphology of the macro structure, be it an arch or vault. As considered above, the morphology of each precast element is topologically defined as a prism: the bottom face is perfectly flat, and the side faces are doubly ruled surfaces; the top face gets close to horizontal due to hydrostatics flat, but the viscosity of the material creates opportunities for different morphologies.

Depending on the material used to create the cast element, different constraints may apply. If the material is mainly compression resistant, such as unreinforced concrete or adobe, the structure should
Figure 1
Voussoir geometric relation to thrust surface

Figure 2
Generation of pin location and rubber band adapted geometry
be mainly compressive, resulting in a stereo-funicular form. If reinforcement is added to the casting material, such as glass or carbon fibers, traction resistance may be incorporated to the structural design.

In this experiment unnecessary extra material considerations such as traction resistance were eliminated. Adding this to a quick setting time, plaster was chosen in favour of concrete or adobe.

The area of contact in contact surfaces contributes to the structural efficiency in stereotomic structures. Using flat voussoirs might introduce skew elements, thus reducing this contact surface. As such, another design constraint is the proximity of adjacent voussoirs’ intrados edges.

Digital design and fabrication. This experiment relies in digital design tools in two main moments: design and fabrication. For both of these tasks, Rhino’s Grasshopper graphical algorithm editor was used.

The macro stereo funicular thrust surface is a discrete single sheet mesh modelled with Kangaroo using the forces Anchor, Length (Line) and Load. The proximity of adjacent voussoirs’ intrados edges is tackled by the force CoPlanar, which is configured as to bring vertices of the same intrados face to a common plane. This calculation yields discretized planar cells of the thrust surface, each corresponding to one voussoir (see figure 4). At each vertex the normal to the thrust surface defines the normal edges vector which will eventually be the direction of the skew lines that will define the bounding doubly ruled contact faces. For achieving volume, a bounding box based of the thrust planar cell with equal offset to the intrados and extrados side is used to trim the normal edges vectors. This experiment features a natural rubber band with limited elasticity; this elasticity variation was measured with oblique traction and found to be 70mm: this constraint was taken into account as a limit between lower and upper perimeter. As this first version of the fabrication apparatus features a significant diameter pin, this feature was added to the vault visualization by subtracting a cylinder from each corner of the voussoirs.

Digital fabrication was used to drill the angled holes where pins would fit, and also to fabricated the centering and supports. Each vector’s position and direction was calculated according to the pin’s radius, and the groups of vectors were oriented within the boundary of a 600x600 rectangle. In order to optimize the usage of boards for the base plate, a genetic algorithm was used with minimum distance between holes as fitness and XY moving and rotation around the center of each set of holes as genomes. This allowed for a quick calculation of a layout that encompasses all necessary drills (9 sets of a total of 39 holes) in the same wood board (see figure 7). A helical tooling path was created for the smaller diameter mill to carve all the extents of the larger diameter hole.

Figure 3
a) All bands in same board generate hole overlapping; b) Solution found with a genetic algorithm for non-overlapping holes; c) Milling preview
CASTING VOUSSOIRS
This fabrication system theoretically allows for any castable material to be used, such as concrete, adobe or GFRC. The criteria used was the practicality of the experiment, so plaster was chosen for its quick setting time. The first experiment yielded a too fluid plaster that spilled underneath the elastic band; for dealing with the problem it was decided to use a thicker plaster that would not spill; this was achieved by having two different sets of plaster with the same ratio but with different curing times before casting. No demoulding liquid was used; instead, a thin plastic sheet was used to avoid the adhesion of the plaster to the base plate. The first cast used 1/5 of the total material and cured for 120s before being poured as a thick paste that needed to be spread in the bottom but did not spill through the sub millimetric gaps between the band and the base plate. The second cast used 4/5 of the material and cured 60s before being poured as a very fluid material that would create a horizontal surface on top. The casting would be gently rocked to let air bubbles out and let to set for 20 minutes from the second mixing of plaster with water. At this point, the elastic band could be pushed outwards so it detached naturally from the base plate.
plaster, and the band could be released to reveal the cast block. The pins were removed tangentially and the block removed as to allow for the final setting. The whole process took less than 40 minutes, allowing for the same apparatus to be used for another block casting.

**CONCLUSION**

The successful decentering of a vault is always somewhat a proof of accuracy of the fabrication system. Although some bulging appeared in the plaster cast blocks, the general geometry was maintained, which is verifiable by the structural integrity of the compression only three legged vault (see figure 10). Having spent less than eight full hours fabricating the full set of nine solid plaster voussoirs is another achievement of this experiment, together with having close to zero waste of material.

A clear opportunity of improving this system is on avoiding the bulging effect in the elastic band caused by the horizontal outwards pressures caused by the weight of the casting fluid. Reducing the weight of the fluid material - by mixing lighter materials such as aerated aggregates or cork - would reduce this effect, but it might prove not desirable in every situation. Strengthening the band as to avoid its lateral deformation seems to be the solution to the problem. This can be achieved in various ways:

1. by exerting a greater traction force in the band by means of industrial machinery;
2. by using a different kind of material that stretches in its tangential direction but not in this normal, like some kind of telescopic arrangement;
3. by using additional supports along the external face of the band, materialized as pins positioned in a similar fashion as the main ones in the vertices.

Future of research avenues lie in the optimization of the fabrication system as well as diversification of scale and materials. Although there are clear advantages in the simplicity of the hole drilling for pin fixation method, it wastes board material and is time consuming. Using servomotors actuated by an Arduino style micro controller creates a closed ecosystem for variable mould casting. Another possibility relies in each pin being controlled by an articulated robot, showing advantages towards space uncluttering. Plaster was used mainly for its quick set-
ting properties. Adobe is an interesting material alternative for its availability and compression only resistance; concrete is also interesting for its resistance and durability, as well the possibility of incorporating reinforcement for other structural requirements.

This experiment shows that stereotomic research can benefit from creative approaches to its fabrication methodologies, stressing the symbiosis between project and materialization technique.

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Figure 10
Built three-legged vault with cast voussoirs
Geometry as Assembly

Integrating design and fabrication with discrete modular units

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This paper proposes a design and fabrication approach based on the conceptualization of architectural formations as spatial assemblies of discrete building blocks to be aggregated through custom robotic procedures. Such strategy attempts to create synergies between different technological methods and to define a new and open design space where discrete design, serial prototyping and robotic assembly can be exploited to create complex reconfigurable structures. With the aim to allow users to explore the field of discrete geometries for architectural application without need for prior programming knowledge, we developed a software framework for representing and designing with discrete elements, different digital fabrication techniques integrated with conventional production processes for serial prototyping of repetitive units, and custom robotic fabrication routines, allowing a direct translation from aggregated geometry to assembly toolpath. Together these methods aim at creating a more direct connection between design and fabrication, relying on the idea of discrete elements assembly and on the parallel between modular design and modularized robot code generation.

Keywords: Digital Materials, Robotic Assembly, Discrete Design, Modular Fabrication, Design Tools

INTRODUCTION
Contemporary advancements in computational design methodologies fueled an unprecedented interest in the aesthetics and performative capabilities of complex morphologies. This explosion of formal possibilities determined the creation of high pressure towards the development of novel fabrication processes and machines for the materialization of such designs. In response to this, additive manufacturing technologies (Dillenburger and Hansmayer, 2013), digital materials research (Ward, 2010), and robotic assembly processes (Willmann, Gramazio and Kohler, 2014) offer novel perspectives for the design and construction of architectural artifacts. However, the translation of these methods, originally conceived for different applications and to operate at different scales than the one of architecture, present several issues and exposes drawbacks about each of them.

To address such issues, this paper proposes the integration of a design approach based on the con-
ceptualization of architectural formations as spatial assemblies of discrete building blocks to be aggregated through custom robotic procedures. The aim is to integrate the complexity-independent nature of additive assembly with the assembly simplification and reversibility of discrete aggregation and the open spatial nature of robotic processes. Such configured strategy attempts to create synergies between different technological methods, to define a new and open design space where discrete design, serial prototyping and robotic assembly can be exploited to create complex reconfigurable structures.

BACKGROUND

Discrete Design and Digital Materials
The application of the concept of digital to physical materiality allows for the definition of novel materials composed of a set of finite discrete elements with discrete connection details (Ward, 2010; Gershenfeld, 2012). Digital materials aim at bridging the gap between the physical and the digital worlds, with the goal to provide full reversibility and digital programmability of fabrication processes and matter itself. As part of the search for post-parametric design methodologies (Sanchez, 2016), architectural research has turned its attention towards similar concepts of discrete assemblages of modular components, exploring ideas of combinatorial design (Sanchez, 2016), digital assembly (Retsin, 2016) and reversible interlocking (Tessmann, 2012).

Different approaches towards design with discrete assemblages have been proposed in the recent years. Tibbits (2011) developed a framework for the representation of assemblies of intelligent blocks, able to reconfigure in response to environmental feedbacks. Savov et al (2016) developed collaborative environments for design within a Minecraft-based game environment, where the discrete nature of the design process serves as base for crowd-sourcing design ideas. Jonas et al. (2014) proposed strategies to create discrete assemblies both from discretization of existing geometries, as well as from a generative aggregation process. As a shared issue, most of these approaches rely on custom developed solutions, and as such, lack potential for scalability and usability for designers not trained in programming.

Discrete Fabrication
The use of discrete structures in fabrication is historically common in architecture, given the component-based nature of most of the building industry. However, fewer contemporary fabrication methods take a discrete approach as their base, preferring to work on continuous isotropic materials, which are processed irreversibly to achieve the final form (eg. CNC milling, additive manufacturing). Gramazio and Kohler (2008) developed several projects where the discrete nature of bricks was used as base for the generation of varied architectural formations, to be assembled by robotic arms. Research at MIT Cen-
Figure 2
Aggregation procedures: left, stochastic; center, geometry-driven; right, field-driven.

Figure 3
Aggregation driven by a material density field resulting from topology optimization under custom load conditions.

Figure 4
Fabrication process for truncated octahedron modules (Student: Felix Hinz).

center for Bits and Atoms explored the concept of digital materials as fabrication strategy at various scales (Ward 2010, Gershenfeld 2012), demonstrating the effective possibility of creating a direct connection between digital representation and assembly procedures, and proposing an effective model to bring digital programmability to the material world. More recently, Retsin and Garcia (2016) proposed to apply discrete logics directly to fabrication instructions, using modular code generation for custom robotic additive manufacturing processes.

METHODS
To overcome current limitations of available CAD design tools for modular design, allow users without prior programming language to explore discrete design, and develop a tight integration between design and fabrication, this paper proposes a set of strategies to integrate modular geometry as both design and assembly strategy. Such approach requires:

- A computational description of modular units and aggregation procedures.
- Hybrid fabrication processes for prototyping of repetitive modules in an efficient way.
- A direct link between modular aggregation description and robotic assembly toolpath generation.

Computational Framework for Discrete Design
With the aim to allow users to explore the field of discrete geometries for architectural applications, with-
out need for prior programming knowledge, this research relies on a custom developed software framework, consisting of a set of components, developed in Python for the Grasshopper algorithmic modelling environment, directed at representing and designing with discrete elements (Rossi and Tessmann 2017). This is achieved by combining geometric representation and abstract graph information (Klavins et al. 2004) of individual modules, as well as providing different procedures for modular aggregation.

The description of each individual module includes basic information necessary for the aggregation process (module geometry, connections location and orientation), as well as custom attributes connected to fabrication logic (gripper geometry for collision check, necessary supports locations) and to possibility of actuation of the modules (module state, reconfiguration possibilities). The set of connections define the topological graph of the module, which is then used to define the possibilities of aggregation with other modules (Figure 1).

The core of the framework relies on a set of aggregation procedures, allowing generation of specific structures from the combination of different modules. Each of these procedures is composed of strategies for the selection of basic aggregation rules, described as an instruction to orient one module over a selected connection of another module. In the development of such procedures, attention has been placed in the combination of the fundamental bottom-up nature of assembly processes, relying on adding components in an iterative process, with top-down modelling strategies, which allow users to better control aggregation processes towards specific design goals (Jonas et al. 2014). Moreover, the sequential definition of the aggregation process allows the user to dynamically edit the aggregation rules and parameters within the process, hence allowing for the differentiation of generated structures of different parts of the assembly. Currently available procedures include stochastic aggregation, explicit aggregation description, geometry-driven aggregation, and field-driven aggregation (Figure 2).

At the moment of writing the paper, particular focus is being placed in the development and improvement of field-driven aggregation methods, understood as a possibility to combine discrete design with current developments in voxel-based design and multi-material 3d printing (Michalatos 2016). By using scalar fields to drive the aggregation process, it becomes possible to develop aggregations able to respond to different performance-based requirements, such as daylight control, space subdivision, material density, structural performance (Figure 3). Such processes are also looking at possibilities of extending discrete logics to other aspects besides geometry, such as modularized connections, material properties and module behavior (eg. active components with embedded electronics).

**Serial Fabrication of Repetitive Units**

The conceptualization of materials as digital, and hence composed of repetitive units, requires a redefinition of the application of digital fabrication technologies, which are commonly understood as methods to generate continuous variability, to define specific strategies within which these could be employed for the serial fabrication of small batches of repeti-
As the research does not attempt to define an ideal modular system, but rather to open the space of possible systems to design explorations, it is fundamental to leverage the advantages of both serial manufacturing (speed, reliability, low waste) and CNC fabrication (precision, ease of customization, fast design-to-production cycle), hence defining workflows for fast production of modular systems to assembly.

To achieve this, different digital fabrication techniques (3d printing, CNC hotwire cutting, laser-cutting) have been integrated with conventional production processes (casting, sheet folding, rotomolding). This combination allowed for quick prototyping of different module geometries, while also taking advantage of the repetitive character of the units to increase production speed. One exemplary production process (Figure 4) involved the use of 3d printing to produce one positive copy of the desired unit (in this case, a truncated octahedron), and the subsequent use of such module to create a negative silicone mold. The resulting mold has been then used to quickly cast several copies in gypsum. At last, connection magnets have been added with manual drilling, taking advantage of a guide for correct placement. Other processes used involved combining hotwire-cut geometries with 3d printed connectors, robotic hotwire cutting, laser-cutting and heated folding of polystyrene sheets into solid geometries.

Another approach looked at the use of CNC hotwire cutting for the quick generation of volumetric modules via simultaneous cutting of several blocks of foam into basic shapes. Such shapes have been equipped with inlets where custom 3d printed plated could be added to precisely define the connection geometry, one of the key elements for assembly (Figure 5).

In this way, the time-consuming nature of 3d printing is counterbalanced by reducing the amount of material to be printed to thin connecting plates, while the lack of precision of CNC hotwire cutting in creating detailed connection details is avoided by replacing the connection parts with the 3d printed ones. Moreover, such techniques allows the extension of the idea of modularity to the composition of the unit itself, allowing to customize connections and place different connectors according to requirements within the aggregation.

**Robotic Assembly**

Given the discrete nature of the modules and the sequential nature of the aggregation process, it becomes possible to operate a direct translation from aggregated geometry to assembly procedures (Tibbits, 2007). What this allows is to overcome the conventional division between design and manufacturing, and using the geometry of designed aggregation as direct instruction for fabrication. By extract-
ing each module's position, as well as the configuration of their neighboring units, a custom robotic routine, implemented in Grasshopper using the Scorpion plug-in (Elashry and Glynn 2014), allows to extract the correct approach path for robotic placement of individual units (Figure 6). By carefully defining the aggregation rules, it becomes possible to generate structures where aggregation sequence matches assembly sequence, hence avoiding need for sorting of units. However, in order to simplify aggregation design explorations and remove some of the assembly constrains during design, sorting routines are provided to allow user to redefine correct assembly sequences after aggregation.

Moreover, by pre-defining module placement direction, geometry of the robotic end-effector, as well as specific stability conditions directly within the module definition phase (Figure 7), it is possible to continuously check, during the aggregation process, for fabrication issues, such as collisions and instabilities, at every step in the process. Rather than relying on post-rationalization of the generated aggregations, which requires complex algorithms to identify correct assembly steps, checking for fabrication issues within the aggregation allows to identify the feasibility of a certain operation within its exact position in the assembly sequence. In this way, thanks to the fully discrete nature of the process, the geometric configuration of the designed aggregation and its assembly procedure become coincident, overcoming the need for translation from digital design processes to analog fabrication (Ward, 2010).

It is however important to note that, by increasing the number of parameters to be checked for buildability, the search space for the aggregation algorithm becomes highly narrowed and structured, hence requiring the integration of more complex search methods to create structures with a certain level of order and variability (e.g. more articulated algorithms, or integration of human intuition in the search process).

Additionally, robotic fabrication technologies allow the integration of real-time sensing, offering the possibility of defining custom rule-based adaptation strategies of design within the production process, integrating feedback from the environment as well as from users (Feringa, 2012). This allows designer and manufacturing machine to share a common rule set, allowing the user to edit and control the aggregation process not only during design, but also during assembly, and the robot to adapt to design changes in real-time. Such procedures can be applied to develop collaborative processes between users and machine, hence reducing the separation between design and manufacturing currently existing within architecture (Carpo 2011).

RESULTS
The approach and methods described in the paper aimed at allowing the exploration of discrete design and fabrication methodologies to users not necessarily trained in advanced computational techniques. Both digital design framework and discrete robotic assembly routines have been and are being employed in the teaching of design studios and seminar focused on the application of discrete logics to architectural production.
Discrete Design Exploration
The proposed digital tool for discrete design allowed student to quickly explore and generate large aggregation of repetitive units (Figure 8). Such explorations required no prior programming knowledge, and little knowledge of visual programming within Grasshopper. The generic nature of the tool, which does not prescribe any specific geometric typology, but rather offers the tools to connect geometric and topologic information of modular systems, proved to offer the required flexibility to the user to explore a variety of geometric structures, ranging from linear elements aggregations, 2-dimensional components, space filling patterns, interlocking structures, and others. Current explorations are being developed to include the possibility of defining custom states for the modules, hence allowing the representation of active and/or reconfigurable units.

Assembly Design Simplification
Similarly, the tight integration of design and fabrication allowed fast prototyping of robotic assembly processes for the developed modular systems (Figure 9), hence allowing to test already during design the performance of the system for assembly. As a common trait, tolerances appeared to be one of the most challenging issues for the development of modular geometries. However, fast iterations between design and fabrication allowed to test each module, and develop strategies for tackling tolerances, such as corners chamfers, geometries and joints tapering, and adaptive grippers.

The variety of the geometries produced during different design explorations has taken full advantage of the flexibility of the method. Indeed, different geometries required changes in the assembly sequencing, approach directions, placement strategies and gripper geometries. All such changes have been successfully implemented within the proposed process, and allowed to generate aggregations designs, fabrication data and assembly instructions (Figure 10).

Design-to-production Workflows for Discrete Assemblies
The developed methods explore possibilities offered by discrete thinking for design and fabrication. Such approach presents significant differences with more common approaches towards generation of complex morphologies, where the design phase is focusing on the generation of continuous NURBs surfaces, which are then subdivided in components in another moment (Pottmann et al. 2007). In the case of discrete design, discrete units are defined as the initial condition, and designed structures are generated as aggregation of these basic units under custom rules. While such approach constrains the designer to work within a specific rule-set and geometric system, it also allows to highly reduce the number of steps needed to move from design to fabrication. What this determines is a more direct connection and aesthetic resemblance between design intent and fabricated form.

Additionally, such approach, besides determining this stronger connection between design and manufacturing, allows also for the extension of the design phase beyond the realization act. Indeed, by embedding reversibility possibilities in the connections of different modules, the fabricated design remains open to change through disassembly and reassembly of the modules composing it (Figure 11). The discrete nature of the assembly allows for direct
Figure 11
Assembly, disassembly and reassembly process for a modular system (Student: Cornelius Dormann)
identification of placement of each unit within the assembly, and hence also allows for the identification of such unit for either disassembly or re-use in a novel aggregation. What this allows is the creation of fully reconfigurable structures, which can be adapted dynamically to changes in environmental condition or usage requirements.

CONCLUSIONS
The presented process aims at creating a more direct connection between design and fabrication, relying on the idea of discrete elements assembly and on the parallel between modular design and modularized robot code generation. This aims at overcoming the need for translation between digital design and analog manufacturing, as well as providing a compact procedure to represent both geometry and assembly information, creating a more direct link between design and fabrication. Moreover, such discrete model for architectural production aims at embedding the possibility of change and reconfiguration in the resulting assemblies, offering an alternative to current models of production mostly relying on non-reversible processes, such as large-scale additive manufacturing.

The proposed methods have been tested extensively in different teaching contexts, and proved successful in allowing users with low or no prior programming experience to quickly design, manufacture and robotically assemble aggregation composed of several units. This allowed also to introduce students to the required abstract formalism necessary to represent such assemblies and their constituent rule-sets, as well as facing different issues associated with fabrication constrains, such as stability and fabrication tolerances. Thanks to this, the proposed processes appear to be a relevant and effective method to offer a first approach to a wide range of topics relevant to computational design research.

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Digital fabrication with Virtual and Augmented Reality for Monolithic Shells

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The digital fabrication of monolithic shell structures is presenting some challenges related to the interface between computational design and fabrication techniques, such as the methods chosen for the suitable parametrization of the geometry based on materiality characteristics and construction constrains, the digital optimization criteria of variables, and the translation of the relevant code used for digital fabrication. Specifically, the translation from the digital to the physical when a definite materiality appears during the digital fabrication process proves to be a crucial step, which is typically approached as a linear and predetermined sequence. This often-difficult step offers the potential of embedding a certain level of interactivity between the fabricator and the materialized model during the fabrication process in order to allow for real time adjustments or corrections. This paper features monolithic shell construction processes that promote a simple interface of live interaction between the fabricator and the tool control during the digital fabrication process. The implementation of novel digital and physical methods will be explored, offering the possibility of being combined with automated fabrication actions controlled by real time inputs with virtual reality [VR] influenced by 3d scanning and 3d CAD programs, and the possibility of incorporating augmented reality [AR].

Keywords: virtual reality, augmented reality, monolithic shells

VR AND AR IMPLEMENTATION
The implementation of several prototypes for monolithic shell construction has been explored with additive manufacturing techniques, by using deposition spraying with different paste like materials, such as clay mixes of diverse characteristics and performance ratios. The fabrication workflow includes traditional material practices by using branches that form self-standing peripheral and internal bending arches, from which an elastic membrane (Lycra) is stretched by hand to create a tense surface. A clay mix is robotically sprayed on top of this fabric and could be mixed manually with fibers in between layers that merge creating an assembly of interlocked materials. The temporary formwork is removed once the clay surface is dry and the structure is self-standing.

Preliminary experiments reveal that one of the most determining factors is related to the protocol established in a sequence to complete the process of 3d printing, which has been denominated “phasing”.


The organization of this critical time-based sequence must be properly defined and formulated, following these steps:

1. Formwork setup
2. First scan
3. Material preparation [Mix - Type of sprayer - Trajectories]
4. Deposition [Robotic spray protocol]
5. Optimization [3d scanning - Export Scan to 3d model - 3d model optimization - Re-adjusted spray]
6. Curing time and formwork removal [temporary, or lost].

Despite some promising initial results, some of the key challenges observed during these experiments prove that additive manufacturing is far from being a linear and predetermined process, because during construction material properties and the structure in progress are constantly evolving. Some features observed include: the sagging of the temporary formwork due to the material weight; deformations or settlement of the supporting arches; the displacement of the structural elements due to shrinkage during curing time; some unexpected weakness areas around the supports, etc. These critical elements require immediate rectification while under construction, to avoid severe problems with the resulting structure, and to correct inconsistencies between planned and fabricated forms. To help resolve these issues, a singular digital fabrication process needs to be implemented to allow real-time adjustments between digital tools, structure and matter. The potential of carefully calibrating this phasing, in terms of the continuous optimization of materials and labor, and the feasibility of the builder to be involved during the fabrication phase, might prove critical for the renewal of shell construction processes. The interdependence between materiality and the fabrication methods has proven to require different tests and iterations, which has been implemented using two different protocols: virtual reality (VR), and augmented reality (AR). AR is used for the constant readjustment of the fabrication process has been implemented, and VR tests were adopted to project optimization simulations on the physical as a live tool to fabricate directly on the physical structures. These steps required to take advantage of the recursive process involving digital modeling techniques, matter characteristics, shell structure behaviour during fabrication, digital tools using robotics (Block, Veenendaal, 2015), and real-time adjustments, will be further explored.

VIRTUAL REALITY AND DIGITAL FABRICATION
Computational design techniques facilitate the implementation of design and optimization of possible solutions using Rhino 3dm, and Grasshopper plug-in, as well as providing the opportunity to make adjustments during the process of digital fabrication by using scans with Agisoft together with optimization softwares (Karamba) that are able to correct the robotic trajectories during the fabrication process in the Kuka PRC interface. VR proves critical as an tool to collect data and to make adjustments in the structure in progress, showing some potential to navigate into Rhino 3d space of the simulated structure at different stages of fabrication to better calibrate the robotic actions using Kuka prc interface. Some relevant projects that use VR techniques include the iaac seminar in Valldaura (Figures 1, 2 and 3) with drones used to test trajectories and collect data for mud shells. Another relevant reference was
recently used clay wall (On Site Robotics, collaboration of Iaac, Tecnalia, and Noumena, at the Barcelona 20th. edition of Construmat 2017) using drones to monitor with multispectral cameras collecting thermal analysis of the structure in progress.

Of particular interest is the exploration in depth of the possible remote operator control of fabrication in Realtime using VR, revealing an unexpected degree of freedom and creativity such processes could bring to monolithic shell construction.

Figure 2
Kuka robot taking pictures of the structures from a minimum distance, different angles and in a logical sequence that can be at a later stage translated into a 3d mesh using Agisoft software.

Figure 3
Engineer Daniele Ingrassia from Fab Lab Kamp Linfort- Real time temperature 3d scanning of the clay wall being 3d printed

AUGMENTED REALITY AND IMMERSIVE ENVIRONMENTS
The use of AR for human machine interaction is also not common in architecture, although it has been a field of research for decades in other disciplines. Interesting examples, such as an augmented toolkit for robotic fabrication (Bard et al 2014) or hybrid digital / physical robotic plastering workflows (Bard et al 2015) demonstrate the potential of augmented and mixed reality for automation and assistance in human-machine creative interaction workflows, while recent examples of AR use in construction sites (Abe et al 2017) show the future possibilities of the technology in the building industry.

The distinctive use of VR and AR techniques can allow a constant recalibration of the spray at different phases during the fabrication progress, and could help to rectify or stop the process early if some part of the structures are revealed to be non-viable, or if they are subject to unforeseen dangerous conditions and efforts. For example, if some arches are deforming too much, the spraying should immediately stop and ranges of acceptable deformation are to be set after iterative physical experiments and precise mapping of the acceptable fluctuations. This step can allow the immediate re-adjustment of critical parameters, such as the angle of deposition, speed, pressure of spray, trajectories, distance to the structure in progress, and changes in the matter characteristics while being applied, such as the level of humidity, viscosity, amount of fibers, size of gravels, among others.

AR has already a significant amount of application in the construction industry as a control tool. It is used in construction site for the builders to have a better understanding of where errors can have some critical negative implications in the buildings. AR has not been significantly used yet as a design and optimization tool during the fabrication process. This is part of the challenges the 2 small scale case studies will highlight.

Real time drone 3d scanning is developing at fast pace especially in the precise agriculture domain.
Companies like yellow scan in Montpellier France in partnership with eca are putting in place 3d scanning devices that are not only based on photogrammy, but thermal data can also be translated in real time. This has recently been implemented in iaac’s installation at Construmat in collaboration with Tecnalia and Noumena where custom made drones were developed. Such developments are of particular interest for the technique used in case study 1 and 2.

Some construction and material manufacturing companies are increasingly interested in bridging their knowledge with the academic digital fabrication and augmented reality research community to seek diverse objectives, such as to renew their business models, to learn more about the potential of different materials, to study the hybridization of matter performance, or simply to explore different techniques for digital fabrication.

An argument defending the importance of this set up will be exposed, to create a viable construction system incorporating the craftsmanship and the knowledge of the builder as an active input during the fabrication sequence, and its potential for producing unexpected novel forms. Therefore, it will highlight significant changes that digital fabrication can engender in the use and the resulting aesthetics (Huijben, Van Herwijnen, Nijsse, 2011).

IMPLEMENTATION (EXPERIMENTS / CASE STUDIES)
Recent academic experiments investigate new methods of using digital fabrication for raw materials, involving industrial partners (manufacturers, architectural firms) to provide a more realistic setup for the students towards patented fabrication techniques. Two case studies are featured, with solutions implemented with an easily mounted temporary or lost formwork, explaining the specific phasing loop related to the 3d scanning, the export scan to 3d model, the 3d model optimization, and the re-adjusted spray.

In general terms, a 3D scan protocol must be carefully established for all experiments. Some tests with off the shelf Parrot drones 3d scanning were implemented in the case studies but were not real time, and around 50 pictures from different angles were taken by the drones in a logical sequence around and on top of the shell in progress and then exported into Agisoft to generate a CAD mesh (Figure 4).

The first scan is performed when the fabric and the formwork branches are mounted with a minimal fabric formwork pulled on the supporting arches, with a series of marks on the surface to facilitate the scanning process. A minimum of 50 pictures from as many angles as possible in a logical sequence are then exported into Agisoft to extract a 3d mesh, that can be exported as an OBJ file which can be opened in Rhino 3d. In Agisoft, the precision of the simulated mesh can be varied and the more precise definitions require a significant amount of computation power that not all computers can provide. Furthermore, rendering the textures help recognizing the shapes but contributes to the computational weight while performing the render.

During phase 2, a 3D scan of the shell is performed once the first layer of watery clay mix (“barbotine”) has been applied. The board on which the shells are attached can be used as reference to be able to superimpose the shells at different stages and be able to map their distortion precisely.

A protocol of 3d scanning it’s implemented with cameras or drones to collect images using Agisoft, a photogrammetric processing of digital images that generates 3D spatial data in McNeel Rhinoceros 5.
Rhino. The raw scan was then simplified using principal curves (arches), after which the mesh was rebuild (Figure 5), deformations from previous scans were evaluated, and the resulting form was ready to run an optimization software using Karamba, a parametric finite element engineering tool.

After the optimization is completed, the digital reconstruction of the form in Rhino 3d does allow implementing some tests using VR to navigate inside the constructed forms with the resulting optimization simulation embedded into the Rhino geometry. The potential of including AR in the mud shells experiments featuring Minddesk with HTC Vive goggles offers an immersive navigation inside Rhinoceros space that is recently being tested in public at the AWE Expo, featuring some of the experiment models included in this research. Another interesting method for the implementation of the mud shell is to superimpose the optimized geometry view from Rhino on the physical shell and perform actions on it accordingly. For example, stress lines can be generated on Rhino Karamba and translated into the design, projecting the image of the simulation on the physical shell can allow new design processes to emerge. These relatively new methods are not yet embedded in architecture, but have the capacity to provoke new design methods and aesthetics. For example, the location and type of perforations can be tested and decided upon using this virtual reality strategy. Very few recent architectural projects are investigating the correct setup of the the use of remote-control tools to facilitate this process.

Some deformations are predictable as they’re part of the recurrent features offered by the technique: such as the sagging of the structure on both side of each of the ribs. On the contrary, some other areas of the shells will distort in an unpredictable way (as the experiment involves too many parameters for the result to be predictable: air humidity, clay mix invisible properties such as air and water, bending and rods and lycra formwork computing their own shape once the initial formwork is mounted). The non-predictable morphologies particularly happen when the span in between arches is relatively large (equal or superior to the radius of the arch). Unexpected form distortion also happens when the edges of the shell meet the support base, as significant amount of forces are applied on those junctions. The iterative 3d scanning has been implemented to readjust the trajectories and actions performed by the robotic arm.

CASE STUDY 1 - PHRIENDS FOR SHELLS.
May 2016; 25 hrs. seminar. First year master students. IAAC, Barcelona. PARTICIPANTS: 23

Seminar: “Phriends for Shells” (“Phriends” was defined as the safe interaction between people and robots during fabrication progress).

Tutors: Author 1, D. Stanejovic (robotic expert), Y. Mendez (assistant).

Five earthen vaults of 1m x 1m x 0.8 m in height with perforations were built during this seminar. Bending rods in clusters of 2 or 3 members bundled together by a rope were the supporting arches where the stretched lycra was secured. The openings for the perforations needed to be defined before applying the first coating of clay mix, and laser cut rings and triangles were mostly used to create those temporary formworks removed after the last layer of clay mix was applied, so that the holes could be formed. This phase of the fabrication was both digital and manual, as the study of the perforations that were tested in both digital and physical models appeared to lead to the most successful designs (Figure 6).

The 3d scan was performed using Agisoft, and the 3d scan protocol had the following phases:

- 1st. scan: After arches and stretched fabric were installed;
• 2nd. scan: After the first layer of clay spray was completed.
• 3rd. scan: After all sprays are completed and the structure is set.

Karamba was used to perform these structural analyses by applying the following criteria: 1) Displacement to verify areas that are most stable, that have the least displacement, and with the most deformations or buckling. 2) Utilization to detect compression and tension areas and concentration of forces. 3) Isolines to detect changes in the forces where most deformations were anticipated. The trajectories of the deposition were adjusted in the Kuka PRC interface to correct some potential problems with the structure in progress.

Case Study 2:
May 2017; 25 hrs. seminar. First year master students. IAAC, Barcelona. PARTICIPANTS: 12

CASE STUDY 2: EARTHEN SHELLS, MANUAL CRAFT AND ROBOTIC MANUFACTURING

During this seminar three 1 m x 1m x 1m earthen shells were constructed. The brief given to the students was to design with the earthen shells fabrication technique explored in various previous workshops (successive clay mix coating on fabric formwork performed manually or robotically) while designing with robotic natural resin pouring and perforations types variations.

The trajectories of resin pouring by gravity in continuous lines were implemented and varied according to the regions of the shells of distinct geometries. For example, in the more horizontal parts of the shells the resin doesn't pour down and some branching liquid patterns solidified just after meeting the edge of the peripheral arches. Temperature of both the upper layer of clay and the resin when the latter is robotically poured on the shell were to be explored aiming as highlighting different finish while varying basic parameters such as height of pouring and velocity of robotic pouring. (Figure 7)

The 3d scan process was identical to the previous case study, using cameras and translated to Agisoft, then converted to a 3d mesh in Rhino that was optimized. The 3d scan protocol has 3 stages: First scan after the supporting arches and stretched fabric...
are installed; Second scan after the 1st layer of clay spray is completed; and third scan after all sprays are completed and structure is set. Karamba was used to highlight different zones of the shells giving different colors ranges according to compression and tension forces applied. In addition, stress lines were highlights and a ride diversity of resulting stress lines configurations were given according to the resulting form found geometries (Figure 8).

For the development of the AR application, the Unity3D game development engine was used along with the Vuforia AR framework for image tracking. Unity and Vuforia were chosen as platforms as they are freely available, easily accessible and straightforward to implement. The aim of the AR application was to visualize the changes that happen to the structure during the various fabrication stages and thus to enable the user to understand the effect of their actions on the structure. At its current stage the AR application visualizes the ‘before’ and the ‘after’ states of the spraying process. A 3D scan of the structure with its arches and membrane stretched is compared with a 3D scan after the layering of spray and the openings are created and the structure is set.

Both 3D scans are optimized for 3D visualization and imported in Unity. The application is developed for Android devices and Android tablet is used to augment the structure over a target. Each state of the process is assigned to a different virtual button in the AR application so that the user can switch between the different modes (Figure 9). At a later state the AR application can be further developed to allow for augmentation over the structure itself, by superimposing a projected state of deformation on the physical structure, thus assisting the fabricator in the fabrication process and in real time. (see Figure 10)

Vive will be implemented at an international event on VR and AR California, the AWE expo where the Karamba simulation on the mud shells from this seminar will be used as demonstrators on how to navigate inside the simulation space in Rhino with the Vive Goggles and the 2 remote control in hands to move inside the optimized model.

CONCLUSIONS
The experiments featured in this paper have showed that superimposing a level of interactivity between the fabricator and the physical form under construction with the distinctive use of VR and incipient developments of AR proves to be beneficial for the integration of innovative design tools leading to the structural optimization and new resulting aesthetics. In addition, navigating inside the virtual reality space inside Rhino with AR helps changing viewpoints, unveiling design aspects that cannot be visualized with the naked eye.

However, this interactivity has been conducted using drones or photographs in a non-real-time manner, but could potentially include other devices using tablets and smart phones iteratively or in real time. The benefits of real time feedback loop between constant 3d scanning’s can allow significant progress in the technique, making it more efficient in terms of timing and helping to minimize further errors. An
opportunity is detected to incorporate the 3d scanning device with the actions performer tool, where for instance the robot depositing the material could as well be the scanning device by having a camera fixed close to the end effector. In this scenario, AR could be used to run the Kuka prc code to still have the control of the robot, so if a crack or a suspicious deformation is detected in AR, the robotic action can be stopped on time.

These examples feature the procedure of onsite fabrication of mud shells construction based on the iterative analysis and monitoring, allowing the final form to fit into a certain range of constraints for shells structures optimization, and will defend the thesis that a process of continuous adaptation might prove more suitable than pre-established forms. A complete parametric approach might be desirable not only for the design, but also for the fabrication protocols, allowing certain variables to fluctuate in importance according to the structure’s development. The novelty of the resulting constructed forms lies in the input from both users and fabricators proved crucial for the possible -and multiple- outcomes of new fabrication and design techniques for shell construction, claiming that this process engenders forms and results that are different than outcomes from the same process done entirely by the machine.

Lastly, the digital fabrication of mud shell construction is currently carried out primarily in academic environments, and its immersion into the construction industry depends on the implementation of precise real scale prototypes, in the formulation of a suitable fabrication protocols, and in the wider and deeper integration between matter behavior, digital tools, and AR/VR devices.

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Digitally Conscious Design

From the Ideation of a Lamp to its Fabrication as a Case Study

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This research tries to reflect on the idea of digitally conscious design, from the inception to the manufacturing process of a prototype. A theoretical reflection on the topic is followed by the discussion about the results at two different universities (Alicante and Naples) where students have been proposed a similar assignment: a digitally conscious design of a lamp. In Alicante, the methodological approach was guided by the relation of the ideation process and the use of specific digital fabrication strategies; students were encouraged to develop and rework their designs taking into account the way in which they should be digitally fabricated. In Naples the teaching proposal involved a disciplinary approach; a deep understanding of the digital fabrication processes including the manufacturing limitations of the machinery employed involving a precise geometric control over the design. In both cases, students had to face a real study case of the design and production making use of digital tools. This comprehensive approach implied the consideration of the project as a process making students aware of the difficulties of getting their ideas materialised through digital fabrication and how their designs had to evolve in order to step over the problems encountered in the manufacturing process in different ways.

Keywords: digital consciousness, digital fabrication, digital ideation, design constraints

THEORETICAL BACKGROUND
Any creative activity seriously undertaken needs referents produced by others whose work has achieved a distinguished recognition and that could therefore be taken as an example to be imitated. Both, disciplinary knowledge and referents are necessary conditions to develop any creative valuable task as we learn through imitation and those referents nourish our imaginary. Drawing, modelling and more recently programming are the languages we use as architects and designers to produce our designs; not only do we communicate and represent architecture through drawings, models or scripts - in the case of parametricism, we even think and conceive architecture through them.
Antoine Picon (2010) has extensively referred to this shift of cultural and tooling referents in architecture. The historical tension between innovation and tradition (Deleuze 1994), between revivalism or literal reinterpretation of the past and disruptiveness, is the engine of progress. But it has truly been during the last two decades when computers have started to affect not only the way architects design or construct their buildings but architectural language itself. These tools have generated an unquestionable imprint on the aesthetics of the discipline which, for the first time in history, are neither indebted to an architectural past nor to the emergence of new materials nor constructive systems. Bold designs have become somewhat frequent relying on a new aesthetic ever since architects became aware of the extraordinary possibilities that these tools entail. Digital architecture has driven innovation to stages that are expanding the boundaries of architecture, which, in return, is mingling in the milieu of the cross-disciplinary.

However, the question to be posed in the realm of digital design is whether their use is only to make more efficient our design processes or whether the digitally conscious designer should take advantage of all the potentials of these tools. Terzidis (2006) has pointed out the difference between computerisation and computation in relation to the kind of task we assign computers in the design process. A digital conscious design could be defined as the one that truly takes advantage of the computers’ potentials generating a specificity that could not be reached without their use. Obviously, different degrees of digital consciousness may be reached.

A first level of digital consciousness can be achieved through 3D modelling. The control over the geometry is three dimensional instead of based on simple projections which are always a reductionism of the real complexity of space and therefore imply a loss of information in the process (Allen 2009). One of the crucial achievements emerged from the advent of C.A.D. is the creation of a virtual space capable of lodging our three dimensional models. A certain level of complexity in our designs implies the need for this tool to have full control in the design process. Irregularity, as a consequence of complexity, has become increasingly common in digital designs especially with the emergence of parametricism. The realm of complexity and irregularity that these practices allow is unmatched throughout the history of the discipline. This irregularity also implies the need for digitally fabricated elements as their geometric variability is too complex to follow conventional production processes thus following “non-standard modes of production” (Cache 1995). This increasing complexity and irregularity can be observed in some of the state-of-the-art digital designs by architectural practices such as THERVERYMANY or MATHSYS.

This research involves two fundamental aspects of the creative-production process. On the one hand, the use of innovative modelling techniques and parametric representation tools, such as Rhinoceros and Grasshopper, make it possible to create 3D models that can be modified according to parameters. On the other hand, technologies for digital production, albeit innovative, also have limitations; overcoming these limits is an opportunity for experimentation and research, as well as a stimulus for the improvement of the tools themselves.

Our students have to be aware of the design implications of this digital revolution afoot and be able to achieve digital consciousness in their designs. Even though contemporary trends in digital design are focusing on the role of information and the interaction between architecture and its dwellers (Saggio 2010), we decided to limit the scope of the assignment to a process from the ideation of the object to its prototyping.

We proposed our students of the Master in Architecture at the University of Alicante and of the Master of Science-Design for the Built Environment Diarc at the University Federico II of Naples to produce a digitally conscious design of an object -a lamp- which they should digitally fabricate as a prototype, engaging them in the whole production process.
In both institutions an initial design restriction was established to guide the student’s designs giving them confidence to develop their creativity within a well-established framing. In Naples an initial geometric restriction to direct the design process was set to frame the assignment: every lamp should be based on the geometry of a ruled surface; the class would thus be working on variations of lamps based on this topic. Of these, three were based on the same geometric matrix: a hyperboloid, yet the results resulted very different from each other as the apparent formal restriction became a stimulus for creativity. They were all printed in a home built 3D printer 18x18x18 cm. in PLA (Poly Lactic Acid) taking advantage of the lighting qualities of the translucent type (Figure 1).

In Alicante, the restriction implied that the designs had to involve different digital fabrication strategies consistent with the taxonomy proposed by Iwamoto (2009) -sectioning, tessellating, folding, forming and contouring-. This implied reflecting on the essential relations between the ideation process, the digital fabrication and the materiality of the design itself. Some of the lamps were laser cut -those following sectioning fabrication strategies and also the luminescent cube- exploiting the possibilities, in some cases, to use different materials with varying levels of transparency, translucency or opacity to achieve suggestive lighting results. Others were 3D printed in PLA -those following tessellating additive fabrication strategies- exploring the potentials of the chosen material in relation to the use of the lamp itself. Parametric design was implemented in three of them while the other was simply 3D modelled.

DIGITAL FABRICATION AT THE UNIVERSITY OF ALICANTE

At the University of Alicante, the students of the Master in Architecture following the course “Herramientas gráficas para la arquitectura” led by professor Carlos L. Marcos were asked to design a table lamp. A theoretical background on digital culture in architecture was given to students surprisingly unaware in many cases of the progress made by these contemporary trends in architecture.

The ‘digital turn’ in architectural design can be related to complexity; Mitchell (2005) referred to it as “the ratio of added design content and added construction content”. A digitally conscious design could be regarded as a design which could not have been attained without the assistance of computers. If one critically looks at current winning competition entries most of them could not be regarded as really digitally conscious. Even if the use of computers is evident in the presentation drawings, models and impressive renderings the architectural geometries are more indebted to modern architecture than to truly digitally borne architectural imaginaries. Some architects as is the case of Eisenman, Gehry, Zaha Hadid, Coop. Himmelblau, Libeskind to mention some of the most acknowledged, have made use of computers and their potential to shape their projects achieving in many cases results that are clearly indebted to their digital conception and/or materialisation. The realm of complexity that can be achieved using these tools -especially in the definition of the geometry through scripting languages- cannot be reached otherwise. It
is in this sense in which we refer to as digital conscious design; something that also implies geometries based on new imaginaries distinct from any kind of historicism including the modern.

Computational use of computers’ implies making use of the intelligence we can introduce in a script, therefore using computers rather as a mate within the design team instead of considering them as simply efficient machines (Terzidis 2006). Accordingly, the course included different assignments to ensure that the students not only made a sensible use of computers to achieve digitally conscious designs but were also shown a varied imaginary of digital architectural designs involving different levels of digital consciousness intended to nurture their imaginary.

Four of the designs developed in groups of two students in Alicante are discussed in the paper. The first is a lamp design inspired by sectioning fabrication strategies which consisted of laser cut and subsequent assembly. In this case only the use of 3D modelling could be regarded as a digitally conscious conception strategy. A simple geometry -a cube- was successively transformed adding layers of complexity through rotation in space, cut, sectioning and varied rotations of the different slices achieving double curvature surfaces during the initial stages. However, the geometry to be imposed to the lamp was up to this point a simple container which had little to do with thinking in terms of lighting or how should it be constructed. Moreover, the design was too obvious and mechanic. To enrich the design a more constructive approach was needed, especially tackling the issues of functionality -a lamp bulb needed to be cast inside and the light should traverse the skin of the object. Steps 8 to 14 (Fig. 3) involve design decisions taken addressing these issues. Thus, a Boolean subtractive strategy allowed for the space to host the lamp bulb as well as the ribs that should support the whole structure.

The materiality of the lamp was further developed combining different materials: transparent, translucent methacrylate and some opaque slices to achieve improved material qualities in the design (steps 12-13). Finally, other Boolean operations were implemented subtracting numerous small prisms to the geometry of the lamp to produce diffractive lighting possibilities gaining in the complexity for the light transmission through the skin (step 14). Figures 2 and 3 show the cutting layouts and the assembly process as well as the built prototype lighting effects achieved through the design and the fabrication process, respectively.

Schumacher (2009) has claimed parametricism to be the ‘new global style’ of digital design. Although some debate could be held in relation to this statement it is quite evident that parametric design implies a real disruption in the design process swapping representation for codification, on the one hand, and is increasingly becoming a benchmark of digital design in the last years. The other three examples
shown here were designed parametrically. The first two are in fact a model of what could be regarded as a digital typology stemming from a same parametric definition applied to different geometries, further developed and altered. Figure 4 shows the design process of this same parametric definition applied to a cube and to a compressed sphere that generate two different prototypes: 'Romeo and Juliet' bound by a common fate. Successive operations of layering and subsequent Boolean subtractions -typically digital strategies- generate the final versions of both designs.

Whereas the rounded shaped lamp uses two different coloured PLA, the cubic design favours the contrasting lighting effects produced by the openings on the mass and the thick layer of translucent material allowing light to be diffused in varied ways (Figure 4). The first of the two involved a more elaborate process of production and assembly as the hollow interior implied the modelling of additional construction ribs necessary to support the geometry while the filaments dried to be later discarded once the model had solidified. It is to be noted that the more ‘solid’ design of the cubic lamp was much easier to build as no additional ribs had to be added.

The fourth lamp design follows a clear digital fabrication strategy of tessellating and is also inspired by parametric design. Applying subtractive parametric three-dimensional Voronoi definitions to different geometries these were further developed in a subsequent stage in the design process following form finding strategies, something characteristic of open forms or script based formal structures (Marcos 2010). Thus, varying the thickness of the three-dimensional meshes a typology of cubic shaped parametric cages was reached. Varied densities of the meshes applied to the cube faces were tested to choose one that allowed enough light to
pass through considering the lining of the interior with Japanese paper to produce a warm soft tone against which the silhouette of the mesh might contrast with. Moreover, taking into account the possibility of exploring other kinds of lighting effects, the PLA used in the materialisation of the mesh was luminescent (Figure 5). Thus, once the light was switched off the lamp gleamed in the darkness, something that could be of use, for example, in the design of a night table children’s lamp.

DIGITAL FABRICATION AT THE UNIVERSITY FEDERICO II OF NAPLES
At the Modeling and Prototyping Laboratory, led by Mara Capone and Sergio Pone (collaborators Davide Ercolano and Eliana Nigro)- Diarc, DBE - Master of Science in Design for the Built Environment, University of Naples Federico II - the potential of these innovative production processes were tested. Five PLA suspended lamps with LED light E27, E14 were produced: Kasa, Cup, Eureka, Pierlumen and Cream, using AM (additive manufacturing) techniques (Figure 6). The aim of the research was to address and solve all the problems related to building a printable 3D model. It was achieved following a methodological path that began with the analysis of the issues related to the technology used, allowing to define the concept and the geometry of the executive project. Geometric properties knowledge of ruled surfaces allowed to define optimised solutions for the connection joints of the objects produced in several parts, such as in the case of the Kasa lamp design. The main goal was to verify how the geometry is always a very important guideline in the design process, independently of the tools employed, and especially how this apparent geometric constraint may produce very different outcomes.

The five lamps were the result of working with digital manufacturing strategies; they were conceived to be produced and marketed using innovative techniques rather than traditional production systems. We used geometry to identify optimized solutions in relation to limitations associated with the use of RA (rapid manufacturing) techniques: the dimensional restrictions of the 3D printer and the constraints linked to the materiality (angles and supports). The topic of discretization, and therefore the manufacturing in several parts, was addressed in the Kasa and Cup designs, while Eureka, Cream and Pierlumen projects explore the different translucency effects of additive manufacturing.

Building a “printable” 3D model requires attention and, above all, knowledge of the issues involved and the limitations inherent to the manufacturing technology. Thus, the goal was to define an ‘optimised’ solution that might fulfil the different project’s needs: aesthetic, functional and economic. The concepts and the projects were developed following different strategies sharing a common denominator. Far from being neutral, modelling and prototyping tools played a key role.

The executive project is the result of a process in which the steps before printing, modelling and slicing, have included testing in-progress procedures. The slicing step, during which the 3D model was converted into GCode -3D printing instructions- turned out to be a substantial milestone within the process. Depending on the settings of the printing parameters and in relation to the problems encountered, 3D
models were modified to find geometries suitable for the available technology. The 3D model was divided into layers thus setting some fundamental features that determined the appearance of the printed object. In order to optimise the result, it was necessary to make 3D models according to different setting possibilities, such as layer height, shell thickness, filling density, printing speed and temperature.

Knowledge of the issues involved was crucial to build a printable 3D model and, in some cases, imposed constraints that heavily influenced the design. Some problems such as warping, corners lifting due to the behaviour of the material used that expands and retreats depending on the temperature or the layer separation for PLA prints can be solved by increasing some degrees the extrusion temperature to enhance the mechanical strength of the 3D print without compromising the appearance directly at the slicing and printing steps. The use of the Mudra MK2.5-3D printer implied two initial geometric constraints: the printing plate size (18x18x18 cm.) and the absence of material gaps to avoid stringing, “hairy” printing, which occurs when the material comes out from the nozzle in the case of large breaks.

In order to print 3D models with large “bending angles” using additive manufacturing we needed to provide additional supporting structures. These are needed to support some parts of the model while the PLA filling filaments solidify. In our case, we decided to avoid these supporting structures; this choice was a key element that affected the definition of the geometries to be used in relation to the generation angle. The angle limit, with respect to the horizontal, was determined by an overhang test taking into account the size of the nozzle. Once the limit was established, the projects were redefined to avoid exceeding that angle; thus, the prototypes needed not additional supporting structures.
GEOLUX 3 - PIERLUMEN
The GeoLux 3 - Pierlumen lamp (Figure 7) was printed in one piece. Geometry led the design process from the start and problems linked to printing technology were solved considering the geometric features of the surfaces. The lamp is characterized by ribs and the main fabrication problems depended on the modelling of these. Figure 7 shows the design process and different solutions that were studied. A rib grid, following the double order of generatrices of the round hyperboloid, created a matte texture overlaying the translucent surface. The lamp's geometry was parameterised: the application of generative modelling tools allowed to analyse different solutions to achieve the optimal configuration. The key theme of the design process concerned the imprint of these ribs as it was the leitmotif for all the subsequent stages to reach the final design. The lamp silhouette is always generated as a revolution of a curve, a generatrix, that changes shape in all versions to optimise the printing space and the lighting effects, from the classic dome shape to a drop one and finally to the hyperboloid (Figure 8). The implementation of parametric modelling shows how through the use of Grasshopper we were able to monitor the result as well as the importance of geometric knowledge.

Descriptive Geometry is a necessary discipline for researchers and students of design. Although recent scientific production allows us to observe exuberant experiences related to the use of IT technologies in the architectural field, there is a compara-
tively limited number of in-depth geometric research papers. The automation allowed by many software applications drive students away from learning and deepening on geometric topics whose knowledge enables full control of processes. Some software tools can model free-form surfaces, however being unable to control the proposed structure during the digital fabrication phases. Today’s architectural and design software uses different procedures, tools and interfaces to achieve a similar result. Descriptive geometry seems to be outdated through the automatic training of traditional software for 3D modelling, something which does not favour the control and application of theoretical contents that may feed and enrich design as well as research (Casale 2013, [1]). Descriptive Geometry is a necessary discipline for researchers and students of the design area. Although recent scientific production allows us to observe an exuberance of experiences related to the use of IT technologies in the architectural field, there is a comparatively limited number of in-depth geometric research papers. The automation allowed by many software applications drive students away from learning and deepening on geometric topics whose knowledge enables full control of processes. Some software tools can model free-form surfaces, however being unable to control the proposed structure during the digital fabrication phases. Today’s architectural and design software uses different procedures, tools and interfaces to achieve a similar result. Descriptive geometry seems to be outdated through the automatic training of traditional software for 3D modelling, something which does not favour the control and application of cultural theoretical contents that may feed and enrich design as well as research (Casale 2013).

Today we are able to witness the birth of an ever-increasing development of instruments for computational and parametric design. These are able to renew descriptive geometry by promoting a more careful study and management of levels of complexity unattainable through traditional approaches. However, only the precise geometric control over the designs may optimise not only the shape but, significantly, the way it may be digitally fabricated with computer manufacturing tools. Moreover, the geometric properties of the surfaces are crucial to find the most convenient structural solutions (Capone, 2012, 53). Therefore, the pedagogical experience proposed at the Modeling and prototyping Laboratory was based on the coordination between this Lab and the Parametric Design Workshop, a course for free training credits, organised by professor Mara Capone, professor Carlos L. Marcos and arch. Ph.D. Emanuela Lanzara, held in Naples.

Grasshopper’s intuitive interface allows to tackle traditional modelling problems more efficiently. At the didactic level, computational design allows students to develop, control and refine their ability to solve real problems by tackling and reducing the limitations and the amount of errors in traditional 3D modelling processes. In addition, 3D printing of student’s designs allowed to test and improve their conceptions thanks to quick prototyping techniques.

Product design courses encourage the acquisition of the knowledge and tools needed to enter into the design professional sphere and the possible subsequent marketing of industrial products, of-
ffering interesting prospects for social and cultural improvement. Therefore, this experience suggests and encourages the teaching of computational design within institutional courses promoting the fertile symbiosis of traditional disciplines such as Descriptive Geometry with Computational Design.

The introduction to Grasshopper, guided the students in the parameterisation of their modelling of the surface of their lamp’s design. To generate the hyperboloid the principles of the genesis of this surface have been translated into a deliberately intuitive and explicit grasshopper definition which allows to separately control the different parameters involved in the geometric configuration of the round hyperboloid. In our case, to manage the shape in Grasshopper, the hyperbolic hyperboloid was generated by the revolution of a straight line around a straight vertical axis (Figure 8).

CONCLUSIONS

Digital manufacturing technologies broadens the landscape of geometries to be achieved as well as the complexity that may be handled. However, the systematic use of certain type of geometries may produce a proliferation of these forms which, while being complex and initially appealing, are now beginning to be repetitive thus undermining the creative prospects made possible through the convergence of C.A.D.-C.A.M. technologies.

It is to be noted that irregularity as a consequence of addressing complexity has become a hallmark of digital architectural design. Our capacity to address complexity has greatly been enhanced through the use of computers, however, it should not be simply regarded as an aesthetical value in itself but rather as the result of enhanced design qualities.

This research shows how a methodological approach related to contemporary imaginaries and disciplinary principles, can stimulate the use of these innovative tools by yielding original results, both figuratively and productively. The Naples laboratory aim was to explore the potential of this innovative expanding process of “digital crafting”, a practice which stimulates the definition of new ways to market the design product. The potential buyer could print the prototype himself, using a 3D printer or in a fab lab. This is a major shift that supresses the packaging problem as it can become “virtual”. Currently a detailed study to define the possibilities for implementing this prospect linked to the makers world is being studied.

This experience shows that institutional courses on computational and parametric design taught at universities, organized considering the number of laboratory hours required and the choice of appropriate theoretical contents, would allow students -future designers- to handle problems of different complexity related to product design and manufacturing.

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Kinetic Shading System as a means for Optimizing Energy Load

A Parametric Approach to Optimize Daylight Performance for an Office Building in Rome

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Current research, as a part of on-going PhD research, explores the possibilities of dynamic pattern inspired from biomimetic design and presents a structured framework for light to manage strategies. The experiment stresses the improvement of daylight performance through the design and motion of kinetic facades using various integrated software. The impact of kinetic motion of hexagonal pattern was studied by integrating triangle and triangle covering through blooming pyramids on south-facing skin to control the daylight distribution, using a parametric simulation technique. The simulation was carried out for a south oriented façade of an office room in Rome, Italy over three phases. The first optimized results represent the static base case, which were compared to the other two proposed dynamic models in this research. Results demonstrate that dynamic façade achieved a better daylighting performance in comparison to optimized static base case.

Keywords: Bio-Inspired Pattern, Parametric Design, Dynamic Façade, Daylighting

INTRODUCTION

Architecture and its dynamic facilities are important ways to actively respond to variable ambient conditions and requirements while also meeting the needs of occupants and addressing issues of building performance. Within contemporary architecture, there is a growing interest in motion buildings and their components are gradually shifting from static to dynamic to improve performance and occupant satisfaction (Goia et al., 2013). A dynamic ‘filter’-the envelope-between interior and exterior unquestionably allows for a desired change in building use or a rapid adaptation to new ambient conditions only through its modification. Moreover, mechanical shading device systems allow not only light, view, sound, or smell to be filtered, but also a ‘filter’ motion that can also enhance aesthetic architectural experiences (Mahmoud, A. H. A., & Elghazi, Y., 2016). A building façade plays a vital role in reducing artificial lighting and heat transfer by improving precise control over the use of natural light in interior spaces. To obtain appropriate natural lighting for indoor work
spaces, much research has been conducted and current technology focuses heavily on optimizing the architecture composition of façade properties opening. Hence, parametric design and a computer simulation prepare the grounds for a research to generate dynamic facades and evaluate it in accordance with daylight transmittance in the early design stage (Goia et al., 2013).

Contemporary office building facilities require tremendous energy consumption to meet the comfort level needs of their users, and that results in adopting active technologies such as lighting and HVAC systems. Biomimicry's inspiring design has become a promising approach, as it provides different design alternatives that attain adaptability of the environmental concerns (Mahmoud, A. H. A., & Elghazi, Y., 2016). While the type of office building is used as a particular illustrative case study for the on-going PhD research, a part of it is used in this research paper (Jahanara and Fioravanti, 2016). Here, the biomimicry and parametric design process for designing a kinetic pattern are point out which are formed by multiple singular movements through the lens of morphology. The proposed bio-design approach has been employed as a prototype to generate an adaptive dynamic façade in relation to daylight. This paper explores the possibilities of kinetic composition afforded by geometry’s façades in motion. Composition is analysed in terms of pattern, being defined as the relative movement of individual kinetic parts in time and space - the way in which multiple singular kinetic events cluster, or propagate across a façade, over time. That exploration results a better understanding of adaptations in relation to the organisms, their environment and biological mechanism. In addition, the study explores dynamic façade that parameterises and evaluates its performance in regards to integrating motions as a response to dynamic day lighting.

**BIOMIMETIC STRATEGY FOR MANAGING LIGHT**

Biomimetic brought about a design approach that applied nature as a guide for innovation technologies which carry out the future of building facades. It represents an innovative alternative that reconciles energy efficiency with integrating adaptability that responds to high-quality indoor climates needs. Therefore, innovative techniques in constructions and designs are now offering more adaptive facades that respond and ‘behave’ as a living organism to their environmental context (Goia et al., 2013). Efficient light management is necessary as a design requirement aspect of building’s facades that are exposed to solar radiation. Taking biomimetic-living organisms, as design solutions for buildings, is a unique strategy to manage light: it is a design framework that facilitates the selection of appropriate strategies of nature. Not only the framework enhances the light management by elaborating on the involvement aspect which too many organisms’ nature systems can provide, but also it behaves as an analogical design development that responds to light (Fox and Kemp, 2009). Nevertheless, biomimetic is not about creating an exact replica from nature, but is about translating its functional biology aspects into the architecture in a performativity level (Goia et al., 2013). Morphological, behavioral, and physiological means influence light management efficiency strategy and its ability to manage light intensity. For instance, some plants are able to transmit light because of their intricate structural assembly, while others optimize light by solar tracking and enhancing body exposure (Goia et al., 2013). Through exploration and learning from those strategies and techniques of nature, a design discipline for a new light system management is emerging, aiming at building skins. Biomimetic design field is still in a challenge with architecture, especially with the growing integration between the biomimetic design, engineering, and material science (Fox and Kemp, 2009). In this regards, many experiments have been carried out to represent biophysical information systematically in a similar context to buildings. However, a systematic representation of building application for light management strategies is limited. Figure 1 shows schematic diagrams of Biomimetic impacts on architecture with the light management efficiency.
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<th>Morphology</th>
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<td>Hazza Bin Zayed Stadium - UAE</td>
<td>Water Reaction - Royal College of Art - 2015</td>
<td>Pavilion - Germany Project year: 2013</td>
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<td>Project Year: 2014</td>
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<td>Stadium inspired Pattern design</td>
<td>Pattern inspired by a pinecone, that open and closes naturally to protect seeds from the wet weather and spread it when it is dry. That happens when outer layer expands more than the other layer which therefore causes different scales to bend and close its cone. The cone is a tile where the outer layer elongates and curves the material away when wet. (Archdaily, 2015)</td>
<td>Pavilion is a particularly interesting way in moisture-driven movement which is observed in spruce cones. This movement takes place through a passive response to humidity changes, just like plant movements from cell pressure metabolism. Hence, movement is independent with no energy consumption from the plywood sheets’ metabolic function. (Archdaily, 2013)</td>
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Based on the schematic diagram in figure 1, this research paper is considering and underlying the environment process at initial stages of a design process, taken by the morphological strategy. Therefore, the order in nature can promote and develop adaptive solutions for building envelopes. The current paper consequently focuses on how the morphological applications of biomimetic can produce an adaptive geometry pattern which responds to the efficient design factor of the daylight.

ASSESSING BUILDING FAÇADE’S DAYLIGHTING PERFORMANCE
Daylight is the best source of light as it most closely matches the human needs. It is free and does not increase energy consumption for lighting (Li and Tsang, 2008). Accordingly, a design pattern is proposed for building facades which is responsible for the amount of daylight in indoor workplaces to achieve a better performance with respect to light quality, energy consumption and occupant satisfaction. The proposed dynamic façade’s geometry is inspired from the structure of living organism responses to daylight in Lotus plant. The geometry optical structure is aiming to adapt the building to control the natural light and reduce the need of artificial lighting so to respect visual comfort and environmental concerns Nabil and Mardaljevic, 2005). The “Useful Daylight Luminance” (UDI) predictive method was then used to measure the amount of natural light. The UDI method divides annual daylight illuminance in a workplace into three sections. The first one includes areas that receive less than 100 lux, which is not appropriate, and thus demand additional artificial lighting; the second section corresponds to the range of 100 to 2000 lux, which is suitable for working activity; and the last one includes illuminance exceeding 2000 lux which results in potentially visual discomfort. This method is more realistic than the conventional “Daylight Factor Approach” -DFA- which only considers a single factor (Nabil and Mardaljevic, 2005).

RESEARCH AIMS AND METHOD OF INVESTIGATION
Current research aims to create an adaptive kinetic folding pattern which highlights the significant effect of dynamic facade design on indoor day lighting quality inspired by Biomimicry. Biomimicry has become a trend in interactive architecture as an inspiring concept. It uses the organism as a successful case which is able to control and utilize energy in harsh environments. The natural organism uses minimum amounts of material to build intelligent structures so to successfully optimize its energy in reaction to the environment. The proposed design pattern in this study has also been inspired by the blooming motion for Lotus flower that mitigates over-lit conditions. There are many types of plants in nature that open their flowers and leave them under the sunlight and close them when it is dark at night (Fox and Kemp, 2009). They have a basic behaviour guided by this simple rationale that can be performed by ‘agents’. The structure scheme of the blooming shape defines the spatial design and how the pattern reacts to the sunlight. The Lotus flower’s geometry reacts to the sun by changing from a triangular shape to a hexagonal, maximizing the differences between its extended and folded states. This pattern acts as a receptive unit to control the daylight conditions, affecting occupant satisfaction while saving A.C. energy (Mahmoud, A. H. A., & Elghazi, Y., 2016). In this regard, a case study for a geometry which applied in an office building’s façade, not in an urban area, was conducted to simulate the environmental setting similar to Rome’s geographical location. Likewise, a proposed pattern was generated by integrating performance analysis tools with parametric modelling i.e. implementing Rhino and Grasshopper programs. Hence, it was determined that evaluating the office workspace conditions by means of DIVA software analyses to enhance energy saving, daylight, glare, and performance, depends on balancing these objectives,(see figure 2).
PARAMETRIC OFFICE MODEL
A side-lit office space was constructed as the base case study model for an office building located in Rome, Italy. The area is 37.31 m sq. and dimensions of 4.10 m width, 9.10 m depth and 3.20 m height, facing south and located at the third floor (Figure 3).

Although the façade’s configuration sets in the case study changes, the space dimensions remain the same throughout the entire study. Initially, the simulation was run for clear and overcast skies for different types of motion test. The interior surfaces were assigned a reflectance of 80% for the ceiling, 50% for walls, and 20% for the floor. The kinetic skin was made of sheet metal material. The opening was assigned a doubled-glazed material with 65% visual transmittance. The kinetic skin is an external layer of a double façade which acts as a shading screen coupled with glazed interior layer that has an in-between buffer of 35 cm, see (figure 4).

DESIGN PROTOTYPE
The concept of dynamic façade’ geometry is influenced by the adaptive behaviour of the plants and the concept of Lotus flower that reacts to the sun by changing from a hexagonal shape to a triangle one, and the triangle part being covered by a blooming pyramid. The geometry pattern has two parts: dynamic and static states are created by integrating the triangle shape into the hexagonal. The dynamic part is maximizing the differences between its extended and folded states’ receptive unit to control the daylight conditions when day lighting increases and affects the occupant satisfaction while saving A.C, see figure 5. Likewise, in the proposed design, two methods are used to operate the blooming panels. The first method is the regular plane of the dynamic blooming pyramid, (see figure 6), while the second model eliminates some blooming part to provide more visual comfort for occupant spaces and decreases the mechanical part of structure, see (figure 7).

DAYLIGHTING EVALUATION
Research work was divided into three consecutive phases to evaluate the daylight by Diva for Rhino. The case study model with the two phases of proposed pattern was then simulated. The simulation was planned to perform for four months per year (March 21, June 21, September 21, and December 21) at three hours per day (9:00 am, 12:00 pm and 3:00 pm). Those times and dates were chosen, to have a fairly accurate evaluation of the performance in the case study model for its two proposed patterns as well as the base case: a) The first simulation focuses on the analysis of delighting performance for a window with dimensions of 3.20m width and 1.2 m height. The Window Wall Ratio (WWR) is set to 25% as the base case model, (see table 1).b) The second simulation represents a daylighting performance, using parametric tools for kinetic hexagonal geometry to a triangle, and the triangle being covered by a blooming pyramid. The blooming motion has intelligence sensors to achieve the near optimum day
lighting adequacy. In the case of first set A, the daylight's assessment for the dynamic facade was simulated at three circumstances: when the assemblies are closed, partly open and fully open, see (table 2).c) The third stage of the simulation represents the dynamic facade's pattern set B. The blooming pyramid's geometry was assigned according to the visual work space comfort, see (table 3).

**DAYLIGHTING SIMULATIONS - RESULTS**

As mentioned, Grasshopper Simulation for Diva to assist the day lighting performance was used in plan-
Grasshopper simulation was used to identify the parameters and inputs for the proposed model and set up the evaluation criteria for the daylighting assessment. Then Diva was applied to simulate the process of daylighting and send the results back. Daylighting requirement was set to three illumination evaluation levels for the floor area: “daylit”, “partially daylit” and “overlit” areas. The “Daylit” area achieves illuminance levels between 100 lux and 2000 lux for the floor area; “Overlit” area achieves illuminance greater than 2000 lux for the floor area with potential glare; and “Partially lit” area achieves illuminance below 100 lux for the floor area. The simulation parameters were set to measure daylight illuminance sufficiency for the room. Diva parameters were set to calculate the percentage of analysis points that achieves illuminance levels between 100 lux and 3000 lux.

In this stage, the base case was evaluated for daylighting adequacy in summer; nearly half of the base case floor area was found to be “daylit”. However, the
other half of the floor area has been “overlit” which causes problems with visualization and glare. On the other hand, in winter, the “overlit” was relatively high and nearly less than half of the area was found to be in “daylit” area, while the other half was divided into “overlit” and “partially daylit” areas.

This means that in case of using traditional windows, only 50% of the space has adequate daylighting for most of the year. These results of daylighting performance for the proposed dynamic geometry’s sets (A), indicate that a recommended dynamic façade as a shade device improves the daylighting conditions in the workspace. In all kinetic geometries cases results were acceptable and the required daylighting was achieved better than the base case.

The results showed that in the summer, the “daylit” area was significantly increased and there was a relative decrease in the “partially daylit” area, while in winter time, only the “daylit” area was increased. In the case of selected net for the proposed blooming’s geometry, set B, represented the best daylight performance see in table 4 below.

The proposed blooming geometry cases were found acceptable at all times where “daylit” percentage reached 99% of the space at the value ranges in June, the closed and the totally opened geometry, in both case study sets, gave the most appropriate “daylit” area.

While, the partially opened geometry in both the case study sets, increased the “daylit” to almost 100% in March and September (table 2, 3).

In case study set A, the daylight performance was only achieved at opened and partially opened geometries of 95% in the winter. Hence, some acceptable results where the “daylit” area percentage that was achieved at 12:00 pm to be 93%, and its performance in afternoon at 3:00 pm, while it was slightly low in the early morning, see (table 4).

In general, results indicate a significant impact of the geometry pattern’s parameters and types of geometry organization on the overall daylighting performance in the workspace. The proposed model coupled with the two proposed organizations of dynamic skin improved the daylight performance. The blooming geometry acts convincing as a dynamic shading device to control the excessive daylight level. It is also clear that the “overlit” area was relatively improved in winter time and was mainly concentrated at four working hours of the day.

Table 2
Results of Set A-
Model: regular plane, Source: Alireza Jahanara

Table 3
Results of Set B-
Model: Selected blooming pyramid, Source: Alireza Jahanara
DISCUSSION & CONCLUSION

The research paper presents a bio-inspired geometry design driven by daylighting performance as a design factor for office workspaces in Rome, Italy. The proposed blooming geometry pattern was parametric by Rinho and simulated by Dive 4.0 to control daylight uniformity.

The geometry prototype was designed as a responsive dynamic system inspired by mimicking Lotus plant’s response to light. The adopted methodology can therefore be interpolated for the annual daylighting performance of a dynamic geometry which can be used to generate various geometry motions using parametric exhaustive search. Moreover, the research experimented the idea of selecting partially opened dynamic pattern configuration and static part configuration for less material aligned with the daylight and visual comfort design factors. These types of configurations allowed for the different application purposes: closed for privacy, open for external visual interactions, and partially open to shade in “overlit” hours. Therefore, a full annual simulation gives a better guide to improve the pattern organization and its geometry parameterizes daylighting optimization for the space performance.

Running the simulation, hence, represented a year-round performance for the same blooming geometry motion in different sets of organizations. In order to trace the daily, hourly, and then monthly and annually facade responses to climate changes for testing the unusual luminance level, the bio-inspired geometry was improved as a dynamic screen. It is also suggested a further research and more exploration should be done to discuss the daylight as a parametric, yet a design target, which is going to be covered in the on-going PhD research. In addition, a physical fabrication mock-up for the geometries façade can indeed give another depth to the study. The on-going research of the PhD has a potential to become a basis for the future intelligent and adaptive dynamic patterns that respond to the daylight parameters, aiming to optimize the energy consumption and occupant visual comfortable. Furthermore, it will provide the daylight design factor as a framework to understand the responsive dynamic façade and optimize the office buildings’ energy performances aligned with improving the indoor workspaces’ comfort conditions.

Table 4

Floor area achieved illuminance levels between 100 lux and 3000 lux, Source: Alireza Jahanara
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Implementing the General Theory for Finding the Lightest Manmade Structures Using Voronoi and Delaunay

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In previous efforts, the foundation of a general theory that searches for finding lightest manmade structures using the Delaunay diagram or its dual the Voronoi diagram was set (Ezzat, 2016). That foundation rests on using a simple and computationally cheap Centroid method. The simple Centroid method is expected to play a crucial role in the more sophisticated general theory. The Centroid method was simply about classifying a cloud of points that represents specific load case/s stresses on any object. That classification keeps changing using mathematical functions until optimal structures are found. The point cloud then is classified into different smaller points’ groups; each of these groups was represented by a single positional point that is related to the points’ group mean. Those representational points were used to generate the Delaunay or Voronoi diagrams, which are tested structurally to prove or disprove the optimality of the classification. There was not a single optimized classification out of that process but rather a family of them. The point cloud was the input to the centroid structural optimization, and the family of the optimized centroid method is the input to our proposed implementation of the general theory (see Figure 1). The centroid method produced promising optimized structures that performed from five to ten times better than the other tested variations. The centroid method was implemented using the two structural plugins of Millipede and Karmaba, which run under the environment of the Grasshopper plugin. The optimization itself is done using the grasshopper’s component of Galapagos.

Keywords: Agent-based structural optimization, Evolutionary conceptual tree representation, Heuristic structural knowledge acquisition, Centroid structural classification optimization method

MODEL DEFINITION:
The general theory defined in the backing paper (Ezzat, 2016) was developed based on the need for having a better understanding and explanation of the point cloud. Simple unanswered, but important, questions like the representational question of what if each classified points’ groups to be represented by a curve, a surface, or a mass instead of just a sin-
ingle positional point needed to be answered. Our proposed implementation of the general theory is a skeptic approach. Our proposed model is a skepticism of the centroid method achievements. The model would lay an algorithmic framework for any viable further specific implementation. That framework would guaranty the computational optimality and would assure the viability of answering any pool of questions, including the original representational question. The framework is presumed to give us the optimum needed understanding of the point cloud.

The original paper introduced the concept of zooming-in-zooming-out. After exhausting many of the other available possibilities, we were faced with the reality that the zoom-in-zoom-out technique is the best approach for implementing our model. Actually, the success of the whole model rests on that simple concept. As it would be clear soon, the model’s Big-O Algorithmic Complexity is \( \Theta(1) \rightarrow \Theta(x) \) for all the different processing scenarios is due to that concept (Vrajitoru and Knight 2014, Skiena 2012). Figure 3 contextually represents our proposed model in relation to the centroid method. The family of optimized centroids, the set \( I \) where each \( I_n \in I \) for \( n \in \mathbb{Z} \) (the positive integers), is the initial input of the model. The model is composed mainly of two processes. The first is the analytical process, while the second is the behavioral one. Both of these processes keep communicating, and in certain occasions, the centroid model is used to assure the correctness of the conclusions and/or to enrich the inputs’ set with new updated ones. Both of the processes are structured based on the zoom-in-zoom-out concept. The zoom-out represents the summary of the data, the zoom-in represents the detailed analysis, while the optimized version is located in between (see Figure 2). Figure 2 represents our “conceptual tree”, which would link the two analytical and behavioral processes. It will also facilitate their communication and assure the computational superiority of any further specific implementer. The continuous calculative communications between the analytical and the behavioral processes are done in parallel with the centroid structural tests and optimizations, which are done only when needed because of their relatively costly calculations. These continuous communications are meant to adjust the analytical conceptual lattices themselves and to propose physical variations by the aid of the behavioral agents.

The following procedures are considered as influential computational measurements:

- The searching deep in the “conceptual tree” is always based on the criterion of desperate need.
- Any possible searching duplications are avoided, meaning that the search would not reach the deeper nodes of the tree unless that node is unique and has no other similar nodes in the tree.
- The focus would always be kept as possible on the roots of the tree. The data flow from the
The “conceptual tree” as the communicative method between the different zooming-scales. The analytical data and the behavioral agents are allocated on the tree’s nodes.

• The data should be saved rule-based, maybe functional-based, rather than hard coded as much as possible. For example, similar branches should be saved referentially, meaning that a single branch should be hard coded and the similar branches should be defined referentially by a rule that is dependent on that hard coded branch.

Now we are ready to briefly represent the components of our model, as they are indicated in the figures and in the discussions:

1. The optimized inputs $I_n$
2. The conceptual trees $T_n$
3. The tree nodes structure $N_n$
4. The behavioral families $F_{ab}$
5. The framework’s knowledge lattices $L_{ab}$
6. The general theory outputs $G_n$

The analytical process:
The conceptual analytical data is represented mathematically as related lattices (see Figure 4) (Kaburlasos 2006, Gen and Cheng 2008, Sierksma and Ghosh 2010, Parrochia and Neuville 2013). Lattices are Partially ordered sets coupled with the $\text{Inf}(\wedge)$ and $\text{Sup}(\lor)$ operators. Consequently, to represent the analytical data using lattices, the partial ordering relation $\leq_{ab}$ and the two $\{\wedge, \lor\}$ operators need to be defined for any interpretation of the analytical data’s variations. Other parallel definitions of lattices could also be used when needed. Therefore, the possibility of using the mathematics of the lattice theory to represent the acquired or retracted knowledge of data, actions, or the interactions between them is a needed arsenal during the optimization (Gratzer 1998). The concept theory is an exemplary of using lattices to represent knowledge (Ganter and Wille 1996, Ganter and Obiedkov 2016). Each node of the “conceptual tree” has one or many lat-
tices that represent the different notions related to each zooming-scale (see Figure 4). Later in the paper, a discussion of the ordered relations $\leq_{ab}$, coupled with the $\text{Inf}(\land)$ and $\text{Sup}(\lor)$ operators to represent the model’s knowledge repository of each zooming-scale would be conducted. The “conceptual tree” is adaptive, meaning that it may grow in specific locations only if needed. Proposed techniques for the analytical data storage in the “conceptual tree” would be discussed (see Figure 4).

Each of the three zooming-scales would have different communicative and corresponding schemes between the data lattices and the acting agents based on the following evolution phases:

1. The initial phase.
2. The maturity phase.
3. The optimization phase.

**The behavioral process:**
The behavioral process has three main tasks to perform:

1. The first task is to suggest the best modifications possible for the physical Voronoi/Delaunay diagrams, which would be by adding, deleting, or modifying certain points in specific locations.
2. The second task would be modifying the analytical lattices themselves, which could be done by using the mathematics of the lattice theory.
3. Modifying the “conceptual tree”, which would be done by expanding, contracting, or redefining the clustered point cloud zooming-scales.

The first and the second tasks are related to the **maturity** phase, while the “conceptual tree” modifications are possible in the **optimization** phase. The behavioral process is done by different agents’ families. Each agent family has a certain action to perform. The different agents’ families are to construct a communicative society. No matter the agents are strictly structured or loosely structured, they are always allocated to the proper “conceptual tree” nodes as needed (see Figure 5). The agent’s families, algorithmically, mainly execute the aforementioned behavioral, inferential, or optimization tasks.

**DISCUSSION:**
The proposed framework’s efficiency is founded on two theoretical premises. The first premise is that the framework’s algorithmic performance is fast enough, while the second premise is that the framework is a needed practical infrastructure for the specific implementer. The algorithmic first premise could be easily theatrically proved, the model’s Big-O Algorithmic Complexity is $(\Theta(1) \rightarrow \Theta(x))$. The second practical premise is the one that we may have a hard time trying to prove. One of the reasons of that hardship is the lack of the existence of a specific practical implementer. The existence of a specific implementer may help in assessing the framework’s practicality by comparing its structural optimization results against the counter centroid method’s achieved results. In the next section, we would try to define a possible specific implementer and then we would engage in a qualitative analytical discussion about the practicality and the necessity of the framework. Finally, an analysis of the general theory in the context of structural optimization would be looked over by the end of this section.
An exemplary specific implementer: the specific implementer would start the journey of having a comprehensive epistemological understanding of the point cloud by answering a pool of questions. That pool of questions, including the representational question, may be considered as the possible known variations tested over the possible known Voronoi/Delaunay cells, which represent the design space. There is a simple choice to make, either to test these design space variations and their consequences thoroughly, inapplicable brute-force like, or else to rely on the framework heuristic non-monotonic reasoning during the epistemological journey (see Figures 3 and 6). The point cloud’s knowledge acquisition relies on answering the pool of questions using the family of the centroid optimizations. The knowledge acquisition would be done over any of the three initial, maturity, or optimization phases.

Therefore, in the initial phase, the first thing to do is to define the conceptual tree/s using the family of the centroid optimizations \( I_n \). The best optimal will be used to cheaply and speedily define the tree’s three zooming scales (see Figure 6). The first zoning is defined using the opposite classification curve and then for each of the classified grouping of each zone, a further classification using the same curve is conducted and so. The number of the clusters of each zone is defined by the specific implementer’s interpretations. Consequently, the conceptual tree \( T_n \) is constructed from the best optimal centroid \( I_n \). This elementary form of the conceptual tree would evolve alternatively over the three phases until optimality in conceived. The rest of the family of the centroid optimizations would be mainly analyzed based on their discovered classification curves. The definition of the conceptual tree is an essential mandate of the initial phase, and it should be coupled with initially defined analytical and behavioral conceptual lattices. The creation of these initial lattices could be done by the following:

- The agents at this phase would allocate themselves, or recommend to be allocated, on the proper behavioral lattices \( L_{a,b} \) on the proper tree’s nodes \( N_n \). Optimally speaking, a priori knowledge structure could propose default lattices and then the different agents would subscribe consequently.
The lattices are finite and hence there should be a $[0, 1]$ for each lattice. Each agent could first allocate itself to the proper behavioral lattices then iteratively they would relate themselves to other agents using the ordering relation $\leq_{ab}$ or the $\{\land, \lor\}$ operators.

The initially concluded lattices would be defined based on the $[0, 1]$ assumption and the proposed relational operators. The consequent maturity phase conducts the heuristic search for optimal Voronoi/Delaunay diagrams’ variations, but without changing the corresponding conceptual tree. This phase is mostly a learning phase; the hypotheses of optimal diagrams over the possibilities’ space are more regularly attested using the centroid method. These empirical knowledge acquisition feedbacks are of great help not only to this phase but for the coming phase as well. The agents that may heuristically modify the diagrams by adding, deleting, or modifying certain points in specific locations are the main acting agents in this phase. These altered points always belong to the same node of the conceptual tree. Some actions at that phase may include the following:

- The recommendations of the previous phase are taken into considerations. A higher authority, either elected by the agents or defined by a priori knowledge, would allocate the agents on the proper lattices on the proper tree’s nodes.
- Both the analytical and the behavioral processes will be fully conducted in this phase. Creation and alterations of all the lattices, the agents’ allocations or generations, and the integration between the two behavioral and analytical processes are the main activities that would happen in this phase. This does not include the agents that would modify the conceptual tree, but it would include the agents that may modify the corresponding physical Voronoi/Delaunay diagrams. The main goal of this phase is to epistemologically examine the possibilities of the design space of the corresponding diagrams using a single given unaltered conceptual tree.
- Recommendations for the agents that modify the conceptual tree are proposed for the next phase to take care of. The next phase “conceptual tree” modifying agents may include the agents that expand, contract, or redefine the clustered point cloud zooming-scales.

In this last optimization emergence phase, The agent-families have the full control and the emergence of the conceptual tree and/or its corresponding diagrams are up to the limits. The empirical optimizations of the previous phase are taken into considerations. For the sake of predictability, no huge modifications of the corresponding diagrams beyond the assertions of the previous phase should take place. In the case of massive modifications of
the corresponding diagrams are assumed, a transition from this phase to the maturity phase should take place.

- This phase concludes by a reformed “conceptual tree”. Aged agents are defined by the end of this phase. Sometimes, the transitioning may happen to the initial phase rather than the maturity phase in the case of major changes in the conceptual tree itself. The already developed lattices have better chances of survival.

**The practicality of the framework:**

The exemplary specific implementer is an agent-based solution that epistemologically exhausts the infinite design space variations using non-monotonic heuristic uncertain searching for global optimal conceptual tree/s, and their corresponding diagram/s (see Figures 3 and 6) (Rothlauf 2011). In other words, this is not an environment simulated by agents but rather it is a goal-driven process. The specific implementers’ Adaptive agents are pieces of software that are autonomous, have brains, cooperative, share the same goal, and asynchronous (Barbucha, et al. 2013). For this multi-agents’ epistemological solution to exist, infrastructural Architectures are needed to produce qualitative optimal solutions by establishing a platform for the agents’ collaboration and communication. This infrastructural architecture is the proposed framework. The agents’ non-monotonic heuristic reasoning is meant to discover rules and to define concepts (Resconi and Jain 2004). The adaptive agents are hierarchically structured over the conceptual tree nodes, and the conceptual tree is the most important element of the proposed framework. This nodal structure implies the existence of hierarchical contexts over the various zooming scales. The agents make their rules’ or concepts’ inferences based either on their internal contexts, the nodal context they occupy, or on the external nodal contexts, either higher or lower in the hierarchy (Resconi and Jain 2004). Concepts are suitably represented and processed using the lattices’ mathematics (Ganter and Obiedkov 2016). For the agents to discover rules, they need to be intelligent. Their internal architecture is adjustable or neurally defined at the run-time, and they could use the AI machine learning techniques to empirically make their epistemological inferences (Smajgl and Barreteau 2014). Their intelligence is not limited to their internal architectural adaptability, the main goal of defining the emergence of the behavioral lattices is to define various convergence schemes between these agents. These various convergences are to guarantee rich combined intelligent behaviors between the suitable agents.

The conceptual tree is a representation of our in-depth understanding of the point cloud, this understanding simply incepts from the optimized classification bell-shaped curve of the centroid method and gets evolved and developed until plausible optimal understanding of the point cloud is discovered (see Figure 6). The life cycle of the conceptual tree keeps evolving over the alternating three states; and ends by conceiving optimal understandings. The second maturity phase is full of the potentialities for learning, and the analytical centroid method is mostly visited to assert hypotheses at that phase. All the behavioral/analytical activities are conducted in that phase, except the modification behaviors of the conceptual tree itself. The agents at different levels would have a synergic non-monotonic decision of which variations are eligible for the centroid method to examine and which are exempted from further analysis. In the last optimization phase, the conceptual tree modifications are viable based on the learnt experiences from the previous maturity phase. A decision is taken afterward to transit the conceptual tree back into one of the earlier two phases, mostly the second phase unless major modifications are expected in the conceptual tree or the corresponding diagrams. The agents should act according to each phase functionality; they collectively, electively or combined with a priori controllers, should define their aging schemes, the dependability on the nodal internal or external in-
ferences, and the conceptual tree’s *transitioning times between the phases*. The computational and functional superiority of the conceptual tree is more obvious by now. Nevertheless, the conceptual tree may have two possible variations by the implementers, both of which would still support the necessity of the conceptual tree:

1. The conceptual tree may ultimately transform into any other homomorphic graph type that is favored by the specific implementer
2. There could be other favored parallel graph types during the analytical evolution of the conceptual tree that link the tree’s nodes differently (Chein and Mugnier 2009).

lattices and their capabilities of representing concepts, which are intrinsically hierarchical, are of great support for the conceptual tree’s *evolutional optimization*. The analytical and behavioral lattices would always entail that ordered *evolutional optimization* of the conceptual tree and would have a positive contribution to memory management.

Although The design space variations are virtually continuous, plenty of discrete variations, the main goal of the general theory is to transform the virtually continuous solution space into a combinatorial one using the hierarchical property of the conceptual tree. The hierarchical structure of the conceptual tree should aid in the dynamic evolving of the infinite population of solutions of the design space. The agents should heuristically *elevate or remove solutions* from the population during the *conceptual tree’s evolution* over the *alternating three phases*. That addition and removal of the solutions’ population should ultimately culminate into fewer possible optimal conceptual trees and their corresponding diagrams (Barbucha, et al. 2013). The role of the questions’ pool is to prioritize the variations that need analyses or examinations during that population’s selectivity process. We may now mention two main criteria for evaluating the successfulness of the specific implementer as of the following:

1. The less the amount of revisions needed by the centroid method during the whole optimization process the better the specific implementer is.
2. The quality of memory management and the ability to integrate it with the evolving rules and concepts of the framework, to keep it probabilistically reliable and small as much as possible, is of high importance.

The optimal memory utilization and migration during the general theory optimization can mostly be achieved using rules rather than using declarative reserved memorial spaces. This can be achieved by learning proper rules for managing the centroid calculations. Rule-base memory managements are probabilistic and repeating centroid calculations of same cases is possible.

The last point to discuss would be to clarify some of the reasons behind selecting this bottom-up distributed decentralized multi-agents’ searching solution over the centralized monotonic deductive approaches (Weyns 2010). The autonomous intelligent multi-agents’ solution is more suitable to the complex optimizations, like ours. The suitability of that approach may be clearer from the eyes of Software development. Although the multi-agents’ solution would require a developed core to build upon, that is the modules of our proposed infrastructural framework, the multi-agents systems are always computationally more efficient, reliable, and maintainable. But most importantly, it is extensible (Barbucha, et al. 2013). This extensibility property would prove to be of primal importance to our optimization. The proposed agents’ families in the paper are exemplary and are not meant to be exhaustive by all the means. Actually, this is the main task the specific implementer should tackle. The specific implementer may be in need for specific optimizers or any other objects, it will only be needed to code that simple agent’s piece of software and then extending the solution by simply plugging new agent in it. The speed of the algorithmic optimization engine is expected to grow over time, based on the built-in learning capabilities of the agents.
The general theory in the context of structural optimization:

The field of structural optimization flourished during the previous decade. The three main applications of structural optimization and control are topology optimization, shape optimization, and size optimization (Bendsøe and Sigmund 2004). Comparing these applications with the general theory would give us a better understanding of the general theory in the context of structural optimization. Size optimization is interested in optimizing the sizes of the already optimized layouts. Size optimization is an integrative part of the centroid method itself, and it is done using the same classification algorithms of the centroid method. Physically wise, size optimization enhanced the structural performance of the optimized Voronoi/Delaunay diagrams from two to three times. On the other hand, the centroid method’s size optimization is considered as a paired algorithm with that of the centroid method’s classification optimization. As an explanation of that algorithmic coupling of the two algorithms, the centroid method’s classifications are done against the single Deflection criterion, the chords’ structural utilization criterion is not included in that centroid’s optimization, that is because the centroid method is meant to be fast and computationally cheap for the general theory possibility be built on it. The size optimization, as a coupling algorithm with the centroid method, may give us a further insight of which chords that could be deleted, and hence a proposed consequent rephrased final diagram is viable.

Nevertheless, the most important structural optimization to compare against the general theory is topology optimization (Bendsøe and Sigmund 2004). Topology optimization searches for the optimal layout of the material in the design domain. That design domain is very much similar to the point cloud of the proposed general theory. We would try to relate the general theory to topology optimization using the following comparative or integrative methods:

- The comparative method: topology optimizations are mostly 3d free forms that can be produced using Additive industrialization, 3d printing, while the general theory Voronoi/Delaunay diagrams produce straight lines, which may be industrialized using the standard profiles cut to the needed lengths. A deflection criterion comparison between the two theories, using the same mass of materials under the same load case/s, is viable using the specific implementers of the theory, which are viable using the centroid method and the proposed framework.
- The integrative method: the possibilities of integrating the analytical techniques of the two theories could be investigated. The epistemological approach of the general theory could be applied to the topology optimization applications. The topology optimized structures could be integrated with the specific implementers in structuring the questions’ pool or in prioritizing the agents’ efforts in spanning the infinite design space.

Shape optimization is another viable, possibly parallel, application of the general theory. The general theory could be merely a shape optimizer of an optimized centroid diagram; the centroid method and the proposed framework would then be utilized by the similar techniques introduced in the paper. In this case, the general theory could produce free formed optimizations or other geometric forms of the already optimized diagrams’ chords (Akbarzadeh, Mele and Block 2015). These aforementioned variations are expected to participate positively in the architectural-structural various integrative scenarios.

CONCLUSION:

We propose an indispensable complementary framework of the general theory. It does not matter how sophisticated or successful the communicative, behavioral, or analytical algorithms used by the specific implementations are, our framework would always persist as a factual implication. Therefore, the framework needs serious comprehension and elab-
oration. There are two main benefits of the framework. The first benefit is the epistemological parallelism between the behavioral/analytical modules and the centroid analyzer/optimizer, while the second benefit is the framework’s Big-O Algorithmic Complexity of \( \Theta(1) \rightarrow \Theta(x) \). Our understanding of the point cloud is represented using the conceptual three that initializes based on the defined classifying curve of the centroid method’s optimal Voronoi/Delaunay’s diagram. To have a comprehensive understanding of the point cloud, we need to discover optimal conceptual trees and their corresponding diagrams. The initialized conceptual tree would keep heuristically evolving over the alternating three phases until optimality is conceived. This heuristic non-monotonic probabilistic search of optimality is fast and suits the complexity of the problem in hand; it is done using adaptable intelligent multi-agents’ solution that builds on the proposed framework. For our future work, specific implementers would be defined and their structural optimization’s deflection results would be compared to that of the centroid method and to that of other structural optimization theories. Integrative analysis between the specific implementer and other structural optimization theories would be practically investigated too.

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Stereotomy originated as a technique that accumulated theoretical and practical knowledge on stone material properties and construction. At its peak in the nineteenth century, by pushing the structure and construction limits, it gained the ability of using "the weight of the stone against itself by making it hover in space through the very weight that should make it fall down" (Perrault 1964, cited Etelin, 2012). The modern architectural tectonics, based on structural comprehension in architecture, found no value in stereotomy beyond its early, Gothic period. Similarly, digital architectural theory recognized in Gothic the early examples of a material systems. This paper reassesses stereotomy at its fundamental levels, as a material system based on generative processes that assimilate structure and construction through parameterization. In this way, a theoretical framework is established that exposes stereotomy's intrinsic potentials: the continuity of historic and contemporary examples, overlaps between current research endeavours, and its genuine relevance for contemporary digital architecture.

**Keywords:** stereotomy, material system, Abeille vault, parametric design

**Introduction**

Stereotomy is a technique that accumulated theoretical and practical knowledge on stone material properties and construction. It was primarily based on essential, complex geometric relationships embedded within stone masonry. In recent years, the advancement of digital design and fabrication tools that easily handled complex geometries had caused a renewed interest in stereotomy (Fallacara, 2012; Fallacara, 2016; Rippmann, et al. 2011; Rippmann, et al. 2017; Burry, 2016; Varela, et al. 2016; Fernando, et al. 2015; Weir, et al. 2016; Clifford, et al. 2015). Historically, stereotomy was connected to certain structure and construction choices. Contemporary research initiatives, driven by various motivations and objectives, explored and questioned these choices at different levels.

Paper proposes a theoretical framework where the continuity of historic and contemporary stereotomy and overlaps between current research endeavours are exposed. Stereotomy is observed beyond its formal resolves and approached at its fundamental levels. More specifically, paper moves away from analysing stereotomy using traditional tectonic notions and approaches it as a generative material system.

**Historic Overview**

Stereotomy (Greek: στερεός (stereós) "solid" and τομή (tomē) "cut") originated in the Gothic period...
as a result of a reversal in construction thinking. Throughout Antiquity and the Middle Ages, buildings were thought of in the same way as they were made, from the ground up. For the Gothic builders, supported parts gave shape to the supporting parts, and imposed construction thinking from the top down (Sakarovich, 1998). Stereotomic form was seemingly based on a paradox: it used “the weight of the stone against itself by making it hover in space through the very weight that should make it fall down” (Perrault 1964, cited Etlin, 2012). It was actually derived from the underlying interdependencies that varied its constituent ashlars towards coping with the contextual forces.

Figure 1

As a technique, stereotomy explored the limits of spatial, structural and material principles through the application of current fabrication technologies and geometric knowledge. It offered immense novel possibilities that brought about an enthusiasm for amplifying the force flow complexity while providing solutions that purposely obscured structural comprehensions. By the nineteenth century, stereotomy became known as a ‘bizarrely daring acrobatic architecture’ (Etlin, 2012) (Figure 1). Concurrently, from the seventeenth century onward attitudes had developed that sought architectural “visual qualities capable of convincing a viewer about its solidity, and in this sense vraisemblance (plausibility) became important” (Sekler, 2009). “A structure should always look stable as well as be stable” (Evans, 2000). Stereotomy, an audacity bordering on foolhardiness (Evans, 2000) was shunned and abandoned.

Structural plausibility and legibility continued into twentieth century tectonics, and greatly remained a yardstick for architecture until today. In this context, any reassessment of stereotomy praised the early period, the Gothic, for its tectonic clarity, while the late ‘acrobatic’ (Etlin, 2012) variations were continuously found offensive and frivolous.

**Stereotomy in Contemporary Architectural Theory**

Similarly, the Gothic found relevance within digital architectural theory. It was recognized as an organizational system that defined the form from the convergence of forces (gravity, perception, and social organization) resolved through the elements’ mutual relationships. Form was an amalgam of variations driven by operational and procedural rules (Spuybroek, 2011). In short, the Gothic provided digital design processes with historic case studies on topological form conceptions instigated by active space of interactions.

Moussavi interpreted Gothic as a system of bays acting as base units. Each base unit was versatile, not fixed and could vary as it repeated, or even mutate, when hybridized with other base units. The novel and unpredictable forms were temporarily and spatially specific, yet capable of responding to external concerns (Moussavi, 2009). Likewise, Spuybroek interpreted the Gothic as a system that changed through ever-shifting combinations of variable and flexible subelements: the ribs. The system’s relation-
ships were fixed, but not the resulting forms (Spuybroek, 2011). In conclusion, the Gothic was understood as an early example of a material system, where fairly simple behaviour by individual elements resulted in complex and irreducible collective behaviour (Spuybroek, 2011).

Although relevant, the interpretation remained limited. Its analytical processes, derived from traditional tectonics, observed solely the expressive potential of construction techniques (Frampton, 1995) through the parts-to-whole relationship logic. Stereotomy, on the other hand, required analysis beyond the visual legibility offered by Semper and Frampton, that recognised “classicism was as much parametric and generative” as the Gothic (Carpo, 2011). The understanding of stereotomy could not be divorced from a procedural analysis of its formation processes.

Material System Based on Generative Rules

Sekler recognized architectural formation processes in his definition of tectonics, the expressive result of a structure realized through construction. Structure, an abstract concept, was an arrangement system or principle destined to cope with the contextual force flow, and construction was its concrete realization (Sekler, 2009). Construction encompassed material properties, tools, technology and procedures, fabrication constraints, and design, geometric, and instrumental knowledge (Witt, 2010). Tectonic was not a result of mechanistic notions as form reproduction tools, but machinic notions that determined elements’ variations, interrelation, multiplication, and complex organizations (Moussavi, 2009). It was inseparable from the architectural form in general, stereotomic in particular, albeit varied visual comprehensions that were unintentionally clear in the Gothic period, and intentionally ambiguous during the stereotomic peak.
Defined in this realm, stereotomy was a material system that assimilated structure and construction negotiations as a set of generative rules that were themselves subject to evolutionary change, and once fixed could be fleshed out in a wide variety of [tectonic] forms (Heyman, 1998).

**Stereotomic Analysis Methodology**

New Structuralism theory argued for digital architecture based on spatial, structural, and material principles synthesis in lieu of the traditional form-structure-material sequence. (Oxman, et al. 2010). Due to their intrinsic overlaps, New Structuralism offered relevant analysis procedures for assessing stereotomy as a material system. A set of historic stereotomic assemblies was analyzed (corbel, circular and flat arches, corbel and circular domes, barrel, groin, helicoidal, trompe and shallow vaults, and Abeille, Truchet and Frézier flat vaults (Figure 2)) through New Structuralism’s processes (structuring, digital tectonics, and digital morphogenesis).

In the first step, the structuring process, the mathematical/geometric, syntactic and formal stereotomic logic was analysed and recognized. Specifically, structural patterns, geometric attributes, and configurative transformations were discretised into generative rules. In the next step, the digital tectonics, generative rules were formulated into parameters and their interdependencies to establish the digital parametric model design substance. In the last step, the digital morphogenesis was enabled within the parametric models and provided diverse topological outputs, design explorations and prototype fabrication information. The analysis actualized novel forms that explored adaptive, configurational, and transformability potentials beyond their original design intents (Oxman, et al. 2010). Finally, the analysis exposed common underlying stereotomic parameters.

**Stereotomic Parametrization**

The four common underlying parameters that activate a stereotomic material system were: base surface geometry, distribution grid, and two relating to the single unit configuration: perimeter faces rotation and thickness.

The base surface geometry was determined by the force flow, the line of thrust, and directly reflected

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Figure 3
Configurational variations of the Abeille stereotomic material system
structure. Structure varied during the construction process due to varied force flow. It also had varied final intents, from pursuits in the force flow optimization to specific aesthetics. The base surface geometry was interdependent with the single unit geometry, since an assembly was concurrently a whole subdivided into single units and a propagation of single units creating a whole.

Distribution grid was determined by structure and construction choices. Historically, typical distribution grids used were: running bond, rectangular grid, hexagonal grid, radial grid, and irregular grid.

The rotation of the single unit faces that were neither intrados nor extrados, the perimeter faces, defined the structural action of the whole, or parts of, the assembly. Faces perpendicular to the force flow determined arches for linear assemblies and shells structures for surface-based assemblies. Alternating inward outward perimeter faces rotation established either a topological interlocking or reciprocal frames type structure.

The single unit thickness was the distance between intrados and extrados faces. For statically indeterminate assemblies it was dependent on structure, as the force flow had to be accommodated within the material thickness. In statically indeterminate assemblies it was dependent on construction.

The four formulated parameters and their interdependencies defined the stereotomic material system. Specific structure and construction choices were assimilated within the material system by providing specific parameter values. In conclusion, structure and construction choices were not necessarily predetermined, as they informed the stereotomic material system, but did not activate it.

Abeille Flat Vault Material System
The stereotomic parametrization process was illustrated through the Abeille flat vault example. Firstly, the Abeille vault was defined as a material system, followed by formal explorations through parametric variations. Further, nontraditional, non-masonry structure and construction assimilations within the material system were explored through the design and construction of a stereotomic plate pavilion, technically an oxymoron.

Visually, the Abeille vault was based on identical ashlar truncated tetrahedral configurations: a poly-

Figure 4
Stereotomic Plate Pavilion, Malta 2014, Irina Miodragic Vella (University of Malta), Steve DeMicoli (DeMicoli & Associates, dfab.studio) Dr Professor Toni Kotnik (Aalto University)
hedron with axial sections in the shape of an isosceles trapezium. The ashlar geometry and the rotation of neighbouring ashlers by ninety degrees established their mutual arrangement: each ashlar was carried on two neighbouring ones through its protruding cuts, and at the same time provided support for two others on its sloped cuts resembling reciprocal frames structures (Miodragovic Vella, et al. 2016).

Defined parametrically, as a stereotomic material system, the Abeille vault was based on a planar, horizontal base surface and a square distribution grid. Each parameter face was rotated 54.7 degrees from the base surface, in the direction opposite to the rotation direction of the adjacent faces, instigating topological interlocking structure. Thickness was determined by two trimming planes, differently positioned base surface tangent planes, one at the surface level, and the other at some distance below. Finally, the parameters interdependencies were established (Miodragovic Vella, et al. 2016).

The Abeille stereotomic material system's configurational variations were explored. Initially, the focus was on parameter values, assigned arbitrarily, often extremely to amplify possible inconstancies and limits in the validity of the digital tectonics formulation and corresponding digital morphogenesis. The resulting outputs remained virtual, without any pursuits for their physical resolve (Figure 3). Next, the Abeille stereotomic material system was further complexified by increasing the number of polygon sides that made the distribution grid and/or increasing the number of rotation alternations per ashlar face. In this way, other established stereotomic elements were derived confirming the parameters' validity (Miodragovic Vella, et al. 2016).

Finally, the Abeille stereotomic material system structure and construction assimilation was tested through a full scale prototype, a pavilion built for Malta Design Week 2014, held at Fort St Elmo, Valletta (Figure 4). It was a collaboration between the authors and Steve DeMicoli (DeMicoli & Associates, dfabstudio). Due to site sensitivity and budgetary concerns the material used was not stone masonry, but a sheet material, marine plywood. This allowed for “in-house” prototyping and fabrication, fast, manual on-site mounting/demounting and total reversibility requested by the organizers.

The design process started with the translation of the structure and construction choices into values to inform the stereotomic parametric model. The solid blocks assembly logic was discretized into an assembly of plates. The plate configuration was derived by ‘merging’ the touching single unit perimeter rotated faces of adjacent elements: the two faces that shared the same rotated plane became a six-pointed plate (Figure 5). The resulting structure remained topological interlocking, of single unit perimeter faces, rather than the volumes they enveloped.

The base surface geometry was a linear extrusion of a catenary curve defined by the force flow and fabrication optimizations. The result was a five meter span, four meters long, parabolic vault. Although the plate configurations varied along the changing cur-

Figure 5
Discretization of the solid blocks assembly logic into an assembly of plates
vature of the catenary profile, the linear extrusion allowed for repetitive plate types, and thus, faster fabrication.

The structure also determined the plate rotation angle. Through full scale prototype testing, a sixty degree rotation angle from the base surface was determined as the optimum to avoid deviation in the vertical plates that formed the arches. The limited CNC bed size defined the irregular rectangular grid field sizes, maximum plate lengths and widths.

Due to site, budget and mounting constraints, elaborate falsework had to be avoided. To deal with the varying force flow during construction a self-stabilizing structure was achieved thorough plate rotation and plate configurations. Through topological interlocking, corbelling and nominal propping various stable configurations were achieved prior to the vault sides being connected and the arch mechanism activated. By following a diagonal, weave-like mounting sequence the assembly stiffness was continuously increased (Figure 6).

In the final outcome, the traditionally solid stereotomic appearance was transformed into a lightweight lattice assembly (Figure 7). Still the generative rules that activated the material system remained apparent showcasing that it was driven by underlying parameters informed by the structure and construction choices.

Figure 6
Various self-stabilizing configurations during construction

Figure 7
Stereotomic plate pavilion (Photo by Alex Attard)
Conclusion

“Similar processes do not necessarily beget similar shapes. Understanding these processes, on contrary, will help us shape better things” (Carpo, 2011).

The main objective of the presented assessment, and resulting theoretical framework was to view stereotomy beyond its formal visual comprehension of traditional tectonics to include generative processes that assimilate structure and construction through parameterization. Any stereotomic assembly, historic or contemporary, could be referenced, defined, and described to establish a productive relationship between stereotomy’s past and future. In this way, stereotomy’s intrinsic potentials were exposed and its genuine relevance for contemporary digital architecture could be traced and recognized.

Finally, the proposed theoretical framework is neither final nor conclusive, but open to further contributions and revisions.

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Form is Matter

Triply periodic minimal surfaces structures by digital design tools

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Architecture and biology teach that the shape affects mechanical behaviour of structures therefore geometry is the basic concept of design, with an ethic responsible and sustainable approach, following the nature's organic model. Industrial design may apply formal properties of elementary shapes and basic design rules to manage the "geometrical behaviour" of new structural surfaces. The research aims to apply digital tools to the design of surface structures that maximise the matter efficiency in the development of "solid fabrics" with parametric controlled geometry.

Keywords: Minimal surfaces, Parametric and generative design, Shape and form studies, Digital fabrication

INTRODUCTION AND RESEARCH GOALS

Architecture and biology teach that the shape affects mechanical behaviour of structures, therefore geometry is the basic concept of design, with an ethic responsible and sustainable approach, following the nature's organic model. Industrial design may apply formal properties of elementary shapes and basic design rules to manage the "geometrical behaviour" of new structural surfaces. In facts nature's objects have been fundamental model since antiquity and the concept of Nature as a design model drives the theory of Architecture and the man's reference to natural forms a recurring statement in literature and it incorporates many basic design concepts, but the affirmation of digital technologies is changing the concept of organic design. Actually nature's patterns solve several project requirements, as it fulfils Alber-ti's concinnitas and the main architecture requirement, meaning Vitruvio's triad of firmitas, utilitas, venustas. [1]

Arts applied the reference in different ways: the first was the bare imitation in the pattern of ornaments and decoration, due to the admiration of the beauty of harmony and perfection in regular conformation in natural phenomena. Then Architecture applied skeletons' and trees' model to structures, imitating nature's balance in the proportioned relationship of building elements. Later it was the connection of parts in machines. Finally the imitation is fulfilled in the process of growth, which is the expression of life. In its digital procedures, the responsive Design copies vital process of life. Rules of basic shapes evolved in growth and form-finding processes.
The late development of digital technologies allows an important leap in the organic reference of design, improving the evidence of organic forms in design. *Imitation* is still the first way of learning, but to *imitate* does not mean to *copy*. In design it means to *reinvent*, therefore to understand and transform. Thus the imitation requires the very knowledge of form finding processes, which are due to a careful observation.

In the classical world the formal beauty was linked to a recognizable law that order the multiplicity in the unity: *symmetry*, *proportion* and *direction* resume rules that generate the shape starting from a *module*. Together they express the *eurhythm*, which in 1860 Gottfried Semper referred to in treatise *Der Stil*, as a ‘concatenated sequence of spatial ranges, similarly shaped’.

Everybody know what module means in architecture, and its importance about measurement, that is just ratio between quantity and unit; so this concept is directly connected with modular grids to control composition and proportion: thus design means measurement, which is geometry. The basic rules of form apply the same simplest operations of arithmetic and geometry: *addition*, *multiplication* and *division*. Growing and living processes implies *transformation*, that is changing in dimensions without changing topological relationship in between elements, and/or responsive adaptation to external inputs. In computational design the concept of *module* plays the living principles of cell in organic fabric.

The biologist D’Arcy Thompson gave a wide explication of the geometry’s evidence inside natural phenomena and architectures. Nature finds a static force balance in the symmetry of structures but in living beings it plays with different rules due to asymmetrical forces of growth, which imply dynamic transformation. He just stressed that life is tied to asymmetry and continuous transformation. [2] His work was fundamental to several architects, who pursued organic concept in architecture, such as B. Fuller and F. Otto. The first one applied the study of surface balance in cells to geodesic domes and the second designed light structures from the minimal surfaces’ study with soap sheet and bubbles.

Minimal surfaces offer a great attraction to many disciplines. Some reasons for the common interest lie in the deep problems, which open up during closer investigation of their properties, and others in the widespread possible applications of minimal surfaces in completely different areas of research. Configurations of minimal surfaces have been found in a wide variety of different systems: from the arrangement of calcite crystals that form the exoskeleton of certain organisms to the theories that explain the nature of astronomical phenomena.

In design-building research, structures derived from minimal surfaces have led to the design of various typologies, such as tension-active roof structures, compression-active shells and large-scale architectural systems. This is, however, only one in between all possible uses. But in architectural structures, minimal surface structures remain rather unexplored for their suitable applications in design. Frei Otto in undoubtedly the main reference in the experimental development of minimal surfaces in light architecture, imitating self-formation processes in nature. He tried successfully application of the same efficient concept to different typologies of light architectures: tent structures, net constructions, pneumatic constructions, suspended constructions, shells, branched constructions and umbrellas as example of convertible constructions (moving and transformable). Actually Otto didn’t *copy* the nature, but he referred to explaining it through technical developments. He stated that “Technical object for which self formation process occur to a high degree form the natural border between natural and artificial” [3]

Such as Frei Otto applied minimal surface theory in quite simple aggregation to architecture, as well mathematicians developed a larger set of surfaces from different boundary constraint with their further aggregation in modular lattices. *Triply Periodic Minimal Surfaces* (TPMS) are probably the ones that have the most interesting characteristics, including for de-
sign purposes. They are called periodic because they consist of a base unit that can be replicated, theoretically ad infinitum, in Cartesian space in three dimensions (triply), thus creating a new surface seamlessly and without intersections.[10]

Triply Periodic Minimal Surfaces, as it is visible in many natural systems, have a great potential, due to their structural efficiency thanks to overall area minimization, and efficient material distribution. Actually they comply Otto’s requirements for natural architecture, because they apply/follow the nature’s teaching in the balance of forces. [5] This is ethical and ecological approach, because it minimize the energy waste, saving material. [6]

Probably, despite at a theoretical level, the properties of Triply Periodic Minimal Surfaces have been investigated, the complexity of morphology has so far limited their use to manufacturability and design purposes.

The research aims to apply digital tools to the design of surface structures that maximise the matter efficiency in the development of “solid/permeable fabrics” through parametric controlled geometry.

This paper focuses on both the form-finding and the fabrication related to the geometric properties of TPMS. The aim is understand how the translation from the virtual three-dimensional space to the built artefact could be embodied into a computational process, which would also solve the issues within the fabrication framework.

**METHODOLOGY**

The research follows two different paths, concerning basic topics:

- first, the definition of computation tools, meaning the selection of design parameters and the scripting of the digital form-finding process,
- next, their design experimentation, testing mechanical properties of different TPMS fabric.

Main computational design tools are:

- drafting formal and mechanical features according to shape;
- drawing basic shapes, by developing formal geometry features, starting from different minimal surfaces in a 3D modular lattice and developing modular aggregation by symmetrical repetition;
- selecting basic shapes that optimize the use of materials (minimal surfaces);
- defining tiles’ parameters and lattices’ aggregation rules, then to script formal codes and their transformation range;
- modelling selected modular lattices from basic geometry.

The design experimentation regards:

- to check formal behaviour of new structures in plane and in curved surfaces (flexibility, permeability, stiff movement and elastic responsiveness) and their adaptability to morphological transformation;
- to verify mechanical properties on printed prototypes (strength, lightness);
- to stress shape effects according to parameters variations, then optimize application range to different cases study.

The further development will inquire topics related to practical applications to case studies in design of printable objects, evaluating the adaptability to the object’s shape, to their function and use as well to production requirements.

**DESCRIPTION AND GENESIS OF MINIMAL SURFACES**

A minimal surface is a surface whose mean curvature is always zero. This definition answers to the Plateau problem[11] proposed by Lagrange in 1760: if a closed polygon or oblique plane is assigned, then there is always a system of surfaces, including all possible surfaces that touch the frame, which are able to minimise the area. The minimal area of the soap film’s surface of is one of the many examples that illustrates a well-known physical principle governing
forms and motions of natural objects: the principle of least energy waste (or least action). It states that any physical configuration assumes its state or path in such a way that the energy requirement is minimal. In soap films, the shape minimizes the potential energy balancing the intermolecular force. Therefore this energy is directly proportional to the surface area of the soap films (assuming that the thickness of soap films is uniform) and, as a result, the soap films achieve minimal area.

This means that minimal surface combine structure and material in a very efficient manner by aligning force and geometric form in an organic shape.

A triply periodic minimal surface (TPMS) is a minimal surface, which is periodic in three independent directions (Figure 1). TPMS are described in terms of a fundamental patch or asymmetric unit from which the entire surface may be built up by its symmetry elements. A single minimal surface is characterised by different curvatures: in other words, some surfaces are flatter than others. It follows that not all points of the surface support any concentrated loads equally well. If the same surface is, however, associated with a periodic distribution the physical iteration between the modules causes a compensatory effect that greatly increases their structural efficiency.

Because of that, the study of TPMS for design purposes is particularly fascinating (Figure 2). These surfaces may be made by defining and evolving their fundamental region, which is usually very simple due to the high symmetry, and then displaying many suitably transformed copies. Several fundamental regions are one of Coxeter’s kaleidoscopic cells. Many of these surfaces were described by Alan Schoen in a famous NASA report. [10] The first step was to find a way to generate and control the TPMS in digital environment. The computation played an essential role in the simulation and modelling process of such complex phenomena. It was used Grasshopper, a graphical algorithm editor tightly integrated with Rhino’s 3-D modelling tools in order to create an algorithm able to describe and to control various types of TPMS.

This research applies minimal surfaces that can be described by implicit form, typically a linear function of three variable, \( f(x, y, z) = 0 \). The trigonometric form is appropriate to the digital description because it allows the handling of the large number of elements that characterize TPMS, without overload the calculation process and also does not allow self-intersections. Using Grasshopper it’s possible to define algorithms that are able to describe with good approximation any minimal surfaces directly from its implicit formulation. The algorithm translates the algebraic equation into a finished form that can be studied, manipulated and replicated.
Figure 2
Construction principles of TPMS based on gyroid
The process can be conceptually simplified imagining that, in the domain of Cartesian space, the equation “selects” points, belonging to the surface you decide to represent (Figure 3). The next algorithm’s instruction connects them by triangulation creating the surface. It is now possible to exploit the symmetry characteristics of the single unit by replicating it in a symmetrical cell, which is suitable to further replication in a modular lattice and to study the processes of adaptation to any required morphology. [7]

TPMS ANALYSES
The testing strategy applies the algorithm to a standard triply periodic minimal surface and it identifies the efficiency of the algorithm testing the level of accuracy in generating the geometry, comparing the two porous structures generated by Gyroid and P-Surface, in comparison with a solid bar.

To investigate the mechanical behaviour of different minimal surfaces structure, numerical simulations were also conducted. The model was implemented into finite element software code (COSMOS), which allowed the simulation and predicted the deformation characteristics of the designed porous structures and its mechanical behaviour, depending on the thickness changes.

A stress test was carried out (Figure 4). The application of 1kgf (10 N) was then evaluated on an iron...
parallelepiped sized 10x10x100 mm and compared the result with two equivalent-sized structures with different thicknesses, composed respectively of the P-surface and the Gyroid.

Table 1 summarizes main results.

This analysis leads to some data, which stress two main interest focuses.

First, in minimal surfaces element, even for very thin thicknesses (0.1 mm), the bar does not break even though it deforms considerably. This is because the stress does not focus on one point, but it is distributed among the different units that work in synergy: overall performance improves that of individual parts.

Second, the behavior changes with increasing thickness. When thick is 2 mm thick the deformation decreases considerably: if the solid iron bar deforms 1 mm, the one articulated in P-surface deforms 2 mm, while the Gyroid bar is deformed by 1.6 mm. The interesting aspect is that the two bars weigh, respectively, ten (P-surface) and eight times (Gyroid) less than the solid one, while maintaining good stress resistance properties.

Table 1
Stress test results

<table>
<thead>
<tr>
<th>THICKNESS (mm)</th>
<th>DISPLACEMENT (mm)</th>
<th>STRESS (Kgf)</th>
<th>WEIGHT (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLID</td>
<td>0.00005</td>
<td>0.031</td>
<td>780</td>
</tr>
<tr>
<td>a</td>
<td>0.1</td>
<td>0.013</td>
<td>2.36</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0012</td>
<td>0.273</td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>0.0003</td>
<td>0.111</td>
<td>37</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
<td>0.0001</td>
<td>0.044</td>
</tr>
<tr>
<td>c</td>
<td>0.1</td>
<td>0.016</td>
<td>1.1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0008</td>
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<td>25</td>
</tr>
<tr>
<td>1</td>
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<td>49</td>
</tr>
<tr>
<td>d</td>
<td>2</td>
<td>0.00008</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Figure 4
Stress test results
FABRICATION AND TEST OF TPMS
The possibility of designing TPMS would be pointless if they couldn’t then be created.

In recent years there has been a convergence towards the digitalisation of production processes thanks to machines able to construct, either in whole or in part, the designed object, starting from its digital model. This process is known as Digital Fabrication and does not require any additional interpretations to that of the designer, as the file is planned and the object can be fabricated without the involvement of other intermediaries. With other words, we could say that the scripting is both the design representation and the making input. Furthermore this new manufacturing permits the creation of forms and structures that were once considered extremely complex (Figure 5).

After assessing the cost-benefit ratio and research intentions, the first experiments were conducted with the Z-corp Spectrum Z510 plaster-based 3D Printing. Considering that printers deposit layered material, moving vertically, usually it is necessary to provide the most correct arrangement to support the protruding parts to prevent the structure’s collapse during the printing. It is worth noting that structures created using TPMS do not require additional support. If we consider that even in nature they are in processes where the generation takes place by layering, they are likely to be self-supporting body. This property makes it particularly suitable for 3d printing technologies, allowing a considerable saving of the production times and the construction material.

TPMS APPLICATIONS
A design application comes from an ergonomics research carried out simultaneously to this work: a study about safety of construction workers has shown as, especially in the summer, many operators do not wear helmet due to the weight and heat [7]. Furthermore, the three marketed sizes are not sufficient to meet the anthropometric variable, increasing the discomfort of many users. The example in figure 6 shows how, via computational modelling, it is possible to integrate the properties of the minimal surfaces into a protective artifact capable of solving these problems. After comparing the different minimal surfaces we chose to use the Gyroid-based Tpms. In nature, these structures are present where you need strength and lightness, such as in the sea.
Figure 6
Comparison between the different Tpms and the ultimate safety helmet
urchin exoskeleton or butterfly wings. Stress tests performed (See TPMS analysis) confirm that the Gyroid is a structure that optimizes the ratio of used material, lightness and mechanical strength. These features, associated with the breathable characteristics due to the porosity of TPMS, make Gyroid particularly interesting for the design purposes proposed.

It has previously been explained how the algorithm allows to digitally describe the Tpms. It is now necessary to continue with scripting to adapt the fundamental cells to the protective helmet morphology. The helmet model was solved with a NURBS surface, discretized in parallelograms coinciding with the lower base of the pyramid trunk in which each single Gyroid will be recalculated. The limit of this procedure is the anisotropy of the fundamental cells that the hemisphere geometry involves. The mesh elements are more elongated in correspondence of the poles of the hemispherical dome. For compensation effects already mentioned, and for the small size of individual cells, this is not a problem from a structural point of view.

Assuming that future production costs for 3d printers will decrease,[7] it would be possible to obtain a helmet customized on anthropometric characteristics of the user, and that it is also lightweight, strong and which allows the circulation of air.

CONCLUSION
The study focuses on Triply Periodic Minimal surfaces and their structural system as a suitable manufacturing method. However, the potential of the suggested generative tool is not limited to these solutions, as the geometry could reach higher levels of complexity by exploring the design possibilities of all known periodic minimal surfaces or even to explore new types of surfaces or hybrid typologies.

The purpose of the research is to open a new direction within the computational design methodology, as part of design process, involving a multiple purpose design strategy, which takes into consideration various constraints, as part of an articulated parametric system.

Porous surfaces generated by TPMS could be interesting to various applications at different scale, from architecture to reach the level of industrial design artefacts, furniture or installations. Due to the cellular logical structure of the system, in correlation to the fabrication method, a feasible field of applications could include even fashion and textiles design.

So far is the beginning, concerning lightness and strength, because several interesting properties are still to be tested: permeability, optical effect on color, sound absorption...The research must go on.

REFERENCES
This paper uses a Light Detection and Ranging (LIDAR) device with multiple building materials to provide guidance for developing an autonomous robotics-friendly environment. The results demonstrate various materials that not only provide missing data, such as for clear glass, but also can provide inaccurate data, a dangerous situation in the context of indoor autonomous mobility. Finally, the paper proposes ideas for how designers can compromise between the materials they would like to use while facilitating the necessary information for an autonomous vehicle.

Keywords: Smart City, Autonomous Navigation, Indoor Navigation, Personal Mobility

OVERVIEW

Recent developments in autonomous navigation for self-driving vehicles have brought to light the issues around infrastructure and technological limitations in the context of the built environment. The role of architects and designers is becoming increasingly important in providing an appropriate interface for the successful integration of people and autonomous agents in buildings and cities. In order to facilitate autonomous navigation, the infrastructure can play a vital role in increasing both the rate of deployment and the safety associated with machines interpreting the world we live in. One of the key instruments used in autonomous navigation is the Light Detection and Ranging (LIDAR) sensor, a device that uses the reflection of a laser beam to accurately measure the distance between itself and the object the beam hits. While in most cases this technique provides accurate data, a variety of surfaces can cause errors in these measurements. In the façade of a building or the interior hallways, the materials used in designing spaces can have a drastic effect on the accuracy and ease of sensing the environment. It is therefore in the architects’ and designers’ interest to understand the relationship between the common building materials and LIDAR functionality.

BACKGROUND

Various technologies are used when developing an autonomous vehicle (Borenstein 1996). These vehicles can be considered robotic technologies, and vary in size and use from a personal wheelchair to a city bus. Similarly, autonomous navigation has a wide range of implementations for outdoor, indoor, and mixed environments. The technology for controlling all aspects of a vehicle is well established. However, determining how to use this control in unknown environments is what makes autonomous vehicle integration difficult. These unknown environments include structures, topographic configurations, and moving objects (cars or people). To put the level of difficulty in autonomous navigation in perspective, it has been 10 years since the Defense Advanced Research Projects Agency (DARPA) ran the Grand Chal-
lenge in which multiple teams demonstrated vehicles controlled autonomously, while all having issues with completing the course (Buehler 2009). While highways may be out of scope for architects and designers, the navigation through cities and particularly indoor environments can be facilitated, or hindered, by design.

For indoor navigation, Amazon has been using robots inside their automated warehouses and fulfillment centers to sort and pick items purchased. To spur the advancement of robotic technologies associated with automated storage and retrieval systems, Amazon Robotics, a subsidiary company of Amazon.com, organized a competition for indoor autonomous robots to pick items (Correll et al. 2016). Amazon is one of many merchandise companies, including The Gap, Walgreens, Staples, Gilt Groupe, Office Depot, Crate & Barrel, and Saks 5th Avenue, that deploy robotic automation in their warehouses. While these robots can be seen as isolated and working with within relatively controlled environments, others, such as social robots, are designed to both navigate human built spaces as well as interact with people (Gockley et al. 2007). Similarly to autonomous cars, personal mobility vehicles offer a revolution in transportation not only throughout cities but indoors as well. Given a vehicle similar in size to an electric wheelchair, people both with and without disabilities can have an autonomous vehicle transport them throughout nearly any indoor environment. Particularly in places with high numbers of mobility- and vision-impaired people, autonomous assistance could significantly redefine occupancy type, usage, and efficiencies.

The benefits of indoor autonomous mobility will go beyond the transportation needs of building occupants, and will significantly impact maintenance and material handling within buildings in the same way as automated fulfillment centers presently do.

In the United States, the Americans with Disabilities Act (ADA) has dictated requirements for facilitating public facility access for people who use wheelchairs. This significantly solves the physical navigation challenge for personal mobility vehicles associated with indoor topography, finish materials, and signage. However, software aspects are still not refined enough for immediate deployment.

TECHNOLOGIES USED IN AUTONOMOUS NAVIGATION

LIDAR is a system relying on the sending and receiving of pulsed laser light. A light beam is sent, and as it hits an object, the detection sensor determines the length of time it takes for this beam to come back, allowing for accurate distance measurements. While the alignment of the sensor itself is vital for accurate measurements (Latypov 2005), the material being sensed also greatly determines the accuracy. One of the cornerstone methods developed with LIDAR is Simultaneous Localization and Mapping (SLAM) (Gonzalez-Banos 2002). Naturally, a device relying on the sensing of light requires materials both to be present and to afford reflections suitable to the device. Unfortunately, many of the materials used in architecture and building construction present conflicts for this type of sensor. As the LIDAR provides one of the most accurate and complete maps of the environment, providing infrastructure that caters to this technology increases its effectiveness, leading to faster integration of autonomous vehicles and safer interpretation of the surroundings.

METHODOLOGY

As the technology behind LIDAR is the same in most consumer products, but the implementation can vary, specifications of the LIDAR are necessary in order to allow for repeatability of this study. As such, the LIDAR used in these experiments is a LIDAR Lite v3 developed by Garmin. It is a single-channel 905 nm 1.3w laser with 10-20 KHz pulse repetition. The range is listed at 40 m with a resolution of $\pm 1$ cm. Under a 5 m distance, accuracy is $\pm 2.5$ cm. The LIDAR signal is read on the computer through an Arduino Mega using PWM. The beam is $12 \times 2$ mm with a divergence of $8$ mRadian.
All materials were placed in front of a gray painted wall perpendicular to the LIDAR. Various perforated metals, glass, and plastic architectural sample materials were used. A constant distance of 125 cm with a perpendicular axis to the material was used to compare the measured distance among the multiple materials, with 1 cm steps to determine the variance across the material. To determine reflective or refractive variance, an angle of 45 degrees to the material was also measured.

**HARDWARE SETUP**

The hardware setup (Figure 1) consists of a Ø12 mm lead screw with an anti-backlash nut, a 12 V 1.4-amp Nema 17 stepper motor, an Arduino Uno, and a TB6600 motor driver with 1/16 microstepping enabled. A basic program for controlling the motor and receiving LIDAR data through serial communication was implemented on the Arduino. Python programming language with the pySerial module was used to send and receive data with the Arduino.

Three measurement positions were installed with brackets on the baseboard: (1) a distance of 55 cm from the LIDAR at a 90-degree angle (perpendicular to the LIDAR ray), (2) 106 cm from the LIDAR at 90 degrees, and (3) 106 cm from the LIDAR with a 45-degree angle. The samples were slid into these brackets for consistent location placement. The LIDAR was translated by the lead screw in 1 mm increments over 16 cm. A barrier was placed in line with the experimental setup to prevent the beam and image sensor convergence from becoming offset from the edge of the material. To prevent these edges from affecting the data, the middle 8 cm of samples were used in the analysis. Additionally, multiple passes on each sample were conducted to ensure the data collected were repeatable and not a matter of random sampling. Finally, a cardboard backplate was placed at the end of the baseboard to prevent erroneous data being collected when the LIDAR passed through materials.

**MATERIALS**

Multiple samples of base measurements and architectural glass were used in the experiment. Nine glass samples, two plastic samples, a steel perforated plate, clear glass, opaque plastic, and a cardboard material were used (Figure 2).
In Figure 2 photos of the material samples are displayed. The numbers the blue tap correspond to the numbers used in the experiments for the results section. From left to right, top to bottom: (1) Carvart Glass C135 2. (2) Carvart Glass C135. (3) Carvart Glass CLCR-019. (4) EG9916 Drawn Linen. (5) Cream Crush AC-841-201-LL. (6) Square Frost AE-818-101-HH. (7) ChromaFusion CF3461. (8) ChromaScreen CV1121 Standard Dot. (9) Emboss Glass EG9922 Cube Large Caesar Color Inc. (10) ChromaFusion FC2375 / Custom 1/8” Dot SO2913. (11) EG9917 grid. (12) Steel perforation 2 mm (not pictured). (13) Matte white. (14) Brown cardboard. (15) Brown cardboard at back of baseboard. (16) Clear framing glass.

A majority of the architectural glass samples were created by laminating multiple pieces of glass together (Figure 3). Select experiments were conducted on both sides of the glass to investigate the effects of having the lamination facing the LIDAR or away from it.

RESULTS
The three sets of experiments reveal important information on how different samples are read by the LIDAR. First, the measurements at 55 cm from the LIDAR demonstrate significant variation. This is due in part to the close range of the sample to this particular LIDAR. However, a 55 cm distance is reasonable to expect when cars are either passing on the road or parked on the side, or in most indoor navigation situations. (see Figure 4)

Table 1 demonstrates a few key variations in the overall data analysis. In particular, two standard samples, 13 and 14, show a standard deviation under 1.5, while sample 9 is as high as 13.7. Continuing with sample 9, it can be seen that while both sides 1 and 2 have a similar standard deviation, the measured distance has a large variance. Side 1 shows a maximum distance calculated of 108.5 cm, while side 2 has a maximum of 87.5 cm. Equally of interest is the measured distance of the sample from the LIDAR at 55 cm; an error in distance of approximately 100% was recorded. Comparatively, samples 13 and 14 had a recorded average distance of 61 cm, with 9 cm of error from the actual distance.

Figure 2
The specific samples are detailed in this table. The sample number is used in the Results section.

Figure 3
Sample 9, embossed glass. Side 1 (left) is flat, while side 2 (right) contains a lamination.
Figure 4
Full sample set of data for sample 14 (left) and sample 3 (right). Blue circles are the measured data points. Red line is the linear regression. Horizontal axis shows the 1 mm spacing of samples. Vertical axis shows the measured distance.

Table 1
Results from a 55 cm perpendicular sample. Sample numbers correspond to the specific names described in the methodology. Both sides of the samples were tested. The average, maximum, minimum, and standard deviations of the data are displayed, followed by the average, maximum, and minimum errors from the actual distance. Color gradient from white to red, where red is the highest value per column.

The large variation in data of sample 3 compared to other samples is likely attributed to the random structure of fibers embedded in the glass (Figure 2, sample 3). This sample, while not containing the same properties as textured glass, demonstrates the difficulty architects and designers may have in assuming which building materials improve LIDAR accuracy.

As described in the methodology, multiple passes of data collection were done on each sample. This ensured the data being used in analysis were not random and were repeatable. Figure 5 shows a plot of four scans of sample 3 described above. This graph demonstrates that the repeatability of the experimental setup was strong and the data are reliable.

The second experiment was performed at a distance of 106 cm and perpendicular to the LIDAR. The backplate to the system is located 120 cm from the LIDAR. With the measurements of samples 13 and 14, the most accurate distance measurement from the LIDAR can be seen as 110 cm (Table 2). Sample 16 in the table is the measurement with no sample and directly measuring the backplate, with a measurement of 124 cm.

In this experiment, sample 3, which had a large deviation in measurements in Table 1, has been largely normalized in relation to other samples. In this test, the largest errors in measurements came from samples 1, 9, and 11. When inspecting the data of sample 1, a clear repetitive pattern can be seen (Figure 6).

While this sample had a higher error rate than others, the reliable repetition corresponding to the patterned glass provides the most opportunity for controlled data communication through LIDAR. If architects use patterned glass that can provide dimensional information on a 2D surface, autonomous vehicles can gain information about the environment.
By modifying the frosted pattern on the glass, information such as the start or end of a wall can be embedded into the wall, acting as a type of binary communication through the material. Additionally, glass installations using this system could have unique information notifying a robot or vehicle that it is a door rather than a wall, as well as the direction the door opens.

The largest errors recorded were in samples 9 and 11. Both of these samples have an embossed square grid pattern, as seen in Figure 2. By comparing the two sides of sample 9, it is clear the orientation has a significant effect on the sampling accuracy. Side 1 is the flat glass, non-embossed side, with a 15 cm error, while side 2, containing the embossed glass laminate, had a 5 cm error.

As the angle of reflection has a significant effect on the ability for LIDAR to measure the materials distance, the experiment of 106 cm distance with a 45-degree angle was conducted. This experiment shows the largest problem with glass for measuring distance with LIDAR. As seen in Table 2, sample 15 of the backplate shows a distance reading of 124 cm. As the samples are located with the center of rotation at 106 cm and in front of the backplate, the averaged measurements of 124 cm demonstrate the inability of LIDAR to accurately sense the material. In particular, sample 3, as with the first experiment, had the highest error, with an average measurement of 133 cm. As the maximum value should be the backplate of 124 cm, sample 3 demonstrates a dangerous situation in which the LIDAR reads a value far beyond the actual location (Table 3).

While any errors in accurately measuring the distance of a material from the LIDAR are dangerous in autonomous navigation, false readings of a wall being further than it is can give a robot or autonomous vehicle a false understanding of how much space is available for maneuvers or manipulation. Furthermore, it is not only the glass samples that were found to have errors, but the plastic of sample 6 as well. Conversely, the plastic of sample 5 was the most accurate sample, with the exceptions of the matte plastic and cardboard used as base measurements.

For metal façades, circular perforations in metal of 2 mm or less are able to facilitate an accurate measurement as seen in Tables 1-3, sample 12. The accuracy of these measurements also demonstrate the usefulness of metal in facilitating accurate LIDAR sensing over glass.
The measured results of the glass samples showed a large range of errors. These errors were not consistent among the different glass samples, nor was the error consistent among the varied angles of the material. The experimental data collected demonstrate how an autonomous vehicle relying on LIDAR may not only miss a glass wall during the 3D map building, but incorrectly determine its location. More specifically, the use of architectural glass poses a significant challenge for interpreting LIDAR data, a topic that has yet to be discussed in any significant amount within both architecture and autonomous navigation. While algorithms have been developed to understand noise in LIDAR data, and to a certain point the data created by scanning large metal perforations, the integration of autonomous navigation, indoors in particular, can be greatly delayed due to the use of these materials.

Although the use of off-the-shelf architectural glass in these experiments demonstrates the difficulty in accurate LIDAR building mapping, it does not mean that architectural glass cannot be used at all. Rather, the data findings show how specific angles and surface textures of the glass are still able to be accurately sensed. By understanding this relationship, alternative embossed glass can be developed in which patterns are coded into the material itself, feeding a ‘message’ to the LIDAR map-building algorithm to inform an autonomous vehicle of the actual location of the boundary, and could be taken further to codify general information that may be imperceptible to people beyond seeming like a textured glass pattern.
DISCUSSION

Multiple methods can be implemented in order to enable glass to be visible to LiDAR. While options exist for the type of glass itself, coatings can be used on top of the glass. In this paper, the most promising results for utilizing the architectural glass in design are with sample 1, a glass by Carvart (model C135), using a frosted pattern. These types of patterns can be integrated into the built environment not only to improve the ability for robots to scan the environment, but to increase the information communicated to the robot through materials. This ability is becoming more relevant as robots and autonomous vehicles integrate within human spaces, such as autonomous personal mobility vehicles or robotic baggage carriers in hotels.

An important aspect to understand in the LiDAR sampling is the ability for onboard algorithms to average and estimate the correct LiDAR value. Furthermore, the starting position of the LiDAR may also affect the results due to these estimation algorithms. In this paper, the experiments were done with the LiDAR beginning to scan on the barrier and staying on across the sampling range in order to provide consistency. Some limitations to this experimental setup exist. As the LiDAR relies on optics, reflections of the beam on glass samples may have a differing effect in various environments. A larger isolated room with a suspension system for the samples would give a more isolated analysis of the glass samples. Likewise, more experiments are needed to see how various lighting sources, both natural and artificial, can also influence the LiDAR measurements.

This research study identifies limitations of the use of LiDAR sensor for autonomous navigation within the built environment, particularly in the indoor applications where the majority of interaction surfaces are made of manufactured materials such as glass. The study also points to opportunities designers and architects face when considering autonomous mobility and robot-friendly environments. Beyond ensuring that materials used cater to the needs of autonomous vehicles, architects and designers can take an active role by intentionally integrating landmarks, analogous to braille, into the environment. While this would be best done by a unified standard, various methods could be developed and the specific method for a building released to developers for the vehicle or robot to automatically switch depending on their location. Finally, architects could provide leadership in material research developing embedded technologies that would facilitate a transition toward autonomous mobility-enabled buildings and cities.

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Energy Model Machine (EMM)

*Instant Building Energy Prediction using Machine Learning*

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In the process of building design, energy performance is often simulated using physical principles of thermodynamics and energy behaviour using elaborate simulation tools. However, energy simulation is computationally expensive and time consuming process. These drawbacks limit opportunities for design space exploration and prevent interactive design which results in environmentally inefficient buildings. In this paper we propose Energy Model Machine (EMM) as a general and flexible approximation model for instant energy performance prediction using machine learning (ML) algorithms to facilitate design space exploration in building design process. EMM can easily be added to design tools and provide instant feedback for real-time design iterations. To demonstrate its applicability, EMM is used to estimate energy performance of a medium size office building during the design space exploration in widely used parametrically design tool as a case study. The results of this study support the feasibility of using machine learning approaches to estimate energy performance for design exploration and optimization workflows to achieve high performance buildings.

**Keywords:** Machine Learning, Artificial Neural Networks, Boosted Decision Tree, Building Energy Performance, Parametric Modeling and Design, Building Performance Optimization

**INTRODUCTION**

The building sector as the largest consumer of the United States primary energy has been seeking to take necessary actions to reduce its energy use. Due to the considerable impact of the buildings on the environment and with the rise in environmental concerns, designers are increasingly expected to conform appropriate minimum requirements regarding energy efficiency (Rahmani Asl et al. 2015). They need to identify design parameters with the significant impact on the building energy performance and optimize them in the process of design to achieve building models with higher energy efficiency (Yu et al. 2010).

Multiple software applications have been developed for simulating building energy performance,
renewable energy, and sustainability in buildings (Zhao and Magoulès 2012). While these simulation tools produce high accuracy results, the simulation process is computationally expensive and time consuming. On the other hand, these tools are based on physical principles and they require high levels of expertise and detail building and environmental parameters as input. As a result, building energy performance analysis is typically performed for final design validation and at the later phases of design process.

During the early design stages, designers often need to quickly explore multiple design alternatives and optimize multiple performance factors at the same time make preliminary decisions. At this phase, designers do not require high fidelity simulations for decision making and they just need to compare multiple design options and find the most appropriate alternatives for their problem. This process is difficult with whole building energy simulation tools due to slow feedback from conventional energy simulation engines (Tsanas and Xifara 2012). Therefore, building science researchers proposed different approaches for developing practical surrogate models to replace actual simulation in the early stages of design. Significant efforts have been done to make conceptual design tools environments interactive, so that designers can get instant feedback for continuous design iterations. One of the alternatives to high accuracy energy simulation is the use of fast surrogate models (Guo et al. 2016). Among these models, data-driven surrogate models become more and more practical and important because getting access to large volume of simulation data and computation power is getting easier. Over the past years, machine learning approaches and in specific deep learning methods were very successful in learning from data.

In this paper we introduce Energy Model Machine (EMM), a Machine Learning (ML) based tool that uses Artificial Neural Networks (ANNs) and Boosted Decision Tree (BDT) methods trained on the existing simulation results to predict the energy performance of the buildings without the need to perform the actual simulation. EMM is developed to provide instant feedback to designers in the early phases of building design and guide them to better building energy and environmental performance. EMM uses a data set of simulated models for optimising the weight parameters of ANNs algorithm and and BDT varies maximum depth of pruning and number of models for the ensemble set for each experiments. The trained models is then used to predict the energy performance of the newly submitted models by users and provide instant feedback to help them design energy efficient buildings. Basically EMM is an Artificial Intelligence that uses the results of the existing simulations to predict the performance of the user models as a service. It can be integrated with generative design and parametric performance analysis workflows to enable designers study a large number of design alternatives in a short period. In this paper, we provide details about the EMM development process, and we compare the EMM predicted results of arbitrary models and actual building energy simulation results. The paper provides a case study of use of EMM in a generative design application to explore the design space of a medium size office building considering annual energy use as the main performance factor.

RELATED WORK

Building energy simulation engines are widely used for energy performance prediction to help designers in the process of high performance building design since practice has shown that these tools can often generate results which accurately reflect actual building energy use (Tsanas and Xifara 2012). These tools use physical rules and principles to calculate thermal dynamics and building energy use. Most of the initial work on developing building energy simulation algorithms was done a few decades ago. Nevertheless, these tools became more accessible to designers over the past few years with the advancement of computational services. The U.S. Department of Energy (2012) has been publishing the “Building Energy Software Tools Directory” that provides detail information for over four hundred simulation tools for evaluating energy efficiency, renewable energy,
and sustainability in buildings. Crawley et al. (2008) provided a report comparing the features and capabilities of twenty major building energy simulation applications. These resources can be used as a reference for detail information about the widely used building energy simulation tools.

Using advanced building energy simulation tools may provide reliable solutions to estimate the energy performance of building design alternatives; however, this process can be very time-consuming and requires user-expertise in a particular program. Hence, in practice designers have to rely on surrogate models to study the energy performance of building design alternatives in generative design and optimization workflows to explore building design space and optimize building performance. In the literature there are various studies that used surrogate models to predict building energy performance. In multiple studies, regression model is used to correlate one or multiple building parameters to building energy consumption (Bauer 2008; Ansari et al. 2005; Catalina et al. 2008; Lam et al. 2010; Al Gharably et al. 2016). Other machine learning methods such as Support Vector Machine (SVM) (Dong et al. 2005; Lee et al. 2009), Decision Tree (Yu et al. 2010), and Artificial Neural Network (ANNs) (Kalogirou et al. 1997; Ben-Nakhi and Mahmoud 2004; Ekici and Aksoy 2009; Zhang et al. 2010) has been used to predict building energy performance. In this study we chose ANNs they are the most widely used artificial intelligence models in the application of building energy prediction they are good for solving complex problems. EMM also uses BDT as it is able to generate predictive models with interpretable flowcharts that enable users to quickly understand the model.

**ENERGY MODEL MACHINE (EMM)**

**Building Energy Model Representation**

In this study, we use building design parameters to represent building energy model. These parameters are identified based on their architectural and functional relevance and their potential impact on building energy use. These parameters can be categorised into three groups: 1) geometry parameters, 2) construction parameters and 3) load parameters. Table 1 lists all of the parameters studied for EMM.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Climate Zone</td>
</tr>
<tr>
<td>2</td>
<td>Number of Floors</td>
</tr>
<tr>
<td>3</td>
<td>Total Exterior Wall Area (and Wall Area Height)</td>
</tr>
<tr>
<td>4</td>
<td>Wall Weighted U-Value</td>
</tr>
<tr>
<td>5</td>
<td>Wall Area (North, South, East, West) (and Wall Area Height)</td>
</tr>
<tr>
<td>6</td>
<td>Window Area (North, South, East, West) (and Window Area Height)</td>
</tr>
<tr>
<td>7</td>
<td>Window to Wall Ratio (North, South, East, West)</td>
</tr>
<tr>
<td>8</td>
<td>Weighted Window U-Value (North, South, East, West)</td>
</tr>
<tr>
<td>9</td>
<td>Weighted Window Solar Heat Gain Coefficient (North, South, East, West)</td>
</tr>
<tr>
<td>10</td>
<td>Total Roof Area (and Roof Area Height)</td>
</tr>
<tr>
<td>11</td>
<td>Weighted Roof U-Value</td>
</tr>
<tr>
<td>12</td>
<td>Total Slab on Grade Area</td>
</tr>
<tr>
<td>13</td>
<td>Total Area [and Area Height]</td>
</tr>
<tr>
<td>14</td>
<td>Total Interior Floor Area (and Floor Area Height)</td>
</tr>
<tr>
<td>15</td>
<td>Total Exterior Floor Area (and Floor Area Height)</td>
</tr>
<tr>
<td>16</td>
<td>Total Area [and Area Height]</td>
</tr>
<tr>
<td>17</td>
<td>Window to Wall Ratio (North, South, East, West)</td>
</tr>
<tr>
<td>18</td>
<td>Weighted Lighting Power Density</td>
</tr>
<tr>
<td>19</td>
<td>Weighted Plug Load Efficiency</td>
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<tr>
<td>20</td>
<td>Weighted Infiltration</td>
</tr>
<tr>
<td>21</td>
<td>Total Area (and Area Height)</td>
</tr>
<tr>
<td>22</td>
<td>Total Area (and Area Height)</td>
</tr>
<tr>
<td>23</td>
<td>Total Area (and Area Height)</td>
</tr>
</tbody>
</table>

*Area Height is the area many by height of each surface and it is used to track the geometry characteristics that are not tracked by other parameters.

In this study, we considered building wall, roof, and floor area and window area by direction. Furthermore, we studied the impact of cross-terms parameters that consider wall, window, roof, floor area with their level height in the building as potential variables. These parameters are designed as a set of new geometry related parameters that help to track the variations in geometry more accurately and they are not studied in the previous studies focused on ML-based building energy performance prediction. Also, we gathered directional resolution for walls and win-
dows to increase the accuracy of the regression models. Parameters such as U-Value and Solar Heat Gain Coefficient (SHGC) of building objects are included in the model as construction parameters. Lighting Power Density (LPD), Equipment Power Density (EPD), and Infiltration are some of the load parameters that are included in the model.

Building energy models are created using Autodesk Insight energy analytical model creator from architectural (conceptual and detailed) models and exported as Green Building XML (gbXML) files. We prepared the input parameters for machine learning algorithm by running a parser on gbXML files for the models in the data set and prepare a data set of desired parameters. The ML algorithm is then run on this data set. The following section describes the underlying working principles of some of the ML algorithms implemented on the data set.

**Machine Learning**

We used two machine learning methods, Artificial Neural Networks (ANNs) and Boosted Decision Tree (BDT), for EMM. These two methods have been successfully used to predict building energy performance in other studies. ANNs are very good in modeling complex relationships between input parameters and outputs to predict accurate results. However, ANNs usually operate as black box and are very difficult to interpret especially for architects and designers in case they want to understand more about the generated model and the way it works. EMM also uses BDT method which is much simpler to utilize and its result can be interpreted easily compared to ANNs.

**Data.** Our dataset comprises of over 180,000 data points, each representing a building energy simulation output. The Data has over 97 features including both categorical and quantitative data types. For our experiment and prototype we stored the data as a local csv file for data transformation, cleaning and building our machine learning model. However, for future use cases with more data points, we envision to setup a database and use the current software architecture on it. We cleaned the data of any unwanted features like, project ids, weather id, or sparse fields which did not add much to the information set any way. After removing such features from the data, we were left with 87 features.

**Data Modeling.** We built our machine learning models with an iterative approach. On each iteration of model building we verified their performance by 10 folds’ cross validation on the whole data set. With multiple iterations, we compared Root Mean Square values and R2 Scores across different instances obtained by tweaking model parameters. We picked the model instance with best performance based on the above metrics. Next we split the dataset into 67% training set and 33% test sets. We trained our selected model instance on the training set. Our case, is a regression problem, where out of the 87 features, we have 86 independent variables (‘X’). From our dataset, our dependent variable or unknown output ‘Y’, is the Energy Simulation Output. We computed our model performance based on how accurate the prediction of the energy simulation output is with respect to correct results as present in the test data set. We conducted experiments on two machine learning models ANNs and BDT. We also tested the results with and without feature selection or dimensionality reduction algorithms. Our intent was to explore the trade-off between speed gain and accuracy from the various experiments.

**Technology Stack.** We used Python for all the data cleaning, data transformation and model building processes, using numpy, pandas, and scipy packages (Walt et al. 2011). For machine learning models, we used scikit learn (Pedregosa et al. 2011) and Keras deep learning toolkit using Theano as a backend to handle the computational heavy lifting for ANNs. For data visualisation to evaluate model performance and to compare model output, we used Python’s Matplot (Hunter 2007) library package. Below we describe our machine learning models and experiment setup in detail.
**Artificial Neural Networks (ANNs)**

ANNs are the most widely used artificial intelligence models in the application of building energy prediction since it is good for solving nonlinear problems with complex interdependencies. In the past twenty years, researchers have applied ANNs to analyze various types of building energy consumption in a variety of conditions, such as heating/cooling load, electricity consumption, sub-level components operation, and estimation of usage parameters. For more information please refer to Krarti (2003) and Dounis (2010) research which provide review studies of artificial intelligence methods in the application of building energy systems.

Interest in this direction resurfaced in 1982, when John Hopfield (Hopfield 1982) in his paper presented methods to create useful systems, using bidirectional connections between neurons. The idea was to learn from biological processes and mimic them on a computer system to help model systems better. With the current advent of Big Data sources and commendable advances in hardware and compute speed availability, use of these systems, has potential to show very good results. Neural networks are capable of generating their implicit rules by learning from provided instances. Their ability to generalise the model has been proved superior to other comparable machine learning systems spanning application in a wide array of fields (Ayat and Pour 2014).

**ANNs - Experimental Setup.** We created ANN models using Keras library with Scikit Learn package in python. We followed the same pipeline of cross validation, model building on train set and then verifying performance on test data as mentioned before. Keras library runs by building a ANN model first. We created several such models and compared model output and compute time. We describe the width of such a model by the number of features it uses as neuron for each ANN layer. Similarly, we describe the largeness of such a model as number of hidden layers it contains to compute the output. As our problem is a regression problem, unlike a classical classification problem on ANN, our model has only one node on the output layer (here output, is a number, rather than yes or no values for different classes). Output is the predicted energy simulation result based on the input independent variables ‘X’ in the model.

**ANNs - Experimental Result.** Below, we briefly describe the range of models we have experimented to build our model on the training data. For all the models below we used Rectified Linear Unit (RELU) as the activation function. However, we also have tested models with other activation functions like softmax, sigmoid and linear, but RELU's performance was much better than others for our data set.

- **Base Model:** This model was the simplest of the models studied. It had only one hidden layer. The number of neurons used were 13. This model was much faster than others because of its simplicity and gave accepted result with R2 Score 0.999777.
- **Wide Model:** This model was bit more complex than the base model. It had only one hidden layer but we increased the number of neurons to 50. This model was slower than the previous with a marginal increment in performance, having output with R2 Score 0.999899.
- **Wide and Large Model:** This model was the most complex we tried. It tested with 3 hidden layers having over 50 neurons on each layer. This model was way slower than all previous models with a very slight increment in performance, having output with R2 Score 0.999977. Owing to its too much dependence on input features on train data, this model showed signs of overfitting.

The charts in Figures 1 and 2 explain some of the model performance comparison of our ANN Model. After experimenting with different models with changeable parameters, for this dataset, we recommended the baseline model. However, we foresee a scenario, where end users can select the parameters and the model type from Dynamo Node when we query our model engine.
**Boosted Decision Trees (BDT)**

Further, we tested our dataset on Boosted Decision Trees. This method is able to generate predictive models with interpretable tree flowcharts that enable users to quickly understand the model and extract useful information which is an advantage of this method over other widely used techniques (Yu et al. 2010). We used a list of weak learners and iteratively predicted scores on our dataset and tested its accuracy. On each iteration, we upweighted those data points with predicted value was different from actual results. Our final predictor is the weighted average of all the predictors from the weak learners. BDT works by incrementally fixing those data points with predicted score was off from the actual results (Roe et al. 2005).

**BDT - Experimental Setup.** We used Scikit Learn’s DecisionTreeRegressor and AdaBoostRegressor (Pedregosa et al. 2011) to model simple decision trees and boosted decision trees respectively. We followed the same pipeline of cross validation, model building on train set and then verifying performance on test data as mentioned in the previous section.

**BDT - Experimental Result.**

- **Decision tree models:** We experimented with simple decision trees with varying maximum depth of pruning for each of our experiments. From model comparison, we realized a maximum depth of 10-12 gave good results. As decision trees were simple yet powerful models, the runtime for our experiment was way faster than ANN models. Our best result from decision tree model was output with a R2 Score of 0.999715.

- **Boosted Decision tree models:** We experimented with boosted decision trees with varying maximum depth of pruning and varying number of models for the ensemble set for each of our experiments. From model comparison, we realized a maximum depth of 10-12, with 4 models in the ensemble, gave good results. As boosted decision trees were more complex than decision trees, the compute runtime for our experiment was slower than that of decision trees. However, BDT runtime was significantly better than ANN models with almost same performance output. Our best result from BDT model was output with a R2 Score of 0.999985. Figures 3 and 4 show the comparison of the predicted results with energy simulation results for BDT method.
We tested both ANN and BDT models with feature selection to test if we can decrease model compute runtime without losing performance, especially for ANN. We tested feature selection algorithm Principal Component Analysis (PCA) by setting number of desired features as a model parameter. Out of available 87 features we tested with 20, 30 and 50 needed features. There was little improvement on the runtime, but our results were not as precise as the one we got from the model without feature selection. We also tested other feature selection algorithms like Select K Best and Recursive Feature Elimination (RFE). In some cases, the results were significantly bad and unacceptable with very low R2 score. For this use case and data set, we recommend modelling without using feature selection, but in future use cases, we would like to test feature selection further and refine our model.

CASE STUDY
In order to show the usefulness of the EMM in the early design process, we created a case study of an office building. In this case we use Autodesk Dynamo Studio, a graphical programming interface as the design tool, to parametrically design the model and study its energy performance as a measurement factor. In this study, Window to Wall Ratio (WWR) of North, South, East, West directions as well as Shading Size, Window Width, and Balcony Extension parameters are evaluated as parametric building parameters. All of these parameters are controlling the amount of the lights that enters in the building (balconies of the upper level act as horizontal shading for the lower level). Annual energy use (kBtu) and average WWR are the decision making parameters that are studied in this case. Average WWR is a simple average of the WWRs per direction. To evaluate the energy performance, we pushed the trained model (in this case BDT model) as a service that is accessible by Representational State Transfer (REST) Application Programming Interface (API) as a node in Dynamo Studio. Figure 5 shows the view of Dynamo graph and the geometry in Dynamo interface.

In order to parametrically study the design, Dynamo Studio enables users to publish their model on the web and open the model in project Fractal. Project Fractal enables users to manage exploration of design space providing different generation options and facilitates decision making by Parallel Coordinate Chart (PCC) and visualization of design options in design grid. Figure 6 shows the same model in project Fractal which generated about 7000 design options using cross product generation method.

This case study shows the usefulness of EMM as a energy prediction approximation model which enables design space exploration in a timely manner. Evaluating this large number of options by simu-
Figure 5
Dynamo graph and the geometry in Dynamo interface

Figure 6
Building model in project Fractal
FUTURE WORK AND CONCLUSION
The objective of the research is to find potential ways to bypass the process of energy simulation for building designers in the early stage of building design. This is mainly for the fact, that energy simulation takes a significant amount of time, is resource intensive and needs a certain level of detail in the building model, which is usually low in early stages. EMM uses an extensive set of parameters to track all of the impactful variables on energy performance of building model and learns from existing data by using ML algorithms providing quick and real-time energy simulation feedback to designers. These parameters cover geometry, construction, and load related building variables. Considering these parameters from all of the three categories mentioned above in the training process of the machine learning methods and making the service available to be easily used in design applications is the main contribution of this paper.

Current implementation of EMM uses ANNs since it can predict accurate results for complex interdependent problems. EMM also includes BDT since it enables users to quickly understand the model and extract useful information which is very useful for architects. As it was demonstrated in the body of the manuscript, both models have acceptable accuracy in predicting the energy performance factor. EMM makes the trained model available as a service and make it easy to be accessed by any parametric design tool. The user would only need to call the service through the provided API and add it to the design process.

The case study of the office building model design exploration using two of the common parametric design tools demonstrates the usefulness of this approach. Using EMM we were able to explore about 7000 building design options and their energy performance and make informed design decision in the conceptual design phase.

As part of the future work, we are also adding multiple images of the building model from various angles as training parameters to be able to track the geometry of the building model more accurately. We are training the models on the top of these images to categorize building model geometry and increase the accuracy of the results. One of the drawbacks of the current system implementation is that it is feeding all of the features in the dataset into the ML Model for prediction. However, from expert’s domain knowledge, we know every parameter of the building design does not have the same impact in building energy use computation. Thus, our in-progress work includes implementing feature selection and dimensionality reduction algorithms to the data set, before we pass it on to the selected ML algorithm.

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MATERIAL STUDIES - METHODOLOGIES
A framework to evaluate the architect-friendliness of environmental impact assessment tools for buildings

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Legal actions towards a mandatory environmental impact assessment (EIA) of buildings can be expected in the (near) future. Due to the complexity of EIA, software tools will become an indispensable aid in the architectural design process. Especially in early design, feedback on the environmental impact is needed, since early design decisions have a major influence on the final impact of the design. However, most existing EIA tools insufficiently take into account the architect's needs as a user and are especially not suitable for use in early design. Therefore, an evaluation framework with criteria for architect-friendliness of EIA tools, with a specific focus on early design, is developed based on a large-scale survey, interviews and a focus group with practising architects. This framework can be used to evaluate the architect-friendliness of existing EIA tools and as a guidance for the development of new architect-oriented tools.

Keywords: user-friendliness, architect-oriented, early design stage, design-support, evaluation framework

INTRODUCTION

Context

The last decades, in Europe, building sustainability was mainly associated with energy efficiency during the use phase, as a consequence of the implementation of the Energy Performance of Buildings Directive or EPBD and its recast (EPBD 2002, EPBD 2010). This directive aims to reduce the impact of buildings in climate change and depletion of fossil fuels. However, the responsible use of raw materials in building construction and the reduction of the environmental impact of buildings throughout their life cycle is gaining importance. Several initiatives on resource efficiency and sustainable management of materials in construction have been initiated.

An evolution towards a life cycle assessment (LCA) based evaluation of the environmental impact of buildings can be expected (European Commission 2011). In the ‘Closing the loop - An EU action plan for the Circular Economy’ report (European Commission 2015, pp. 17) it is stated that “The Commission will take a series of actions to ensure recovery of valuable resources and adequate waste management in the construction and demolition sector, and to facilitate assessment of the environmental performance of buildings".

In Europe, a wide range of Environmental Impact Assessment (EIA) tools has already been developed, e.g. Elodie [1] in France and MRPI-Freetool MPG [2] in the Netherlands.
Since 2013, the assessment of the environmental impact (without benchmark) of small-scale residential projects and offices is already mandatory upon building permit request in the Netherlands. In 2018, a legal benchmark will be implemented to stimulate the design of buildings with a lower environmental impact (Quelle-Dreuning 2017). In Germany, the application of an EIA tool is not yet mandatory, but it is part of global sustainability certification systems such as BNB (i.e. German assessment system for sustainable construction for federal buildings) (Brockmann et al. 2014). In Belgium, a beta version of an EIA tool, developed by the government, is expected to be released by the end of 2017 [3]. Similar to the requirements for buildings’ energy performance, targets for the environmental performance of a building are likely to be set in the (near) future.

Need for architect-friendly EIA tools

In this perspective, EIA tools should help lowering and/or optimizing the environmental performance of building design. Especially in early design, feedback on the environmental impact of building design will become indispensable in order to facilitate the inherent integration of sustainable material use in the building design process. At this stage, decisions are still flexible and adaptable, whereas, later on in the design process, decisions become more concrete and complex and more difficult to reverse (Weytjens 2013, Basbagill et al. 2013, Hollberg and Ruth 2016).

This was also already established by Wallhagen (2010, pp. 5): “The complexity and difficulty in linking buildings to environmental impact create a need for interactive tools measuring environmental performance, which can be useful as decision support in the early design phase”.

In the context of energy efficiency research, the need for design-supportive assessment tools, specifically for architects from early design on, is already widely recognized and aspects to increase the uptake of energy performance simulation tools by architects in early design have been investigated (e.g. Bleil de Souza 2009, Bambardekar and Poerschke 2009, Attia et al. 2012). Weytjens and Verbeeck (2010) composed a framework with criteria that reflect the “architect-friendliness” (i.e. user-friendliness specifically for architects) of these energy performance simulation tools, subdivided in five main themes, being:

1. Data-input
2. Output
3. Usability in the design process
4. Interface
5. General

A number of these criteria, e.g. the ones related to the usability of performance simulation tools during the design process, are almost directly applicable to the context of environmental impact assessment (EIA). However, EIA is much more complex and broader than energy performance (see Figure 1).

Figure 1
Instead of focussing solely on the building envelope and systems, the whole building needs to be incorporated in the assessment and the focus is not only on the expected performance in the use phase of the building, but on the performance over its entire life-cycle.

Additionally, architects’ knowledge on sustainable building is currently still mostly linked to energy efficiency and their insights in sustainable material use, life cycle assessment (LCA) and environmental product declarations (EPDs) are quite limited (Meex and Verbeeck 2015, Meex et al. 2017).

Due to both the complexity of EIA and the lack of knowledge and insights of the architects, there is a clear need for EIA tools with an explicit design-supportive value for the early design stage. In this paper, a framework with key-criteria for architect-friendliness of EIA tools is presented.

**METHODS**

In this research, the framework on architect-friendliness of energy performance tools by Weytjens and Verbeeck (2010) was used as a starting point and further elaborated and adapted to become useful to evaluate the architect-friendliness of EIA tools during the early stages of building design. Literature studies (e.g. Forsberg and von Malmborg 2004, Haapio and Viitaniemi 2008, Bayer et al. 2010, and Han and Srebric 2011) on LCA-based methods and tools for assessing the environmental impact of buildings, building components and building materials were used to move, alter or add framework criteria. Although no specific attention was paid to the architect-friendliness of the tools in these literature studies, user-related criteria that are relevant for the determination of the environmental impact of building (elements/materials) are found and added to the original framework, especially with regard to the framework themes Data-input, Output and General characteristics.

In a next step, the framework criteria were validated and fine-tuned with the Flemish architectural design practice by means of:

1. A large-scale survey
2. Semi-structured interviews
3. A focus group

**Large-scale survey**

A large-scale survey (N=364 Flemish architects) was conducted in January-May 2014. Overall goal of the survey was to investigate the architects’ current knowledge and practice regarding sustainability in building design, sustainable material use and environmental impact calculations and their future expectations and wishes for EIA tool functionalities. The main findings and more detailed survey results are described in Meex and Verbeeck (2015). The results on expected features and characteristics of an EIA tool for buildings are used to refine the Data-input and Output criteria of the framework on architect-friendliness.

**Semi-structured interviews**

In addition to the survey, five semi-structured interviews with Flemish practicing architects were conducted between May and July 2014. Goal of the semi-structured interviews was to gain a better understanding of architects’ wishes and needs when using an environmental impact assessment tool. The architects were asked to indicate the aspects they consider to be determinative for each theme of the framework by means of own suggestions and by imposing an order of importance for the framework criteria (by means of a card sorting exercise). The qualitative analysis of the interviews gave deeper insights in the underlying concerns of the architects.

**Focus group**

A four hour focus group (held in September 2016) with 12 Flemish architects (10 practicing architects, one recently graduated architect without practice experience and one architecture student) was used to check the validity of the framework criteria, fine-tune them and add new ones if necessary.
Since the survey and interviews revealed that the architects’ knowledge on environmental impact assessment is quite limited, the first part of the focus group consisted of two lectures to demonstrate the importance and main principles of EIA on a building level and to give an overview of the current situation in the Netherlands and Belgium.

The second part of the focus group consisted of three participatory steps: an individual brainstorm, a small group brainstorm and a large group discussion. For the first two steps, the participants were randomly subdivided into four groups of three participants, according to the four most specific framework themes: Usability in the design process, Software environment and interface, Data-input and Output. At first, they were asked to come up individually with 10 criteria (related to their theme) which could enhance the usability of such a tool in the early design stage. Then, the individual criteria were discussed in the small theme groups. New, additional criteria could come up at this stage. All criteria were placed on an A0 sheet and participants were asked to indicate the level of importance of each criterion (three levels). As a final step, the small groups presented their findings to all participants during a group discussion. The results were used to fine-tune the framework into its final version.

Since in the focus group the architects were first informed on the subject before delivering input to the framework development and the focus was specifically on the early design stage, the insights and results are considered as more reliable than those from the survey and interviews and therefore also used to a greater extent in the fine-tuning of the framework. In addition, the findings from the focus group are used to determine the main focus points in the development of EIA tools within the themes Data-input, Output and Usability in the design process, based on the number of criteria that the participants spontaneously suggested per framework theme and based on the order of importance which they had to provide during the brainstorm.

**RESULTS**

The final result is a framework with 43 criteria for architect-friendliness of EIA tools (see Table 1), structured according to the five main themes of the original framework: Data-input, Output, Usability in the design process, Software interface and General tool characteristics.

**Data-input**

Based on insights from literature, the criteria for Data-input are subdivided into two subthemes: Input data (which data to enter) and Input method (how to enter data). The empirical research was used to fine-tune the input criteria. The main goal was to specify the preferred input method of the practicing (Flemish) architects.

In the large-scale survey (N=221, multiple options possible), 55% of the respondents indicated that they prefer to input the data from a 3D model (26% prefer a simple 3D model, 19% prefer an advanced 3D model and 10% did not specify the type of 3D model). 43% of the respondents prefer the input to be integrated in the EPB (Flemish implementation of the Energy Performance of Buildings Directive) software. Separate manual input was only selected by 33% (14% with standard adaptable elements, 9% with specific product information per material and 10% did not specify this further).

According to the card-sorting in the semi-structured interviews (N=5), importing a complete (3D) model from drawing software into the EIA tool is desired most as input of building geometry (which corresponds to the survey results), followed by separately modelling the building components in the EIA tool itself, and importing building components already composed in other software packages (e.g. energy performance simulation software). However, as most architects in Flanders do not use advanced 3D CAD (Computer Aided Design) or BIM (Building Information Model) drawing software packages, which allow complete modelling of a building and its building components (geometry and materials) in 3D (Neven and Selke 2016), a link to this type of
Table 1
Final framework for the evaluation of the architect-friendliness of EIA tools in early design

| DATA-INPUT |
|------------------|------------------|
| **Input data**  | Limited data-input  |
|                  | Input consistent with design phase: general (early phases) to detail (final phases)  |
|                  | Default values / default settings available (facilitate data-entry)  |
|                  | Extensive library / database of standard materials, building components, EPDs, etc.  |
|                  | Clearly structured library / database, with search function  |
| **Input method** | Quick data-input  |
|                  | Simple, intuitive input procedure  |
|                  | Preferred input method: linked to simple 3D drawing model (e.g. SketchUp), no manual input  |

| OUTPUT |
|------------------|------------------|
| **Output data**  | Simple but supportive information for design decisions  |
|                  | Adapted output for different design phases  |
|                  | Preferred output level: aggregated environmental score with easy access to more detailed data (per element, per life cycle stage, ...)  |
|                  | Link to energy calculation  |
|                  | Results for non-impact related aspects (e.g. comfort, health, economic costs, ...)  |
| **Output format**| Easy to interpret, clear and limited e.g. visual elements such as graphs, a grading scale, ... but no extensive report  |
|                  | Benchmark or reference provided  |
|                  | Convincing, communicative result representation  |
|                  | Compliance with building codes and regulations  |

| USABILITY IN THE DESIGN PROCESS |
|------------------|------------------|
| **Time use**  | Quick application, minimal time required to operate tool (learning vs. using later on)  |
|                  | Short calculation time: no (additional) heavy load  |
|                  | Minimal interruption of the design process / implementation in workflow architect  |
|                  | Interoperability: integration in / add-on to existing [drawing] software  |
| **Adaptability & flexibility** | Adaptable to design stages [simple versus extended calculation]  |
|                  | Adaptable default values [customized choices]  |
|                  | Easy data review / change [without loss of data]  |
|                  | Quickly and easily create and test alternatives [parallel within software]  |

| SOFTWARE INTERFACE |
|------------------|------------------|
| **Comparison & feedback loops** | Allowing intermediate evaluation [calculation in tune with design process]  |
|                  | Comparing a number of different design alternatives in detail [parallel within software]  |
|                  | Real-time feedback on impact of design decisions / changes [sensitivity, ...]  |
|                  | Clearly indicate problem areas and generate suggestions/alternatives  |

| GENERAL TOOL CHARACTERISTICS |
|------------------|------------------|
| **General selection criteria** | Availability / accessibility of the tool: public, free  |
|                  | Simplicity: intuitive, easy to use and clearly structured, ...  |
|                  | Easy to learn (without education)  |
|                  | Decision support value of tool application  |
|                  | Tool adapted to use by architects [user skills, background knowledge, preferences, ...]  |
|                  | Adequate for different types and [design] phases of buildings [one tool for range of different applications]  |

<table>
<thead>
<tr>
<th>Calculation preferences</th>
<th>Database with verified and independent data</th>
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<tbody>
<tr>
<td></td>
<td>Data adequate for local use [units, language, regional and time specificity]</td>
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<td></td>
<td>Transparency of the tool [underlying assumptions, calculation methodology, ...]</td>
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drawing software is not preferred, especially not in early design. This was also confirmed during the focus group (N=12): input of the geometry in early design should be linked to a simple 3D drawing software package (e.g. SketchUp, used by 68% of the respondents in the large-scale survey (N=354)), not to a BIM-tool since most architects do not work with BIM (yet) and BIM is not considered as a design tool, but more as a tool for the later design stages. Similarly, a link with the energy performance should be present in the assessment to allow simultaneous calculations for energy performance and environmental impact assessment. As no material-related information can be imported from SketchUp (low level of detail), a database with standard materials and building components and default values / settings was also found to be important in early design.

**Order of importance.** First of all, a link with a simple 3D drawing software tool is preferred; separate input or modelling of the geometry should be avoided as much as possible, since this would be too time-consuming in early design. In addition, material-related information should be based on a well-structured and clear database with standard material and component solutions. The use of default settings and default values is inevitable in early design, as, at this stage, architects just need a quick check of a design option, which is still subject to change. Therefore, the tool should also be simple, quick and limited (and thus cause as little as possible additional time or work investment).

**Output**

Similar to the Data-input theme, the theme Output was subdivided into two subthemes: Output data (which results are obtained) and Output format (how the results are displayed). Since different levels of complexity and detail in the outcome of an environmental impact assessment are possible, the main focus of the empirical research was on determining the architects’ preferences regarding the output data and the output representation format. In the survey, multiple options could be selected for the output data level (N=220, multiple options possible). An aggregated score for the total environmental impact of the building was most preferred (61%), followed by more detailed scores such as an environmental score per building element (33%) or per material or product (29%), more detailed information on environmental impact in the use phase (24%) and an environmental score per life cycle phase of the building (19%).

In the interviews and the focus group, an aggregated environmental score on building level was also most preferred for a quick overview, but always with easy access to more detailed information (e.g. building component, etc.) in order to derive the origin of this score. Most architects are not really interested in the environmental score per impact category (e.g. global warming potential, expressed as kg CO2 equivalents), as this is too difficult, abstract and meaningless to them, due to their limited background on environmental impact. Nevertheless, some of them want to consult more detailed environmental impact scores, depending on their own interests and knowledge level. However, it should be noted that this comes with a risk: taking decisions based on one single environmental impact category can lead to burden shifts to other impact categories that are not taken into account. Therefore, this detailed information should not be the primary information source for decision-making, especially not in case of limited knowledge and insights.

In the focus group it was also clearly established that a link to the energy performance should be integrated and results for non-impact related aspects (e.g. comfort, health, economic costs, ...) should be added, as these allow participants to have a more global overview of the impact of their design decisions and relate the impact to aspects they are more familiar with. This overview can help them in finding the right balance for the impact of their decisions. For the output format, the interviewed architects mostly preferred to have a report (most suited for communication with the client), closely followed by
output in graphs and tables (which can also be part of the report). The focus group participants asked to limit the size of the report to one A4 page in early design. A visual representation of the output that is easy to be interpreted by architects is needed, as, in early design, the focus is more on testing a number of different design solutions that are not always communicated with the client. In case the client wishes to be informed on the environmental impact, the output should facilitate this communication. Furthermore, the output should be comparable to benchmarks or references to ease interpretation and enable comparison. In early design, ranges for the environmental impact can be presented instead of an exact calculation due to the high degree of uncertainty. In addition, in light of the growing attention for the environmental impact of a building, the assessment should be compliant with (future) regulations and building codes.

**Order of importance.** The criteria regarding the output data and format were less numerous and concrete than those for the data-input. A possible explanation for this is that EIA is not part of the architects’ daily design practice yet, so they do not really know what to expect. However, there were some clear requests, e.g. easiness to interpret, quick access to an aggregated score (and underlying detailed results) and a link with other aspects of the building (e.g. energy performance, but also economic costs, health, ...). The results should also be clear and limited and visually represented on a grading scale or in graphs. All results should be design-supportive throughout the design development and communicative towards clients (if necessary).

### Usability in the design process

Based on the interviews and the focus group, a classification of the criteria into three subthemes was made: Time use, Adaptability & flexibility and Comparison & feedback loops.

Regarding the subtheme Time use, in the focus group, the architects emphasized that the evaluation should not take over half an hour per design solution in early design. To obtain this, interoperability and integration in or add-on to existing (drawing) software was frequently mentioned by the participants of the focus group (to avoid double work and having to learn a complete new tool and to have a visual input of data).

In the subtheme Adaptability & flexibility, it was specified that data and defaults should be easily adaptable, without loss of data. In addition, an EIA tool should allow architects to quickly and easily create and test alternatives (parallel within software e.g. by means of the copy-paste method which is often used by architects (Weytjens 2013)), especially in early design when many different design options are considered.

In subtheme Comparison & feedback loops, criteria mainly reflect the need for comparison and feedback on the output part of the tool. The architects in the focus group also prefer real-time feedback, as this directly reflects the impact of decisions and enables comparison of different situations. Furthermore, the participants in the focus group really require recommendations on how to improve the performance of their design. This could help them to broaden their horizon, deviate from their own standard choices and introduce a learning process on the environmental performance of buildings.

**Order of importance.** All criteria related to the time investment and the adaptability and flexibility of the tool were very important to the participants in the workshop. The core feature is that the tool should operate fast, integrated in the design process, so that it can be used as a quick check along the way. Comparing multiple design options to each other (and to a reference), indicating problem areas and generating suggestions for improvement or alternatives and real-time feedback on their design decisions were a little less important, but still very valuable.

### Software interface

These criteria are more general and reflect the practical usability of all facets of the tool. Most of all, the interface should be visual (e.g. large font size, clear lay-
out, ...), with a clear follow-up structure. In addition, a clear help function or discussion platform should be present, so that the architects can look for helpful information and/or contact people with similar problems if necessary. During the interviews and the focus group, some criteria were also specified in more detail to increase the usability, e.g. restrained set of options was specified as picking things out of a list and clicking instead of typing; flexible navigation had to imply without constant need of a manual or (online) help function.

General characteristics
Based on the literature review (e.g. Haapio and Vitanen 2008, Forsberg and von Malmberg 2004, Bayer et al. 2010, Han and Srebric 2011), a number of criteria were added to the general tool characteristics, which were all found to be relevant throughout the empirical research: the tool should be adapted to use by architects (user skills, background knowledge, preferences), have a decision-support value and be adequate for different types and (design) phases of buildings (one tool for a range of different applications), so that the application can be integrated in the design process and the workflow of the architect. Furthermore, the tool should be available and accessible to architects. In light of the expected requirement to use a tool to calculate the environmental impact of a building design, this is further specified as a tool which is publicly and freely available (which was very important to the focus group participants). These criteria can be considered as selection criteria, prior to actual tool application and therefore they are classified in the subtheme General selection criteria.

During the interviews and the focus group, also some other criteria related to the preferences for the calculation methodology were mentioned. For instance, all data in the database should be verified, independent and adequate for local use, so that they form a reliable starting point for the assessment. Since the architects’ knowledge level on LCA and EIA is quite limited, the architects mainly require transparency, with insights into the underlying assumptions and the calculation methodology used by the tool developers (cfr. with the energy performance calculation). These criteria are classified in the subtheme Calculation preferences.

DISCUSSION AND CRITICAL REFLECTION
The framework, including the order of importance of the framework criteria, can serve as an evaluation tool for existing EIA tools and as a guidance for the development of (new) EIA tools, which are adapted to the needs of architects in early design.

Currently, architects mainly trust in their gut feeling and intuition to implement sustainable material use in building design. Therefore, such a tool, which covers all criteria for architect-friendliness, can help in creating a support-base for and an awareness on environmental impact assessment. However, it should not just be a calculation tool, but a supportive tool which also introduces a gradual learning process among architects to increase their awareness and knowledge level regarding the environmental performance of buildings and the integration of sustainable material use. This increase in knowledge level on sustainable building through tool use was also mentioned by 64% of the respondents in the large-scale survey as an expected advantage, closely followed by a higher quality of the design (61%, N=224, multiple options possible). However, it should also be noted that the implementation of all criteria for architect-friendliness would not automatically imply the uptake of the tool by architects. For instance, although the majority of the focus group participants claims that they would use such a tool, for most of them this would still require a change of habits which is not easily made. In addition, they fear extra work and budget implications of this additional assessment. Nevertheless, an EIA tool which meets all requirements for architect-friendliness would be a good step in obtaining more sustainable buildings.

In an exemplary study (Meex et al. 2016) an intermediate version of the framework was already applied to four existing EIA tools and all framework criteria were evaluated on a scale of 0 to 5. It was found
that none of the existing assessment tools met all criteria for architect-friendliness. Although the focus of that study was not specifically on early design, most of the evaluated tools lack a gradual data input, the presentation of an aggregated one-number score for the whole building to the user and real-time feedback on design-decisions, which are essential aspects of architect-friendliness and inducing a learning process among architects.

**Limitations of the research**
The framework development is performed from a Flemish perspective. In Flanders, the design context is characterized by a large number of small-scale architectural offices (1-2 people) who are mainly involved in dwelling design for private clients (T’Jonck 2013). However, according to “the Architectural Profession in Europe 2014” report (Mirza & Nacey Research 2015), the situation in the rest of Europe is quite similar: 74% of the practices are one person practices and 53% of the European architects’ work is private housing. Therefore, these findings are also valid for countries with a similar context. Nevertheless, this specific geographical, cultural and professional background of architects should be taken into account when interpreting the results of this research, as a different context might lead to (slightly) diverging needs and desires.

**CONCLUSIONS**
Early design decisions have a significant influence on the final environmental performance of the building. In light of the upcoming importance of reducing the environmental impact of buildings, architects should be able to evaluate the environmental impact of building design, already from early design on. However, currently, architects lack knowledge and appropriate tools to do this.

As a result of this research, a framework with criteria for architect-friendly EIA tools is developed, with a specific focus on usability in early design. In addition, an order of importance of the framework criteria is provided. It is found that especially the data input format and the type of data input, the time spent on tool application and its adaptability and flexibility to the architects’ way of working are very important criteria when evaluating the architect-friendliness of a tool.

This framework is an important step in obtaining more architect-friendly EIA tools. By means of an evaluation with the framework, strengths and weaknesses of existing EIA tools can be established and recommendations for future tool development can be formulated. In future steps of the research, the feasibility of implementing all these criteria in an EIA tool will be investigated.

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3D Concrete Printing in Architecture

A research on the potential benefits of 3D Concrete Printing in Architecture

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This research explores the use of large-scale 3D Printing techniques in architecture and structural design. First we will analyse the various methods in large-scale 3D printing in order to choose the method with the most potential to be used to build large-scale residential buildings in the Netherlands. Then we will investigate the properties of this 3D printing technique to determine the new building process, related to building with a 3D Concrete Printer. The freedom in movement of the printer and the properties of the concrete mixture used to print will form the guidelines in the creation of a design language in which both material costs and labour costs are reduced to a minimum. The design language is later applied on the design of a house, which shows the impact 3D Concrete Printing should have on the current boundaries in architecture and structural design.

Keywords: Additive Manufacturing, 3D Concrete Printing, Structural Optimization, Personalization

INTRODUCTION
Architecture has changed radically in the 20th and 21st century due to a development in materials and technologies. As stated by Kolarevic (2003) “freely form-able materials, such as concrete and plastics, have led, for example, to renewed interest into ‘blobby’ forms in the 1950’s and 1960’s. But the biggest innovations related to new materials and production methods occurred in the 21th century supported by the computer in the form of digital fabrication. However, these new and significant developments are currently not reflected in the architecture even though they could provide a lot of benefits.

New techniques in architecture and structural design ask for a new way of building, causing a modification of traditional design, adjusted to the new technique. In this research the main question will be:

How can 3D Concrete Printing be beneficial to the construction of inexpensive large-scale residential buildings in the Netherlands?

RELATED RESEARCH
LARGE-SCALE 3D PRINTING TECHNIQUES
3D printing is an additive manufacturing process in which layers of material are deposited upon each other to create an object. An upcoming method in 3D printing is the printing of large-scale buildings or
building-elements with a concrete like material. Today there are more and more companies interested in this way of 3D printing but there are three main techniques.

1. Contour Crafting. This is one of the oldest 3D Printing techniques (Koshnevis, 1998). The technique is based on extruding a cement-based paste against a trowel that allows a smooth surface finish created through the build-up of subsequent layers (Lim et. al., June 2011, p.263).

2. Concrete Printing. This technique is developed by the University of Loughborough and is also based on the extrusion of cement mortar, however, the extrusion process is more focused to retain 3-dimensional freedom with high resolution of material deposition, which allows for greater control of internal and external geometries (Lim et. al., June 2011, p.263).

3. D-Shape. For this technique powder is deposited in layers which is selectively hardened using a binder. Once the printed object is complete, it needs to be dug out of the loose powder bed. (Lim et. al., June 2011, p.263)

In 2011, Lim et. al. did a research on these three large-scale 3D printing techniques and compared them to each other. For instance, the main advantages of D-Shape are the high strengths and the fact that the unhardened sand acts as a temporary support for the layers above, because of which shapes that cannot be made by a single-material layer extrusion can be created using this technique. But the need for unhardened sand is also a huge disadvantage in our opinion. We do not see this technique being used on site, while the use of powder asks for a well-regulated climate; rain and wind for example, can make the printing process impossible. Secondly, according to Lim et. al. (2011), the technique asks for massive material placement, continuous compression of the sand and the removal of unused material, which are both laborious and troublesome.

Both Contour Crafting and Concrete Printing do not require a powder bed; both the processes are based on extrusion, which makes them very similar at first glance. An advantage of Contour Crafting compared to Concrete Printing according to Lim et. al. (2011), is the smoothness of the created surface. In contrast to the roughly layered surface, which is created using Concrete Printing, the constraining of the extruded flow to trowel surfaces in the vertical and horizontal direction make it possible to create a smooth surface. But where the finished product of Concrete Printing is the actual object, Contour Crafting, according to Lim et. al. (2011), only creates a mould which has to be filled per every 125 mm in height with a cementious material, which causes weak bonding strength and a longer production time. The only disadvantage of Concrete Printing as stated by Lim et. al. (2011), are the limited printing dimensions.

At the Eindhoven University of Technology a new 3D printing technique is under development. The 3D Concrete Printer (3D CP) as shown in Figure 1 has dimensions of 11m (L) x 6m (W) x 3m (H). The 3D CP has the characteristics of both Concrete Printing and Contour Crafting as the resolution of the printer can be adjusted to both techniques. This 3D printer must be able to combine the best of both techniques and can be the most promising 3D printing technique for large scale buildings, It is our belief that this technique has the most design freedom, with the least amount of post processing and the most potential to be used on site.

**ADVANTAGES OF 3D CONCRETE PRINTING**

The sustainability of traditional concrete is questionable, a lot of CO2 is emitted with the production of concrete but the raw materials of concrete are well stocked, concrete is 90% recyclable and the CO2 emissions of a concrete building in use is lower than that of other materials. (CRH Structural, 2015)

CyBe Additive Industries, a Dutch company who built their own Contour Crafting robot, created a mortar for their robot, “which produces 32% less CO2 compared to regular concrete, which makes it more
environmentally friendly. In addition the mortar is completely reusable and thus greatly cuts down on waste and pollution” (Alec, 2015) CyBe is not the only company creating a more sustainable mixture for their 3D printer, Winsun, a Chinese company with a Contour Crafting printer, “uses a printing material created from recycled construction waste, industrial waste and tailings” (Starr, 2015). Another advantage, linked to the sustainability of the 3D printed concrete is the reduction of construction waste by 30 to 60 per cent.

Besides the increase in sustainability, Michelle Starr (2015) also argues “a decrease in production time by between 50 and 70 per cent, and labor costs by 50 to 80 per cent.” The reduction in cost and time is also supported by Busswell et. al. (2006) and can be advantageous for both contractors and owners.

The reduction of the production time provides fewer and shorter disturbances in the direct vicinity of the location the 3D printed building or object is being built. 3D printing will also reduce nuisance by a non-traditional layout of the building site, with 3D printing, only the machine is required - maybe in combination with one or two supervisors- all traditionally used equipment which often cause inconvenience is redundant.

A more creative advantage of 3D printing is the ease with which special shapes can be made. This removes the boundaries -for example standard sizes - architects normally must abide. Secondly 3D printing no longer means the mass production of a standard product to fit all purposes, in other words one size fits all. According to Kolarevic (2003) “the technologies and methods of mass-customization allow for the creation and production of unique or similar buildings and building components, differentiated through digitally controlled variation” (p.53). Future owners of a 3D printed building can customize their building according to their own wishes without a lot of extra costs.

**METHODOLOGY**

**CONCEPT**

A potential benefit of 3D Concrete Printing, when applied on large-scale residential housing, is the opportunity for personalization. In the current built environment of the Netherlands the individual is not visible. Political, economic and architectural rules and restrictions define our built environment, which results in an anonymous and monotone landscape. The way we describe our house is something like “I live at number fifteen, the ninth house on the right.” Our house is often just defined by this number, a personal characteristic by which the house can be marked as a personal possession is absent even though the house is considered to be our most valuable investment. Inside our houses the most important moments of our lives take place. This is why there is a need for personalization; the house should be adjusted to needs and satisfaction of the user.

The reason that personalization becomes an option with 3D Concrete Printing is the independency of shape on building costs. Imagine a concrete cuboid from 1m3 in size from which the dimensions are variable. In the traditional way of building a slight change in dimensions of the cuboid results in the need for a new mould to cast the concrete in, so even though the amount of used material is similar in every cuboid, if the dimensions do not fit the standardized mould, the costs of the construction will increase significantly. With 3D printing however, the influence of shape on the price of the cuboid is eliminated; even printing a sphere instead of a cuboid will not affect the price of the object as long as the quantity of used material remains the same. As a result.
of this, standardization of buildings or building elements is no longer needed with 3D Concrete Printing.

In order to provide the maximum possible amount of personalization, the construction costs of the building need to be reduced. Construction costs as shown in Table 1, are a combination of material costs and labour costs. In order to decrease these construction costs it is necessary to consider the requirements of the 3D Concrete Printer. If the printing process is used efficiently, the cost of manufacturing will be minimal.

<table>
<thead>
<tr>
<th>Table 1: Division of building costs. (CBS, 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building</strong></td>
</tr>
<tr>
<td>House</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Apartment</td>
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</table>

**PRINTER LOGIC**

The character of the architectural space depends on how things are made and for that reason it is determined by the technical realization and by the structural composition of the substances and building materials used [...] under a surface lies a hidden secret, which means the surface depends on a concealed structure which existed before the surface, which created the surface and in a certain way the surface is a plane imprint of this structure. Deplazes, 2008, p.19

The custom concrete mixture used by the 3D Concrete Printer consists of Portland cement (CEM I 52,5 R), siliceous aggregate, limestone filler and specific additives for ease of pumping. But even though this concrete is similar to traditionally used concrete 3D printed concrete should be seen as a new material as the structural and aesthetic characteristics of this material do not match with those of other, existing materials. The way we can build with this material is different from building with traditional concrete as well as printing with other 3D printable materials. This means, the possibilities and limitations of the 3D Concrete Printer and its material have to be taken into account in order to create a suitable design. But because 3D Concrete Printing is a relatively young building method, research on the possibilities and limitations is on-going and the full potential of this construction method is still unexplored.

In order to be able to create a design language suitable for 3D Concrete Printing it is important to understand how the printer works. A short explanation about the printer and the printing process is given by Bos et. al. 2016:

Concrete is mixed with water and pumped into a hose by a mixer-pump located on the side of the set-up. The hose is connected to the printer head situated at the end of the vertical arm of a motion-controlled 4 degree-of-freedom gantry robot. [...] Under the pressure of the pump, the concrete is forced towards the printer head an element consisting of several parts allowing the concrete to be printed at the desired location, at the desired speed, and under the desired angle. The end part of the printer head is the nozzle, a hollow steel element with a designated section from which the concrete filament leaves the printer and is deposited on the print surface. (Bos et. al. 2016, p. 4.)

The most important aspect about this explanation is the fact that the printer has 4 degrees of freedom, i.e. it can move in the x-axis, y-axis, z-axis and can additionally rotate around the c-axis, at the tip of z-axis. This fact determines how the printer can move, and determines the range of motion within the printing bed, which influences the possibilities of the printer. This movement of the printer combined with the structural performance of the used concrete mixture will become the two main guidelines in the process of creating a design language suitable for the 3D Concrete Printer.

**PRINT PATH.**

In other 3D printing processes, a 3D printed object never consists of just the shape of the object. In both large-scale architectural objects as well as in small-scale miscellaneous objects the boundary shape of the object is supported by an infill. The infill is supposed to give strength and stability to the bound-
ary and is necessary for a good print and should increase the possibilities of the printer. This combination of shape and infill forms the print path of the 3D printer and within this print path the possibilities of the printer and the material are incorporated. Each combination of printer and material should have its own print path.

Different infills are created for the 3D Concrete Printer and these infills are tested on printability and structural performance. The goal here was to create an infill for every possible shape that is able to increase the possibilities of the 3D Concrete Printer and increase the structural performance of the concrete used.

For the 3D Concrete Printer the most efficient print path, as visible in Figure 2 and Figure 3, is based on one direction to create a 3D printed object with uniform structural performances. Besides, the amount of corners is reduced within this print path, this decreases the amount of changes in direction for the printer, which increases the precision of the material deposition. A disadvantage of this print path is that it does not allow variation. However, a 3D print structure, which is adjustable with change in speed and nozzle height of the printer, can provide the needed variation. An advantage to the fact that variation is not achieved by variation in print path but by the 3D print structure is that this variation does not increase the complexity of the print path.

The 3D print structure is created when the printer moves at a slow speed, high above the printing base or previously printed layer. This causes the extruded concrete to curl up when it is being deposited. This process of the curling of the concrete is visible in Figure 4. The concrete curls, i.e. the 3D print structure, have the potential to increase the strength of the printed concrete. However the direction in which the 3D print structure is used has a big influence on the strength of the concrete, causing the necessity to always rotate a printed object by 90 degrees after printing in order to get the best possible structural performance of the 3D print structure.
MATERIAL OPTIMIZATION

We have seen previously that variation in print path is controlled by the variation in 3D printing structure. Different options of 3D print structure are possible by a change in printing speed, printing height and rotational angle of the nozzle, without having complex print paths. This gives the flexibility to vary the geometry of the deposited material within the same element based on material requirements without altering the print path mid way through the prints. In Figure 5, multiple examples of the 3D print structure are visible. However, these are just a small percentage of the all the different possibilities. Every small change in printer settings will change the way in which the material is deposited.

The enormous amount of possible variations in 3D print structure allows the adjustment of material use per location in the print path and thus contributes to the reduction of material use in the printed object. The 3D print structure itself can reduce the used material up to 25% compared to a print using only flat layers. This percentage can be increased even more when the 3D print structure is adjusted to the structural needs of the object.

TOPOLOGY OPTIMIZATION

However the optimization of the print path for the 3D Concrete Printer results in a reduction of material use and thus a reduction of the building costs, the optimization of the printed material on a large scale can further increase the efficiency of the printer and does still consider the capabilities of the 3D Concrete Printer. For further reduction of material use, topology optimization is applied as visible in Figure 6. This optimization method removes the material from the places in the structure where there are no forces and leaves only material where it is structurally needed. Besides, the structural data found during topology optimization can be used to further optimize the print path. The structural data can be linked to the print speed as shown in Figure 7. Combining this with the created print path and the possible variations in this path, the 3D Concrete Printer will be able to reduce the material use in the building up to 50%.

With traditional subtractive manufacturing of casting in a mould or scooping out materials with CNC, the principle of topology optimization was difficult to apply for manufacturing. However with 3D printing, material deposition according to topology optimization is relatively easy to apply. As the areas of the element that do not require materials can be left out without depositing any materials and printing the remaining structure according to structural performance.

![Figure 5](image5.png)

**Figure 5**
Different 3D print structures.

![Figure 6](image6.png)

**Figure 6**
Advantages of Topology Optimization.

![Figure 7](image7.png)

**Figure 7**
Adjustment of the 3D print structure on the structural data of the optimization.
PRINT PROCESS
The first step in the printing process is the structural optimization as shown in Figure 8. A structural diagram, which includes the bounding box of the object with load and support conditions, forms the input for the structural optimization and the optimization creates the final shape of the object. The optimized shape will be rotated 90 degrees to create the print path as visible in Figure 9; this is to ensure that the 3D print structure will match the direction of the best structural performance after printing. The rotated object is divided into alternate flat layers and layers containing the 3D print structure. On these layers the print path is created. This information will be exported to the 3D Concrete Printer and the printer alternatively prints a 3D curled-up layer along with a flat layer. Additionally the print path takes the forces in the structure into account, so the speed of the printer is continuously adjusted to needed material. As printing the 3D print structure along the height of the layer will decrease the structural capabilities of the concrete, a normal, flat, layer will be printed in this direction, because the 3D curled up layer is three times the height of the normal flat layer i.e. 30mm, the normal flat layer needs to be printed 3 times, i.e. 3x10mm, to match the height. After the complete object is printed according to this logic and the concrete is hardened, the object can be rotated 90 degrees and used structurally in the rotated side.

LABOUR REDUCTION
The only thing left, possible to decrease the building costs of building with the 3D Concrete Printer, is a reduction in labour costs. For this reduction again the possibilities of the printer need to be taken into account. The 3D Concrete Printer is capable to create any kind of shape, starting from a flat printing base, until there is a horizontal part. This horizontal part needs to be cantilevered which is not possible to print with the 3D Concrete Printer without the use of a mould. Since the use of a mould increases the labour costs as well as the construction costs of the building it is preferred to design a house that can be printed without the use of a mould. Therefore a reduction of the amount of horizontal parts, starting from the chosen print base is needed to provide the least possible amount of print parts, which will decrease the amount of needed labour for assembling the parts. This will decrease the labour costs of the building and thus the total construction costs.

DESIGN GUIDELINES
The combination of material and labour reduction in the printing logic of the 3D Concrete Printer results in a set of rules for designing with a 3D Concrete Printer, which differentiate a lot from the traditional way of building. However, the goal was to create a house that is similar to current terraced housing in the Netherlands, a housing suitable for the lower-
and middle class of the Dutch population. The house needs to be designed considering the characteristics of current terraced housing, which means that the average characteristics of current terraced housing should form the minimal needs for the designed house. These characteristics do not only imply the minimal square meters of the house or the size and the amount of openings in the facade but also for example the possibility to personalize the house or the way in which the house is used in a practical sense.

As stated before the characteristics of current terraced housing in the Netherlands form the minimum needs for the 3D Concrete Printed house, combining them with the found guidelines for printing with the 3D Concrete Printer however, asks for a significant change in the design of the house. In this combination, the actual impact of 3D Concrete Printing on the current boundaries in architecture and structural design becomes visible.

Take for example the size of the printer. The average terraced house has a width of 5.638 mm and a depth of 10.346 mm if we want to print a house of these dimensions on site with the 3D Concrete Printer, it means that the longest side of the house will be printed on the side of the 3D Concrete Printer that has a restriction in size, while the shortest side will be printed on the side of the printer that has not got any boundaries. Besides, the rules regarding the reduction of labour costs also do not add up with commonly used floor plans in current terraced housing. The current terraced house has too many horizontal parts, which results in a great amount of printing parts and thus needs a large amount of manual labour, which increases the building costs.

The previously described differences between traditional building and the printing logic of building with a 3D Concrete Printer mostly have an impact on the general shape of the house, which is visible in the layout of the floor plan. The material reduction however, significantly changes the design of the house. Walls for example, will no longer remain flat building elements but due to structural optimization will become interesting structures inside the building that can create new spaces or exciting new thresholds. And within these structures the house can be transformed according to the user’s requirements. An example of a house designed with the requirements of the 3D Concrete Printer is visible in Figure 10 and Figure 11.
FABRICATION
PRINTER MODIFICATION
The existing 3D Concrete Printer from the Eindhoven University of Technology has been the main subject in the creation of a design language for 3D Concrete Printing. The strategy applied by this printer, to use a 4 degree of freedom gantry system has produced most of these guidelines, there are however some issues with this 3D Concrete Printer. For example, the limited dimensions of the printer 11m(L) x 6m(W) x 3m(H) do not allow for printing big elements and the 3D Concrete Printer does not allow for on-site printing. The following modifications in the printer design need to be done to meet the requirements of the project: (see Figure 12)

1. The scale of the printer needs to be increased to increase the size of the printing bed and to increase the size of the printable objects.
2. The length of the printer along the X-axis is increased, to create the possibility to print multiple houses in one print.
3. An additional printing bed able to move along the Z-axis of the printer is introduced to provide the opportunity to print multiple floors.
4. An additional hydraulic system is introduced along the Y-axis, to be able to rotate and lift the printed parts in the right position.

FABRICATION PROCESS
The overview of the fabrication process is visible in Figure 13. The first step in the fabrication process of the house is printing the concrete structure. Each floor of the house is printed separately and each floor is divided into 3 printing parts, related to the facade, core and the functional part of the basic floor plan. The different printing parts are printed when they are rotated 90 degrees. After each of the parts is printed and hardened it will be rotated 90 degrees by the printing bed and assembled, connected to the parts already printed. The sequence of printing is really important since each part supports or is supported by another part. The final step is the finishing, after all parts are printed and assembled the windows and doors can be placed in the printed structure.

CONCLUSION
In order to fully utilize the benefits of new techniques in architecture and structural design it is necessary to change the current ideas about building. In case of the use of a 3D Concrete Printer both the material and the printer kinematics are to be considered as new design constrains that ask for a new way of building. With respect to the design constrains a new design language is created. As seen in our case, the design of a low cost housing type changed radically when the fabrication process became a major design constraint in the design.
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Hygro_Responsive Structure

Material System Design

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Responsive systems have the ability to transform their form in response to changing conditions. The responsive system design has been shifted to material system design. Material system design examines the material and utilizes the material behaviour to accomplish the responsiveness. A material system comprises the interaction of the material with form, structure, energy and environment. The study questions how the material properties can be utilized to develop computationally enhanced responsive system which is not activated by energy or mechanical support.

Keywords: Computational form generation, material behaviour, Responsive material system

The responsive system, named as Hygro_Responsive Structure, integrates responsive material with computationally developed structure. It explores development of computational form and the material regarding the environment parameters. Humidity is response driver for the material and the sunlight is design driver for parametric form generation of the system.

The responsive material system is examined in three phases (see Table 1): (1) Exploration of the wood as material and as natural responsive system, (2) description of the responsive composite material and (3) design of the responsive system structure.

EXPLORATION OF THE WOOD AS NATURAL MATERIAL

The hygroscope (ability to take or yield moisture) and anisotropy (directional dependency of material characteristics) are the embedded properties of wood that affect the material behaviour. First, makes the wood material responsive to the humidity. Wood takes the moisture and swells in humid air, while it yields the moisture and shrinks in dry air. Second, leads to dimensional change when the humidity content changes according to its grain direction.

The dimensional changing of wood has been accepted as deficiency in general since it causes splitting, cracking or opening in wood products. However, the study utilizes the hygroscope and anisotropy as an instrument to design a responsive material system.

Natural responsive system

Pinecone sets a precedent for the natural responsive system that exploits the material behaviour. The scales of the pinecone present the humidity-driven movement [1] arising from the hygroscopic property. They open by shrinking in dry air and close
by swelling in humid air to release their seeds in optimum humidity conditions for the proliferation [2]. The opening and closing movement depends on the bilayer material structure of the cone scales, in addition to hygroscope [2]. The bilayer structure consists of two parts as active and passive layer according to their sensitivity. The active layer (outer layer) is more sensitive to the humidity and reacts by expanding or contracting; in comparison to the passive layer (inner layer) is less sensitive and remains stable [2]. The sensitivity difference between the layers results the cone scales to curve outward (opening) or inward (closing) [2]. The bilayer structure of the cone scales is referred for the responsive composite material.

**DESCRIPTION OF THE RESPONSIVE COMPOSITE MATERIAL**

The case studies for the responsive material system design, that exploit material inherent properties, have been analysed [1,3,4]. In the case studies, the hygromorphic composite is utilized as a responsive material integrating the cone’s actuating principle with hygroscope and anisotropy in wood [3]. Regarding the extracted knowledge from the analysis, a responsive composite material is developed that possesses the hygromorphic properties of wood. The main aim of the composite is to utilize the differentiation in the composite’s layers’ properties for the responsiveness (also refer to Table 2).

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**Table 1**
The design process of responsive material system.

**Table 2**
The stages of the responsive material development.
A bilayer composite is produced as responsive material by combining wood veneer (as active layer) and polymer sheet (as passive layer). The active layer is chosen according to the shrinkage capacity of wood. The polymer materials are tested to select the passive layer. The layers are adhered to each other with the epoxy resin solution. Active wood layer responses to humidity by changing its dimension. Passive polymer layer does not exhibit any dimensional changings and limits the hygroscopic elongation of wood by remaining stable. The stability of polymer layer provides a constraint for dimensional changing of wood and this results wood to bend. Figure 1 displays the response principle of bilayer composite. As the humidity content increases, active wood layer takes moisture, swells and elongates. In the composite, the wood layer cannot elongate and this results wood to bend in the polymer direction.

The humidity response of the composite is observed through the experiments executed in a controlled environment (humidity chamber). A simplified humidity box is provided by referring the mechanism of the climate (humidity) chamber, as displayed in Figure 2. The simplified humidity box consists of a humidifier device (arranges the humidity content), humidity sensor (detects the humidity content) and fan (provides the airflow). The conditioned humidity content (80%) is accepted as the upper limit for the indoor thermal comfort conditions and the highest humidity content of Istanbul according to references. An ideal setup is provided to test the composite samples under controlled humidity conditions, as illustrated in the diagram. Figure 3 displays the setup diagram and the inserted composite samples on the trays.

The material experiments purposes to understand the material behaviour. The parameters affecting composite behaviour are indicated as (1) polymer and (2) wood types, (3) the grain orientation of wood and (4) thickness of the layers. Addition to material parameters, the polymer layer is got fibered in order to facilitate grain directionality of wood. The influencing parameters are tested through material experiments. The material behaviour is improved by adjusting these parameters.

The evaluation of the material experiments is achieved through quantitative (numerical) and empirical (observational) analysis methods. In the observational analysis, the curvature change is analysed and a response graph is drawn to compare the curvature change of the composite samples. Each experiment takes 60 minutes and captured per 4 minutes. The curvature change of each composite material is defined in each caption (Figure 4) and a response graph is drawn as presented in Figure 5. The response graph benefits to compare the curvature change of composite samples, derived from the humidity responsiveness.

The observational (empirical) analysis is justified by using numerical analysis. The curvature change of each composite is estimated through calculations. Holstov and the other researchers adapt Timoshenko’s theory for bi-metal thermostats to predict the curvature change since the bilayer structure of the composite shares similarity with bi-metal thermostats [4]. By using the formula shown below, the empirical process has been justified.

\[
K = \frac{1}{R} = \frac{\Delta a . f(m, n) . \Delta MC^t}{t_{total}} + \frac{1}{R_0} 
\]

\[
\Delta \alpha = a_a - a_p
\]

\[
f(m, n) = \frac{6(1 + m)^2}{3(1 + m^2) + (1 + m.n)(m^2 + \frac{1}{m.n})}
\]

\[
m = \frac{t_p}{t_a}; n = \frac{e_p}{e_a}
\]

According to the conducted material experiments, the optimum parameters for responsive material are listed below:

- Among the tested polymer types (PETG, PVC and PC); PVC polymer type is used as a passive layer of the composite (PVC>PETG>PC). (PC: Polycarbonate-PETG: Polyethylene terephthalate glycol-modified- PVC: Polyvinyl Chloride)
Figure 1
The response principle of the composite and wood.

Figure 2
The simplified humidity box.

Figure 3
The setup diagram and composite samples inserted in the trays.
Among the tested wood types (maple (1), ash (2), beech (3) and oak (4)); beech is employed as active layer of the composite since it has higher hygroexpansion (shrinkage) percentage and displays more dimensional changings (3>1>2>4).

The used polymer (PVC) has 0.15 mm thick since as it gets thinner, the curvature change of the composite increases and its response time shortens.

Among the different cutting direction of the wood veneer (perpendicular cut (1), parallel cut (2) and diagonal cut (3)); the tangential veneer samples cut perpendicularly to the grain direction for the responsive composite material (1>3>2).

The fibered polymer layer is employed to facilitate the curvature change by adding fibers through laser cutting. Among the tested fibered polymer types, the selected polymer has denser fibers whose distance is 2.5 mm.
Based on the optimum parameters, the radius of curvature of the most responsive composite is calculated by applying Formula. The calculations enable to simulate the responsive behaviour of composite through computational tools at further stages. The curving action is simulated by using the curvature change calculations, through computational design tool to represent the responsive behavior of the composite, as shown Figure 6.

**RESPONSIVE SYSTEM STRUCTURE**

The study aims to develop a responsive structure whose responsiveness is accomplished through the responsive material. The design of the structure system relies on the parameters which are evaluated by sunlight. The design process of the structure comprises (1) sunlight analysis, (2) initial form generation and form development. Sunlight parameters are effective for the relative humidity content and accepted as the design parameter for the form generation. The construction process involves the (1) joint design, (2) fabrication and assembly process.
**Sunlight analysis**
Sunlight analysis is conducted through simulation in Ladybug (the environmental analysis plug-in of Grasshopper). The initial form of the structure is generated in Rhinoceros regarding the sunlight simulation. Figure 7 represents the form generation process of the structure according to sunlight simulation. As shown from the Figure 7, as the form becomes more complex, its surfaces get different sunlight in a day. Figure 7.j is selected for the form of the structure, since its surfaces take different sunlight angels during the day.

**Form generation and development**
The parameters of the generated form are modified according to attractor points, whose location is indicated considering the sunlight simulation. Figure 8 illustrates the algorithms for the form development of the structure according to attractor points. The generated form is divided into the modules and each module has openings. Attractor points modify the scale of the modules’ openings since they are determined according to the sunlight simulation. In the resultant form, the brighter surfaces have bigger openings; while the darker ones have smaller openings.

**The construction process of the structure**
Computationally developed structure composes from modules and each module of the structure is made up two parts as shown in Figure 9. The modules are joined through finger joint method. The finger joint is constructed (drawn and fabricated) by using digital tools. Using finger joint aims to eliminate the usage of any adhesive or supportive materials to connect the modules. The joint connection of the modules provides the structure to disassembly and reassembly. 400 unique modules of the structure are regulated through Fabtools Plugin for the digital fabrication and fabricated with a laser cutter. The fabricated modules are assembled according to their joint connection.

The humidity responsive material is utilized as a panel for the structure. The responsiveness of the structure is accomplished through the responsive composite panels. The composite panels are installed into the openings of the modules. The structural system is made up of plywood material since it prevents the deformations arising from the shrinkage due to its multi-layered material structure.

The responsive panels are different from each other due the differentiation of the openings. The openings are regulated regarding the sunlight analysis. The relation between the panels and openings’ scales with sunlight is explained with diagrams in Figure 10. As the size of the openings changes as referred in Section 3.2, the size of the responsive panels changes. The modules of the structure are fabricated with responsive panels and assembled. The partial model of the structure is constructed and the responsiveness of the panels is tested in humidity box. As the experiment shows in Figure 11, the variation of the panels’ size affects their responsive behaviour. The bigger panels responses to humidity faster and achieve more curvature change than smaller panels.

The responsive panels curl inward (in the direction of passive layer) in humid air and the openings get close. However, in dry air the panels curl outward (in the direction of active layer) and the openings get open. The airflow is regulated and the natural ventilation is provided through the humidity driven movement of the panels.

**CONCLUSION**
The responsive material development is conducted with experimental study. The methodology of this study relies on learning by doing experiments. The outcomes of the experiments are analyzed and evaluated through empirical and numerical methods. In this study, the material experiments and numerical evaluations are executed in collaboration with material scientist. The responsive composite material is integrated with computationally developed form to create responsive material system, named as Hygro_Responsive Structure. This structure needs neither energy nor mechanical devices, as it exploits the embedded responsiveness of the material. The sys-
tem offers an energy efficient solution for the adaptive systems.

Further research will focus on the material computation to expand material understanding in design. The responsive behaviour of the material system will be simulated in digital environment and evaluated with analysis simulation tools.

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Photoreactive wearable: A computer generated garment with embedded material knowledge

A computer generated garment with embedded material knowledge

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Driven by technology, this multidisciplinary research focuses on the implementation of a photomechanical material into a reactive wearable that aims to protect the body from the ultraviolet radiation deriving from the sun. In this framework, the wearable becomes an active, supplemental skin that not only protects the human body but also augments its functions, such as movement and respiration. The embedded knowledge enables the smart material to sense and exchange data with the environment in order to passively actuate a system that regulates the relation between the body and its surroundings in an attempt to maintain equilibrium. The design strategy is defined by 4 sequential steps: a) The definition of the technical problem, b) the analysis of the human body, c) the design of the reactive material system, as well as d) the digital simulations and the digital fabrication of the system. The aforementioned design strategies allow for accuracy as well as high performance optimization and predictability in such complex design tasks, enabling the creation of customized products, designed for individuals.

Keywords: smart materials, wearable technology, data driven design, reactive garment, digital fabrication, performance simulations

INTRODUCTION

The advancement in the nanotechnology has led to big inventions in the fields of biology, medicine, and material science. In the information era, technology emerges rapidly providing scientists with more accurate tools to hack existing materials or to create new ones with tailored properties. Therefore, the applications of such materials has started to expand towards the design field.
Driven by technology, this multidisciplinary research focuses on the implementation of a photomechanical material into a reactive wearable that aims to protect the body from the ultraviolet radiation deriving from the sun. In this framework, the wearable becomes an active, supplemental skin that not only protects the human body but also augments its functions, such as movement and respiration. The embedded knowledge enables the smart material to sense and exchange data with the environment in order to passively actuate a system that regulates the relation between the body and its surroundings in an attempt to maintain equilibrium. Unlike most recent projects of wearable technology (Farahi et al, 2013; Farahi, 2016), this research is based on the elimination of electronics, which leads to reactive system with zero energy consumption, low maintenance and low rate of failure. Similar projects, embedding smart materials in apparel, have been conducted from other researchers, aiming for optimized thermal regulation of the body (Yao et al, 2015) or clothes reactive to sunlight [1].

This research, discusses the creation of a reactive to weather conditions garment, that also allows for optimized thermal regulation of the body, eliminating hazards from UV radiation. Its design strategy is defined by 4 sequential steps: a) The definition of the technical problem, b) the analysis of the human body, c) the design of the reactive material system, as well as d) the digital simulations and the digital fabrication of the system. The aforementioned design strategies allow for accuracy as well as high performance optimization and predictability in such complex design tasks, enabling the creation of customized products, designed for individuals.

TECHNICAL PROBLEM AND DESIGN SOLUTION

Harmful effects of UV radiation on human skin

Ultraviolet (UV) irradiation present in sunlight is an environmental human hazard. Divided into three sections, UVA, UVB and UVC, each one has distinct biological effects. UVC is effectively blocked from reaching the Earth’s surface by the tratospheric ozone layer. UVA and UVB radiation both reach the Earth's surface in amounts sufficient to have important biological consequences to the skin. UVB rays are absorbed into the skin, producing erythema, burns, and eventually skin cancer, whereas UVA is supposed to be weakly carcinogenic, and cause aging and wrinkling of the skin. (Matsumura and Ananthaswamy, 2004)

Based on data from satellites, scientists from NASA declared that the decrease of ozone amounts in the upper atmosphere above antarctica has caused an increase in the amount of ultraviolet radiation striking the earth [2]. This fact makes skin protection from UV radiation an urgent problematic.

Photoprotection

Our body has its own strong mechanism against the UV radiation which relies on the presence of melanin, a protein that is produced in the lowest level of our epidermis (Brenner and Hearing, 2008). Epidemiological data strongly support the photoprotective role of melanin as there exists an inverse correlation between skin pigmentation and the incidence of sun-induced skin cancers (Gilchrest et al, 1999). However, melanin can also have toxic properties, especially after exposure to UVR (Kvam and Dahle, 2004). Moreover, commercially available sun protections like sunscreen have been proven harmful for our bodies (Salinaro et al, 1997). Recent research from the University of Copenhagen also states the harmful effect of the sunscreen on men, decreasing their fertility [3].

Design solution

Taking into consideration the aforementioned studies, this research investigates alternative, non harmful ways of photoprotection, through a reactive wearable that fluctuates its permeability according to the presence of direct sunlight, using smart materials. In contrast to photoprotection with conventional clothes, this research discusses an optimized to thermal comfort garment, which increases its porosity at
the parts exposed to direct sunlight, allowing the less exposed parts to remain less porous, increasing the breathability of the body at its warmer parts, keeping the colder parts warmer (Fig. 6). The potential users for such a wearable are people exposed to direct sunlight in daily basis due to their profession or hobby such as farmers, fishermen and construction workers.

MATERIAL SYSTEM

Photomechanical material

By identifying the discussed problematic (UV radiation) as the stimuli for the smart material embedded in the wearable, a less complex and more efficient dynamic system is achieved. Therefore, light has been proven the optimum stimuli for a photoprotective wearable. Furthermore, light is a clean energy that can be rapidly, precisely and remotely controlled, as well as its efficient use is necessary for establishing a sustainable society (Mamiya, 2012).

Regarding the actuators of the system, materials with photomechanical properties which transform photon energy into kinetic energy have been selected. In the nanoscale of such materials, molecules that directly absorb the photon and convert its energy into a chemical reaction are ideal transducers of light into motion because the chemical change is usually accompanied by a geometrical rearrangement. In many cases, photochemical reactions can be reversed, so that the process can be repeated. Ordered media, such as liquid crystals, can align the molecular-scale motions to produce motion, like bending or twisting, on much larger, micron to millimeter, length scales (Kim et al, 2014). Other researches show that the mechanical properties of the photoreactive liquid crystals can be defined by changing the contained photoreactive azobenzene crosslinker, in an attempt to control the photomechanical effect (Garcia-Amoros et al, 2011). This could lead to a gradient of geometrical deformations of the system under direct sunlight according to the needs of the body.

Finally, researchers from China report a novel strategy for the preparation of rapid and reversible photo-driven actuators consisting of an active linear azobenzene polymer layer and a passive silk fibroin substrate, avoiding the need for oriented azobenzene liquid crystalline elastomers, just through depositing linear azobenzene polymer on the top of silk fibroin film (Hongying et al, 2014). This logic, of using bilayer actuators, is known for years and has been applied in both adaptive architecture (Rüggeberg and Burgert, 2015) and wearables (Yao et al, 2015), due to the resulted big deformations, therefore it has been selected for the synthesis of the photomechanical material of the discussed garment.

Reactive component

Embedding the smart material in a flexible geometrical system made of fabric, variation of the system’s porosity according to the amount of bending of the photomechanical part can be achieved, allowing for adaptive skin thermal comfort and photoprotection. The control of the photomechanical reaction by the manipulation of the illumination conditions such as light intensity enables diverse air and light permeability along the wearable (Fig. 7). More specifically, the reactive components that are located on the parts of the body which are exposed to direct sunlight remain open in order to allow for maximum breathing of the skin but also protect the skin from the UV radiation since the opening are oriented in such a way that perpendicular light does not passes through. On the contrary, the components located in the parts of the body that are in shade, remain closed in order to keep the warmth of the body (Fig. 6). Similar behavior can be found in nature in blooming plants, which open during the daylight and close during its absence. Studies on biomimetic photoresponsive polymer springs have proven that shape-shift under irradiation with UV light and can be pre-programmed to either wind or unwind, as encoded in their geometry (Iamsaard et al, 2016), allowing custom deformations and design solutions.
HUMAN BODY ANALYSIS AND RESULTS

Optimization of thermal comfort

As mentioned above, what distinguishes the discussed wearable from conventional clothes in terms of photoprotection, is the fact that it simultaneously protects the skin from UV radiation by covering it as well as allows it to breath. To optimize this function, the design has been the outcome of a digital juxtaposition of various data, such as body thermal maps, sun exposure and sweat maps. Thermographic images, from recent research (Tanda, 2015), indicating the time-evolution of skin temperature during exercise, have been used to define the parts of the body which need more cooling. Simultaneously, empirical data from body exposure to sun has been considered to define the most prominent to sunburn parts, consequently the parts that are exposed to direct sun rays. Finally, data of regional sweat rates across the body of women athletes (Smith et al, 2011) has been taken into consideration for the purpose of this research. The results show that the part of posterior torso and the lower back as well as the area between and under the breast have the highest sweat rates after exercise. (Fig.1)

Optimization of movement

In addition to thermal comfort, the proposed photoprotective wearable has been designed to augment and not disrupt the movement of the body. Analog, two-dimensional images of muscular geometries that show the direction of their fibers as well as the less contacted parts where inputs for the design. Furthermore, Kraissl’s lines have been an additional input of the design process. The aforementioned lines, being perpendicular to the underlying muscle fibers, (Lemperle et al, 2015) correspond to the alignment of collagen fibers within the dermis and define the direction within the human skin along which the skin has the least flexibility. (Fig.1)
Material zones of the wearable

Based on the aforementioned data, body analysis of the upper part of a woman body has been achieved. The conclusion is depicted into an optimized to movement and thermal comfort garment, which consists of 14 different patches categorized into three zones (Fig.2). Zone 1 consists of the highly sweating parts, which are located at less stretchable parts of the body and are mostly exposed to the direct sun radiation. Zone 2 consists of the highly sweating parts, which are located at more stretchable parts of the body and are less exposed to the direct sun radiation. Finally, zone 3 consists of the least sweating parts, which are the most stretchable parts.

Consequently, zone 1 has been characterized more appropriate to place the reactive components, since a) it lacks thermal comfort, b) its parts are the less stretchable, so as the reactive kinetic behaviour of the system will not be affected by the body movement and c) the system can be activated more efficiently by the direct UV radiation. Zone 2 includes the rest of the highly sweating parts and is characterized by its need for thermal comfort and zone 3 is characterized by its ability to be stretched. Based on the aforementioned assumptions three different fabrics have been chosen for the three zones. (Fig.2)

Fabric

In the framework of creating a garment for users that do laborious works under high temperatures, fabrics which are a) light colored, so as they reflect as much as possible the UV radiation, b) breathable, so as the thermal comfort can be maximized and c) comfortable have to be used. Previous research on fabrics states that among the two quantitative common comfort parameters are tactile and thermal comfort. Tactile comfort mainly depends upon mechanical properties such as stretching, bending, shearing and compression at low stress levels. On the other hand, thermal comfort is related to the fabric’s transmission behaviors, namely thermal resistance, water vapor transmission and air permeability (Behera, 2007). Therefore, 100% cotton and 100% linen has been selected as comfortable fabrics made of natural fibers that have high air-permeability. Accordingly to the same research, testing the air-permeability between cotton and linen, it shows that linen fabrics permit more air to pass through, as compared to 100% cotton fabrics of similar areal density. The reason for the higher permeability in the case of linen and linen-blended fabrics can be attributed to the lower hairiness of these yarns, due to their longer fiber length as compared to cotton.
From the above, it is concluded that 100% linen will be used for zone 1 and zone 2, as they need higher air-permeability, and 100% cotton will be used for zone 3, as it has higher stretchability.

**Geometrical configuration of reactive component**

The photomechanical material is placed on the selected patches and its position and orientation has been based on the Kraissl’s lines, at the specific part of the body. As mentioned before, Kraissl’s lines follow the less stretchable direction of the skin therefore the photomechanical material, considered as a rectangular unstretchable strip, has been oriented parallel to them. In order to increase the breathability of the garment, cuts on the fabric have been placed at the sides of the photoreactive strip, in such a way that when it bends, due to UV radiation, the cuts open and let the air pass through the garment and cool down the body, without letting direct sun pass through them (Fig 6).

**DIGITAL SIMULATIONS AND FABRICATION TECHNIQUES**

**Design of wearable**

The design of the wearable has not followed conventional patterns of sartorial techniques but is designed digitally. It has been based on a mesh of a 3D female body with standard proportions. Lines, representing the seams of the garment have been designed on top of the mesh, separating the upper part of the body in 14 different patches, as explained before, creating a T-shirt. By inputting the 3D scanned body of a specific individual, as well as its body analysis data such as thermal map, taken from infrared pictures or sweat rate data, the design can be customized.

Further computational processes have taken place on the reactive patches which host the photomechanical strip as well as the aforementioned cuts. A process of computational design has been followed in order to embed the cuts into a holistic design pattern. Lines, vertical to the Kraissl’s have been designed and distorted through algorithms, so as they create circular cavities, where the photomechanical strip is placed (Fig.3).
Flexible cut patterns

Kirigami is a well known technique of cutting paper in order to create pop up designs that has also inspired scientists to create expandable electronics [4]. The aforementioned cuts that have been designed in order to increase the breathability of the discussed wearable, have been inspired by this technique, allowing the creation of 3D configurations from simple planar sheets. Several physical tests (Fig.4) and digital simulations have been conducted in order to find the most flexible patterns of cuts. During the first trials, linear configurations of cuts have been tested. The samples with the cuts shifted after every second line, showed significant flexibility while the samples with repetitive cuts were static. The distance between the rows of the cuts, the distance between the cuts of the same row as well as the lengths of the cuts appeared to be the key parameters to define the flexibility of the cut pattern. Consequently, the shortest the distance between the rows and the one between the cuts the more the flexibility. Moreover, the longer the cuts, the less force is required to open them. Although most of the resulted cut patterns were flex-

Figure 4
Technical drawing that depicts the tested cut patterns indicating the flexibility of each one (green dot: more flexible, orange dot: less flexible, red dot: not flexible).

Figure 5
Physical test of cut pattern flexibility. Top: Longer linear cuts show more flexibility than short linear cuts. Linear cuts deformations induce creases to the fabric. Bottom: Triangular cuts in opened and closed configuration showing that its deformation does not induce creases to the fabric.
ible enough, crease were induced to their fabric by their opening, which did not cohere with the objectives of the system. (Fig.5)

Therefore, further tests of cutting patterns have been conducted, keeping stable the optimal parameters of the previous tests. This time, samples with triangular and circular configuration of cuts were tested and showed more flexibility than the parallel cuts. Furthermore, no increase of the fabric outline was induced, which makes these cut patterns more appropriate for the system. (Fig.5)

Based on these results, circular cuts longer than 10 mm, shifted every second row, have been placed along the aforementioned distorted pattern of the active patches. The distance between the cuts is 2 mm and the distance between consecutive cuts has been kept down to 2 mm. (Fig.3)

**Digital simulations**

Digital simulations of the kinetic behavior of the system have been conducted using the Physics engine of Grasshopper 3D, Kangaroo. The fabric is represented by a mesh with high stiffness, so as to better represent the mechanical properties of the fabric. Linear forces, pointing at the positive z direction, represent the forces caused by the bending of the photomechanical material. (Fig.6)

The result of the simulation depicts the approximate deformation of the system, although due to the lack of embedding material properties to the algorithm, as well as geometric constraints of the mesh the deformation is not accurate. Therefore the digital simulations precede the physical test, in order to save time and material and when satisfactory results are obtained, physical experiments follow.

The 3-dimensional representations of the reactive component have been created in order to show the shape shifting of the garment according to various sun intensity scenarios (Fig.7). This allows the elimination of design errors, and verifies the performance of the final system by collecting and analysing the resulted data.

**Fabrication of wearable**

In order to fabricate the T-shirt, a digital 2D pattern has been generated by unrolling the 3D geometry of every patch (Fig.2). This process has been conducted with the use of Kangaroo, applying gravitational forces to the oriented parallel to the floor mesh patches. In the unrolled patches, a small difference of max 1% between the area enclosed in their outline and the area of the original 3D mesh has been observed. Nevertheless, these small differences will be covered by the elasticity of the fabric.

Subsequently, the digital fabrication of the active patches has been done using laser cutting technique by engraving the pattern of the distorted lines and cutting through the cotton fabric in order to create the actual cuts for the breathing (Fig.8). A thin film of thermo-adhesive has been placed close to the cuts so as they do not fray. After having laser cut all the patches, stitching by a sewing machine will take place in order to create the complete garment.
Synthesis of photomechanical strip

Regarding the synthesis of the photomechanical strips, the first tests have been conducted in collaboration with the Institute of Nanoscience and Nanotechnology of the University of Barcelona. Nematic liquid single crystal elastomers with the azo compound acting as a cross-linker (Garcia-Amoros et al, 2011) of 46 mm length have been produced and showed 7% (43 mm) contraction after irradiation with white-light, recovering to their initial shape when the light turned-off (Fig.9). Further tests need to be done in order to introduce the bending behavior by applying the bilayer logic. Moreover, improvements to the synthesis need to be made in order to enhance the contraction of the photomechanical strip induced by sunlight, which is currently 1% as well as reduce the time of reaction which is currently 2 minutes. When the photomechanical elements will be finalized and synthesized they will be cut into strips of 30 mm and embedded into the fabric in order to complete the dynamic system.

CONCLUSION

This research aims to expand humans’ capabilities in their everyday life through an informative, tactile environment, that can sense and respond, placed on human skin. The embodiment of responsive materials, such as photomechanical polymers, in a garment, allows the emergence of reactive photoprotective wearables, eliminating the need of electronics.

At the current state the development and verification of the digital design strategies have been accomplished and part of the fabrication of the garment has been completed. The photomechanical material synthesis is programmed to be optimised in the following months. Subsequently, material tests and design probes of the dynamic system will be conducted and documented in order to verify the digital simulations by a multidisciplinary team, involving private companies and public institutions. The final aim is to create a functional demonstrator, a photoreactive wearable that remains in tune with the user and its environment.
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Craft and Digital Consequences

Micro-Hybrid Explorations at (Full) Scale

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This paper presents a comprehensive project-based research investigation that uses both drawing and modeling to challenge conventional design space. Situated at the University of Kentucky-College of Design Applied Computation Center (CoDACC) in Lexington, KY, this independent undergraduate research project reveals an immersive framework that develops, evaluates, and assesses both graphic and three-dimensional information at full scale. This research provides a framework that seamlessly negotiates analog and digital means of communication and prototyping. This paper outlines the micro-hybrid design process to frame topics germane to today's increasingly complex built environment. The paper also includes the micro-hybrid decision-making matrix and discusses the evaluation of the produced artifacts. The research demonstrates how the micro-hybrid process can reveal both the craft and consequences related to design experimentation and construction. Further, the micro-hybrid process has been shown to deepen a student's understanding of the composition of materials and a student's awareness of forces and structural loads, which in turn has produced a deeper appreciation for the principles of structures and an improved mastery of manufacturing jointing details.

Keywords: Digital, Pedagogy, Fabrication, Experimentation, Simulation

INTRODUCTION

Today, the infusion of design thinking methodologies in combination with simple tools, sophisticated machinery, and both natural and machine-made materials enable design students to rapidly explore and experiment in ways that just five years ago were not economically possible. This paper presents a strategy for leveraging this enhanced design fluidity by iteratively producing a series of multi-dimensional design artifacts (drawings, models, visualizations, and simulations) that explore phenomenological visual registers through built form.

This research builds upon an established architectural design process, which has typically been used as a platform for integrating new tools, as a way of extending both unexpected and unknown creativity. As Sylvia Lavin states in her interview with the Los Angeles Forum, “Increasingly, larger amounts of
creative resources are being put into producing new tools and concepts that are designed not to make things, but to amplify the creative capacities of others” (Lavin, 2015). Architecture is driven by the synthesis and integration of these new tools. This has led this research to produce an intuitive and inspirational way of thinking and making referred to as the micro-hybrid. The micro-hybrid is characterized as a process-driven resultant that involves both physically and digitally produced volumes in response to operative considerations. These responses expose digital consequences that inform subsequent iterations. The notion of considering digital technology and using computer aided design tools in this way, is viewed as a way of extending the tenets of design thinking into architecture. In his book, Animate Form, Greg Lynn argues: “Traditionally, in architecture, the abstract space of design is conceived as an ideal neutral space of Cartesian coordinates. In other design fields, however, design space is conceived as an environment of force and motion rather than as a neutral vacuum” (Lynn, 1999). It is within this creative process that the micro-hybrid aligns with Lynn’s use of different software and hardware platforms to increase a student’s understanding of spline, blob, and movement and ultimately their relationship to construction and design.

**Guiding Questions**

This collaborative research project centers on three core topical areas: process and parametric embodiment, rigorous physical and digital integration, and situated decision-making. From this context, three primary research questions emerge:

- How can the proposed micro-hybrid feedback loop model a workflow that results in a hybridized design research and challenges the traditional conventions of drawing, rapid prototyping and additive/subtractive fabrication methods?
- How can the digital design experience be more connected to the tangible and physical outcomes of the design process?
- Why is the micro-hybrid technique a necessary component of a design process in education and practice today?

**Informal Observations**

This research stems from a current frustration with today’s prescribed and limited design studio curriculum that does not keep pace with industry innovations and focuses on generating details of traditional architecture, rather than using the detail as a formative departure point for design. This research builds upon the current exhibition at Sci-ARC entitled Close-Up, that showcased modern methods of designing as a mechanism for advancing architectural knowledge. The intent of this research is to take design methods to another level and to involve the full capacity of opportunities that digital tools currently allow, while also framing design education as an ever-changing pedagogical model. This enhanced capacity involves simulation, computation, rapid-prototyping and iterations using digital fabrication techniques like 3D printers, CNC milling, and robotic assembly to build form.

**Methodology**

This paper presents five case studies that probe two intrinsically linked categories: the methods of making and the means of simulation. With an end goal of advancing building technologies using both theory and hands-on investigation, the micro-hybrid process advances research in the domain of abstracting craft while adding new knowledge to understanding the impact on learning. In design self-efficacy (DSE) research studies conducted by Dr. Gregory Luhan at the University of Kansas, Texas A&M University, and the University of Kentucky, these areas are shown to significantly deepen and positively impact the study and design architecture (Luhan, 2016). As part of a larger typological exploration, this research simultaneously works across three scales of hybridization: the micro-hybrid, the mild-hybrid, and the full-hybrid. While this research focuses specifically on the micro-hybrid, emergent trends revealed through the study point towards scalar implications. The micro-
hybrid reveals simple, intuitive mechanisms that control functions associated with the means of making and the simulation-based tools used to examine form. In this sense, the boundaries between the drawing and the model process narrow, closing the gap between representation and reality.

Neil Spiller when discussing the new generation of architects says, “Those architects featured in the issue agree that the four dimensions of architecture (three spatial dimensions and time) are not enough for a new century; each is grasping for a new fifth dimension in their work, and developing new protocols of drawing to discover it” (Spiller, 2013). On the other hand, while analyzing Neil Denari’s 1989 project for Tokyo International Forum, in his book Drawing the motive force of architecture, Peter Cook brings up the comparison between different types of drawing; information drawing and art drawing. “This last, rather loose epithet is often used in architectural circles to describe a drawing that may be used by the author for exhibitions and books, but where the “useful” version has already become part of the working process” (Cook, 2014). After evaluating these two ideas, the search for a fifth dimension in drawing is responded to by the materiality and color used in the representation of micro-hybrid as well as the combination of informative and artist drawings described by Cook. This representation correlates to the actuality of the model material, and the necessity to designate difference between the physical and digital realms of the project. Beyond this fifth dimension, the micro-hybrid looks at the possibilities of “drawing” qualities. As Bryan and Grosman describe the drawing is another layer to hybridize a design medium as a result of the dialogue between digital and physical modeling. “Drawings are explorations of time; models are exploration of space. The digital model as traditionally understood has no advantage over the physical model except for expediency. The digital drawing, on the other hand, creates new opportunities” (Bryan and Grosman, 2016).

The analog methodologies used in this study include: precise measuring, drill pressing, belt sanding, Dremel sanding, chiseling, and oil coating. These methodologies align with the designer’s intuition whereas the digital explorations are situated as structured responses that increase in complexity as the project shifts in scale or are used in simulations of gravity, weight, and material plasticity. These other layers of information seems to be necessary for maintaining the project’s relationship with architecture as Pallasmaa describes, “… in my view, architecture turns into mere formalist visual aesthetics when it departs from its originary motives of domesticating space and time for human occupation through distinct primal encounters, such as the four elements, gravity, verticality and horizontality, as well as the metaphoric representation of the act of construction” (Pallasmaa, 2012).

**Research Design**

The formal process for developing the micro-hybrid is rigorous and reflective. The procedural experiments begins with creating a primitive solid. For the initial iterations, a cube is used.

This was followed by establishing an operative condition assigned to the cube and used to determine the project “cost” - a numeric value or price point for the micro-hybrid. Subsequent gestural drawings were generated to determine the “loose fit” of the project. The impact of this process led to the development of the digital model and machine-made artifact. The digital model was developed from guidelines that emerged from the gestural drawing. The models use geometric primitives in randomized, hybridized or ordered ways. Both digital and physical models are edited in digital space and then reprinted. The digital print was then analyzed, evaluated, and assessed by the design team. The team evaluated each artifact based upon the conceptual elements of each of the operative micro-hybrid conditions. These elements are measured against: initial orientation of the primitive, the relationship to the ground plane, and the apparent recognition of the operative condition. If conceptual purity is determined successful, the artifact is reflected upon. If conceptual fail-
ure is determined, the artifacts were re-edited in real
time and corrected by hand. A fitness test verified the
machine-made object’s ability to plug into the core
of the primitive. This stage revealed issues related to
play, tolerance, and looseness of fit. The end result
a successfully completed project, includes the possi-
bility for future improvement, but subsequent iter-
ations were beyond the scope of this research study.

Limitations and Delimitations
The primary limitation of this study conducted in the
spring 2017 semester was the modest number of it-
erations and students involved in the research. Data
collection was limited to students who participated
in the study.

The limitations of the study related to the micro-
hybrid were:

- Since this was not a controlled experiment, re-
  sults may have been affected by outside influ-
  ences.
- Because the student participants self-
  reported data, the study was limited to the
  student’s unverified perspectives.

In spite of these limitations, every possible effort was
made to design the research in a way that maxi-
mizes the potential contribution of the study’s find-
ings about how the micro-hybrid process is regis-
tered in architectural design studio education.

The delimitations of the micro-hybrid research
design include a focus on both undergraduate and
graduate architectural design research. The results
of this study could be generalized to teaching meth-
ods in courses that involve research-driven, project-
based learning such as design studios of all types. In
further studies, generalizability will focus on the use
of the micro-hybrid decision-making matrix.

Definition of Terms

- Operative Conditions - The input which is a re-
lational driver between the individual parts,
their orientation and their influence on the ar-
chitectural composition.
- Digital Consequences - The design method
and thought process, including the phe-
nomenological and physically observed toler-
able, that inform the resultant product (ar-
chitectural artifact)
- Micro-hybrid - The scale of the object
- Mild-hybrid - The scale of the installation
- Full-hybrid - The scale of the building
- Primitives Forms - The initial geometric input
for the process: cube, sphere, torus, pyramid,
cylinder, and cone.
- Subtractive Core - The connection method of
the natural and machine made materials (tan-
gential plane, incised plane, and cored plane.)
- Gestural Drawing - A digital drawing to visual-
ize the operative conditions as a 2D architec-
tural composition.
- Parasitical Geometrical Relationship: The use
of the machine-made form to directly host to
the primitive’s cores.
- Randomized Digital Response - Assigning geo-
metric primitives randomly to create a mass-
ing.
- Ordered Digital Response - Assigning geo-
metric primitives in order and following a se-
quence, to create a rhythmic massing.
- Hybridized Digital Response - Assigning geo-
metric primitives both in order and random-
ized to create a massing flow.
- Purity assessment - Comparing the final tan-
gible outcome with the initial concepts of the
Operative condition and Gestural Drawing.
- Fitness test - Checking the tolerance between
digital and manual fabrication methods, and
how the natural and machine made materials
fit together.

The Micro-Hybrid
The term micro-hybrid has been borrowed from the
automotive industry. In the automotive industry,
a hybrid car switches between the use of battery
and combustion engine. The choice of one en-
ergy source or another is based on a variety of fac-
tors including the environmental conditions, auto-
motive speed, and necessity for acceleration, etc. In the architectural design context, the micro-hybrid, switches between digital and physical design and fabrication platforms as a way of increasing the intellectual design performance. Rooted in the processes of design-thinking and fabrication, the key drivers of the micro-hybrid design process center on the efficiency and rigor of making at the regional and global scale whereby registering the micro- and macro-factors that influence the decision-making process, including: pragmatic functions of form, aesthetic, a structure's response to force, and orientation to local context (Figure 1).

The micro-hybrid process is an iterative twelve step process. The micro-hybrid process includes:

1. Manufacturing a primitive geometric form using natural materials;
2. Defining physical subtractive cores as connection methods;
3. Developing a digital model of the primitive geometric form;
4. Establishing an idea-based typological framework that can be modeled;
5. Orienting the digital model to the framework;
6. Generating a 3-dimensional gestural drawing;
7. Initiating the digital design of the typological addition;
8. Adjusting the physical design of the typological addition through the integration of machine-made materials;
9. Conducting an alignment and fitness test;
10. Modifying the tangible outcomes to meet the evaluation requirements (feedback loop);
11. Photo-documenting the final artifacts; and
12. Reflecting on the design process and lessons-learned.

As part of the micro-hybrid research, these twelve steps were tested against five operational conditions ranging from implied adjacencies, direct connections, surface reliefs, balance, and cantilevered projections. The resultant product was a compositional strategy or spatial dialogue that adhered to or responds to the material selection (natural or machine-made) and the corresponding detailed joinery (Figure 3).

Referring to architecture as a spatial “dialogue”, in relation/response to form, forces, and motion, has started a new design thinking about the architectural design process and how it can be driven to maximize the design possibilities. Tom Wiscombe, whose work can be described as a cohesive combination of parts that create an object-oriented architecture, uses the term “worlds” to explain his work, not as an extension of “world” or “nature” but rather, as a new way of thinking about architectural design. Wiscombe contends that architecture must be viewed as an individual object not only in relation to its context, as a field of forces, information, interaction and in a variety of forms and scales, but as an independent “world” (object) that has its own relations, connections inside and out. Wiscombe introduces the idea of “loose-fit” design, as he borrows the theoretical physics vocabulary: “I'm definitely attracted to idea of things existing discreetly but signaling to one another without touching or fusing together - this provides the basis for a new, non-literal coherence of things while also avoiding superposition and collage” (Wiscombe, 2016).
Whether analog or digital, this research continues to examine the impact of gravity, weight, materiality, aperture, and fluidity on the produced artifacts and the means used to assess the fitness of its outcomes. In each case study, the students' work the designs to failure to iteratively refine the resulting artifacts. This design research drives investigations which act as a result of an innovative and rigorous design methodology and pedagogical structure that tests and calibrates both additive and subtractive processes. In addition to the artifact, the consequences of the selected tool and the digital means used to evaluate each study are viewed as enabling devices that inform the design solution's construction means and methods. This research produced results that demonstrate the impact of the decision-making process. The consequences of these actions are presented as a rubric-based decision matrix. This matrix enables the design team to evaluate the fitness and the alignment of each design iteration to a given set of criteria. Information obtained through the decision tree is subsequently fed back into the model so that additional investigations can be studied. The analog methodologies used in the study align with the intuitive design process, whereas the digital explorations have demonstrated a more structured response that aligns more with project complexity and material plasticity.

### Micro-hybrid_Adjacency

This prototype examines dead-load as an operative condition for which the relational driver is between the individual parts and parametric inputs. The design process starts in analogue mode with the selection of a cube as a primitive geometric form. As part of the physical design modifications, one core is physically assigned to the form as the first means of design modification. This core allows for the adjacent connection of the natural and machine made objects. The first set of modifications informed the decision process of primitive orientation as a flat relationship to a resting plane.

The starting point for the continued design process centers on digitally collected information that is gathered from the initial primitive and its modification. Based upon this information, a gestural drawing is made and serves as a guide for decision-making. This parasitical geometric relationship also serves as

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**Figure 2**

OPERATIVE CONDITION SYNOPSIS, Synopsis of decisions made for each operative condition - relative to the physical, digital, and evaluative properties of the process

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Operative Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Operative Conditions:</td>
</tr>
<tr>
<td>Primitive Preparation</td>
<td>Adjacency: 1 Form - Cube, 1 Core - Nested</td>
</tr>
<tr>
<td>Primitive Orientation</td>
<td>Connection: Flat, Twisted - Adjacent</td>
</tr>
<tr>
<td>Operation Designation</td>
<td>Relief: Flat</td>
</tr>
<tr>
<td>Digital</td>
<td>Operation Designation:</td>
</tr>
<tr>
<td>Gestural Drawing</td>
<td>Adjacency: Parasitic, Bridging</td>
</tr>
<tr>
<td>Digital Response</td>
<td>Connection: Random</td>
</tr>
<tr>
<td>Digital Fabrication</td>
<td>Relief: Random</td>
</tr>
<tr>
<td>Artifact Evaluation</td>
<td>Balance: Hybridized</td>
</tr>
<tr>
<td>Purity Assessment</td>
<td>Balance: Hybridized</td>
</tr>
<tr>
<td>Fitness Test</td>
<td>Balance: Hybridized</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Operative Conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artwork</td>
<td>Adjacency: Very Minimal</td>
</tr>
<tr>
<td>Long Spans</td>
<td>Connection: Long Spans Fail</td>
</tr>
<tr>
<td>Engravings</td>
<td>Relief: Engravings Are Unrelated</td>
</tr>
<tr>
<td>Unnecessarily Chunky</td>
<td>Balance: Unnecessarily Chunky</td>
</tr>
<tr>
<td>Price Point</td>
<td>Balance: Price Point</td>
</tr>
<tr>
<td>Failure</td>
<td>Balance: Failure</td>
</tr>
<tr>
<td>Maintained</td>
<td>Balance: Maintained</td>
</tr>
<tr>
<td>Altered</td>
<td>Balance: Altered</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operative Conditions</th>
<th>Adjacency</th>
<th>Connection</th>
<th>Relief</th>
<th>Balance</th>
<th>Cantilever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primitive Preparation</td>
<td>1 Form - Cube</td>
<td>1 Core - Nested</td>
<td>2 Forms - Cube</td>
<td>1 Form - Cube</td>
<td>1 Core - Nested</td>
</tr>
<tr>
<td>Primitive Orientation</td>
<td>Flat</td>
<td>Twisted - Adjacent</td>
<td>Flat</td>
<td>Go Corner</td>
<td>Floating - Angled</td>
</tr>
<tr>
<td>Operation Designation</td>
<td>Pattern</td>
<td>Adjacent</td>
<td>Surface</td>
<td>Balance</td>
<td>Projection</td>
</tr>
<tr>
<td>Digital</td>
<td>Operation Designation:</td>
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<td>Fitness Test</td>
<td>Balance: Hybridized</td>
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</table>
design guidelines for connecting the individual elements (Figure 2).

Using the information obtained from the physical modification of the initial primitive and the corresponding gestural drawing, the design combines information from the digital realm with the digitally scanned versions of the initial primitive. As a critical next step, the randomized geometric primitives are added to the digital model. This insertion is in direct response to the orientation of the initial primitive form, its subtracted core and the aforementioned parasitical geometric guidelines. Upon completing the design, the digital fabrication process begins. This process uses machine made materials to produce a 3D printed object. The physical translation of the digital design goes through validation tests that produce results that either completing the process or putting the gathered data back into the feedback loop to produce another iteration. This micro-hybrid considers the medium shift (digital/physical) as a minor digitally fabricated addition that adheres to the tenets of the initial primitive. As a result, it stays connected to the main concept of adjacency. As the last step in the process, the tolerance between the two fabrication methods and scanning are measured. The core of the main primitive is modified to fit the 3D printed part and close the loop of physical, digital and physical design/fabrication process (Figure 3).

Micro-hybrid_Connection

This prototype examines “connection” by linking two separate primitive forms. The orientation of the two forms were flat on a ground plane, but rotated so that the faces of the forms were not parallel to each other. Considering the connective nature of this operative condition, the gestural drawing produced a bridge-like structure between the two forms. Akin to the previously described adjacency micro-hybrid, the digital response involved randomized geometric forms that maintain a consistent formal language. The digital fabrication failed to produce the desired bridge outcome (Figure 4).

The digital fabrication method used for this study is a 3D printer using printed polycaprolactone and a dissolvable plastic for structural supports. Since this printer works by layering, the object’s orientation to the printer bed is imperative as it would maintain contours that were necessary to structure the print. This contouring was unforeseen and unfortunately led to the failure of the aspired fabrication. Upon examination, the attempt to create long spans of digital material not only induces issues related to fabrication, but also results in extensive amounts of structure material that produced cost overruns. While the fabrication failed, the purity assessment demonstrated the possibility of a potential adjustment that could re-instate the connection-based operative condition. An additional study was completed. This new study re-oriented the primitive,
integrating color between the disconnected forms. The subsequent fitness test proved to be acceptable (Figure 5).

**Micro-hybrid_Surface Relief**

The “surface relief” operative condition explores the use of responsive directionality on digital and physical procedures. Since the cube held no relationship to the operative condition, it was oriented flat. The digital process deployed on this prototype integrated a random response that brought directionality to the micro-hybrid’s planar surfaces (Figure 5).

The gestural drawings engraved on the planar surfaces were etched onto the artifact using a laser engraver. The transition from the digital representation to the final artifact failed to take into account the primitive’s materiality. The engraving was intended to provide a direct response to the gestural drawings, however its visibility was varied due to the perceived direction (Figure 5).

The artifact ailed the purity assessment test. However, the surface relief micro-hybrid passed the fitness test when controlling for object smoothness.

**Micro-hybrid_Balance**

This operative condition uses balance to drive the iterative conceptual development. The process starts with modifying a cube and uses two nested cores as physical modifiers. This initial concept allows the orientation of the primitive to sit on its corner, thus challenging the idea of equivalency that is apparent through the remaining design process. As the first digital response, the gestural drawing re-balances the composition by illustrating how the existing digital primitive could be modified aesthetically. Drawing reinforces the initial operative concept in a more visible/tangible way and guides the hybridized digital process (Figure 6).

The digital method of fabrication and its contour language was integrated into the decision-making process as a new aesthetic-based parameter. Although the final 3D printed part was characterized as “chunky”, it produced a balanced visual composition (Figure 6). Similar to Micro-hybrid_Adjacency, the physically fabricated primitive was modified to perfectly fit the 3D printed part, thus closing the (digital/analog) fabrication loop.

**Micro-hybrid_Cantilever**

This operative condition explores “cantilever” by liberating the primitive from the ground plane. The design projects the artifact into the air, thus disallowing a parallel relationship between the ground plane and the faces of the primitive form. This prototype considers the cube’s liberation from the ground as the increased dynamism of the physical primitive (Figure 7).

The response uses iterative simulation-driven digital models and knowledge gained from the previous Micro-hybrids. The considerations taken from all previous primitive iterations and increase in size...
compared to the previous micro-hybrids. When these considerations were evaluated, the price point exceeded the original projections of the artifact. What was learned from this form of failure was how the iterative workflow produced the digital consequences that brought about unintended consequences to bear upon the project. For instance, the influence on the set price points for the artifact, became a factor in the editing process. In addition, it challenged the ability to achieve conceptual purity. The resultant did maintain purity of the intended cantilever, but sacrificed formal aesthetics (Figure 7).

Figure 7
CANTILEVER CASE
STUDY | DRAWING
and MODEL, An
axonometric
drawing of the
artifact shows the
dynamic usage of
the primitive cube.
The model
photograph
presents the
resulting artifact, as
it allows for an
enhanced visibility
of multiple
projections within
the composition.

RESULTS
This research points towards regenerative, support-
ive, adaptive, and assistive methodologies that could
expand the micro-hybrid research into the mild-
and full-hybrid domains. These domains leverage
this project’s design decision-tree enabling a deeper
alignment with increased design efficiency, opera-
tive control, power generation and smart design pro-
cesses. The micro-hybrid exploration uses the draw-
ing as an operative model. In this particular case, it
is simultaneously both the detail and the abstraction
in which a process of emergent articulate how draw-
ings become form. Working across scales the metric
method of working links the learning process to the
crafting process, exposing the consequences of con-
tinual translation and embedding them in the pro-
cess.

The primary findings, implications, and contribu-
tion of the study include: a micro-hybrid pro-
cess informed a workflow that breaks the constraints
of modern pedagogy thus allowing the designer to
practice more intuitively. The micro-hybrid intro-
duced craft and representation as codependent ele-
ments that directly focused on the relationship be-
tween making and simulation. This resulted in allow-
ing the architect to inform design through variations
in dimension and scale and see firsthand the conse-
quences of dimension, materiality, physicality, virtu-
ality, and scale. This research has produced three re-
results:

- The extension of the design process beyond
digital screens and physical paper through
the micro-hybrid design process
- The interactive, real-time design evaluation of
the built prototype
- The positive impact on student Design Self-
Efficacy (DSE)

Knowledge gained by this research presentation
could impact design studio curriculum in three ways:
- extending the pedagogical framework beyond the
University of Kentucky-College of Design - Applied
Design Computation Laboratory (ADCL); defining the
methods and means of evaluating the design arti-
fact as a project score (PS); and providing critical
new insights into the analog/digital means utilized to
enable the artifact construction. Collectively, these
three topics, have also been shown to positively influ-
ence student design self-efficacy (DSE) and deepen
learning.

CONCLUSIONS
This research discusses an improved design process
that integrates fabrication and (physical) simulation
in order for students to gain better insights into build-
ing design and technology related aspects. In addi-
tion, the approach takes into account a decision-
making matrix that assists in assessing the effective-
ness of the design solutions. This process is intrin-
sically linked to design thinking processes where ar-
chitecture students are challenged to think creatively and simultaneously about digital technology. In this context, the micro-hybrid is positioned as an emancipator of design that capably expands the possibilities of design. However, the research also revealed the social art form of architecture as being an existing tangible being, that needs to be calibrated with parameters of the outcome medium. Simply put, what can be added to the aforementioned design-thinking, is to not only think about physical translation of the design as part of the test simulation or final construction, but to use prototyping and fabrication as a design tool side-by-side with other digital tools.

What the micro-hybrid research project suggests is the continuation of existing methods coupled with the hybrid use of digital and physical design methods. The research presents an integrated design process that acts as a feedback loop at all stages of architectural design, not just at the earliest stages. This research articulates how the micro-hybrid attempts to fill the gap between the digital design process and the physical world. The information collected before the simulation stage and during the modeling/design phase uses feedback from the physical world, not only in terms of materiality, but in terms of design and aesthetics. The micro-hybrid project is the first step in a larger research initiative to explore simple and intuitive design systems. This project is targeted at controlling functions associated with the methods making and the simulation-based tools used to examine form. As this research continues at larger scales and across other primitive geometric forms, it will expand to include functions such as planning and design that will improve architecture and design education globally.

**FUTURE RESEARCH**

The micro-hybrid research aligns with the advancement, discovery, and understanding of the design process as it relates to the built environment. It also outlines areas of future research beyond this research study and its intellectual merits, leading to broader design impacts. There is direct evidence to support the impact of the rigorous nature of the micro-hybrid specifically the education and training of design students. There is also early evidence to support a range of pedagogical implications where design research can inform the teaching methodologies used in the studio setting or where student-based, self-directed research can inform discovery. To determine the resiliency of the process, in addition to the cube, the future micro-hybrid iterations will be tested on all primitive forms (sphere, torus, pyramid, cylinder, and cone) and then analyzed in relation to their core connection method (tangential plane, incised plane, and cored plane) to test this experiment further.

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Embedded Building Components

Prototyping with Emerging Technologies

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This paper discusses research into embedded building assemblies with a focus on distributed sensing, real-time building envelope monitoring, and smart material integration. It looks into extending the concept of the Internet of Things from devices and appliances housed within a building to assemblies and a structure itself. The paper presents a number of embedded research prototypes that address thermal and moisture monitoring as well as introduce capacitive sensing as an opportunity for user monitoring and engagement. Finally, the paper points to opportunities for further extending sensing and actuating capabilities of a building envelope by combining them with embedded materials as a form of user interface.

Keywords: Embedded Systems, Distributed Sensing, Smart Buildings, Internet of Things, Prototyping

INTRODUCTION

As interconnected devices and autonomous agents continue augmenting daily lives through virtual networks and new communication modes, the built environment remains relatively isolated from the pace and the intensity of technological progress associated with the third and fourth industrial revolutions. The built environment is still heavily invested in the mind-set of industrialization with mechanical mind-set without the added benefits of informational technologies and modern sciences. While there is certainly an increase in adoption of various smart technologies in buildings and cities (Achten 2015), there is a lack of more comprehensive rethinking of what buildings should and could be—rethinking of systems, materiality, and conceptual frameworks. On the business side, authors like Klaus Schwab (2017) point that the fourth industrial revolution—characterized by the amplification of the technological progress by fusing the physical, digital, and biological worlds—is a disruption that will affect all aspects of our lives. This fusion of disciplines [1] and existential realms (physical, virtual, biological, or human-made) is perhaps the main characterization of the future built environment. With the memorable statement that it is not a matter of “if” but rather “when” and “in what form” this change will come, Schwab assures readers that “The question is not am I going to be disrupted but when is the disruption coming, what form will it take and how will it affect me and my organisation?”

While these words do represent a futuristic mind-set, they also reflect the current state of affairs in many disciplines. If correct, this statement signals significant incoming changes to the way buildings
are made and used. Building automation is an example of what is often referred to as the framework behind intelligent buildings. However, it is currently limited to controlling already mechanized and electronic devices such as cooling and heating systems, without broader implementation of embedded technologies (sensors and actuators) into building components and assemblies. This may be partially a result of the fact that building automation systems (BAS) and building management systems (BMS) are developed by companies that manufacture building system components and their controls (HVAC or air handling units), not by construction companies or building component fabricators. BASs/BMSs facilitate an improved performance of installed equipment and provide feedback to the manufacturer, not necessarily helping the building to approach it more comprehensively. What is needed in the next wave of transformation of the building industry and buildings themselves—the fourth industrial (construction) revolution—is to develop technologies that integrate and take advantage of the embedded systems within building assemblies as well as a biological paradigm. Windows, doors, floors, and wall panels all could and should function as part of the building digital interface, sensing user and environmental inputs as well as actuating desired spatial outcomes.

**FUTURE DIRECTIONS**

There is a strong interest in designing materials with novel properties and behaviors (Addington and Schodek 2005); (Furuya and Shimada 1990). Many of these materials will be made of hybrid structures incorporating what are commonly considered “smart” materials and embedded electronics. For the purpose of this discussion, a separation is made between nonelectronic and electronic smart materials. Many sensors and actuators are considered smart materials, since their properties can be controlled and changed by outside stimuli, such as force, temperature, moisture, light, and electric or magnetic fields. The distinction made here considers nonelectronic smart materials as quasi-equivalent to embedded systems on the level of operational logic, meaning that smart materials are capable of performing computationally equivalent actions—resolving simple logical statements. However, the addition of electronic capabilities into materials allows for outside communication with other distant physical objects or materials and for access to a database. This larger connection can lead to new material properties typical for electronic networks, such as awareness and anticipation, driven either by concurrent events happening within a building assembly or by accumulated knowledge residing in the database and crystalized through machine learning and statistical methods. These new material properties, associated with embedded (smart) materials, would further transform the idea of materiality, particularly when the integration of computational capabilities becomes fully distributed and indigenous to base materiality, as it often is in smart materials.

Another important development and distinction coming from embedded material systems is that their “smartness” to a significant degree resides outside their own physicality and depends on external knowledge systems. This is particularly true for properties such as awareness and anticipation, which benefit greatly from outside connectivity. This significantly shifts the concept of physicality from “here and now” to a broader chronological and spatial framework.
This paper presents research focused on the embedded systems driven by electronic logic with a high level of integration with an actual base material. The goal of these systems is to be distributed, autonomous, and self-reliant-like any physical material—yet fully interconnected within broader networked systems such as the Internet of Things (IoT). Ideally, the sensor and actuator integration would be scale independent, so that a part of the embedded assembly (subset) would display the same set of behaviors and functionalities as the assembly itself.

SENSING AS INTERFACING

Distributed sensor and actuator systems provide an opportunity for data collection that can be used for building management, performance analysis, and real-time interconnection with other devices and appliances. Many of the sensors that are deployed in monitoring buildings and tracking users could also function as a form of user interface (UI). This dual approach not only allows for buildings to respond to human activities but also provides opportunities for users to interact with them intentionally. While this seems like a relatively straightforward idea, there are different types of sensors and sensor arrangements used for both ways of interacting. Humans interact with their hands and bodies through touch and gestures (Kinect) as well as through voice commands (Amazon Alexa). Sensors that simply track motion, such as passive infrared (PIR) or microwave radar, would not work effectively as interaction devices, since they have binary inputs: on or off. Hand, gesture or voice recognition can provide a large diversity of feeds and possibilities. Similarly, touch sensors are used to provide user feedback, as is the case with touch screen devices that use capacitive sensing. Even though many of the implementations of touch interface have binary inputs, they can be easily used in multiple button or keyboard scenarios.

The Hidden Touch Interface project (Figure 1) looked into an integration of capacitive sensors into various building materials, both as an explicit interactive element and as a hidden functionality. Philosophically, the project was looking at both conscious and unconscious computer-human interaction, and ways both could be used and interconnect. Touch is a type of interaction that can be intentional (conscious) as well as unintentional (unconscious). People step on objects as part of walking or climbing, not paying attention to where and how; they also use the foot as a pedal for precise actuation. Similarly, we use hands and other body parts to accomplish tasks and also as output devices. Capacitive and pressure sensors are good examples of sensing technologies that could service both types of interactions. They provide a gradient of input values and can be visually present or hidden.

The Hidden Touch Interface prototype utilized an MPR121 capacitive sensor controller module driven by an I2C interface on ESP8266 (Figure 2). The chip can control multiple individual electrodes. Electrodes and connecting wires have a certain amount of inherent capacitance that is balanced against user-induced capacitance. Since the sensor electrode and user’s body (human flesh has a relatively high dielectric constant) form a capacitor, the overall capacitance is increased and can be measured by the microcontroller. The convenient part of this system is that electrodes can be (1) nonmetallic as long as they are electrically conductive, (2) connected with only a single wire, (3) concealed under any nonmetallic materials, (4) used to detect objects centimeters away, and (5) inexpensive. This allowed the Hidden Touch Interface project to test a wide range of building materials, from wood and ceramic/stone tiles to acrylic, glass, and mirror (Figure 3). Depending on the types of resistors used, direct touch or just proximity could be implemented in both on-surface and under-the-surface arrangements.
BUILDING INTERFACE OPPORTUNITIES

The introduction of capacitive sensing into construction assemblies allows for greater integration of building materiality and enhanced user interaction without making technology visually explicit or dominant. It extends the user interface (UI) qualities present in everyday objects into the building itself and opens new possibilities for architecture and the ways users interact with it. This presents an important aspect of new embedded architectural systems, with potential for designers to use various building materials and assemblies not only for sensing and actuation but also as controls and UI. Since these controls can be seamlessly integrated into the materiality of architecture, they can function in less explicit ways and on an as-needed basis, leading to further virtualization of materiality in architecture.

The design benefits of using capacitive sensing in building assemblies come from the ability to integrate sensor pads within the base material: hiding electrodes and allowing finish materials to maintain their uninterrupted visual presence as well as protecting sensors and electrodes from the impact of an outside environment. The depth of encapsulation and the effect on capacitance can be controlled by the size of the capacitive surface.

Capacitive sensors can be made from variety of different media, such as copper, aluminum, indium tin oxide (ITO), or printed conductive inks. Metallic capacitive sensors can be implemented on surfaces of solid and flexible materials, extending the range of possible design applications. Capacitive sensing works effectively through various nonconductive materials, even relatively thick ones, that do not ground the charge present when an object or a person interacts with sensor pads. ITO-based electrode pads allow the capacitive sensor to be up to 90% transparent, providing yet another important design opportunity. This approach is commonly implemented in touch screens. However, the same technology could be integrated into building assemblies using ITO-coated glass and films to provide extended sensing opportunities as well as using electrically conductive properties of ITO to support various actuation needs. A common example could be combining capacitive-sensing UI with digital displays or illumination. Integration of multiple functionalities into a conductive capacitive surface would require a careful study of the electrode sizes and spacing to maintain the optimal sensor performance. Since indium is a rare metal, which most likely would prevent its large-scale application in the building industry, there is a line of research that looks at replacing it with other materials while maintaining conductive properties.

SENSING WALL

The Sensing Wall project (Figure 4) aimed to create a sensing building skin for real-time performance monitoring. The first prototype focused on thermal sensing using an array of thermistors on 10 cm by 10 cm (approx. 4 inch by 4 inch) grid.

TECHNOLOGY DISCUSSION

The ESP8266 chipset comes with a single analog pin (port). Since the Sensing Wall project requires a significant number of analog inputs—the ability to measure continuous changes in input voltage-thermistor multiplexing was required. Similar to LED displays (actuators), multiplexing of multiple sensors allows for reading individual analog values of a larger thermistor array. Multiplexing comes at the cost of time,
since each sensor reading is performed separately. With a larger array of sensors, this may add up to a longer period of time, particularly when considering multiple samplings for each reading to average them for higher precision. However, in the case of sensing a building wall, where the temperature change is relatively infrequent and gradual, the reduced refresh rate associated with multiplexing is acceptable.

The multiplexing was achieved with a single 74HC4051 8-channel chip. While the prototype panel deployed only 16 thermistors (sensors), the ESP8266 and 74HC4051 setup could be scaled up to 40 with full use of digital pins and up to 32 (one digital pin less) in cases when the chip hibernation would be desirable. These values could be scaled significantly using a 16-channel multiplexer and a demultiplexer. However, the intention of this approach is to provide embedded and highly localized solutions that would serve relatively few sensors and actuators but at the same time would be deployed in large numbers. In this scenario, each piece of gypsum wallboard or plywood sheathing could be embedded with multiple separate logical units.

Other considerations include the quality of soldered connections; the distance between distributed sensors, with their susceptibility to noise (electrical interference); and the need to calibrate the panels, since the electrical resistance of long connecting leads can add to the sensor reading. However, the electrical resistance of the system can be easily established and adjusted for.

Finally, to address energy consumption and conservation, chip hibernation (sleep cycle) was implemented. During the wake state, the assembly used on average 30–40 mA, with peaks around 300 mA for WiFi communication as compared with the sleep state of 0.1 mA. The recovered sleep mode values were higher than those provided by the manufacturer datasheet [2] (10 µA for deep-sleep), so there is a possibility of further lowering this value. Energy consumption is an especially important consideration in large-scale sensing wall implementations, so proper fine-tuning would be required. The prototype used the generally available ESP8266 microcontroller, with
features that were not utilized. In an actual implementation, the microcontroller would be designed for the specific function without LED indicators (5 mA drain) and fine-tuned power regulators.

APPLICATION AND INSTALLATION CONCERNS
While the initial prototyping of Sensing Walls worked effectively as a distributed sensory assembly, the actual fabrication technology relied on embedding sensors physically into sheathing (in this case medium-density fibreboard (MDF)). To increase the adaptability of this approach and potentially also the range of applications, alternative installation methods were tested by embedding thermistors into building wrapping membrane and using copper tape as a conductive trace (Figure 6). This approach (Sensing Wall 2) provided the same performance as Sensing Wall 1, and it could have been installed in a broader range of conditions, including renovation projects (not a new construction), with no need to replace or modify sheathing. The issue of fragmentation and scaling down the system could be addressed by developing smaller sensing zones, with each zone functioning as a self-contained and autonomous system. This would allow for the embedded building wrapping membrane to be treated and installed in a similar way as conventional systems such as Tyvek. Any damage to an individual zone associated with cutting the membrane would be alleviated by the installation practice of overlapping membranes on the seams and sealing them with aluminum or copper tape. Currently, building membranes are sealed with synthetic tape. The membrane overlap would provide continuous or occasionally doubled sensor coverage. The use of the metallic tape would provide an opportunity to power individual zones. If the exposed electrically charged (3.3-5V DC) aluminum tape were to be a problem—a possibility of a galvanic action or shorting a circuit—a second layer of a protective nonconductive tape could be installed over the conductive tape.

INTEGRATING MULTIPLE SYSTEMS
The second prototype (Sensing Wall 2) provided opportunities for doubling the functionality of the sensing membrane beyond temperature monitoring and led to the development of the third prototype: Sensing Wall 3. Sensing Wall 3 (Figure 7) departed from the approach used in the previous two prototypes, measuring thermal conductivity, and focused on measuring moisture penetration of the membrane itself—a common concern for outside building envelopes. The conductive leads, similar to the copper stripes used in the second prototype, were used in combination with various building papers to measure the electrical conductivity of moist building paper. This approach was based on the fact that the amount of moisture in building paper or felt-like substrates impacts their electrical conductivity, which can be measured with microcontrollers such as ESP8266. By developing initially imbedded conductive threads and measuring conductivity between them, a coordinate system could be implemented to track moisture and water penetration within a wall. Two approaches were tested: one- and two-dimensional grids with leads going in one
or two directions (Figure 8). Since the water tends to travel vertically within the building envelope, driven by gravity, systems using single-direction conductive threads could be implemented in a vertical direction.

Initially inspired by the use of copper tape leads in the second prototype as a way to double up on wiring infrastructure and provide multiple sensing capabilities, Sensing Wall 3 looked at a number of other technologies to embed conductive leads within building wrapping surfaces. Three-dimensional (3D) printing with conductive graphite polylactic acid/polylactide (PLA) filament (Figure 9) originally seemed a natural extension of fabrication technologies that could help to accommodate other electronic parts (serve as joinery), eliminate resistors, and provide electrically conductive wiring. Since PLA is bioactive thermoplastic aliphatic polyester derived from renewable resources, such as cornstarch, it provides opportunities for the use in building assemblies of carbon-neutral and recycled materials [3], lowering the energy footprint and extending the life cycle. It is also semiflexible, which makes it a good candidate for building surface applications.

The tests showed high resistance between connections, which started to impact the reliability of the entire electronic assembly. A number of connection strategies using electronic parts and copper wiring, with 3D printed components were studies. The goal was to validate the easiness of the integration of electronics and related components with the wrapping building paper. These tests were successful in achieving basic conductivity, but again the issues with electrical resistance were significant.

While the electrical resistance could be controlled through the thickness of printed layers, a broader intent was to reduce the visibility and amount of electrical connections. Another concern is its biodegradability as bioactive thermoplastic.

Finally, the conductive PLA filament has lower level of adhesion to a paper or membrane substrate, which can be overcome by providing a regular PLA base, easily achievable with dual-extruder 3D printers. This filament is also not designed for higher temperatures, as it should be used at temperatures below 50°C. While 3D printing was not used for the final prototype, this was due to the types of available materials, not to any limitation inherent to the technology itself.

CURRENT LIMITATIONS

The ideas discussed in this paper port technologies used in everyday electronics into a broader realm of the built environment. While this is a natural way to extend applications for these technologies, there are many limitations that impact quick adoption of these technologies. The concern about increased energy use, while trying to save energy, is partially addressed above when discussing microcontroller hibernation and sleep mode. Another connected issue is energy harvesting and storage locally within a building or even a wall assembly. There is a significant amount of research in this area and emerging commercial products, such as glass embedded photovoltaic cells of solar roof tiles.

Another concern about embedded systems is that they introduce an extremely large number of
electronics to a building envelope that would impact the price and technical skill required to install them. The examples discussed above rely heavily on factory-produced systems that should be easy to install and power, with the provision of electrical power as the primary installation focus. The cost of electronics, including sensors, can be significantly reduced by scaling up this approach into mass production, with the exception of technologies that rely heavily on rare chemical elements. However, the issue of rare materials would need to be resolved prior to a broader introduction of embedded technologies into buildings and construction. Furthermore, the introduction of embedded (electronic) systems into wall assemblies reflects similar developments in used with various devices, appliances, and technologies in buildings, such as LED light bulbs or motion-triggered lights.

The prototypes presented here used commonly used and easily available materials, such as ceramic-based thermistors, silicon diodes, and aluminum tape. Therefore, there are no rare-material limitations on scaling up these approaches. The microcontroller is not part of this list but generally is inexpensive to manufacture using commonly available materials.

CONCLUSIONS
This paper discusses strategies to facilitate IoT implementations within buildings and building assemblies. It specifically looks into emerging research in embedded technologies that combine distributed sensors, building performance monitoring, and user interactions. The inclusion of mechanical and electrical systems within a building, and more recently embedded electronic intelligence connecting automated controls with network sets and environmental real-time monitoring, is changing this passive approach to an active and dynamic framework.

In these scenarios-reminiscent of parallel developments characterized by the fourth industrial revolution-building performance goes beyond measuring physical values of solar gains or heat losses, and includes a possibly deeper understanding of user behaviors, individual comfort levels, and material assemblies. It provides users with the ability to interact with a building and also allows buildings to facilitate occupant activities and guide their mobility (Schwartz 2013). Specifically, adding a human factor into building performance considerations, both as actors and reactors, gives an opportunity for developing a greater fit between users and buildings.

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1. Sensing Wall projects developed by Jorge Cruz (Figures 4, 6, 7 and 9).
2. Hidden Touch Interface project developed by Jorge Cruz and Anthony Samaha (Figures 1 and 3).

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PARAMETRIC AND GENERATIVE DESIGN
Analogue Automation

The Gateway Pavilion for Headland Sculpture on the Gulf

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The Waiheke Gateway Pavilion, designed by Stevens Lawson Architects originally for the 2010 New Zealand Venice Biennale Pavilion, was brought to fruition for the 2017 Headland Sculpture on the Gulf Sculpture trail by students from Unitec Institute of Technology. The cross disciplinary team comprised of students from architecture and construction disciplines working in conjunction with a team of industry professionals including architects, engineers, construction managers, project managers, and lecturers to bring the designed structure, an irregular spiral shape, to completion. The structure is made up of 261 unique glulam beams, to be digitally cut using computer numerical control (CNC) process. However, due to a malfunction with the institutions in-house CNC machine, an alternative hand-cut workflow approach had to be pursued requiring integration of both digital and analogue construction methods. The digitally encoded data was extracted and transferred into shop drawings and assembly diagrams for the fabrication and construction stages of design. Accessibility to the original 3D modelling software was always needed during the construction stages to provide clarity to the copious amounts of information that was transferred into print paper form. Although this design to fabrication project was challenging, the outcome was received as a triumph amongst the architecture community.

Keywords: Digital fabrication, workflow, rapid prototyping, representation, pedagogy

INTRODUCTION

This paper examines the integrated processes between digital fabrication and analogue construction methods used to produce a complex, spiralling glulam beam structure, the ‘Gateway Pavilion’ for the Headland Sculpture on the Gulf arts festival. The Waiheke Gateway Pavilion has already been recognised within local architectural journals, lifestyle magazines and won local awards. The cross disciplinary team of students from Unitec Institute of Technology’s architecture and construction departments working in conjunction with Stevens Lawson Architects, engineers Holmes Consulting and building specialist Ebert Construction.

The use of powerful software to design a complex architectural product is increasingly becoming a
popular trend amongst young practitioners (Mamou-Mani and Burgess, 2015). When complex architectural forms are pursued, a set of challenges need to be overcome before any concept can be realised, such as establishing a workflow that accommodates for all possibilities within the project (Garber, 2017). The Waiheke Gateway Pavilion is no exception. The architects design required material and production knowledge to be embed into the developed design phase before any fabrication could take place. The benefits of using a digital software supports both students and professionals in a simple workflow aimed to realise different levels of complexity of design and fabrication of architecture (Aish, 2003).

The original manufacturing method to be employed to create the components for the ‘Gateway Pavilion’ was to utilise an automated Computer Numerical Control (CNC) process to fabricate elements that could be subsequently assembled by students using basic tools such as spanners and drills. The strategy to extract encoded data from a computer generated model and to input it into automated fabrication equipment to produce a high precision and low tolerance structure was considered to be an easy and attainable task, particularly given that the project had to be delivered within a limited time frame. We were confident that this method would be attainable given previous experience with projects such as Chris Moller’s Click-raft, a crafted construction system which utilises CNC machining to form custom structural elements within the design (Moller, 2012). A major part of the project was to communicate information for fabrication and assembly between the architecture and construction disciplines. This required development of a system that was easily understandable and graphical in nature to avoid errors. Even though the Gateway Pavilion’s form appeared complex with over 261 glulam and 51 rough sawn unique parts, it was a deceptively simple fabrication and assembly process when file to factory fabrication methods are employed.

The following paper describes an architectural student’s perspective with the aim of providing an insight into the tension between integrated digital and analogue fabrication approaches throughout the duration of this project. The first portion of the paper will examine the problem that was presented to the team of students. To follow, a discussion into the methodology and findings of the project in regards to an integrated digital and analogue approach. To conclude, as a response to the findings a critique into the pedagogical learning outcomes within this project will be discussed in relation to the cross pollination of learning between the construction and architectural industries.

**PROBLEM**

To realise the concept of the Waiheke Gateway Pavilion, digital tools were employed to accurately represent and to extract those elements for fabrication purposes. Although this could be done by hand, digital tools provided us with opportunities for greater exploration of the shape. Digital and analogue fabrication methods are both a generative medium that hold their own restraints and allow for different possibilities such as narrowing the gap between the representation of architectural information and building (Iwamoto, 2009). In the instance of the Waiheke Gateway Pavilion, this narrowing of the gap allowed for the efficient production (and reproduction) of the many necessary schematic and shop drawings required to fabricate the numerous individual building elements. Digital tools facilitated efficient transfer of information between architectural, engineering, and construction disciplines. The digital model was used to make aesthetic and structural decisions as well as being used for representation for fabrication and construction purposes.

The original plan to implement a file to factory process, where the digital data could be easily translated into a language to run the institutes CNC router (Iwamoto, 2009) became unworkable due to a malfunction, meant a new design-fabrication-assembly workflow had to be developed which required a construction workflow based on hand production. This had to be developed, tested and implemented within
three weeks. A workflow based on hand production required several digital to print paper processes to be performed to inform construction.

This caused problems due to various skill levels within the project team of students. Architectural students were prepared for file to factory processes and otherwise are trained in producing scale drawings that demonstrate design intent, not highly detailed shop drawings. The construction students were at the beginning of their training with limited experience in reading conventional architectural drawings. Added to this, the construction students are being trained in an industry reliant upon pre-assembled framing as opposed to developing skills with tools for elaborate non-standard structures. As students were coming from such a varied background of skill and experience, the method to be developed needed to be simple, clear, and efficient.

**Time frame**
The entire project spanned over three months, between late October 2016 till late January 2017. The detail design and scaled prototyping produced by the architectural students, engineers and project architects was performed in the initial two months of the project, this is when the malfunction of the CNC machine happened. The last month consisted of fabricating components at the institutes workshop before the erection of the Waiheke Gateway Pavilion on-site in early January, leading to completion on-site for the 24th January 2017.

**Task**
Working outside of the standard industry for both the construction and architectural students was a new experience, therefore information derived from software had to meet the following criteria; firstly to produce shop drawings from digital data to allow student fabricators to manufacture components with accuracy. Secondly to convey all the required information needed for hand assembly. This portion of the process was the most difficult, as the structure is reciprocal system and required a holistic approach for overall understanding for all parties involved. Furthermore to create a labeling and tracking system to ensure the project is assembled correctly. Normally this would be a simple task within an automated process but due to the malfunction of the CNC machine this process required greater attention. As each component was unique and needed to be labeling correctly in order to be cut and drilled accurately. The designing of a production line process was to created to ensure all components were produced efficiently. This required deadlines to be set, with targets to met daily. Lastly, if one of these processes fails, all others will as well as they are all intrinsically linked.

**METHODOLOGY**
The development of a design through an iterative process is a staple within any design process and is a fundamental element with architectural practice. The architectural design process is not so dissimilar to the iterative progress within a science experiment in order to resolve problems (Lucas, 2016). Architects must work with engineering and construction consultants to break down design ideas into manage-
able portions. As a result, numerous scenarios can be tested to allow for fewer questions and uncertainties to arise during construction (Anderson and Anderson, 2006). Modelling conceptual ideas in 3D digital space provides an environment for information to be readily available at the discretion of designers and fabricators fingertips. This allows for the embedded data to be used for scale prototyping, visualisations, quantity surveying, and allow for augmentation for design development (Iwamoto, 2009).

There is no doubt that architectural software today can allow for successive design iterations efficiently. The instant visualisations is evolving and fast becoming a part of the every design process (Sheil, 2005). The obvious advantages of working within a digital environment over an analogue hand process is with how information can be manipulated, transferred and replicated with ease (Dunn, 2012). For example, if an architect needed to change a hand drawn design, a workflow to amend it would entail a laborious process to redraw it. Again, if conceptual model was required for spatial validation, a designer cannot simply extract data from a virtual model and print it via a laser cutter. They must be physically measured, drawn, hand cut and checked before any final assembly can be pursued. (see Figure 1)

**FINDINGS**

The development of a conceptual model or hand drawing that needs be transferred from a digital environment to physical product requires several processes to take place. To begin, a discussion into the design development phase by the architect will be discussed. This will be followed by a discussion into the structural and production development of the project conducted by architectural students, project architects and engineers. A reflection into the effectiveness of full scale prototyping with the absence of automation will follow, before concluding with a brief discussion of the implementation of the assembly on-site.

**The design development phase**

Information and understanding with complex forms can be difficult to describe with only two-dimensional paper representation. To overcome such issues there is a need for a representation to provide adequate conceptual information not only for clients, but to fabricators and engineers (Allen, 2009). Stevens Lawson Architects original concept for the Waiheke Gateway Pavilion was not generated digitally but was realised through a narrative. This narrative was described as a whare becoming a landscape and returning back to a whare. A whare is the Maori word for house or hut. The realisation of this concept was assisted through digital software where further design iterations took place.

**The structural and production development**

To ensure the project came to completion on time, a number of processes had to first be established to enable students with varying levels of experience to produce a highly refined outcome. The major component of this process was to establish clear directions for fabrication and then assembly. The computer generated model provided to the students by the architects was a massing form. It needed to be tinkered, transformed, and refined in order to be useful for manufacturing purposes.

Figure 3
1:1 Detail
Prototype: This was used to test for tolerances, check connection details, gauge material aesthetics before material was ordered.

Figure 4
1:1 scale prototype of six portal frames on-site at the Institutes workshop. This prototype was vital in the progression of the project.
The use of prototyping allowed for design, material, and assembly processes to be refined and quantified. Investment into rapid prototyping models and full scale mock-ups assisted to amend faults and miscalculations through the developed design process. Digital prototyping originally allowed for easy production of components. With the malfunction of the CNC router, digital technology was primary used to create documentation to inform production.

Representation via prototyping can be simplified by dividing it into three simple steps that allowed the iterative process to form discussion and decisions. The first prototype to be developed by the students was the creation of a 1:10 scale model (see figure 2). The purpose was to depict information visually that would otherwise be missed within a digital environment. It became an important model to explain the design and how it may be produced. Problems of tolerance, alignment and connection were discovered and quickly rectified through digital software.

A 1:1 detail mock up was important to gauge material aesthetics, timber treatments, tolerances, and connection details to before supporting material was ordered. The malfunction of the CNC was discovered here and with that a new approach had to be defined through drawing representation for fabrication. Fortunately, the vector files required for CNC production where re-purposed to create shop drawings. As each component was unique in nature, with its own set of details and required location markers and diagrams for correct assembly. (see Figure 3)

The effectiveness of full scale prototyping with the absence of automation

The 1:1 scale prototyping for this project was used to form a viable construction/assembly method and was achieved by the erection of 6 spiraling portal frames at the institutes workshop. This prototyping was by far the most important as it highlighted problems in material lengths, and time frame of the erection process. The need for diagrams to aid in the visualisation for projects and their realisation is key to disseminate information for fabrication (Allen, 2009). This concept is highlighted within the prototyping phases, as the original shop drawings needed to be heavily augmented to ensure the communication with entry level labour was understood. The fastest form of prototyping of digitally derived by print media is by augmenting and developing it by drawing over it by hand and pencil (Gage, 2012). (see Figure 4)

Simple excel forms were created to track. The process of translating the encoded data was ongoing throughout the fabrication and construction stages. This form of prototyping lead to multiple changes within the encoded data documentation. The amount of drawings increased to over 600 pages from the original set of 300 that was produced. For example, the bolt hole sizes and allocations. Originally they were designed with a small tolerance to allow for hand assembly. Prototyping at this stage showed that this allowance didn’t work due to movement in the frame and miss-aligned edges. This wasn’t picked up within earlier, scaled models and just goes to show the importance and value of a full-scale prototype prior to full fabrication and construction.

The notion of designers as builders (Kieran and Timberlake, 2004) is demonstrated in this project by the architecture students contributing to aspects such as quality assurance, quantity surveying, fabri-
cation and assembly phases of the project. This was necessary in order to overcome problems that arose due to workflow changes. This project is a showcase of the outstanding skill, craft and knowledge that are key to achieving an integrated process in such a complex design and build. This project became a learning experience for the students involved as it showcased how having the required software on-site during fabrication and construction aided in the completion of the project. It allowed them to learn a new craft whether it was the architecture students learning how to fabricate their designs or construction students learning the importance of the design and documentation stages of a project. (see Figure 5)

**On-site fabrication**
The time frame for the erection of the project was vital due to only having 2 weeks onsite to get the structure assembled and signed off by engineers to allow public access for the event. Although this data was directly extracted from reliable digital files there was still confusion on-site during the early phases of construction. This showed how valuable it was for all necessary people within the fabrication and assembly team to be involved throughout the prototyping processes. The workflow to communicate this information was then changed, an onsite computer with access to the original 3D model was then used to inform rather than rely on the information provided in the printed drawings. Powerful tablets today, can hold all the information needed. It took one tablet, controlled by the senior architectural students to clear up any problems that may have occurred (Krygiel, 2010). (see Figure 6)

**CROSS POLLINATION OF STUDENT LEARNING**
Even though the project represents complex design it is an advocate to the requirement for traditional skill, organisation and construction knowledge.

The disruptions within the project were frequent. A short project time frame, the complexities of the design, and the change of fabrication process contributed to some of this. However, the communication between multiple disciplines arose as a defining issue. It became apparent that in order for the completion of the Gateway to be successful the architectural students were required be more involved as they served as a conduit between the digital and analogue realm, rather than just being observers on-site. This iterates the need for the student contractors and fabricators to understand digital mediums in order to resolve problems within complex builds.

**Organisation**
The communication amongst the team members was resolved by allowing for three different integrated processes to be implemented into the workflow at the workshop and on-site. These three aspects all together would allow for easy and clear com-
munication, allowing lecturers to organise students. Firstly, the creation of small cross-disciplinary units to take charge of particular tasks during fabrication and assembly on-site and at the factory. Secondly, each unit had five construction students to one architectural student in order for digital organisational information to be accessed and to finish, the skill, craft, and knowledge were all important in a particular person’s ability to achieve certain goals and tasks within the time frame.

The architectural student’s obsession for a beautiful assembled detail to ensure quality and craft was contrasted by construction students desire to produce at speed to meet deadlines. These contrasting approaches caused conflict amongst the team on-site, exacerbated at times through inexperience and time frame. There was a realisation by the architecture students that the most important skills they needed to contribute to the project were to present information and communicate their knowledge effectively to all team members, and to efficiently organise the project phases.

When digital production is not an option
A project originally intended for digital fabrication had issues when produced in an analogue manor. Human error and tolerances became problem once the option of CNC machining was replaced by hand cutting and drilling. Prototyping throughout this project allowed for further understanding of how corner joints and detailed information was to be assembled at full scale. This understanding was not only to inform the architectural students, but to also aid professional industry personnel about the project at a scaled physical form (Burry and Burry, 2012). Many had not worked within a project that demanded so much prototyping as there were several different iterations with different approaches whether it be the design itself or trialing a method for the assembly.

There was great reluctance by construction students and building consultants at first to work beyond the drawings and to accept digital processes in conjunction with prototyping. Experience on their part dictated their opinion, which by all means is valid as local building practice do not tend to get the opportunity to prototype or build complex architectural forms (Krygiel, 2012). As the design programme progressed, acceptance and an understanding towards the need for such an approach developed.

The passion of the architecture students drove their desire and sacrifice to work beyond their required daily shifts from the outset. As a collective, they learnt that this practise was not initially shared by other disciplines within the project. By the end however, as the construction students became more a part of the design process they too demonstrated the desire to work long hours in order to successfully realise the project. An acceptance from the architecture students towards building at full scale is tough and takes a lot of energy from an individual which led to an unspoken respect by the end of the project between the two disciplines.

CONCLUSION
This project highlight the value of employing iterative processes and how having an integrated workflow can achieve a successful outcome. In the case of the Waiheke Gateway Pavilion an iterative investigation was first required to find the most efficient approach to develop an alternative fabrication process. It became evident that for this project to be successful a greater understanding of other available construction processes was needed in order to explore comprehensive prototyping at different scales. This process was used to determine the appropriate fab-
fabrication assembly method onsite that would provide greatest efficiency in the short time frame. The Waiheke Gateway Pavilion project also highlights how complex bespoke builds benefit from access to digital information onsite. (see Figures 7 and 8)

Important learning experiences came with re-evaluating the project due to the need for analogue organisation; new skills and knowledge to be understood, acquired, and to be worked back into the design to fabrication process. Aspects on how best to integrate students from collaborating industries that tend to have conflicting purposes between the importance of design and the practicable needed to be negotiated. Overall this project was a learning experience not only for the architectural students that were involved from the designing and documentation stages, but also for the construction students that only joined in fabrication stages of the project. New skill levels have been achieved for the architecture students as they can now not only produce encoded data for digital production and a highly defined computer generated model, but can also create shop drawings that convey accurate information for the construction trades. In addition, the project has highlighted the value to bring closer the disciplines of design and construction in order to effect more collaborative working arrangements, greatly benefiting the final built outcome and contributing to clearer design, fabrication, and assembly processes.

In combining the available digital tools for communication, design development, analysis, and fabrication and assembly with analogue techniques, the Waiheke Gateway Pavilion developed an integrated process which resulted in a simple and efficient design, fabrication and assembly process to realise a complex spiraling shape.

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Foldable Responsive Surfaces

Two Design Studios with a Comprehensive Workflow

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The adopted methodology was defined by a multidisciplinary team with a strong believe in the efficiency of learning-by-doing design studios which resulted in an experimental digital workflow to create responsive surfaces based on the geometry of Rigid Origami. The workflow comprehends all the matters related to the creation of such surfaces, from the conception and definition of the surface's design using Rigid Origami’s geometry, passing through the virtual simulation of the movement, digital fabrication and material’s choice, then the mechanics behind the movement, interaction programming, and the assembly of it all in real scale prototypes.

Keywords: Design Studio, Learning-by-doing, Rigid Origami Geometry, Responsive Surfaces, Parametric Design, Digital Fabrication

INTRODUCTION

Traditional architecture design process starts from principles that architectural structures are singular and fixed, statically integrated on their environment or context and unable to adjust as time passes and needs change. The emergent design processes and technologies require more than this, interactive structures as part of an environment or context with the ability to transform themselves as necessity comes. Consequently, architecture has witnessed a remarkable amount of experimentation with ways of using digitally managed information - be it geometric, structural, kinetic, mechanical - to rethink how buildings are designed (Marbel, 2012). The digital workflows are empowering the opportunity to increase computing capacity. This paradigm shift opened up opportunities for making objects and spaces more responsive, sensitive, and smarter.

In this sense we advocate that architecture should be able to evolve and adapt to user’s needs through the use of architectural elements that can change their geometry in order to change space, interact and communicate with its inhabitants.

Consequently the role of the architect gets a broader range. When designing an interactive structure, it is necessary to anticipate several issues related to the structure’s response to the interaction with the users, the mechanisms that will put the structures in
motion, the electronics behind them and the inte-
gra-
tion of it all in the final design (Fox and Kemp, 2009).

“The outcome of kinetic design is not a singular form,
but a process from which a range of forms manifest over
time. This requires designers to consider the design of
control system and data input, as well as the design of
the physical components” (Moloney, 2011).

In this sense teams from La Sapienza, Rome, and
ISCTE-IUL, Lisbon, got together to create a Summer
School were this paradigm could be tested through a
comprehensive workflow that would ultimately lead
to the creation of foldable responsive surfaces proto-
types.

Both teams, Rome and Lisbon, have ongoing re-
searches on Origami Surfaces and their kinetic ca-
pabilities so the main subject was easily decided, in fact
it was the main reason for both Universities to get to-
gether in the first place.

The primary objective of the Design studios was
to experiment on the kinetic potential of Origami Sur-
faces testing different geometries and their inher-
ent movements, rigid materials and digital fabrica-
tion techniques, origami geometry parametric sim-
ulation, ways to actuate movement and interactions
and at the same time teach all this to the participants
in only two weeks.

In order to do so a multidisciplinary team com-
posed by architects, computer scientists and elec-
tronic engineers got together to define the process
for the design studios and the necessary lectures and
masterclasses in order to provide participants with
the theoretical and instrumental skills necessary to
deal with the design and construction of responsive
surfaces.

The first design studio was called Responsive
Surfaces and was held in Rome at La Sapienza in
September 2015 with students from Italy, Belgium,
Iran, India and Romania, most of them were archi-
tects and PhD students. The 13 students were di-
vided in four groups of 3 or 4 people by the tutors
that had in consideration each person’s knowledge
on parametric design and digital fabrication.

The second summer school was called Surfaces In-
Play and was held in Lisbon at ISCTE-IUL in July 2016.
At this Summer School there were 10 students from
Portugal, Italy, Greece, Belgium, Bulgaria, Canada and
Brazil. The students were architects, architecture and
sculpture university teachers, PhD and architecture
students and were divided in five groups.

On both Summer Schools there was a real con-
cern about giving the participants insight about all
the subjects at stake. The designer does not have to
be an expert on all the fields involved but has to be in
possession of some knowledge about those fields in
order to be able to create transformable objects that
respond to the intended purpose and integrate on
them all the mechanical and computational features.
The designer is the central point, the pivot, through
which the involved areas get to be an integral part of
the architectural object.

“Digital age is forging a very different kind of archi-
tecture and, at the same time, providing unprecedented
opportunities for the significant redefinition of the ar-
chitect’s role in the production of buildings” (Kolarevic,
2003).

In this sense the Design Studios’ goal was to test
the workflow, by using it in a real context at the same
time that it allowed to test Origami geometries, ways
to actuate the movement, materials and digital fabri-
cation techniques.

DESIGN STUDIO’S STRUCTURE
The design studios started with two days of open
lectures on more general subjects like kinetic and
responsive architecture, physical computation and
parametric design. On the first year there were lec-
tures on Responsive Architecture and Environmental
Design by Alessandra Battisti, Physical Computation
by Lorenzo Imbesi, Responsive Surfaces and para-
metric softwares by Anna del Monaco and Applied
Parameterization by Alfonso Oliva from LERA+.

At Lisbon it was additionally made a call for pa-
pers that were presented during the two confer-
ce days, grouped by the subject of each keynote
speaker. Parametric Design with Arturo Tedeschi,
The first two days of lectures had the purpose of making the students familiar with the concepts presented by the speakers with a special focus on built examples and correspondent explanations. This way a sort of "built state-of-the-art" legitimized these kinds of practices and allowed the students to reflect on the positive achievements of these architectures and on ways to resolve the negative ones.

On both years the next two to three days were spent with masterclasses where Rigid Origami was the main topic, like a passage from global (the two days of conferences) to particular. The masterclasses focused on geometry and mathematics of rigid origami surfaces, interaction with objects, digital fabrication, arduino programming, and finally the folding simulations of rigid origami surfaces using Rhinoceros with Grasshopper and Kangaroo and Weaverbird and the communication with arduino using Firefly.

The masterclasses reflected the defined workflow to be used as the methodology of the design studios. The workflow could not be linear because the steps can not fit in an hermetic case, it is often necessary to reassess previous steps when problems are founded further, especially when the students are new to the subjects. So the proposed workflow comprehends several stages but works as an algorithm where critical judgment is essential.

The first step consists on the analysis of the available space for implementation of the surfaces, the existing constraints, either dimensional or locational, and also the formal objectives for the surface. The next step entails the design of a surface that can correspond to the formal constraints and demands through design and paper models. After that the chosen pattern is submitted to the digital simulation of its folding through an algorithm developed on Rhinoceros with Grasshopper and Kangaroo which allows the students to verify if the developed surface is indeed Rigid Origami and if it does not rely on curved surfaces or material stretching.

The fourth step is a point for critique where it must be evaluated if the developed surface is applicable to the initially defined objectives and existing constraints. If the answer is “Yes” then it is possible to proceed to the next step, if it is “No” then the student must retreat to the second step and change the pattern or create a new one and follow the subsequent steps again.

When a positive answer is reached on the fourth step it is possible to start defining the mechanic system that will make the movement happen. This system must respect the chosen fixed points and drive the moving points as defined on the paper models and digital simulation. The fifth step is where is de-
cided the kind of “life” the structure will have, if it will react to atmospheric, lighting or thermic conditions or if it will have a more close relation with the users like moving when they get near it. The penultimate step consists on the choice of the material to formalize the surface. The material choice depends on several factors, if the structure will be used outdoors or indoors, if its dimensions allow it to be fabricated from a single sheet of material and if the material’s thickness allows it to be folded or if every face must be made separately either because of the faces dimensions or material’s thickness, and most importantly if the material has the qualities to be used for Rigid Origami surfaces, i.e. if it is rigid and isotropic.

The final step is the construction of the surface. The digital simulation allows to create the drawings of the crease pattern that will be used with the digital fabrication tools, after that remains only the assembly of the surface and its connection with the kinetic system, the sensors and the actuators. (see Figure 1)

**MASTER CLASSES**

**Rigid Origami**

Rigid Origami Surfaces have a tangible geometry, it is possible to experiment directly and quickly with a simple sheet of paper the transformations that happen during the folding and unfolding of such surfaces.

In Rigid Origami the final model must be the result of the folding of a single sheet, it must be possible to flatten the model without creating new creases and it is required that the faces are plan and have the same area at all times. This means that the material cannot bend neither stretch on the face’s area. From here is possible to infer that the creases have to be straight and cannot change their length during the folding process. The creases work as hinges between the flat faces. By creasing a flat material it acquires structural and elastic abilities. Surfaces folded according to the rules of Rigid Origami can acquire different configurations by the application of forces at strategic points. Such surfaces have the power to grow, shrink and adapt to many configurations (Casale and Valenti, 2012) (Demaine et al., 2011).

During the Rigid Origami masterclass the students learned all the basic geometric rules and tested on paper models some of the most known crease patterns, such as the Miura and Yoshimura patterns and a variety of the patterns included on Paul Jackson's (2011) book "Folding Techniques for Designers: From Sheet to Form".

The masterclass, along with the folding exercises, allowed the students to understand, in the most tangible manner, the implications of the crease pattern’s geometry on the forms assumed by the surfaces after completing the folding process. It also allowed them to understand the kinematics of each model, the possible ways of movement and the structural ability gained by the paper due to its folding.

The conclusions taken from this masterclass guided the design of the crease pattern of each group and the decisions on which movements were envisioned and how to make them happen, which should be the fixed points and the moving ones.

**Digital Simulation**

Generating the surface’s folding process in space is possible by geometrically controlling the basic constituent entities of the ‘articulated surfaces’: the surface pattern, the line/hinge between the faces, and the point/vertex where the hinges meet. By applying the basic rules of descriptive geometry, an algorithm that can control the entire surface was constructed through nodal programming tools (Rhinoceros + Grasshopper + Kangaroo).

The developed method was based on the specification of the geometric algorithms that connect the basic entities of the folded surfaces, guaranteeing topological invariance of the moving form. By acting on the variables in the algorithm, it was possible to control the movement of the form from one configuration to another, thus designing the movement.

The first step of the algorithm is the configuration of the geometry, the definition of the entire surface area as a mesh and the assignment of mountain or valley folds to the edges.
The second step is the establishment of the kinematic scheme for the physical impulses that comprises the definitions of the anchor points, edge hinges and rails for movement. Finally when subject to the proper impulses, the surface reacts by moving the faces, which maintain the geometries established during the configuration step. General rules govern the movement and overall form of the surface without discontinuities during the transformation that is synchronous to all faces, simulating in digital space the actions that will be made on the physical prototype.

In the second part of the masterclass participants were introduced to microcontrollers and particularly to the Arduino. Some basic circuits with sensors and actuators were showed. Using these circuits participants were introduced to what is a program, how does the controller respond to a stimulus and what is a state machine. Several control programs were shown and discussed on the specific purpose of the Summer School.

Digital Fabrication and Assembly
For the fabrication and assembly of the prototypes the students had different materials and machines available on each year. The machines and materials, and how to work with them, were introduced to the students on the first days so they could think about their goals having in consideration the existing techniques.

For the first Summer School the offered materials for the surfaces were 3mm thick Poly Vinyl chloride (PVC) and 0,5mm thick Polypropylene (PP), the digital fabrication tools available were several 3D printers and a Mat Board cutting machine.

With the Mat Board it was possible to cut and engrave the creases on both sides of the PVC or PP which worked perfectly for the origami surfaces and was used by all groups.

For the second Summer School the available digital fabrication tools were a CNC milling machine, laser cutter and 3D printers. For the Origami surface first experiments the students could use paper, paperboard and cardboard. For the final prototype the available materials were 3mm thick plywood boards, 1mm PP or 160g/m² paper.

The students that used polypropylene or paper did the creases directly on the material with the laser cutter or plotter and bent it by hand. The participants that used plywood could not rely on engraving with the laser cutter because the plywood would break when attempting to fold it. Thus the faces where cut on individual pieces and stitched with a very strong nylon thread.

On both Summer Schools the Digital simulations made with Rhino, Grasshopper and Kangaroo were
used to adjust the geometries and create the drawings for the digital fabrication in a very close CAD-CAM relationship. The simulations were also very important to simulate the assembly and understand the relationship between contiguous faces.

RESULTS

Responsive Surfaces, Rome, September 2015

For the 2015 Summer School the groups developed four prototypes to be used together or individually as wall modules that reacted to user’s approximation or light conditions.

Each group had a 1x1m wood frame deep enough to accommodate all the mechanic elements, like cables and pulleys and the step motors that worked in response to distance and light sensors. (see Figure 2)

Each group created one crease pattern to be replicated in four modules. Every group used different movements, linear vertical, horizontal or diagonal and also rotational. The method to make the surfaces move was similar to all groups. Every surface had a fixed edge or point towards or around which the movement was created. Behind the surfaces was the mechanical system composed by one or two step motors that were connected to two or four lines of movement materialised by tense cables that were attached to specific points of the surfaces. (see Figures 3 and 4)

Surfaces InPlay, Lisbon, July 2016

At the 2016 Summer School the groups developed five prototypes to be suspended on the ceiling and that reacted to user’s approximation or manipulation. This Summer School had a similar workflow to the previous one, so the students also did all the geometric simulations on Rhinoceros with Grasshopper and Kangaroo. The movements tested were linear (on the plane XY and Z direction) and also rotational with different centres of rotation.

The squared plywood board with 1x1 meter was suspended on the ceiling and would hold and hide the linear actuator and all the mechanic system. It was only necessary to respect the limits of the board and the four points that would be used to attach the prototypes to the ceiling. The remaining configuration of the boards would be decided by the students so they could draw rails, holes and/or attachment points needed for their specific work. Each board was drawn by the groups and digitally fabricated at Vitruvius FabLab on the CNC milling machine.

Each group could use one motor actuator of 12” (around 30,5 cm) SuperJack. The available sensors were light and distance sensors but the students could also use potentiometers to mimic other kinds of interactions. (see Figure 5)
Although several kinds of gears, mechanisms and ironmongery were available these did not always suffice the needs. Every project was different from one another and was changing and evolving constantly so the students used the CNC, laser cutter and 3D printers to fabricate gears and pieces for the mechanical system customized to each prototype.

At the INPLAY Design Studio the organizing team decided that the students could have more liberty on the division of the 1x1m project base than on the previous year. Group A and B created four modules disposed radially on the board much like the Responsive Surfaces’ set and used PP as the material for the surface. Group C used two bigger surfaces made with plywood, one on the top of the base and the other underneath it. Group D made sixteen paper cylinders that would go up and down in pairs and moved at different speeds. Group E made 6 cloud like PP surfaces that compressed and decompressed on the same direction. (see Figures 6, 7 and 8)

CONCLUSIONS
The results from both Summer Schools were very satisfactory in several ways. The produced prototypes revealed that the students learned from the proposed workflow and were able to do everything from the beginning to the end very independently and in the available time. It is still amazing to notice how much work was done in only two weeks.

At the first year the organizing team gave less liberty to the creativity of the participants for fear that they would not be able to pass through all the stages of the workflow in a positive way. After the first experience it was possible to refine the workflow, by giving the masterclasses on a more focused manner and spending less time of the two weeks. This way was possible to give the students more time to work in group and with the tutors directly on their projects. The students were freer to create their own structure and crease pattern and learned how to solve unexpected problems at every stage the process.

All the students understood the potential of Rigid Origami surfaces to be used in a kinetic context and all of them were able to create their own crease pattern and make it move according to their aims. They were able to do so on the parametric simulation and physically.

It was also possible to conclude that by giving the students several raw materials to use in digital fabrication and by making available various kinds of
ironmongery the capacity to solve mechanical problems gets much easier. Probably because by being architects the ability to understand mechanical issues by using and manipulating gears is almost direct. Nevertheless the knowledge of teachers and tutors and the daily monitoring of the projects was paramount in the positive achievement of the initial objectives.

The only area were the results were not so positive was on the arduino and electronic steps. The groups obtained the basic knowledge necessary to use arduino and to make the motors respond to the input given by the sensors but they needed more help than on any other step of the workflow.

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Tangible Computing for Establishing Generative Algorithms

A Case Study with Cellular Automata

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The work presented in this paper investigates the potential of tangible interaction to setup algorithmic rules for creating computational models. The research proposes a workflow that allows designers to create complex geometric patterns through their physical interaction with design objects. The method aims to address the challenges of designers implementing algorithms for computational modeling. The experiments included in this work are prototype-based, which link a digital environment with an artifact - the physical representation of a digital model that is integrated with a Physical Computing System. The digital-physical workflow is tested through enabling users to physically setup the rules of a Cellular Automata algorithm. The experiments demonstrate the possibility of utilizing tangible interaction to setup the initial cell state and the rules of a CA algorithm to generate complex geometric patterns.

Keywords: Physical Computing, Tangible User-Interface, Cellular Automata

INTRODUCTION

The work presented in this paper explores the potential of tangible interaction to setup algorithmic rules for computational models. Algorithms enable designers to generate complex geometric compositions that are imbedded with design intents (Woodbury 2010, Aish 2005). Algorithms for computational modeling are commonly created through declarative (graph-based) and/or imperative (text-based) programming methods (Appleby and VandeKopple 1997, Davis 2013). Both programming paradigms require designers to explicitly implement mathematical functions and geometrical algorithms to create computational models (Stavric and Marina 2011). However, it is found to be challenging for designers to conceptualize forms mathematically and algorithmically (Woodbury 2010). Research claims that, designers lacking such skills are limited in their creative design process and in their ability to communicate design intents digitally (Kępczyńska -Walczak 2014).

In contrast, the proposed workflow aims to provide designers with a method to setup algorithmic rules through their interaction with physical design objects. The experiments done for this research link an artifact with a virtual modeling environment (Figure 1). The artifact is the Tangible User-interface (TUI), which is composed of (1) a physical model and (2) a physical computing system. The former is a repre-
sentation of the digital model, which designers will interact with and manipulate; and the latter, is the platform used to translate designers’ analog inputs into digital data using a set of sensors. The TUI will assist in capturing design intents into the virtual environment, and it is tested through enabling designers to setup the rules for a Cellular Automata (CA) algorithm to digitally generate three dimensional geometric compositions.

BACKGROUND
Research has shown that computer programming generally is challenging for users, because of their difficulty to (1) comprehend its abstract notions, (2) construct algorithms, and (3) envision the algorithms’ applications in real world situations (Lahtinen et al. 2005). In architecture, research states that programming applications present an additional level of complexity for designers as they are required to learn and implement algorithms in a short period of time without having the proper training and basics of computer programming (Austin and Qattan 2016, Muller and Kidd 2014). Most importantly, designers find it difficult to translate intuitive design knowledge explicitly into digital models (Monedero 2000).

Research suggests that integrated environments (digital-physical) provide designers with an intuitive approach for interacting with digital environments (Gannon 2014, Al-Qattan et al. 2016). Physical design representations in a digital-physical workflow provide designers with familiar objects, which make the process of interaction with digital models intuitive and direct (Dourish 2001). Additionally, manipulating physical design representations takes the advantage of designers’ haptic skills in the digital design process (Ishii 2008). However, examples of integrated environments have shown to be (1) limited to geometry manipulation; and (2) created to work with predefined programming workflows, which the designer has setup prior to linking the artifact to the digital model (Al-Qattan et al. 2017). Current examples of such works demonstrate an additional level of complexity that is added to the overall design process, i.e. the designer in this case must create the computer algorithm and the circuitry for the physical computing system (Vermillion 2014).

For this research, the objective is to provide an approach where the designer will utilize the physical representation to setup the computer algorithm. The manipulation of physical representations will be translated into algorithmic rules, representing design intents, which will then be used to generate the geometric composition in the virtual environment.

Related works
Research by Zuckerman et al. (2005), Klemmer et al. (2006), and Horn and Jacob (2007) show a few of the examples that utilize tangible interaction with physical artifacts that are used in classrooms to teach students the basics of computer programming and to
assist them in constructing algorithms. Moreover, McNerney provides an extended overview of the development of such works using tangible interaction, which explores the feasibility of functional programming in the physical environment to assist teachers and students in conducting experiments (2004). Such works may not necessarily link artifacts to a digital modeling environments for design purposes, yet the method maybe applicable in the context of architecture to assist designers in establishing computational models. An earlier example of utilizing TUIs to establish digital parametric models is shown in the work done by Al-Qattan et al., which enables designers to create design object relationships through manipulating physical geometry (2017). The TUIs developed for their work can deduce the relationship created between physical objects in a mathematical equation form, and set it up as a parametric constraint in the digital model. The work shows the potential of tangible interaction to establish computational models that represent a design intent.

**Cellular Automata**

Cellular Automata (CA) is a generative system that has been largely explored as a design method (Cruz et al. 2016). CA consists of an infinite lattice with each cell having two possible states, Alive or Dead. The eight neighbors surrounding a cell will determine its future in later generations in the system’s evolution. Since von Neumann (1963) introduced CA, it has been extensively researched and developed for several applications across the fields of art and science. Much of CA’s popularity is due to Conway’s Game of Life, which produces emergent and complex patterns that resemble the dynamics of living organisms (Gardner 1970, Krawczyk 2002). The game is represented by a two-dimensional lattice and implements a simple set of rules to determine the life and death of a cell in its evolution (Frazer 1995).

For purposes of the work presented in this paper, which focuses on tangible interaction for generating algorithmic rules, CA provides a good example for testing because the characteristics of the generated geometry can be interpreted as spatial configurations for creating architecture (O’Sullivan and Torrens 2001, Herr 2008). Herr additionally mentions that (1) three-dimensional CA geometric configurations suggest building forms, urban layouts, etc.; (2) CA depends on “procedural rule-based logic”, which can be associated to the rules that govern architectural form and function; and (3) a temporal dimension can be associated with design development in an architectural design process (2008). Frazer mentions that, CA is straightforward to utilize in a design context, where simple rules can rapidly generate complex geometric outputs (1995). Frazer additionally provides an early example of utilizing artifacts to create a self-organizing system that is based on CA rules. Currently, the Grasshopper plug-in Rabbit [1] provides designers with an approach to construct such evolutionary systems in the digital environment. However, the process of generating and elaborating on CA rules remains as a complicated process (Araghi and Stouffs 2015).

Therefore, the objective of the work is to assist in setting up algorithmic rules, using CA as an example, through artifacts for computational models. The work will present a novel method using a TUI to create a generative algorithm for parametric design. In addition, it contributes to the existing works investigating CA in the context of architecture.

**RESEARCH QUESTION**

The proposed work aims to address the current limitations of implementing computer algorithms in the context of design through answering the following questions: What are the types of physical interaction that could be captured and digitally interpreted into algorithmic rules for creating parametric models? A prototype is developed to test the proposed digital-physical workflow. A CA algorithm is chosen for this work, because of its application in architecture study, and its clear algorithmic grammar; e.g. cells are Alive or Dead based on the number of their neighbors. Designers will setup and alter the rules of the algorithm by manipulating the physical objects in the artifact.
**RESEARCH METHOD**

For this work prototype is developed, and it consists of three main parts: a visual programming environment, a CA generator, and a physical representation of the CA base grid and cells (Figure 2). The prototype is used to conduct two experiment, where each explores an alternative visual programming workflow to translate analog data into the digital environment. Experiment 1 tests the artifact to generate initial cell configurations (“Seeds”); and Experiment 2 tests the artifact to setup the rules for CA by determining the surviving cells through counting the number of neighbors. The prototype in this research focuses on providing a TUI for designers to relate both digital and physical models together. The benchmark for evaluating the experiments is the correctness of the system’s inputs and outputs, i.e. user interaction, and generated rules and geometry.

The tools used for this research are categorized into two groups: software and hardware. Software tools include: Rhino (geometry modeler), Grasshopper (visual programming environment and a plug-in for Rhino), Firefly (data communication between the artifact and Grasshopper [2]), Rabbit (CA components and plug-in for Grasshopper). Hardware tools include: Arduino UNO (open source microcontroller with a single integrated circuit), and eight pressure sensitive resistors.

**PROTOTYPING**

For this work two experiments were done to explore the potential of utilizing tangible interaction and artifacts to setup algorithmic rules for a CA algorithm. The artifact for this work included a 3 by 3 square grid resembling a single cell neighborhood and a total of 3 blocks representing the live neighbor cells. The pressure sensors of the physical computing system are integrated with the physical CA grid. Each sensor is directly linked to its corresponding square in the Rhino model (Figure 3). The sensors in this prototype will be used to indicate cell configuration (location of the blocks on the grid) and to count the number of neighboring cells (number of blocks) for each born cell. The eight highlighted squares of the grid in Figure 3 (left) show the Rhino cells that are linked to the sensors in the artifact. The ninth cell (center square) in both the Rhino model and the artifact is the initial cell which will be generated.

The inputs for the CA algorithm in both experiments are the (1) block configuration for setting up the Seed, and (2) the number of neighbor cells for determining the center cell’s state in the next generation: live or dead. The former, is set by having the designer placing the blocks at different locations using the eight cells of the artifact; and the latter, by adding or removing blocks from the artifact. The initial assumption of the work is that, the artifact will be used to provide these inputs and generate the geometric composition; as the designer manipulates these...
inputs, the geometric composition will respond and the overall form will change.

Figure 4
Workflow for Experiment 1.

Figure 5
The different cell configurations set by the designer as the initial state input for the CA generator.

**Experiment 1 - Creating Initial States of CA Through the TUI**

For this test, the inputs are setup as follows: block configuration will be set using the artifact, and the number of neighbors is set (fixed) in Grasshopper to 3. Figure 4 shows the workflow for this experiment. In the graph, the three main components are user interaction, algorithm setup, and modeling environment. The objective is to test the artifact in providing the CA algorithm with the different cell configurations that will guide the evolution of the geometric composition in the digital model.

The Rabbit plug-in used in the visual programming tool Grasshopper is a CA generator for creating 3D geometric configurations and models. The number of cell neighbors are set for Rabbit within the Grasshopper program graph. The born and surviving parameters are set as follows: if a cell has 2 neighbors it is born, and if a living cell has a minimum of 2 neighbors it survives, otherwise it dies, in the next generation. The cells’ initial configuration, will be obtained from the sensors. The physical computing system will detect which sensors are used (holding the blocks) and send that values to the corresponding parameters in the visual program in Grasshopper (Figure 5).

The values obtained from the sensors provide two types of inputs: the weight of the block and its location on the grid. This information is used to indicate which cells of the grid are used and their locations to create the custom configuration input, which will then be used as a Seed input for the Rabbit CA generator. In the case the designer relocates the blocks on the grid and the configuration will update.

Figure 6 shows a number of the different models produced by changing the Seed, the geometric pattern’s configuration is determined by the physical blocks’ layout as set by the designer, and any further changes made to the blocks’ layout on the grid will change the overall geometric configuration in real-time. The link created between the artifact and Rhino through
the plug-in Firefly enables the designers to manipulate the overall form, and provides them with a level of intuitive control over a complex geometric configuration.

In this experiment, the geometric growth is recorded over a 10 second time-lapse. Each of the generated forms are based on the blocks’ configuration in the artifact. Figure 6 shows both the geometric composition generated in the Rhino scene and the initial block layout for each.

**Experiment 2 - Setting Up CA Rules Using the TUI**

The workflow for this experiment is similar to the previous, having all three main components. Yet, in this experiment the work will test the artifact to set the born and surviving cell rules of the CA generator, by providing the number of the cell’s neighbors (Figure 7). The experiment will use the artifact to determine the number of a cell’s neighbors by counting the blocks placed on the grid. As for the initial cell configuration, the experiment will utilize a random cell layout configuration defined in Grasshopper.

A 15 by 15 square grid is generated with the Seed set by a random selection of points using Grasshopper (Figure 8, left image). The rules of the evolution are set through the artifact, and tested for two conditions: (1) a cell is born and surviving if it has 1 neighbor (Figure 8, middle image), and (2) a cell is born and surviving if it has 2 neighbors (Figure 8, right image).

The designer in this experiment defines the number of neighbors by adding or removing the blocks from the physical grid, and each sensor will count for one neighbor. The location of the blocks on the grid will not affect the rule. Figure 8 shows that the increase of the number of neighbors will affect the evolution process. In the case of three neighbors required for born/surviving cells (placing all three blocks on the grid), the evolution will only produce two generations, and then all cells die for the specific initial state. If further flexibility is required by the designer in the
process of setting up the rules using the artifact, e.g. a cell is born if it has 1 neighbor, and survives if it has 2 or 3 neighbors, this process will involve establishing the rule in Grasshopper using a conditional statement, so that the designer can interact with the artifact to manipulate the number of neighbors to meet these conditions.

DISCUSSION
The proposed method has shown the possibility to setup input parameters using the artifact: CA Seeds and number of neighbors for CA rules. The work has shown to be limited to setting up one rule per experiment, and if the designer requires to setup multiple rules in a single workflow, then a procedure must be created in the visual programming environment, e.g. in the case the designer wants to setup simultaneously the Seed and the number of neighbors for the CA rules. Furthermore, the 9-square grid used for this example limits the model’s geometric evolution when compared to using the CA’s infinite grid.

However, the proposed method can provide a useful tool for experimenting with CA through intuitive physical interaction between a designer and an artifact. It may also assist in educating students or designers about the principles of generative algorithms. Research claims that educators must adapt to innovative ways of design thinking in response to the development of the architectural practice (Karle and Kelly 2011). Research also indicates that there is a need to develop educational models that are more “implicit, tacit, and intuitive” to engage designers progressively in digital workflows, which generally require “explicit information which do not mostly overlap with the implicit realms of design knowledge” (Aşut and Meijer 2016). Designers using the method explained in this paper will have a hands-on experience with an intuitive interface to associate between digital models and physical artifacts for generating complex growth systems.

CONCLUSION
The present work is part of an ongoing research that investigates the possibilities of TUIs to create computational models and design object relationships. The work aims to provide a method that extends the capabilities of digital-physical workflows. Previous work developed for this topic explores tangible interaction to generate constraints for parametric models (Al-Qattan et al. 2017). The work presented in this paper expands on the topic by enabling tangible interaction to setup algorithmic rules.

Establishing design intents in computational models is usually achieved through text-based (e.g. Python, C#, API, etc.) and graph-based (Grasshopper, Dynamo, etc.) computer programming tools. The proposed method suggests an alternative approach to the previous two, through tangible interaction. Additionally, integrating generative design systems and physical artifacts for creating parametric models is a novel approach that expands the role of tangible interaction to manage and control geometric complexity in a digital design process. The experiments have demonstrated the possibility through tangible
interaction a designer can setup algorithmic rules. Further development of the work will include setting up other generative algorithms using TUIs for design purposes.

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Square tessellation patterns on curved surfaces:

In search of a parametric design method

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Methods for Tessellating a flat surface with regular or semi-regular patterns of polygons have already been addressed in literature and can be easily parameterized. For the tessellation of curved surfaces using patterns of one or more regular polygons there is not a uniquely defined approach to the problem within the context of architectural research and applications. This paper is focused on the tessellation of curved surfaces with square tiles, where the tessellation pattern consists of four squares with partly overlapping sides. In this study double curvature surfaces were considered first, and subsequently surfaces of more complex geometry such as minimal surfaces. Specifically, a method for the square tessellation of two types of doubly curved surfaces, the spherical and the ellipsoidal, is discussed and presented in the paper. In addition, the square tessellation of two types of minimal surfaces, the catenoid and the helicoid, have also been examined and presented. For each one of the surfaces that have been considered, an algorithm that generates the distribution of the planar square surfaces on the surface and renders possible the parametric description of the problem, was developed and presented in the paper. A discussion on boundary conditions for each developed method is also included. The Grasshopper visual programming language has been used for the parametric description and display of the results in a graphic environment. The research discussed in this paper can find application in several real world problems including surface paneling, or space packing of polyhedral structural units on a curved surface.

Keywords: square tessellation, curved surface tiling, ellipsoid tessellation, minimal surfaces tessellation, geometric approximation methods
INTRODUCTION AND BACKGROUND

The geometric concept of surface tiling or tessellation, defined in simple terms as the covering of a surface by surface units of one or more shapes in such a way that there are no spaces between, and no overlapping of the units, has found many applications in historical and contemporary architecture. Examples of curved surface tessellations in building design include tilings of domical surfaces of spherical or cylindrical shape in interior or exterior building surfaces.

Tessellating flat surfaces with regular or semi-regular patterns constitute geometric problems with known solutions, i.e. there are eight semi-regular tilings of the plane. The tilings in this case are described by their vertex configurations and can be easily parametrized. On the other hand, tessellations of curved surfaces using a single regular polygon, or combinations of two or more regular polygons, require investigation as there are not always uniquely defined solutions within the context of architectural research and applications. Indeed, in some cases, the question of curved surface tessellation, that involves the application of a pattern on a surface, can be considered as a special instance of surface subdivision problem that has been addressed in both regular and free form geometry literature including mesh subdivision processes (Jiang, M., & Wonka, P. 2014). In the same context of free form geometry, curved surface tessellation problems can be addressed as a special case of surface paneling also covered in recent literature (Bommes, D., et. al. 2013). However, when very specific constrains apply with regard to the geometric characteristics of the composing shapes in a pattern, such as planarity, dimensions, etc., then determining a solution may constitute a very difficult problem or simply one with no solution.

The research in this paper addresses the application of a geometric pattern on curved surfaces that which can be described using mathematical equations. Although this problem, at a first glance, may appear as an easier case than the application of a pattern on a free form surface, it also involves a great deal of complexity and in most cases requires geometric approximation approaches. Within this general frame of surface tessellation questions, the paper is focused on the tessellation of curved surfaces with planar square tiles, where the tessellation pattern consists of four squares with partly overlapping sides. In this study curved surfaces of regular geometry are considered first, and subsequently surfaces of more complex geometry such as minimal surfaces.

SQUARE TESSELLATION PATTERNS ON A SPHERICAL SURFACE: GEOMETRIC CONSIDERATIONS AND SOLUTION

In architectural practice, there are several instances where there is a need for determining a method for covering a curved surface with planar surface elements. The covering of a surface of regular geometry with planar panels, where the panels need to maintain a square shape and a fixed connection pattern throughout the surface is one of them. Environmental applications, involving the integration of solar panels on a curved roof could be another example. Furthermore a tessellation problem with square shaped panels that form a pattern may refer to the covering of a reciprocal structure frame.

The space packing of polyhedral structural units on a curved surface constitutes another field for potential application of the question at hand. As a specific instance of space packing problems, the design and construction of tensegrity double layer structures composed of units of square base also constitutes another field for potential application of this geometry. In this case, maintaining the square tessellation pattern on both the layers of the structure is a requirement. Departing from this specific research topic, earlier research has focused on the development of methods for generating a four square pattern on a spherical surface (Liapi, K. 2001; Liapi, K. and Kim, J. 2005). In this case the four square pattern results from the connection of the tensegrity units on each layer of the structure. In the method already developed by Liapi an effort was made to restrict the solution to the problem to only one size of square-base units throughout the structure.
As shown in Figure 1, in the above mentioned method that involves the parametric generation of a double layer tensegrity surface of spherical or domical geometry, the appropriateness of the resulting geometry, based on constructability criteria, depends on the ratio between the radius of the spherical surface and the length of the side of the square unit. By decreasing the value of the ratio, the accuracy of the tessellating pattern also decreases. This consists a limitation of the method.

In the current study, the constrain according to which only one size of identical square-based units should be used on the entire surface has been waived, and the progressive reduction of the size of the two composing square-based units of the pattern has been allowed. In brief the objective of this study was to come up with a parametric method that: a) will not depend on the size of the radius b) will allow for the uniform distribution of the squares throughout the surface of the sphere.

Working in this direction, we approached the problem of the spherical surface tessellation by following various existing methods. A literature review of the Mercator projection method, also named isocylindrical projection was considered early on in this research. A main feature of this method is that it can generate a network of points which, when connected, form lines that are perpendicular to each other (parallels and the meridians) (Deakin 2002; Karney 2011; Osborne 2013).

In order to simplify the problem at hand the four squares of the pattern are replaced by a point at their centers. This reduces the tessellation pattern to a square tiling problem. To solve this tiling problem the distances between the points need to be properly determined, so that, once replaced by squares, or near-squares, their sides should be touching each other and the connection pattern should be maintained. To achieve this, a code that constructs a sphere by applying its parametric equation, that is \( x = \cos(u) \cos(v), \) \( y = \sin(u) \) and \( z = \cos(v) \) where the fields for \( u \) and \( v \) are defined respectively as \( 0 < u < 2\pi \) and \( -\pi/2 < v < \pi/2 \) was developed first.

Then, a network of equidistant points on the parallels and the meridians was constructed. Since the distances of the points along each parallel is fixed, while, along the meridians the distances of these points towards the poles are increasing, when connecting these points to form squares, the squares become rectangles as they come closer to the poles (Figure 2a). This specific problem has already been addressed in cartography by applying the Mercator projections which in essence can increase the number of parallels while moving towards the poles. So at a following stage, a code that redistributes these points by inverting the parametric equations of the Mercator projection of the sphere \( x=R\lambda \) and \( y(\varphi)=R\psi(\varphi)=R\ln(\tan(\pi/4+\varphi/4)) \) was developed (Figure 2b). The new distribution of the points rendered possible the creation of adjacent near-squares (Figure 3c).

For the creation of the four square tessellation pattern on the sphere, the centers of the squares in Figure 2c, were placed first. So the code included a function that places the centers of gravity of all the squares on the surface. Once all the points were translated in lists and the proper descriptions were made, a network of squares was generated.
In order to utilize the developed network of squares on the surface of the sphere for the creation of the four square pattern, some additional geometric rules were applied. Specifically the squares that represents the ‘void’ between each set of four adjacent squares were created by rotating each one of the squares on the surface of the sphere by the same angle around a perpendicular axis that passes through its center. The rotation angle depends on the desired overlap of the sides of the adjacent squares that form the pattern. At the same time, the code calculates the required change in the size of the squares (scale) after rotation so that their sides still overlap (Figure 2d). It is interesting to note that, as the rotation angle increases, the size of the squares that compose the pattern decreases and respectively the void space between adjacent squares increases. A value that constrains the rotation angle so that the overlap between adjacent squares is maintained is also determined by the code.

GEOMETRIC SOLUTION OF THE ARRANGEMENT OF A FOUR SQUARE PATTERN ON AN ELLIPSOID

Departing from the problem solved previously that refers to the geometric solution of the arrangement of a four square pattern on a sphere, the creation of
a set of points on the surface of an ellipsoid has been attempted. In fact an ellipsoid with the same set of points as the sphere is created by changing the radius of the sphere on the z axis. The Mercator projection technique, that is, the projection of the points on the surface of the sphere to a plane, provides a 2D network of points that are equidistant and form square panels on the 2D plane. However, by repeating the next step of the projection process for the ellipsoid, we can easily observe that the points on the y axis are no longer equidistant and, as a result, the projection of the points on the surface of the ellipsoid does not form square panels. Therefore, a method that will allow us to redistribute these points on its surface was needed.

Various techniques have been examined in order to proceed with the appropriate geometric transformations. A method that approaches the problem graphically, using numerical approximations is also developed. Specifically, in order to approximate the point position change rate along the axes, sinusoidal curves are created to represent this proportion, which are translated afterwards to polynomial expressions.

Specifically, the discrete values that indicate the ratio of the z axis to the x or y axis of the ellipsoid are taken (such as c = 1.1, c = 1.2...c = 2.0) and the curves that represents the rate of the change of the points in each case were derived. These curves are sinusoidal and their rate of change remains fixed as the dimensions of the z axis increased. Based on this, an equation that generates the mapping of the points of these curves on the surface of an ellipsoid was developed. By changing these curves in a MATLAB environment to 7th order polynomial expressions and by inserting the coordinates of various points on the curves, a set of points that reflect the square patterns on the surface of ellipsoids of various ratios (c = 1.1, c = 1.2 ... c = 2.0) were generated as shown in Figure 6. As for example for the case of c=2.0 the polynomial expression $av + bv^3 + cv^5 + dv^7$ was used, where a=0.003, b=-0.015, c=0.180 and d=0.5015.

This followed process made clear that in the case of the ellipsoid a purely analytical expression to generate the four square pattern on the surface of its surface could not be determined. Instead, for the solution to the problem an approximation method had to be used. It was also shown that by decreasing the size of the squares, the square pattern on the surface of the ellipsoid is not affected (Figure 4).

Subsequently, other approximation methods for tessellating the surface of an ellipsoid were explored.
So, in addition to the polynomial approximation, a second method that makes use of fixed point iterations (Osborne 2013) was also explored. It is shown that the accuracy of the method is not affected when the ratio between the two main semi-axes of the ellipsoid changes (Figure 3).

Both methods generate highly accurate results throughout the entire surface; their accuracy depends on the number of the polynomial terms and the number of iterations respectively.

**GEOMETRIC SOLUTION OF THE ARRANGEMENT OF A FOUR SQUARE PATTERN ON MINIMAL SURFACES**

Minimal surfaces are defined as surfaces with zero mean curvature and may also be characterized as surfaces of minimal surface area for given boundary conditions (1). Despite the complexity that most of the times characterizes their form, minimal surfaces, because of their specific geometric properties, can be tessellated with planar square patterns by applying
the method describing earlier without the need for any modifications. Accordingly, for the generation of a network of equidistant points on a minimal surface, and subsequently for the tessellation of the square tile pattern, the parametric equations of the surface suffice and there is no need for any approximation method. Following this method two types of minimal surfaces, the catenoid and the helicoid, have been examined as shown in Figures 5 and 6.

For each one of the used methods, an algorithm that generates the distribution of the planar square surfaces on the curved surfaces and renders possible the parametric description of the problem, was developed. For the iterations, a code, written in Python, was inserted in the basic code. The Grasshopper visual programming language has been used for the parametric description and the display of the results in a graphic environment. The visualization of the results has facilitated the comparison of the developed methods.
5. CONCLUSIONS
This study successfully addressed the tessellation problem of curved surfaces with a four square pattern.

At the first stage of this study, the distribution of a pattern of square tiles on the spherical surface was studied and an algorithm has been developed. A code that utilizes the Mercator projection for the implementation of the algorithm was also developed.

At a following stage, a parametric method that allows the uniform arrangement of a four square tessellation pattern on the surface of the ellipsoid has been developed as well as a code that implements the steps of the algorithm. The developed method involves geometric approximation processes. The Grasshopper visual programming language has been used to this end and the boundary conditions for the arrangement of the square pattern on both the surface of the sphere and the ellipsoid have been determined.

The visualization of the results in the graphical interface of the grasshopper programming environment has facilitated the study of the effect of various parameters of the problem and the comparison of the results of the developed method.

The developed algorithms and parametric processes are expected to offer a valuable design tool that will facilitate the exploration of the application of planar square tessellation pattern on a wide range of curved surfaces, including spherical and ellipsoidal, as well as certain types of minimal surfaces.

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Parametric design

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**Tool, medium or new paradigm?**

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Parametric design is an emerging research issue in the design domain. However, discussions about the creative process in parametric design are limited. What is more, despite the passing of 57 years of parametric design's existence we still do not know what parametric design is. Is it a simple tool, which is useful in some kind of optimization of the architectural form, or it is a medium, which helps architects develop unexpected solutions, and perhaps this is already a new design paradigm? The presented paper will contain general considerations relating to the nature of parametric design, the history of which starts in 1960, when D.T. Ross has formulated the thesis that our main objective is to formulate constrains and all needed parameters of the solved problem. Please write your abstract here by clicking this paragraph.

**Keywords:** optimisation, parametric design, design tool, design media

**HISTORICAL BACKGROUND OF THE PARAMETRIC DESIGN**

As a result, the development of a design methodology, caused by the increasing complexity of both the object and the design process, as the main principle of improvement of architectural design approach has focused on the objectivization and rationalization of the design process. The main principle was defined as follows: “When we know exactly what is and also exactly what ought to be we are able to establish a direct efficiency relation. By appropriate comparisons of what is and what ought to be, efficiencies, both ideal and practical, can be established.” (Emerson 1964, p. 23) The first attempt of applying something like parametric design was undertaken in 1960, when D.T. Ross in Computer-Aided Design: a statement of objectives, has formulated the thesis that “...we now declaim that our main objective is not to solve problems, but to state problems”, which meant to formulate constrains and all needed parameters of the solved problem. (Ross and Mann 1960) The first computer program conducted under the Computer-Aided Design Project was written by Ivan Sutherland in 1963 in the course of his PhD thesis at MIT.

In the following years research has focused on the problems of how computers can aid the facility layout process and the designer’s interaction with multiple design databases. The classical layout programs are: block diagramming software - CRAFT (minimizes nonadjacent cost and used when quantitative data is available) and relationship diagramming - CORELAP (based on location preference between areas and used when quantitative data is not available). (Lee 1967). CRAFT: Computerized relative allocation of fa-
ilities’ technique (Buffa, Armour and Vollmann 1964) was one of the most popular computer based layout procedures. Algorithms elaborated by Buffa et al., based on the heuristic approaches, were used to place factory spaces in a way which would reduce the total material transportation cost. The cost was a parameter defined by a function of the distance between work centers, the frequency of movement of material between the centers, and the cost involved in each move. The algorithm starts with an initial layout and proceeds to improve it by interchanging spaces in pairs to achieve its goal. The combinational problem lengthens the solution process as the number of work centers increases. If designing layout for 20 work centers, exchanging two work centers simultaneously, would require 190 evaluations. Exchanging three work centers simultaneously increases the number of evaluations to 1140, and if we would like to change 20 centers it would need n! - 20! evaluations. With this amount of points, making changes manually is practically impossible.

The time requirement for a computer is trivial for an evaluation of these possibilities. This technique permits a considerably larger number of evaluations in a short time. It does not give the optimal layout; but the results are good and near optimal, which can be later corrected to suit the need of the layout planner. CORELAP: Computerized Relationship Layout Planning is the oldest Layout Planning routine and was developed by Lee and Moore. CORELAP generates a layout on the basis of the total closeness rating (TCR) for each department and begin with two major inputs: a relationship chart and space requirements. The starting point is creation of the Muther’s grid table which displays designer’s preferences for relative (pair-wise) department locations. Muther has proposed a six points scale: A - absolutely necessary, especially important, I - important, O - OK, U - unimportant, X - undesirable. To obtain a layout, the user is required to input the following: number of departments, relationships weights, relationships cut-offs, partial adjacency value, and relationship. Then the computer generates the layout. The total closeness rating, the order of entry of departments in the layout, the numerical closeness value and distance between the departments are also shown. CORELAP accepts relationships between as many as 40 departments. (Lee and Moore 1967) The new version of the CORELAP algorithm can be obtained from Tompkins et al. (2003) where a new interactive version of the software is presented. The user interface in this implementation of CORELAP is the spreadsheet and the user inputs data through Microsoft Forms.

In 1980, the author has in his diploma work used the routine, a modification of CORELAP, developed by Maria Ostrowska in 1977. The diploma subject was a Primary School. As the first step the functional program was defined and it was decided that the school should consist of 9 areas: A - Library, B - Classes 1-4, C - Mathematics and Environment, D - Humanities, E - Technical Lab (DIY), F - Art, G - Sport, H - Recreation, I - Administration. In each area, different functional blocks were placed, and as a result a matrix of 40 x 40 elements was obtained. Connections between the elements were evaluated on the basis of a 4-point scale: 1 - direct connection, 2 - strong connection, 3 - medium connection, 4 - weak connection. These values were the design parameters. Due to hardware limitations, this large matrix was simplified to a symmetrical matrix of 9 x 9 elements, which meant that firstly the location of the 9 school areas was calculated - the computer produced a graph which graphically represented the links between main functional elements. The same procedure was then repeated for areas A, B, C, H and I. As a result a comprehensive scheme of functional links was created. On the basis of the schemes the building plan was created manually. To get many variants of the plan, values of the chosen parameters were changed, and matrix was calculated again. (see Figure 1) Practice has shown little usefulness of these methods, especially if the laboriousness of preparing data at the initial preparatory stages is taken into account. It was not possible to apply subjective parameters, which led to oversimplification of the plan. These programs were characterized by a primitive input and output as
they worked on the principle of batch processing. The old programs were very user unfriendly. Despite the difficulties caused by the imperfection of computer hardware (time consuming batch processing) and simple software, the relational method was helpful in designing the building plan. It should be noted that with the development of computer technology, these programs have become one of the basic tools for industrial facility planners. This has profound effects on organizational productivity and profitability. Optimal layouts reduce materials handling costs, help streamline all operations in a facility, and reduce energy costs. With large amounts of money being spent on new facilities each year, it is natural that industrial facility planners, designers, and architects long for a superior Facility Layout Optimization software. On the market, we may find many professional computer programs for Layout Planning. One of the interesting layout optimization tool is VIP-PLANOPT (formerly known as Layopt). This software is an improvement algorithm for developing alternative and efficient block layouts from an initial block layout provided by the user. In the absence of an initial layout, one may be also randomly generated by the program. The algorithm used in the program is based on the algorithm developed by the Bozer, Meller and Erlenbacher. It extends a well-known facility layout algorithm (CRAFT) to facilities with multiple floors. It also enhances CRAFT by controlling department shapes by allowing flexible departmental area requirements. (Bozer, Meller and Erlenbacher 1994) BLOCPLAN is an interactive program developed by Donaghey and Pire. Quantitative and qualitative data can be used as input. It can develop a single story or multi-story layout. As the BLOCPLAN generates an initial layout and makes enhancements of this layout, it can be explained as both a construction and an improvement method. The user may optionally choose the random construction and automatic search. (Donaghey and Pire 1991) Micro CRAFT (MCRAFT) is an extended version of CRAFT, presented by Hosni, Whitehouse and Atkins. MCRAFT divides the plant area into bands and assign these bands to one or more facilities. Moreover, MCRAFT eliminates the pair-wise exchange limitations. By using MCRAFT, all pairs can be tried with the pair-wise exchange method, which makes a large contribution to finding an optimum solution. (Hosni, Whitehouse and Atkins 1980)
PARAMETRIC DESIGN AS AN “OPTIMIZATION TOOL”

All computer programs discussed above are a kind of an optimization tool, the goal of which is designing a cost-effective product in minimum time. In order to achieve this goal, the requirements of optimum designs are becoming more important. Parametric design modelling platforms and scripting environments allow for rapid generation of 3D models and enable multilevel evaluation of parametrically-driven design alternatives. The key to understanding what is parametric architecture, is the word “parameter”. Design is based on carefully described parameters, which are used by computer programs for generating original, unusual and difficult to describe spatial forms with mathematical precision, optimizing them mostly in terms of environmental or functional conditions. Parametric design is treated as an “optimization tool”. In architectural design, different parameters were used to “optimise” the architectural form. Each parametric design starts with a parametric variation, which can be employed for the differentiation of a field, layer or subsystem. The most common are the parameters associated with the structure of the building, energy efficiency, sun exposure, location, acoustics or aerodynamics. This is fully understandable because, for example, in the design of high-rise buildings the cost of “architecture” is only 40% of the total cost, MEP (mechanical, electrical, and plumbing) - 25%, structure - 30% and elevator system is 5%. (Nicknam and Elnimeiri 2011)

In the current design practice, issues described above are typically left to be dealt with after the architectural form is well articulated. This approach is time consuming when the architect proposes multiple options. The solution is a full integration of optimization tools with the CAD system, where all drawings can be automatically updated after achieving the optimum and satisfying all imposed constraints. The advantage of this way of working is a shortening of the optimization cycle time and radical reduction design time. Another advantage of this approach is also the ability to reduce investment costs, as the most important design decisions, which have the most significant cost impacts, are made at the concept stage of a project. The serious disadvantage is that parametric methods are mostly used at the stage of detailing of the project when the designer may update the CAD model only after receiving an optimum design from optimization tools. Consequently, in traditional Computer Aided Design the main consuming factor is the design optimization cycle.

PARAMETRIC DESIGN AS A DESIGN MEDIUM

In 1994 Ranulph Glanville has asked: “What is the difference between a tool (or toolkit) and a medium?” and then answered: “The difference is that the tool does what we want, amplifying, in some sense, our natural abilities. It applicable within the field of its intention. The medium, on the other hand, “bites back”. It suggests other uses, may not quite work as we want (...) with a medium, the side-effects may become more important than the original intentions.” (Glanville 1994, p.11)

In this chapter, we will discuss parametric design as a design medium which is immeasurable in potency and in its ability to help our thinking - and thus can take a role as a partner in enhancing our creativity. The second thesis is that the serendipity is an early, especially turning point of the very process of evolution. Serendipity is the effect by which one accidentally discovers something fortunate, especially while looking for something else entirely. As Lawrence Block said: “Serendipity. Look for something, find something else, and realize that what you’ve found is more suited to your needs than what you thought you were looking for.” (Parker and Talbott 2008)

Traditional CAAD systems limit designers’ creativity by constraining them to work with prototypes provided by the system’s knowledge base. The design is creative if it cannot be composed from the prototypes in the system’s knowledge base. A CAAD system supports creative design if it allows the designer to define novel prototypes to cover these ideas. It is creative if it discovers new prototypes by itself. If we analyse the process and results of
the implementation of parametric methods, we can conclude that most of the obtained forms totally differ from designers’ expectations. (see Figure 2) A subjective/emotional factor has a great effect on the decision-making process in designing. Intuition, unpredictability and no logic are the essence of creativity. In design, often an inappropriate use of tools gives better results than the proper. This way of working with media may surprise and stimulate the designer, offering him or her unforeseen shapes and solutions. The goal is to change creative boundaries of contemporary design tools. In many publications on architectural parametric design we may read the statement that Architecture is simply the collection of principles and operational requirements that are being applied in order to solve design problem. This leads to the conclusion that architectural design is an objective based activity whose primary purpose is to define what is required to provide a solution. If architecture is an objective-based activity, then what
place do emotions and subjective meanings take in this activity? We need the theories and methods for innovation and creation. If we treat parametric design as a medium, we should formulate new parameters for aesthetic design on the conceptual design level. These parameters usually result from subjective assumptions. (see Figure 3) To connect parametric design and creativity, Lee proposed to adopt the concepts of divergent and convergent thinking, two critical factors in the creativity model, to understand parametric design. In parametric design, divergent thinking generates a variety of solutions with the parameters as the “potential answer” to a question, while convergent thinking identifies the most appropriate solution as the “right answer” to a question with rules. (Lee 2014, p. 266) An interesting approach, in which the subjectively selected parameters and the optimization process were connected, was undertaken at the Faculty of Architecture, Bialystok University of Technology. The goal was to
create space elements which may be used as a mobile partition for dividing the space of an auditorium. The auditorium is a multifunctional space for lectures, consultation, meetings, and exhibitions. Organisation of such different activities simultaneously needs mobile dividing partitions, while until now a large black box was used. Students wanted to make the space more attractive by introducing a new element. An additional function of this element should be a space for leaving information (“a mailbox”) and a bench for sitting. Because these elements should contrast with the boxes, it was decided to use curved lines. The first step was to model the black boxes and then draw curves which defined multi-curved volume. In the next step, in the Grasshopper, this volume was divided onto vertical and horizontal parts. Then the algorithm for creation of frame joints was created. As a result, it was possible to generate the optimum contours of the ribs and prepare information for CNC machine. The next stage of optimization was performed after determining the thickness of the particle board plate. After design, the elements were cut and assembled without the need to use any tools. (see Figure 4)
CONCLUSION - IS PARAMETRIC DESIGN A NEW DESIGN PARADIGM?

The Oxford English Dictionary defines the basic meaning of the term paradigm as “a typical example or pattern of something; a pattern or model”. The historian of science Thomas Kuhn in his book The Structure of Scientific Revolutions has defined a scientific paradigm as: “universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of practitioners” (Khun 1996, p.10). On this basis, we may assume that this is the replacement of one methodology over another on the basis of a consensus of the majority. However, in the case of architectural design it seems to be a premature statement. It is difficult to accept the idea of a “majority consensus” in the case of replacing traditional computer-aided design methods by parametric design. Opinions about the architectural revolution caused by parametric methods are exaggerated. The history of architecture shows that designs have always been created in relation to changing factors - climate, technology, usage, environment, culture, and even the character of the building, in other words: they have always been designed parametrically. As was shown in Chapter 1, parametric architecture was the subject of architectural considerations in the 1960s - a few decades before the digital revolution.

Nowadays, parametric design is one of many design methods. If we analyse the prevalence of the use of this method, we can note that it is only used in a small number of prestigious design offices and innovative schools of architecture. We can only hope that this method will be applied more widely in the future.

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SHAPE AND FORM STUDIES
Parametric modeling applied to the virtual reconstruction of the damaged sculpture of St John Nepomuk in Petrovaradin

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Valuable cultural heritage may be permanently damaged as a consequence of different man-made influences, as well as natural erosion. In cases where no documentation is available about the original shape, an analysis of the typological group of similar objects is commonly used as a base for reconstruction. The interpretation of typology can be based on explicit method relied on relevant shape data. The aim of this paper is to propose a method which may be used in the virtual reconstruction of the damaged sculpture of St John Nepomuk in Petrovaradin, Serbia. Virtual reconstruction presented in this paper was based on parametric analysis of the typological group. The spatial characteristics of the sculptures were transformed into measurable parameters which were further used to determine the missing shape such that the reconstruction has the highest probability of representing the true shape of the damaged sculpture based on attributes the same typographical group. We propose three different ways based on how the most likely shape of the missing part may be computed: i) the reconstruction in which average values for each parameter are used; ii) the reconstruction in which average values are used for numerical parameters while spatial parameters were selected from the sculpture with the highest probability for these parameters; iii) the reconstruction in which all of the characteristics are inherited from one real sculpture, closest to the average shape.

Keywords: virtual reconstruction, parametric modeling, image-based modeling, cultural heritage
INTRODUCTION
Valuable cultural heritage may be permanently damaged as a consequence of different man-made influences, as well as natural erosion. Several different approaches and digital tools may be used for surveying, virtual reconstruction, and restoration of cultural heritage. One approach to cultural heritage analysis is parametric modeling, which was used in the process of restoration (Ma et al. 2015; Michel et al. 2014), virtual simulations and shape analysis (Varinlioglu et al. 2014; Tepavcevic and Stojakovic, 2013; Coutinho et al. 2011) and reproduction (Slawomir et al. 2015; Scopigno et al. 2014).

Regardless of the quality and quantity of documentation, the reconstruction of missing parts of permanently damaged cultural heritage is usually the result of an artist’s interpretation (Pereira et al. 2009). The individuality incorporated by an artist necessarily includes his/her interpretation of the documented influences, and his/her perception and understanding of the cultural heritage. In cases where no documentation is available about the original shape of the cultural heritage, an analysis of the typological group of similar objects is commonly used as a base for reconstruction. However, the reconstruction does not necessarily have to be based purely on artistic interpretation. Instead of an artist’s interpretation of typology, type analysis can be based on explicit method relied on relevant shape data.

The aim of this paper is to propose a method which may be used in the virtual reconstruction of the damaged sculpture of St John Nepomuk in Petrovaradin, Serbia. Sculptures of St John Nepomuk within other symbolic portrayals are usually depicted wearing a biretta. This detail is highly common in local sculptures from the same typological group (Roth, 2014). We will focus on the virtual reconstruction of the biretta that was likely to cover the top of the head of damaged St John’s Nepomuk sculpture in Petrovaradin. Virtual reconstruction of the biretta presented in this paper was based on parametric analysis of the typological group - sculptures that share similarities in shape and style with the damaged sculpture. For the purposes of the analysis presented here the spatial characteristics of the sculptures were transformed into measurable parameters. Parameters were further used to determine the shape of the biretta such that the reconstruction has the highest probability of representing the true shape of the missing part of the damaged sculpture based on attributes of the same typographical group.

METHODS AND MATERIALS
The approach for virtual reconstruction of the damaged sculpture consisted of several phases:

i) The representative sculptures were selected. Selection criteria consisted of a similar style and geographic area.
ii) The relevant characteristics of different birettas’ shapes were determined in order to make comparable 3D models of the representative shapes.

iii) Single image-based modeling of the selected representative sculptures was used for biretta’s shape reconstruction.

iv) Parametric models of the selected representative sculptures were made and the relevant parameters were analyzed and compared.

In textual descriptions St John Nepomuk is depicted to wear a biretta as an iconographic characteristic of a saint (Roth, 2014). Photographs of the free standing sculptures and sculptures in church niches of St John Nepomuk are used as an input data for the analysis.

SCULPTURES OF ST JOHN NEPOMUK

The sculpture of St John Nepomuk in the niche of the St Juraj’s church in Petrovaradin, Serbia, has been highly damaged. There is no data (photographs, drawings or descriptions) about the original shape of the sculpture. The top of the head has completely eroded, and the original shape of the head is unrecognizable (Figure 1).

The sculpture is unapproachable, located in facade niche at a height approximately 7m. The sculpture was surveyed by structure from motion photogrammetric method supported with an elevator bucket truck. A precise 3D model of the sculpture was reconstructed from these images (Figure 2).

As inputs for the analysis of the potential shapes of the missing top of the sculpture’s head, we used photo documentation, available online, of the sculptures of St John Nepomuk. We made further selection of these images in order to choose a group of sculptures with similar geographic area, material of which the sculpture is made and style. We choose only sculptures made out of stone, and omitted the ones made out of bronze or wood. Considering the style and shape, we selected sculptures with a biretta and omitted sculptures which used modern styles of sculpting (characterized by primitive based shapes, different proportions and hard surfaces). According to the described criteria a group of six sculptures was selected (Figure 3) to be used as the input for the shape analysis.

SINGLE IMAGE-BASED MODELING OF THE SCULPTURES

For each of the six selected sculptures, a single photograph was used to reconstruct the 3D shape of the biretta. Single image-based modeling considers 3D reconstruction based on a single photograph as an input. Single image-based modeling produces models of low accuracy (compared to photogrammetry or laser scanning) (Styliadis and Sechidis, 2011), especially in unfavorable cases such as the reconstruction of a complex sculptural shape. However, single image-based modeling does not require on-site work and additional surveying costs, and high accuracy is
not obligatory for parametric analysis, which is why single image-based modeling was selected as a suitable method for this research.

In single image-based modeling the most critical part is photo orientation because it depends on the constraints (Hauvel van den, 1998). It is necessary to use constraints in the image because of the single image ambiguity, in order to find the position of the camera’s optical center (Stojakovic et al. 2013). In photographs in which complex free-form shapes occupy the most of the image, it is not possible to use common constraints, such as perpendicularity and equal distances for orientation.

The orientation problem requires a specific approach to be used for single-image sculpture reconstruction. The head of the sculpture, which is present in each photo, is used for photo orientation. One constraint that was used is the symmetry of the face. Another aspect that can be used to solve the orientation problem is that the symmetry plane is perpendicular to the line which connects eyes and to the line of the mouth. Beside these, at least one more constraint is needed for photo orientation. Since there were no other reliable constraints, available assumptions about common proportions of the face were used. Here, the common distances and distributions of facial elements and face contours were used to perform photo orientation. The 3D model of the average head (Burt and Perrett, 1995) was imported as a reference and was matched to the oriented photo (Figure 4 a).

Because of the complexity of the model and limitations of single-image based modeling in the reconstruction of complex shapes, the biretta had to be simplified to basic lines and spatial relationships. The simplification was performed by taking into account the capabilities of parametric analysis that followed.

The shape of the biretta was simplified in order to be represented by angles, lengths and curves, which are suitable for the latter parametric analysis. Data to be compared were parameters that define:

- the position of the biretta on the head
- the longitudinal curve of the biretta (the section that is the symmetry plane of the head)
- the position and shape of the cross curve of the biretta (through the plane in which the characteristic seam is)
- the dominant spatial shape of the biretta.

In single-image based modeling of complex shapes it is important to follow the workflow in which the single image ambiguity problem is solved during the modeling phase (Stojakovic and Tepavcevic, 2011). To determine the position of the biretta on the head, the automatic texture extraction from the photograph to the imported 3D model of the head was used (Figure 4 b). In that way the line where the biretta meets the head was reconstructed in 3D.

The longitudinal curve of the biretta was in the symmetry plane of the face, and therefore the contour curve of the longitudinal shape could be reconstructed in that plane. In the same plane the section of the longitudinal and cross curve can be noted in the photo, and therefore its 3D position can be re-
constructed. When the position of that section was computed, the plane perpendicular to face symmetry plane was placed. That plane was used for the reconstruction of the cross section of the biretta, and it is constructed in the same way as the longitudinal curve. In that way all of the characteristic curves of the biretta were reconstructed in 3D (Figure 4c).

Other visible parts and symmetry constraints were used to check the model’s accuracy. As expected, due to the quality of input data and limitations of the single image-based modeling of free-form shapes, the models do not have high accuracy. We note that deviations go up to 5% of absolute magnitude.

**PARAMETRIC ANALYSIS**

After the characteristic shape parameters are recovered in 3D for all birettas, they had to be analyzed in order to find which features have the highest probability of occurrence in the typographical group. 3D models of the heads with the reconstructed curves that define biretta’s shape were scaled and rotated to match size and position in order to gather the required measurements.

The shape of the biretta was interpreted in a way suitable for parametric analysis. Angles and distances, which are numerical values, were measured. All distances were represented as a percentage of the head’s height, and angles were measured in degrees. The average curve was constructed so that all curves have same horizontal length. All of the curves were valued in comparison to the average curve. The height of curve points was calculated as the average height of all points on curves that share the same horizontal coordinates.

Shape parameters which were measured for the analysis are (Table 1, Figure 5):

1. **Position of the biretta on the head** - defines the position of contact curve of biretta and the head
   a) Angle between the horizontal plane and the touching plane of the biretta and the head
   b) Distance of the front part of the biretta to the top of the head

2. **Longitudinal curve** - defines position and shape of longitudinal curve
   a) Angle between normal to touching plane of biretta and head and the front linear part of the longitudinal curve
   b) The length of the front linear part of the longitudinal curve in the vertical direction
   c) Average vertical distance between the longitudinal curve and average longitudinal curve

3. **Cross curve** - defines position and shape of the cross curve
   a) Horizontal distance from the point at the forehead to the cross curve plane
   b) Angle between normal to the touching plane of biretta and head, and side linear part of the cross curve
   c) The length of the side linear part of the cross curve in the vertical direction
Table 1
Values of the biretta’s shape parameters for each sculpture.

<table>
<thead>
<tr>
<th>Sculpture</th>
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<th>1b</th>
<th>2a</th>
<th>2b</th>
<th>2c</th>
<th>3a</th>
<th>3b</th>
<th>3c</th>
<th>3d</th>
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<th>4b</th>
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<th>5b</th>
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Figure 5
Parameters of the biretta shape in the right and front view. Average curve is in green color.

Table 2
K factors for all relevant parameters used for the generation of the resulting model.

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</table>
d) Average vertical distance between the cross curve and average cross curve

3. Shape of the spatial curve - defines overall shape of the biretta
   a) General shape of the curve in the middle of the biretta (for an elliptical shape the value is 0, for other shapes the value is 1)

5. Spatial relationships - analysis of some parameters makes for a more logical final shape if the relationships between parameters are analyzed together rather than independently
   a) Variation in the angle of the lower conical part of the biretta: the difference between the angle between normal to touching plane of biretta and head, and the front linear part of the longitudinal curve (2a), and angle between normal to touching plane of biretta and head and side linear part of the cross curve (3b)
   b) Variation in length in the two lower conical part of the biretta (in the longitudinal plane and in the cross plane): length of the front linear part of the longitudinal curve (2b) and the length of the side linear part of the cross curve in the vertical direction (3c)

In order to find the most likely shape of the biretta based on the typographical group, we compared the numerical values \( (m) \) of the six selected sculptures \( (s = 6) \) to the average value for each parameter. For the numerical data, average values may not be used in reconstruction. This is because using the average value in the shape analysis of realistic sculptures can sometimes lead to illogical results (e.g. in the analysis of curve shapes). Instead of this approach, we used the existing shape of the curve which is closest to the average shape across all sculptures. In this way we can measure the deviation of any particular sculpture or its specific parameter from the average shape.

For each parameter \( (i) \) influence factors \( (K_i) \) were assigned to each sculpture \( (j) \) according to their difference from the average value. Differences from the average value \( (D) \) were calculated as

\[
D_{i,j} = \left| \left( \frac{\sum_{j=1}^{s} m_{i,j}}{s} \right) - m_{i,j} \right| .
\]

That means that sculptures which have smaller values of \( D \) are closer to the average value in that parameter. In order to get values comparable for the different parameters, the influence factors were scaled to between 0-1, \( K_{i,j} = D_{i,j} \sum_{j=1}^{s} D_{i,j} \). The introduction of \( K \) factors (Table 2) allows measuring of how typical a biretta’s shape is, according to a multiple parameters. By adding all factors \( K_i \), we can compare how much the specific biretta reflects the average biretta shape (it is the one with the smallest \( \sum K_i \)). Or we can add \( K \) factors representing a group of parameters (e.g. just the cross curve) and find which cross curve is closest to the average. The comparison of \( K \) factors allows us to generate the average shape of the biretta in several different ways.

RESULTS

The most likely shape of the biretta may be computed in several different ways based on different starting assumptions. We propose three different approaches for the virtual reconstruction.

i) Since the biretta is presented as a logical spatial formation, separate analysis of each parameter may not be an adequate statistic by itself. This is because when all the parameters are independently averaged across all of the birettas, the resulting parametric model may not conform to the original logical spatial formation because of potential discordance. The first proposed reconstruction used average values for each parameter, adjusted (scaled and rotated) so that the curves meet in one central point and outline the logical shape (Figure 6a). In the figure dark purple/blue curves are calculated values, and green are adjusted curves.

ii) The second proposed virtual reconstruction uses the average values of independent numerical parameters (angles, lengths and relationships). Other parameters, such as curves that have to correspond to one another, were selected from the sculpture with the smallest \( K \) factor for the sum of curve parameters \( (K_{2c}, K_{3d}, K_{4a}) \). So, in this example, the parameters have average values, except for the
Figure 6
Results generated by different approach to parameter analysis presented in right, front and perspective view; a) all average values, b) average numerical parameters, curves with minimal K factor, c) shape that has minimal total K factor.
curves, which are same as the sculpture in Pancevo (Figure 6b).

iii) The third way is to select all of the characteristics of one real biretta, the one with the smallest \( \sum K_i \) factor when all of the criteria are considered, \( (K_3 b \text{ and } K_3 c \text{ were omitted, since they are already included in relationships } K_5 a \text{ and } K_5 b) \). In this way we can detect which biretta is closest to the average shape (Figure 6c) across the typographic group. In this research, the biretta on the sculpture in Pancevo was found to have the smallest \( K \), although the one in Krapina has almost the same \( K \) factor.

**CONCLUSION**

In this paper parametric spatial data analysis is proposed and applied on a case study of the damaged sculpture of St John Nepomuk to show a statistical approach to the virtual reconstruction of cultural heritage. Single image-based modeling and parametric modeling were used for 3D data representation. Parametric interpretation of the spatial structure was made and the values were analyzed statistically. The analysis determined the shape most likely to appear in selected typological group. Variation in the analytical approach can cause small discrepancies in the resulting shape. The results demonstrate that it is possible to generate a statistically representative average of the typological group which can be used for the virtual reconstruction of damaged heritage, when no data about the original shape is available.

Since the resulting shape is sensitive to input data and preferred statistical approach, it should not be treated as imperative for real reconstructions, but more as a useful guideline. Engagement of cultural heritage professionals is advisable during the input and approach selection. The limitations of the presented study are a small number of analyzed sculptures and a variation in the quality of input photographs. Future research includes applying a similar methodology to a larger set of data, and the use more automatic steps in the analysis.

**Acknowledgments**

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The Interplay of Figures Using Superimposed Arrays

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This paper introduces the theoretical considerations underlying the design of a digitally designed and Computer Numerically Controlled (CNC) fabricated public installation project in the city of Austin, Texas. The project, The Creek Zipper, is an assemblage of exo-related units that symbolically reconnects two divided city neighborhoods, establishes a new relationship between the synthetic and natural, and inflates a two-dimensional graphic into a three-dimensional form. The project can be clearly read as a whole from a distance, but as one approaches, the legibility of each part begins to overwhelm the perception of the whole. As the form of the whole dissipates, the project gains a field-like presence, revealing different sets of discrete figures nested within the larger whole. The Creek Zipper addresses these multiple overlapping dichotomies that act as design generators and promote a dynamic expression of the project.

Keywords: Array, CNC, Part Whole, Curve, Installation, Fabrication

PROJECT BACKGROUND

The Creek Zipper is one of five temporary installation projects located on Waller Creek, which is in the process of undergoing a radical infrastructural transformation.

The city of Austin is constructing a flood-control tunnel to mitigate the devastating effects that torrential rain has imposed on the area. In the past, flooding at Waller Creek has made roads impassable, disconnecting the east side of Austin from downtown. Once the tunnel is complete, this incredibly active and important thoroughfare will remain open even during the worst storms, providing a connection between two vastly different but equally important neighborhoods.

The Creek Zipper fosters a new experience of the creek that is grasped from multiple perspectives, including from the pedestrian bridge that spans it, a stairway that leads down to the water from the bridge, and from the level of the creek.

Although the tunnel will alleviate flooding, the potential for flood-like conditions remains. Nature consists of a dynamic set of relations, including an occasional overabundance of rain. Despite our every effort to contain it, excessive rainfall will continue to pool in highly constructed, urban areas that lack adequate soft scape to shed and absorb water. Even though the tunnel will control flooding caused by excessive rainfall in the immediate future, we shouldn't forget the fragility of artificial structures—a mistake that led to the devastation of New Orleans when a levee failed during Hurricane Katrina. This installation addresses the temporality and instability of synthetic structures that attempt to interface with and control natural dynamical processes. (see Figure 1)
Flooding is an example of what Timothy Morton calls a hyperobject. A hyperobject is a “thing that is massively distributed in time and space relative to humans . . . they involve profoundly different temporalities than the human-scale ones we are used to.” (Morton 2013, p.1) Flooding can have an effective range far greater than any singular event and is often so vast that we have a difficult time predicting its frequency or impact on our environment. A flood is more than the weather event itself; it is the infrastructure that fails, the displacement of people, the destruction of property, and more. Conceptualizing flooding as a hyperobject forces us to design our interventions in relation to the past, present, and future.

Once the tunnel project is complete, people will be able to enjoy a walk along the creek with a reduced fear of sudden and catastrophic flooding. But we must not forget the power of nature: a release of a valve and this safe paradise could become awash in ruin and destruction. The goal of The Creek Zipper is to make visible the ebb and flow of a dynamic creek, so our awareness of its energy-including its capacity to flood as a result of heavy rains—is also dynamic, never lulled into complacence.

**THE CREEK ZIPPER: PRODUCTIVE CONTRADICTIONS**

The zipper installation is, like the creek itself, an open and dynamic system. The form of the project responds to a series of limestone shelves that sit just below the water line. The project is made up of interweaving strands divided into unique modules. The modules, fabricated of aluminum, are raised at intervals, by a series of adjustable pedestals. The flat bottom of each module coincides with the average water level. When the water level is below average, the water passes underneath the strands and is only minimally affected by the legs that support the modules. When the water level rises even a small amount above average, the water interacts with the folded geometry of the modules, causing a turbulent flow. Without the installation acting as a gauge, this rise in the water level would be nearly imperceptible. The zipper—as both an object and a representation of wa-
ter flow—makes the force of water more legible, and serves as a reminder of the power of the creek in flood. The project represents a momentary and unstable synthesis between a natural process and synthetic construct. (see Figure 2)

The Creek Zipper is a group of strands that emulate the zipping of two strings of teeth. Each tooth in the string is connected to its neighbor, as well as to a spine that is anchored to a series of existing concrete steps used by pedestrians to cross over the creek. A zipper operates as a nonlinear system—that is, it maintains the capacity to shift between the poles of “open” and “closed”, or back, at any given time. By delaminating a single pair of zipper strands into a series of strands that split, merge, and intersect, the project exposes the full potentiality of a zipper; sometimes open, sometimes closed, and often in between. The superimposition of overlapping systems provides balance to the project, both conceptually and structurally, and affords a multiplicity of meanings. (see Figure 3)

In Complexity and Contradiction, Robert Venturi argued that “an architecture of complexity and contradiction . . . tends to include ‘both-and’ rather than ‘either-or.’ If the source of the both-and phenomenon is contradiction, its basis is hierarchy, which yields several layers of meanings among elements with varying values.” (Venturi 1966, p.23) The delaminated zipper expresses variation at multiple levels of the project: in each module within a strand, among strands, and in the overall project form. Variation is applied at each level, introducing conflicting sets of data that are resolved hierarchically according to part-to-whole relations. Venturi continues: “Both-and refers to the relation of the part to the whole. Both-and emphasizes double meanings over double-functions.” (Venturi 1966, p.34) By delaminating a single pair of strands into multiple strands, we reveal all possible meanings at once, expressing a zipper form’s full potential, even when such multiplicity invites contradiction. In this case, contradiction is not a reduction, but an amplification of meaning.

PART WHOLE LOGICS AND ARRAYS
The Creek Zipper is an array of arrays. The project is a stable and complete whole, but is also made up of strands that are wholes in and of themselves. Furthermore, each strand is made up of parts that are likewise wholes, with each part able to stand on its own. Each part, strand, and whole is parametrically linked to each other through a Grasshopper definition. Although each part is a whole, properties of the parts are linked to the parametric properties guiding the form of each whole, whether that be an individual strand or the overall project form. While each part is a subset of a whole and some parts are subsets of larger wholes, there is another category of part-to-whole relation that influences the form of parts

Figure 3
Exploded axonometric of module and module prototype
across sets: that is, there are parametric relationships between disconnected sets. Though some parts are not physically connected to each other, some of their parameters are linked, such that a change in one value of one part might have an effect on the parameters of another part, or even a whole form of a different set. (see Figure 3)

The units and strands are part of an assemblage that oscillates between these part-to-whole identities. (DeLanda 2006, p.9) Because the entire project, each strand, and each unit can be read as a whole in and of itself, the traditional hierarchical part-to-whole relationship that has dominated art and architecture for much of their histories is called into question. Though the strands and units are similar to each other and have the same generic properties while retaining coherence with the larger project whole, the specific geometry of each one is unique as a result of its association with the overall assemblage, the site, and how it joins with neighboring units.

Breaking a whole into parts further allows for the introduction of additional object properties, which increases the qualitative impact of the project exponentially and diversifies the capacity of the project to connect to its environment. (Harman 2007, p.26) The high level of differentiation from unit to unit promotes the variation of shared qualities. For example, reflectivity, light, form, size, and color are properties common to all units, but vary from part to part to fully express a range of effects found in the whole. (Bryant 2011, p.20) By nesting multiple arrays within different sets, we expand the project’s effects, qualities, and properties. Conflating the sets introduces more productive contradictions.

**OTHER CONTRADICTIONS**

The creek flows between 6th and 7th Street in downtown Austin, Texas; thus, one encounters the project from two vantage points. As Sigfried Giedion notes, “the presentation of objects from several points of view introduces a principle which is intimately bound with modern life-simultaneity.” (Giedion 1959, p.369) The first view of the project is from the bridge above. Visitors see the overall form as a two-dimensional graphic overlaid on the creek behi-
low. Once people descend the stair and view the project at eye level, the two-dimensional form inflates into a three-dimensional series of highly differentiated units. One experiences the project as both graphic and form. As Robins Evans notes in his book Translations from Drawing to Building, “To imply depth with in a sold three-dimensional body is to conceive of it as being made up of flat surfaces modulated within a thin layer yet giving the impression of being much deeper. It is to attempt to make virtual space and real space at one and the same time and in the same place . . . for into patterns of lines stopping and starting we project, by a well understood reflex of overdetermination, a deeper space.” (Evans 1997, p.169-170) This deeper space is activated by the creek over time and the piece is transformed as the water level rises and falls. (see Figure 5)

To add another reading of the project, we used over one thousand battery powered lights in the installation. By including so many lights, we were able to introduce subtle variations by mixing different light types and colors, further decomposing the whole. The low-intensity light reflects off the water, adding a dynamic quality to the project, connecting the synthetic qualities of the installation to the natural conditions of the environment. During the day,
the satin-finish aluminum reflects the surrounding context and sky. At dusk and dawn, the aluminum reflects the first and last vestiges of sunlight, while the “artificial” light seeps out from beneath each module’s hood.

**PARAMETRIC DESIGN**

By mixing different, yet continuous fluid forms into one geometry, we introduce disruption in the form of overlap. This subtle distortion in the form of the zipper demands a certain level of attentiveness that is not evident on first view of the project. To achieve this effect, we used Grasshopper to govern the parametric relationship between the strands and the individual parts. By using one Grasshopper definition, we were able to retain full parametric control over every aspect of the design. This allowed us to introduce design variables that affect the geometry in various ways throughout the project. For example, design changes at the scale of a module impact parameters...
of a strand that are not physically connected to the module that is linked to the effect. (see Figure 6)

The process began with a drawing of the initial curves on a plan of the site. The curves included three unique conditions: (1) single strands of individual modules; (2) overlapping strands, in which two sets of modules are superimposed using the parameters of each to define a third module type; and finally, (3) modules at strand intersections. We used the intersections to define the transition points for the different strand and module types. The modules at these intersections are unique parts in the array that compound the object properties from each strand at one moment, causing a feedback of new properties to ripple back into the individual strands. These units are what Deleuze and Guattari refer to as operators. (Bennett 2010, p.9) The operators act as culling mechanisms and determine which data to use when conflicting data sets feed into a single parameter. They also initiate transformation in the form of module and strands both locally and globally. (see Figure 7)

Once the overall strands were outlined, each strand was divided into two series of interlocking teeth. The teeth are inset to provide a pedestal from which the rest of the module, including flaps that fold up to support a hood, are generated. We used a gradient bitmap to control subtle parametric variations of the project, including the module width and height, the size of the flaps, and the height of the hood. The final step added details for fabrication, including bolt holes, numbers, and tooling profiles.

Though the modules appear to be similar and vary only slightly, a deeper level of variation is evident on closer inspection. The modules are based on a generic prototype, but the exact form differs de-
pending on whether they fall within a single strand set, an overlapping set, or a superimposed set of strands, or if the module is at the intersection of multiple strands. These unique module types drive the differentiation found in the project and yield different readings of the project, depending on the viewer's standpoint. The project is only fully revealed once it is viewed from multiple locations and from multiple distances.

CONCLUSION
To make visible the capacity and effects of something as all-consuming and complex as flooding, we designed an installation that not only represents the dynamic form of the event, but fully exposes all the possible states of itself at one time through differentiation and multiplicity. The form of the project is a zipper, a form that works through overlap and interconnection. Rather than construct a single zipper that is static, we chose to delaminate the project and use multiple strands to convey multiple configurations and states of the form. As a result, the Creek Zipper expresses a temporal range that allows for a multiplicity of meanings and effects to emerge. By delaminating a single strand into many, we introduce additional module types that increase the qualities of the project while providing additional ways for new effects and meanings to emerge. (see Figure 8)

Only when we acknowledge that the past and future are as impactful on a site as its present conditions can we be conscious of the energy potentials that are latent to any particular site. Waller Creek has flooded many times in the past, and no amount of infrastructural investment will remove its inherent capacity to flood in the future. As David Ruy notes: "The mythological image of nature in equilibrium continues to be a dominant cultural mindset despite its obvious sentimentality. All observable evidence indicates that nature is not and never has been in a state of equilibrium. Careful observation has always revealed nature to be in a perpetual state of flux. If we are to take the flux of nature seriously, we would then have to understand sustainable practice as a willful act that seeks to maintain an artificially constructed equilibrium." (Ruy 2012, p.40) By creating an installation that actively engages the material of the site (water) and its capacity to change, we shed light on the dynamic nature of the environment and offer a better fusion of the synthetic with the natural. By using a relational part-to-whole model that oscillates between hierarchical systems, while offering sometimes contradictory sets of data in the code for the design, we compound the effects produced by the project. By using pattern and form to weave a two-dimensional graphic into a three-dimensional volume, we open a new space for meaning, heightening one's awareness of the project and the site itself. Only when the latent capacity of the site is made visible are we able to appreciate the flux that is always operating at some scale, and the comprehension of that flux needs to be constantly refreshed if we are to achieve a balance with nature that is stable and sustainable.

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A value-driven perspective to understand Data-driven futures in Architecture

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This paper reports on an investigation of the potentials of data utilisation in Architecture from a value generation and business creation points of view, based on an ongoing PhD research by the first author. It is of crucial importance to, first, identify what data actually signifies for Architecture, and secondly to explore how the value obtained through data-driven approaches in other industries could potentially be transferred and applied in our professional context. These objectives have been achieved through a qualitative comparative analysis of various cases. Additionally, the paper discusses the multiplicity of factors which contribute to different interpretations and utilisation of data with reference to various value systems embedded into our profession (e.g. design as ideology, design as profession, design as service). A comparative analysis of the existing data utilisation methods in connection with various value systems provide crucial insights in order to answer the following questions: How can data assess values in architectural design/practice? How can data utilisation give way to the emergence of new values for the profession?

Keywords: Big Data in Architecture, Data-Driven Architecture Design, Data in Architecture Design, Computational Data Design, Digital Value in Architecture

Introduction

Big Data is a common trend, a buzz word and a broad term concerning large amounts of data that is generated, collected and analysed to provide valuable insights and improve businesses. Many industries have experimented and harnessed the benefits of using Big Data in their businesses, and hence, new business channels and disruptive techniques have emerged which provide the necessary intelligence to elicit, process and make sense of data (Manyika et al., 2013). An analytical report (Manyika et al., 2011) indicated construction sector as the least beneficiary and falling behind other sectors in the utilisation of data in decision making and knowledge discovery. However, using data in the AEC industry is not new. Data is fundamental to the architectural design and production where both architects and engineers continuously create, modify, share and simulate data. In this respect, data already underlies much of the modern AECO (Architecture, Engineering, Construction and Operations). However, what is new to the industry is the amount of data that is currently available to us and our improved capacity to share, capture, measure, compile, process and translate data.
into meaningful and actionable information through smart technologies, enhanced data standards and visualisation techniques (Barista, 2014).

Existing research identifies two immediate problems that impede the adoption of data tools within architectural design firms; first is the lack of efficient means to translate and systematize very large and unknown data sets for efficient use; and second is the lack of knowledgeable data experts within design firms who can intelligibly curate diverse data sources and tools according to the project needs (Deutsch, 2015). The proposed paper contributes to the existing research by bringing in the “value” perspectives in order to understand how the different value systems embedded in “architectural design” and “architectural practice” will affect the ways in which data is used and adopted in our profession. The “value” perspective is being raised for two main concerns surrounding architectural profession. The first is the lack of a common understanding of the role architects entail in terms of their contribution to the society. An online survey published in 2012 by the Architect’s Journal showed that participants were not aware architect’s responsibilities (Thompson, 2012). These results were confirmed by a survey (Samuel, 2015) questioning the value that architects bring inside and outside the profession. There is clear evidence to suggest that this value is not clear neither from the point of view of architects, nor clients or other stakeholders in the sector (Petrie, 2016). The second concern is the extensive concentration on the economic (cost) value of architecture. A recent report by RIBA points out how “austerity and the focus on cost have diminished trust in the value of architects’ work” in UK (RIBA, 2015). Reed, the former president of RIBA, indicated to another potential danger of diminishing the quality of life that good design brings and emphasises the necessity to identify the value created by “thoughtful and responsive architecture”. (RIBA, 2011). A recently published report by Arup in collaboration with RIBA addresses the radical transformation in the design of buildings and cities through data-driven approaches and methods (RIBA, 2013). One of the repercussions of these new approaches is the transformation of our perception as to what counts as a “sustainable” design solution. Sustainable design solutions are now expected not only to be “green”, but also intelligent and interconnected and thereby introducing new “economic” and social” value (Kocaturk, 2017).

Architects rely on and are affected by different types of data in their design and decision-making process. Incorporating data into the design process is not a new concept as architects have been doing that since the beginning of the profession (Deutsch, 2015, pn.1). What is new today is the vast amount of digital data that is easily available for low cost and effort (Gupta, 2016). This phenomenon has been described by two fashionable concepts: Big Data and the Internet of Things (IoT). Big Data and the IoT have already influenced new operations and business models to emerge (Manyika et al., 2011) outside Architecture. In order to understand their potential impact on Architecture, it’s crucial, as a first stage, to understand what “data” signifies in architecture and for our sector. To this end, this paper identifies “data”, primarily, as a driver for the emergence of new values in Architecture and an added-value technology to the built environment and AEC industry at large. The paper specifically aims to contribute to the current Big Data discussion in our industry by synthesising the technological and business potential of Big Data and the IoT (Internet of Things) in order to identify their potential to expand the definition of what we deem as “value” in Architecture.

This paper provides insights into the different components of data-driven models in Architecture with recommendations for possible future implementations. In the following sections, the paper first explores the dynamic and intricate relationship between data and architecture, and reveals patterns of data utilisation in response to varying perceptions and reproductions of design in varying contexts, namely: design as ideology, design as profession, design as service. This provides a deeper understanding of the relationship between how the data is
obtained, the purpose its use, and the value it generates for the processes and products of design. This is followed by a more contextualised discussion on Big Data and the Internet of Things (IoT) and the potential they entail to facilitate the emergence of new operational models in our sector. Finally, the paper reports on the analysis of 8 cases set-up to identify various data-implementation approaches in design across different sectors. This leads to the development of a framework for data implementation and operational model that can be adopted in the architectural profession.

**Data in Architecture Design**

Data in architecture design has long been associated with the standard resources of technical data such as the likes of Neufert, Time-saver Standards and the Architects’ Handbook. These books provide a comprehensive range of technical information for architects regarding the standards and requirements of the different types and aspects of buildings. These data do not have any impact on the design unless the architect consciously searches and applies the selected solution to the design. Data has therefore been seen as simply inputs which architects are required to connect and transform into meaningful designs. Data is mostly understood as constraints and opportunities and rely on architects’ reasoning capabilities and institution to influence design decisions.

Data and information utilisation in and for architecture reveals specific patterns according to the varying perceptions and reproductions of design: design as ideology, design as profession and design as service. Architectural design as ideology focuses on the design of forms which respond to perceived social needs with underlying theoretical assumptions. It goes beyond the pragmatic function of architecture and largely associated with the cultural and ideological positions taken (by the architect). The data which drives the ideology is often qualitative, symbolic, philosophical and unquantifiable. The design process depends on the architect’s intuition, his personal ideological and subjective standpoint

Most architectural styles are ideological in their core. Design as ideology provides a system of values based on symbolic meaning.

Thinking of architecture as a profession rather than an ideology eludes its deep connection with its social, political and cultural roots, and rather focuses on the economical and market values. Architecture as a profession focuses more on the functional and economic value generated from its pragmatic function. This representation of architecture is relatively contemporary and came into play with the increasing influence of capitalism (Mako, Lazar, & Blagojević, 2014). Also, architecture as profession is mostly driven by the market, which it dictates its principle values and trends (De Graaf, 2015).

Architecture as a service focuses on the design process rather than the artefact. This perspective extends the design process to consider the overall service-life of the product (the building) including after-sales (post-occupancy). Architecture as a service sits somewhere between the previous two (as profession and as ideology). Data that drives architectural design as service usually aims to enhance the overall building performance and quality. In other words, data is aimed at improving value within the performance.

The redefining of data in the above table shows that data serves more than just an ‘input’. Its role extends and allows other values to emerge. It becomes quite clear that value is the main objective when assessing data and that the achieved value is crucial in understanding how data could be employed.

<table>
<thead>
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<th>Value form Data</th>
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<td>Data goes through different procedures to allow “new value” to emerge. In the past, the role of processing such data has been the responsibility of the architect solely. However, with the rise of digital technologies and the increase of data volume, this</td>
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role has changed slightly, allowing the machine to interpret data and to provide new insights. This change affects the role of architects and extends his/her capabilities.

In this context: The Data, Information, Knowledge and Wisdom [DIKW] pyramid provides a preliminary understanding of how various processes affect data. Our own interpretation of the DIKW pyramid is created (Figure 1). The pyramid shows that value is an output of all data processes. Value can be obtained at any stage. The more effort leads to more specified and deeper value.

Architect skillset and intuition are keys for the interpretation of data. A survey carried on by Samuel (2015) showed the different types of architects and their skillsets in the profession. The survey listed four types of architects: Social, Commercial, Cultural and Technological. Comparing these types of architects shows differences in data utilization, the achieved value and the communication of this value.

Data does not disappear when the value is achieved but somehow transform into design decisions, objects and facilities. With the advancement of technology, it is possible to keep track of data and allow it to be reinterpreted in the design process iteratively. An example of this is the reuse of stored data from metadata and sensors which are embedded in spaces to refine the design. The space itself is a product of a design decision that is based on data, and at the same time it has sensors that collect data. Data processes are not linear as the output can be reused as an input again.

**Architect’s Role between data and intuition**

When employing data, in addition to reasoning, architects rely on their intuition and that creates their creative impulse (Linzey, 1998). This intuition is intangible and not observed but can be partially described. Intuition determines the difference in the evolution of the design artefact and processes employed by between different architects even when they use exactly the same data.

According to Deutsch (2016) the decision-making spectrum in architecture is either Subjective or Objective based on the input type. Taking design decision based on quantifiable data is considered an objective approach while taking design decision based on unquantifiable data is subjective. The subjective approach is based on intuition and emotions. Figure 2 displays the continuum of decision-making.

However, this analogy and understanding is not totally accurate. The reason is that data and emotions are presented on the same level as separate interpretations in the spectrum while they are not. Data are not the opposite of emotions. On the contrary, data may as well allow the emergence of new emotions. In fact, data becomes a facilitator of all interpretations in the decision-making spectrum. An example of emotion-based data interpretation in design is Singh’s (2013) Emotion-Centred Framework for design innovation. In the diagram below, a refined diagram (Figure 3) of the decision-making spectrum in architecture is suggested. In this diagram data informs different interpretations and eventually allows decisions to take place.
Big Data, the Internet of things and Data-Driven models in Architecture.

Different technologies affect the type of different operational models adopted in Architecture (Grobman, 2008; Picon, 2010; Riccobono, & Pellitteri, 2014). These technologies proposed different operations and altered the workflows. An example of these disruptive technologies is the introduction of Computer Aided Design [CAD]. Although CAD was never meant to be disruptive and its underlying motivation in early sixties was to replace the manual drafting process as a cost-effective and efficient alternative, it opened new paths for other technologies to emerge, e.g. increasing use of 3D data, the possibility to share data/information, and new paths for collaboration; which eventually led to the development of Building Information Modelling [BIM] (Isikdag, 2015).

Architecture and construction are complex processes that rely on the use of data. They operate using two-dimensional and three-dimensional data. Architecture handles financial and corporate records, documents, and schedules. In addition to that, the post-completion of the construction process keeps generating an enormous amount of data on a daily basis. The buildings are becoming hubs of sensors, metres and wires. Data is increasingly digitised. What was impossible in handling data before, became probable today with current Big Data technologies. Big Data and the Internet of Things in Architecture can be defined as significant amount of data generated or acquired through the design, the construction and the occupancy of the built environment, including data generated by designers, constructors, the building, and post-occupant users.

There are certain challenges that contribute to adopting Data-Driven approaches in architecture. One of the challenges is the extra time and effort involved in the process (Sailer, Pomeroy, & Haslem, 2015; Deutsch, 2015). The move to Data-Driven techniques is considered a leap in design operations that requires extra training, resources and time, of which the accurate gain is unverified. This situation creates a risk that most architects prefer to avoid. The change in the processes will undoubtedly affect the current culture of architectural profession and education (Deutsch, 2015). Another challenge is the number of disciplines (and stakeholders) involved in the sector where Architecture operates and the need to efficiently address, manage and integrate data across those disciplines (Mahdavi, Martens, & Scherer, 2014, p. 585). Also, Data is seen too abstract and somehow restricting the design process (Deutsch, 2015). The last challenge is due to contractual complexity (Miller, 2012) and the uncertainty around who owns the data and the liability for the project outcome.

RIBA (2013) has identified four general approaches to working with data for architects, urban designers and planners. These approaches are: (i) meeting users’ needs, (ii) experimentation and modelling, (iii) analysing data to improve local and national policy making and implementation, and finally, (iv) improving transparency to speed up development processes. These approaches to data handling are proposed as a refinement to what architects already do rather than a change or reformulation of the way architects operate. Also in this report, there is no indication and clarification for the actual operations of these data approaches and the achieved values. We argue that Data-Driven operations have the potential to expand the current use of data and introduce new models of operations in architectural profession. These new models introduce new perspectives and methods of embedding data into the design process.
**Case studies Analysis, Methods and Grounded Theory**

The previous sections identified the correlation between data and value. We explained what data mean to architecture and how Big Data affects the architecture industry. We also identified the need to uncover data operations and indicate how value is created. In order to achieve this, various cases have been collected and analysed inductively following the principles and methods of Grounded Theory. This section will describe the selection and analysis of eight case studies in order to reveal the hidden data processes that are employed in the design.

The cases are analysed following two methods: The first is concerned with the process and operation of utilising data to allow values to emerge. This was achieved following the grounded theory methodology. The second is focusing on the value and how the digital data address value. This was achieved following a digital value assessment. The case studies are conducted to achieve the following objectives: Identify the main components of the architecture data-driven operation in design; Identify the data-driven operational models in Architecture Design and the relationship between the architecture data-driven operation components; Identify the types of values that emerged; Propose a structured understanding of the data-driven operational framework.

The first and main method is the Grounded Theory, which is a systematic methodology that permits the construction of theory through the analysis of data (Glaser & Strauss, 1967). It is employed for its capability of explaining complex phenomena, of which there is some ambiguity, and its ecological validity that represents real-life settings. The Grounded Theory is based on continuous coding procedures: Open, Axial, Selective and Theoretical. These coding procedures allow the emergent of themes, categories, concepts and theory through the analysis process. The data must reach a level of saturation in order to consider the theory valid (Charmaz, 2014). The Grounded Theory has its own validation criteria and should be judged according to them. These criteria are: fit, relevance, workability, and modifiability (Glaser & Strauss, 1967).

The second method is the digital value assessment. This method aims to understand how the digital operation in these case studies enables other types of value to emerge, we present a concept of the Digital Value Equalizer. The equaliser is merely a conceptualisation and representation tool used to show tangible values that are enabled through the digital value. The Digital Value Equalizer offers flexibility as values are added according to the case and can be adjusted according to its impact. Some of the architectural values depend and affect other values and this will affect how the Digital Value is enabling them. This conceptualisation of digital value is adopted in analysing the case studies and coding the obtained value in each case. Figure 4 shows the equaliser in a neutral representation.

![Neutral representation of the Digital Value Equaliser](image)

Figure 4 shows the Digital Value Equaliser of case study 1. The figure shows the emergence of five values which are enabled by the digital value, these values are Psychological, Social, Economic, Image and Use. Also, the Digital Value Equaliser shows the degree of each value emergence. In Figure 5, which represents the value emergence in case study 1, Economic and Use value are the most achieved.
It is important to mention that regarding the definition and the vast domain of Big Data and the Internet of Things, it is almost impossible to find one single case that covers all aspects of the technology. Therefore, it was necessary to consider several cases where data was utilised in a definite scope, in different contexts. The limited scope made each case manageable and consequently, the analysis provided more concrete results. Eight cases had been analysed; each with specific and distinct objectives, collectively covering a wide range of data operations applied in current practice. The cases are cross-sectoral. The case studies selection was a continuous process that concentrated on constant collection and comparison of data/information obtained through these cases until reaching a theoretical saturation of data.

Initial criteria for selecting the cases were established following the rational mentioned above and fulfilling the following:

- The case is chosen from the academic or the practice field
- The case has data implementation through design context with no regard to the phase or level of implementation
- The case provides a solution where one or more architectural or urban elements are involved
- The case has one or more technological methods of data integration, analysis and application

Table 2 shows the selected cases and the industry in which it exists. Table 3 provides a brief description of each case and the theme of data it resembles.

### Components of the Architecture Data-Driven Operation

For assessing the data operations in the case studies through the Grounded Theory, initial themes were used in the Open coding. These themes were identified through a thorough analysis of literature on data-driven businesses outside our industry. These themes have been identified as: Data Sources, Key Activity, Offering, Target Customer, Revenue Model, Specific Cost Advantage (Hartmann, Zaki, Feldmann, & Neely, 2014). Through continuous Open coding of the cases studies, these themes have been gradually refined to suit the studied context and the following themes have emerged: Data Sources, Data Handling, Data Offering, Architectural Value Proposition, Value Channels. Table 4 explains these categories in more details.
**Data-Driven Operational Models in Architecture**

An Axial coding of the case studies was completed to connect the Open coding themes which emerged in the first procedure of the Grounded Theory analysis together by identifying relationships through data operations. The Axial coding had two procedures: Horizontal and Vertical. The Horizontal Axial coding revealed the operation of each case in isolation. The data operation consisted of several components, some components allowed human intervention (e.g. by the architect perspective, or occupant). Each case had been represented in a separate diagram of how these components are inter-connected. Figure 6 shows the Horizontal Axial coding of case study 1 as an example.

The Vertical Axial coding interrelated the analysis from the Horizontal Axial coding. The Vertical Axial coding connected all operations together and proposed a global combined interpretation of data-driven operational models in architecture. (Figure 7) shows the combined interpretation of data-driven operations. Four different data processes are identified: Collection and Gathering, Aggregation and Processing, Analytics, and Modeling. These processes are interrelated in a specific order. Each one of these processes allows specific intervention of data through a specific application. An example of this is the Collection and Gathering process (Figure 7), it simply allows direct decision making by human. It also provides an output in the form of information, and finally it serves as an input for the subsequent process of Aggregation and Processing. Table 5 provides an initial definition of each process.

### Table 5
**Operational Processes of Data-Driven Models**

<table>
<thead>
<tr>
<th>Process</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection and Gathering</td>
<td>The simple process of collecting and gathering data</td>
</tr>
<tr>
<td>Aggregation and Processing</td>
<td>The process of selecting and desegregating certain types of data for Initially identified purposes.</td>
</tr>
<tr>
<td>Analytics</td>
<td>The process of coding, applying algorithms, and constructing certain types of data following set of rules.</td>
</tr>
<tr>
<td>Modeling</td>
<td>The process of transforming data from one format into another, such as visualizing text and numeric data.</td>
</tr>
</tbody>
</table>

### Table 4
**The basic themes of the Open coding**

<table>
<thead>
<tr>
<th>Data Sources</th>
<th>The source is identified by the type and hierarchy of stored and scattered data.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Handling</td>
<td>The computational process of acquiring, processing and applying data.</td>
</tr>
<tr>
<td>Data Offering</td>
<td>The output of the Data Handling process in the specific content of the case.</td>
</tr>
<tr>
<td>Architectural Value Propositions</td>
<td>The values realized in each case. These values are applicable in an architectural context, have the potential to contribute to the emergence of new value systems in architecture.</td>
</tr>
<tr>
<td>Architectural Business Channels</td>
<td>The business strategy which the AEC can adopt. This strategy includes the channels for promoting values in the built environment.</td>
</tr>
</tbody>
</table>
of Data were pointed out: Stored, Real-Time and Future, some of these are open data. The recognition of data was identified through these operations: Collection and Gathering, Aggregation and Processing, Analytics, and Modelling. Human Intervention and interaction happens on three levels: Human-Enabled, Computer-aided Enabled, and fully Automated. Finally, the application of data-driven is outputted through: Interface, Smart Materials and Kinesis Architectural Elements. Figure 8 shows the Data-Driven Architectural Operational Framework.

Figure 8
The Data-Driven Operational Framework in Architecture

Conclusion
What data means and signifies for architecture and the built environment is a question that needs to be reconsidered. The paper argued that data is more than the representation of the smallest unit in the complexity of a design process. It is a transmittable component of design knowledge and a value generating input for all operations. Instead of proposing a new definition of data in/for architecture - the paper aimed at bringing a value-driven perspective and understanding of data. Following this perspective, and through the analysis of 8 cases across different sectors, the paper developed a new data-driven operational framework for architectural profession.

The use of Grounded Theory aided the construction of new themes and concepts for the development of the proposed operational framework. The Digital Value Equaliser - which was specifically developed and used for the case study analysis - revealed numerous (hidden) values that were critical to the understanding of the phenomenon and had been instrumental in building the framework.

While the research is still in progress, the presented results provide a deeper understanding of how knowledge discovery and decision making in the AEC is affected by adopting a data-driven approach. Future work will focus on the levels of automation in data-driven design processes in response to the varying levels of human and machine interventions driven by computational processes.

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Mass customization (MC) and personal fabrication (PF) are current relevant topics in architecture offices practice and schools design research. Architects are adopting information based design and production techniques as a response to architectural century challenges. However, it is not clear how various authors used and transformed the concept in practice, research and industry after three decades since the MC term was introduced by Davis (1987). Therefore, it is essential to map the most relevant works in the field in relation to production and design control. The paper presents some of the results of the ongoing study through an evolving map that aims to visualize relationships, layering complexity and revealing difference.

Keywords: Mass Customization, Personal Fabrication, Housing, Map

INTRODUCTION

As parametric design and digital fabrication become increasingly established in both the profession and academia, alternative modes of production, such as Mass Customization (MC), emerge as feasible models for architecture and the building industry (Kolarevic 2013). The MC paradigm has been widely studied and adopted in manufacturing with the purpose of improving customer satisfaction by allowing the user to participate in the design of the product. It is a particularly fitting paradigm for the building construction industry, whose products are mostly prototypical in nature (Kieran & Timberlake 2003). Conversely, PF is the outcome of widely available information and means of production that empowers users to take the design and fabrication of objects, and eventually houses, into their hands. Consequently, control of production and design are key aspects to both concepts. But how has MC been implemented by architects and the building industry in theory and practice? And how do these experiences relate with one another and the MC concept in manufacturing? Are MC and PF overlapping concepts or are they mutually exclusive? These questions have had so far incomplete answers. Therefore, the present work uses a mapping method, that captures the production and design control level of both PF and MC. It is an ongoing work and this paper presents preliminary results. Examples of the implementation of MC and PF where limited to housing, to simplify the presentation and to fit the length restrictions imposed by the paper.

The term mass customization (MC) was first used by Stanley Davis in 1987, in his book Future Perfect, to define the possibility of mass producing customized goods, thus combining the advantages of mass-production, low price, stable quality and availability, with low-volume manufacturing advantages, accommodating personal requirements or preferences. One of the enablers of this possibility is the integration of digital design with file-to-factory processes, which provide “the ability to mass-produce irregular building components with the same facility as stan-

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standardized parts” (Kolarevic 2001), but also instil the “logics of seriality” (Zellner 1999).

Computational design challenges the need for modularity in design and is often seen as an enabler of mass customization. Yet, in the literature of MC on manufacturing, modularity is seen as a complementary aspect of customization, or even one of the two prerequisites to attain it (Pine II 1993; Duray et al. 2000; Fogliatto et al. 2012; Piller & Walcher 2017), the other is digitization.

The definition of mass customization as originally proposed by Davis is considered visionary in the sense that he sees MC as the ability to provide individually designed products, as opposed to a more practical definition by Pine et al. (1993) which propose that MC is the ability to provide diversity that meets specific needs of individual customers (Silveira et al. 2001). Da Silveira et al (2001) eventually proposed a dual definition model of visionary and practical MC, which was further developed by Kaplan and Haenlein (2006). Both definitions are similar in that they consider Mass customization to be a “strategy that creates value by some form of company-customer interaction” (Kaplan & Haenlein 2006, p.176/7). The main difference is the stage of the operations level at which this interaction takes place - at the design stage or fabrication / assembly stage.

There is not an agreement among researchers if MC can be applied to services as well as products. Some authors such as Pine (1993) consider it can be applied to both, whereas others such as Kaplan and Haenlein (2006) argue that services are inherently customized, for two of their main characteristics are perishability and inseparability, or in other words, they must be consumed at the moment of their production and necessarily involve the customer as a co-producer. Such is the case with the services of an architect, which are always offered on a personal customized basis, whereas the building construction industry is responsible for the manufacturing of the product. To mass customize these services would effectively mean offering customized services to a mass market in a cost-effective way, the opposite departure point of customizing a product that is mass-produced. Some authors (Kaplan & Haenlein 2006; Tien 2006) further suggest that mass-customizing is effectively a service that is embedded in the product, which supports Piller (2005) definition of MC as a co-design process. Architects, as independent professionals have direct relations with clients, which may or may not be the customers / building owners or even its users, and are bridging between the industry of building materials, the supply side, and the construction industry, the actual producers, whereas in most other industries the customer has no direct connection with the product designer and the manufacturer is the designer’s client. So for architects to engage in MC there are three remaining options: to act as customers of the supply side, personalizing building materials into customized building components; to collaborate with or to become a building material / component manufacturer as in the Instant House (Sass & Botha 2006); or to integrate with engineers and contractors, overcoming the separation between design and construction phases of the architectural design process as in Duarte’s work (Duarte 2005; Benros & Duarte 2009), reinventing the role of the “master builder” (Kieran & Timberlake 2003).

While architecture based on the logics of mass production is put into question, the most immediate applications of the MC paradigm have been mass produced housing, such as Duarte’s (2005) discursive grammar, or pre-fabricated housing (Benros & Duarte 2009). In fact, MC requires integration of design and production in order to offer company-customer interaction at the operations level at cost levels that are similar to mass production (Kaplan & Haenlein 2006), hence it needs the control of the production tools and processes to be firmly on the manufacturer side (Gershenfeld 2005).

In 2005, Neil Gershenfeld announced a coming revolution of the digitization of fabrication, which will bring the programmability of the digital into the physical world. A shift from scarce means of production to increasingly affordable digital fabrication tools that will promote Personal Fabrication (PF). A
precondition for PF is the open access to knowledge, made easier and widespread by information technology. While Gershenfeld vision of material assemblers might be still in the future, the “rudimentary” digital fabrication tools of today, CNC routers or laser cutters, are already widely available, and large scale 3D printers capable of producing large size building parts are becoming available. Architectural offices and design research groups alike have since increasingly adopted these tools, introducing prototyping into their workflows (Marble 2012). The increasing availability of digital fabrication tools and their connection with digital design allowed the exploration of the expression of the digital on the material and vice-versa, through programming and construction in what Gramazio & Kohler (2008) call a new “digital materiality”. In this process, other boundaries have also become blurred, the separation of the traditional roles of architect, engineer and builder, the difference between the prototype and the product and consequently the questioning of the role of the architect as a provider of services.

Thus, the literature review suggests that, while both MC and PF have been made possible by the integration of the digital fabrication tools with computational design, they depart from opposed directions regarding the access to information and the means of production.

**METHODOLOGY**

To map the most relevant works in the field of MC and PF, a method was adopted with the aim to analyse, organize and present relationships, layering complexity and revealing difference in the field of architecture and construction.

The mapping method is useful for showing and layering concepts and visualize relationships between different authors’ approaches to MC and how they relate with PF. This can also portray tendencies and relations, sometimes revealing unexpected or unexplored fields (Sanders 2006). A map will also be useful to positioning our research in relation to previous work and to clarify new directions for future research.

In the reviewed literature, MC has been mapped in two ways: within the framework of the Product-Process Matrix (Pine II 1993), putting it into the context of volume (low to high) and diversity (customized or standardized) of production; and in the context of point of customer involvement and type of modularity (Duray et al. 2000), providing a clear differentiation between levels of MC. These matrices have some limitations, as they do not consider the access to the means of production, thus do not represent one of the key differences between MC and PF. Another way of looking at MC is framing it within the context of design and production control. Mapping MC in this way allows the possibility to put it into context with PF. In the field of design research, Sanders (2006) has used a bi-dimensional map as tool to clarify the design research landscape and to write about its state. The main difference between Sanders map and the previously used matrices in MC is that the quadrants are not discrete cells but areas, opening the possibility of placing concepts that overlap different areas.

The proposed map follows Sanders methodology and is organized in two axes: design control and production control. The vertical axis of the map - design control - ranges from design controlled by architects or building construction industry, at the top of the map, to design controlled by building owners or customers, at the bottom of the map. On the horizontal axis, the production control is portrayed from manufacturer control, on the left-hand side, to user fabrication on the right-hand side. This creates four quadrants (figure 1): (1) Manufacture/expert designed and produced; (2) Manufacture/expert design and produced and owner produced; (3) customer designed and manufacture produced; and (4) owner designed and produced.

To make the map clearer both axis need further discretization, so it is unambiguous how a building transitions from being expert designed to customer designed or it goes from being manufacturer produced to owner produced.
The design axis has parallels with the levels of mass customization which have been widely studied in the literature. Duray et al (2000) proposes a matrix of point of customer involvement and modularity in design of the product while Tien et al (2004) proposes a linear progression in terms of the customer order penetration point, that is at which stage the order interferes with the supply chain: customer, retailer, assembly, manufacturer, supplier. Figure 2 relates the levels of MC proposed by Tien with the level of design customization in the building industry. Partial MC and MC are coincident with the practical definition of MC by Kaplan (2006), while Real-Time MC is comparable with the visionary definition of MC by the same author but with some limitations. For Tien, Real-Time MC is instantaneous production and delivery of customer designed products. In the context of a design, real-time delivery of customized solutions is guaranteed by the adoption of digital design methods, and consequently only limited by the complexity of the computational configuration process and computational processing power available.

In a mass-produced building, customization occurs aftermarket - the customer can only inhabit the building or do renovations. At the retailer level the customer is offered different types to choose from (e.g. apartments with different numbers of rooms in a multifamily housing building or houses in different styles from a pre-fabricated building manufacturer).

Design control at the assembler level includes the possibilities of the previous level plus the potential to change finishes or swap or add components in a modular system (e.g. adding a window), while at the manufacturer level changes in layout of the building are also possible which in turn have consequences on the manufactured building parts but may occur within a given building system. As proposed by Piller (2005) the design solution space is finite and all possible solutions belong to the same design space (Kolarevic 2013). Design control at the supplier level means that it is possible to choose amongst design spaces and consequently different building systems and different rulesets.

The midpoint of the production control axis is where the control moves from being on the manufacturer side to the owner/customer side. Tasks that are part of the operations level start to be undertaken by the customer. First the assembly (i.e. joining or installing previously manufactured parts or components into a new whole), then the fabrication (i.e: transforming inputs into outputs). On the left side, the manufacturer loses absolute control of the manufacturing process when the customer is given the possibility to make decisions that affect one of the stages of the operations level - first the assembly then the fabrication. Figure 3 integrates the previously discussed gradients of control in the map presented in Figure 1.

**MAPPING MASS CUSTOMIZATION: PRELIMINARY RESULTS**

The use of the proposed methodology allowed to reveal the position of MC and PF and to illustrate that position with some examples in research and practice (Fig. 4). Since these concepts emerged outside the field of architecture, to put them into context, conventional construction space and mass production are identified. First, the reasoning for positioning the concepts is explained, then the position of the examples and their relations are explored. MC is divided into three areas, following the levels presented in Figure 2: Partial MC, MC and Visionary MC. Practice examples are limited to the Partial MC area, whereas research examples are concentrated on the MC area.
To simplify the presentation, the examples of MC in research and practice are constrained to housing.

It is important to understand that in practice, architects almost always work for clients, so it is a very rare circumstance to have a building whose design is totally determined by the architect. But when the client will not be the owner, as is for instance the case in multi-family housing, the architect is designing for a mass market, eventually providing segmentation per some form of market analysis or insight. From the point of view of design control of the customer there isn’t much difference between the previously explained example of conventional construction and pre-fabricated housing that only offers segmentation. The main difference lies in that the pre-fabricated manufacturer builds manufacture- or assemble-to-order houses with a specific design/building system whereas in the former example the building can be sold to the customer already built or, when the customer engages with the manufacturer before it is built or finished, the customer can have higher level of design and fabrication control.

Mass Customization requires some form of company-customer interaction, consequently a MC building can’t be user fabricated and assembled. The opposite is true for Personal Fabrication, for the tools of production to be on the owner side, fabrication must be assumed by the owner: “With a PF [Personal Fabricator], instead of shopping for and ordering a product, you could download or develop its description, supplying the fabricator with designs and raw materials” (Gershenfeld 2005, p.4). Thus, PF is limited to the last forth of the production axis (see Figure 4). Along the Design Control axis, PF clearly occupies the lower three quarters. Even though Gershenfeld doesn’t exclude the possibility of having PF that is expert designed, he states that “the promise of personal fabrication goes beyond consumption to invention.” (Gershenfeld 2005, p.121).

The different levels of MC presented in Figure 2 also distribute themselves differently across the production axis. In Partial MC, customization only interferes with the assembly stage of production, customizing finishes or swapping modules does not
need to interfere with the fabrication stage, while in MC both stages, fabrication and assembly, are affected. The reason is that changes in the dimensions of the building or any of its parts do necessarily have consequences on the fabrication stage. It is also possible within a MC framework, as demonstrated by Botha and Sass’s Instant House, that the assembly stage is performed by the owner. Even though the manufacturer is relinquishing some of the tasks he traditionally performs, there is still customer-company interaction at the operations level. This can be better understood with a parallel with IKEA, its products are still mass produced even if the customer is assembling the product.

Visionary MC, as seen in figure 2, can only happen at the lower quarter of the design control axis. From the point of view of architecture, Visionary MC means that the owner can customize the building across multiple design spaces, that is customization across different design families and different building systems. On the production axis, Visionary MC interferes at the fabrication level of production but the assembly might also be handed to the owner as in MC. Consequently, Visionary MC sits immediately below MC on the map. In the reviewed literature, no examples were found either in research or in practice.

Kolarevic (2015) points to several practical applications of MC in commercial housing, websites by builders of prefabricated houses such as Blu Homes, architect/builders like Housebrand’s FAB House or architects firms like Resolution: 4 Architecture. Blu Homes is an example of Partial MC in pre-fabricated housing, in which the customer can customize interior and exterior finishes of predefined house designs. Another example is Living Homes, which offers LEED certified custom houses through a similar options selection process. But as Kolarevic points out, “none offers dimensional customization”, although the enabling technologies are available and have been demonstrated to work in research.

The examples in research are concentrated in the MC area, within these examples two groups can be defined regarding the design process used: generative (Duarte 2005; Kwecinski et al. 2016; Sass & Botha 2006) or parametric (Benros & Duarte 2009; Khalili-Araghi & Kolarevic 2016).
A common feature within the generative group is that the user of the system doesn’t directly design solutions, but provides details that in turn are used by the system to generate solutions that are then presented to the user for inspection. Then the user has the option to review its original requirements. Even if the user is not defining dimensions it is still interfering with the layout of its house, so examples like Duarte’s (2005) Malagueira discursive grammar or more recent work by Kwiecinski et al (2016) clearly fit in the MC area from the design control standpoint. From the point of view of production control, even though in Duarte’s example is missing a physical grammar that translates designs into building specifications, these examples encode traditional construction systems that maintain the fabrication on the manufacturer side. The Instant House (Sass & Botha 2006) is a design production system composed by a design grammar and a subdivision grammar. Sass does not detail the design system, suggesting that different design grammars may be used to generate 3D houses, and the subdivision grammar by itself is not a customization system, but a way to generate valid construction details for generic customized solutions. The proposed implementation can be positioned in MC area, although on the right side of the vertical axis, since it requires the user to assemble the structure. But the authors recognize the system may evolve from MC towards PF: “Initially the process utilizes the end user exclusively for assembly purposes, but taking a page from Gershenfeld’s (2005) Fablab and given sufficient local resources, the Instant House system could ship as an autonomous factory”(Botha & Sass 2006, p.210). Wikihouse, on the other hand, is an example of a construction system which clearly positions itself on the area of PF. It is freely available online and can be modified by the owner to meet its requirements, although it requires 3D modelling skills to do it successfully.

Benros and Duarte (2009), developed a different approach, based on a parametric model of the ABC system developed by Manuel Gausa and the Kingspan building system. It provides a computer system that integrates design and fabrication addressing that shortcoming of Duarte’s previous work. The parametric system was conceived with the purpose of being used by architects and not customers and it has a smaller solution space than a generative system. Advantages include, being easier to implement and allowing a simultaneous feedback between the options made and the design changes. Although it allows layout configuration, it is limited to the modular grid present in the ABC system. Khalili-Araghi and Kolarevic (2016), propose a framework that aims to overcome this limitation providing dimensional customization in a parametric model. Another important difference is that this system is meant to be used by customers. It is composed by a design system, implemented in BIM (Building Information Modelling), and a configuration system that provides the user interface and a design validation process. Both these examples fit in the MC area, and although the latter example allows dimensional configuration, interior spaces maintain their topological relation, the former example allows topologically different solutions. A user of both systems controls design at the fabrication level and production control remains at the manufacturer side.

CONCLUSIONS AND DISCUSSION

In the reviewed literature and the selected examples of housing there is a clear gap between the implementations of MC in practice and in research. Since the technology and the knowledge of both production and design are available, one possible reason is provided by Kolarevic which suggests that customers might not be culturally inclined towards assuming the responsibility for designing their homes. From this point of view Duarte’s approach seems more promising, since it doesn’t require the user of the system to select options or configure dimensions but instead suggests possible designs solutions per user defined brief.

MC and PF are clearly mutually exclusive concepts from the point of view of production and design control, but as Sass’s Instant House demon-
strates, they might share methods and systems. What
separates MC and PF is the openness of standards
of design and production. Sass’s Instant House also
demonstrates the existence of an area of MC, where
the assembly stage is handed over to the owner, that
is not present in the reviewed literature of MC on
manufacturing.

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Descriptive Geometry 2.0

Define vs. design

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The article presents the 'Digital Geometry Techniques' course taught at the second year of the undergraduate course at the Faculty of Architecture in the Warsaw University of Technology - WUT. The course introduces mathematical theory and generative modeling in order to prepare the students to consciously plan their creative process and to choose the set of tools according to an initial analysis of modeling constraints. The students gain knowledge on advanced CAAD techniques through learning functions of a particular program, and also by tackling geometry-related problems derived from real-world architectural projects. They are able to develop individual solutions using adequate techniques. We present three different students’ semester works as examples to reflect on the significance of mathematics and algorithmization in the process of problem solving and form creation in architecture and urban design.

Keywords: project based learning, generative design, architectural curriculum, conceptual thinking, geometry, programming

An architect’s creative process starts long before a first line appears on a piece of paper. In The Logic of Architecture (1990) William Mitchell points out that when we characterize designs we make claims about constructions of the imagination. These claims can be expressed through sketches, drafts, physical or digital models. We implicitly place our concepts in an environment, which Mitchel refers to as a design world. He describes it as a space with a collection of verbal or graphic symbols that can be inserted in, deleted or manipulated. In other words, a language we need to learn to communicate our intentions efficiently.

In over a hundred years of the WUT Faculty of Architecture’s history, teaching this language was realized by the descriptive geometry course. Descriptive geometry was first introduced in the initial curriculum in 1915 and it remained one of the core courses in the study program since then. The course included lectures and exercises combined in a 90-hour unit (Tulkowska-Słyk 2010). Its importance inside the undergraduate curriculum grew in the following years. During the post-war period it ranged between 120 and 165 class hours, which represented the average program module, matching fundamental courses such as building construction systems, history of arts or structural design.

The course covered drawing complex spatial forms and their transformations with traditional manual drafting techniques. It introduced elements
of visualization, as constructing shadows both on itself and casted on other objects, and visual representation of objects in orthogonal and perspective projections. As these issues have a mathematical foundation, the course’s lectures introduced theories that provide the base for practical exercises solved individually by the students.

Throughout the following decades, descriptive geometry techniques remained the basic mean of design representation as it allowed architects and students to present their creations according to professional standards. Proficiency in geometric drafting was considered fundamental for broadening spatial imagination skills and for building a base of formal inspirations. Therefore, descriptive geometry remained a relevant subject in the study program.

Since 1980s, its relevance has gradually decreased due to the ease of computer techniques. Traditional straightedge-and-compass drafting appeared to be less practical and overall inefficient. The relative simplicity of CAAD tools has dissipated the complexity of form construction processes, both in the professional practice and in architectural teaching (Hersey 2000). The basic reason for studying descriptive geometry has seemingly faded. Parallely, embracing these new methods didn’t go hand in hand with a reflection on their effectiveness in shaping architects’ imagination and creativity (Duarte 2016).

Last year, we evaluated the CAAD-related block of the curriculum and extended the study basis with the Digital Geometry Techniques (DGT) course. The aim of this new course was to address issues considered previously during the descriptive geometry classes adapting it to the digital age context. The complexity of contemporary architecture designs have made the traditional methods of descriptive geometry obsolete. Each architecture project may contain elements, including environmental analysis, structural simulation and generation of sophisticated geometries, that are unique and as such require an individual approach. Contemporary architects should be prepared to create their own custom tools that would enable such a custom approach. Increasingly popular generative tools such as visual programming languages (VPL) that do not require advanced programming skills successfully combine the need for individual methods with professional - yet limited to standard solutions - software.

We observe that in the early stages of architectural education students commonly limit or determine their concepts based on tools chosen a priori. A frequent fascination with eye-catching parametrically generated designs increments the risk of generative tools being misused if not understood correctly. During the development of the DGT course, we assumed that a full understanding of form shaping requires a solid knowledge of its mathematical background. Therefore, one of our main goals was to strengthen the awareness of mathematical basics of designs created with digital tools. At the same time, the works of Duarte, Celani and Pupo (Duarte 2012) show that the creative component is crucial for successful introduction of new techniques to the students. In the DGT course our goal was to provide the creative process with a clear and coherent order. In this creative process the concept evolves from the initial often abstract idea, to mathematical formalization, and finally to its transcription into a CAAD tool. We believe that this approach facilitates the choice of suitable media and creation of custom solutions.

This paper covers our experience in conducting the first edition of the DGT course. We evaluate if we were able to meet the aforementioned goals and reflect on the consequences of replacing the traditional form of teaching descriptive geometry with this new subject.

**MATHEMATICAL FORMALIZATION OF AN IDEA**

The language behind every computer aided architectural model is mathematics - from a line in a simple drafting program to a data-driven parametric definition. Whereas most of the popular design software ultimately hides its functional fundamentals from the user, the generative tools give priority to
the mathematical relationships. In the DGT classes we highlight these relationships by introducing the students to geometry-related problems derived from real-world architecture realizations and encouraging them to develop their individual solutions using suitable techniques and tools.

The course workflow involved three stages. First, students undertook an exploratory research on a given geometric issue. These issues covered a variety of abstract mathematical concepts from non-euclidean geometry, analytical geometry and basic calculus to topology. This initial study lead to understanding the specificity of each theme and identifying its intersection with the field of architecture or spatial design. The exercise included classifying spaces, buildings, details, artworks or other design activities - material or virtual - which feature the examined phenomena.

Secondly, the students selected a specific feature within the given geometric issue for further analysis. We asked them to perform a logical breakdown of a design work of their choice and to use their findings as an inspiration for their own geometric composition. The task was to formalize their ideas using a precise language of mathematics. This process was supported by lectures in mathematical theory in order to facilitate the choice of the appropriate approach. Our aim was to clearly state that the same object can be defined in a number of different ways. For example, a primitive cube can be described as an interval in a three-dimensional linear space, a set of eight Cartesian points, six intersecting planes, radial distance between opposite vertices, extrusion of a plain rectangle, NURBS surface or a span of voxels (Pottmann 2007). Consequently, each definition results in a different degree of flexibility. The variety of definitions can extrapolate to more complex geometries, which can be a boolean composition or deformation of simpler forms. The process of altering the geometry, however, is another crucial question to be addressed. Whereas elementary deformations, such as isometric or affine transformations, are by principle easy to formalize, more sophisticated mappings might not be given explicitly. Such cases require construction of custom morphing procedures.

Eventually, the students algorithmized their mathematical definitions and decided on the best fitting digital technique to be used. This part of the course was backed by tutorial classes linking mathematical theory with modeling and generative tools.

CASE STUDY: EXAMPLES OF STUDENT’S WORKS

The class’ final project was either a virtual simulation or a digitally fabricated physical installation format. We will highlight three examples of representative student’s works.

Conic Sections

Describing a complex geometrical form requires a closer look on possible methods of defining the same shape. In this project students examined methods of constructing a structure generated with the use of conic sections. Inspired by the optical phenomena specific for these geometric shapes, the students created a parametric model of curved surfaces. The project simulated the influence of the surface’s curvature on the illumination and dim-out of certain areas of the object’s surroundings depending on the position of the light source.

Conic sections can be described in a number of ways: as an intersection of a conic surface with a plane, with an analytic formula or a set of parametric equations. Given the curve, tracing the light distribution can be done easily with principles of geometrical optics. Each definition is based on a significantly different set of arguments, and allows a distinct scope of flexibility of the resulting shape. Since the examined physical properties are directly related to the positions of each curve’s focal point, the experiment required the curves’ construction method based on the position of their foci. The students researched that this kind of control can be achieved with polar equations, which depend on two variables: the radius, representing the distance between the curve and the focal point; and the angle, defining the curve...
span. Moreover, definitions in polar coordinates can be translated directly into generative software.

In order to achieve the desired effects, the students needed to predict the trajectories of the reflected light beams and adjust the conic curves and position of the light source accordingly. The simulation of light concentration and dispersion areas required the construction of a simple ray tracing algorithm. The algorithm’s method incorporated basic principles of optical reflection. It defined rays with starting points and vectors, computed curve parameters at intersection points with rays and vectors tangent to a curve at calculated parameters, constructed vertical planes using a point and two perpendicular vectors, and finally, the algorithm reflected vectors along planes.

The simulation resulted in establishing the exact scale and positions of the final project’s elements, which were then fabricated from reflective material. Panels curved into ellipses and parabolas formed an installation (Figure 1). The installation allowed for interactive simulation of light distribution according to the position of a light source.

**Topology**

Could projects like the classical renaissance Villa Capra and a contemporary liquid-like sculpture as Cloud Gate have anything in common? The students researched whether there is a relation between these two types of projects under certain circumstances.

The goal of this task was to explore shape properties that allow morphing of one shape into another without cutting or gluing. These issues concern topology, an area of mathematics bridging geometry and calculus.

The students observed that buildings simplified to their conceptual geometric forms (ignoring all openings, such as windows, doors and others) can be treated as topological manifolds. A manifold is a geometric object that can be locally mapped into Euclidean space of the same dimension. For instance, a two-dimensional polysurface can be considered a manifold if only there is a reversible transformation converting an arbitrarily selected patch of the polysurface to a planar region and vice versa.

The students learned that two manifolds can be morphed into each other if there is a continuously reversible function, named homeomorphism, which maps each point of one manifold to a different point on the other one. Although their geometry might substantially differ, they are topologically identical. This kind of mapping is rarely given by an explicit formula, but its existence can be indicated on the basis of a number of factors. These factors, so called topological invariants, represent properties that are preserved even if the original form is radically deformed. To name a few, connectedness guarantees the integrity of mapped forms (Steen 1970), dimension invariance makes it impossible to match objects of different dimensions (Engelking 1992), genus assures that a morphed object cannot generate handles (“holes”) [1].

The fundamental challenge of this project was to construct an algorithmic transformation morphing two different geometric objects into each other. These objects were represented by two topologically identical manifolds. To find such representations, both geometries were first converted to polygonal meshes - potentially topologically different, consisting of different number of vertices and different relations between them. Secondly, the meshes were aligned to their centroids and projected on the same centrally placed sphere. In order to avoid self-
intersections of the projections, this step had to be performed on convex objects. This convexity was assured by implementing iterative Laplacian smoothing. The projection required finding intersections of the sphere and rays cast from its center in the directions of all vertices. The original non-convex polygonal meshes were topologically identical with their representations in the spherical projection. Such projection resulted in two meshes that were geometrically similar, despite their different vertex structure. Lastly, elements of one mesh (its vertices and edges) were projected onto the other, resulting in a set of new points and creases that were then incorporated into the topology of the target mesh. After rebuilding topological relations of a new mesh, all of its vertices were mapped back onto both original geometries, which resulted in two topologically identical manifolds. This process can be performed for multiple geometries with the restriction that this method works only for closed and compact polysurfaces with genus 0 (closed surfaces without “holes”).

The students constructed transformations that morphed multiple topologically identical shapes into one another (Figure 2). They achieved this by linearly interpolating the coordinates of each vertex constituting one geometry with the coordinates of the corresponding vertices of another. By using any number between 0 and 1 as an interpolation parameter, they were able to generate any stage of morphing transformation. In this case, 0 stands for the first original object and 1 represents the latter. Their final project was a matrix of stages between multiple architecture objects.

**Rigid Origami**

Designing moveable elements is a common challenge for many architecture students. The issue of designing structures composed of rigid faces linked with hinges requires considering a number of mathematical constraints known as mathematics of paper folding. Students investigated the possibilities of obtaining different geometries through creating creases and folding a stiff material. They created a computer simulation for computing mountain-valley schematics of flat folds.

Due to the high complexity of relations between stiff polygonal elements and various possible folding angles, the students used a physical simulation engine for their final project. The process of preparing data for simulation consisted of dividing a planar surface with lines extracted from a pre-designed mountain-valley pattern. Such division resulted in a set of polygonal shapes. These shapes were further divided into triangles, if necessary. The triangles’ stiffness was ensured by converting its perimeter into a set of three lines of fixed length. Both the process of folding and the planarity of polygons consisting of multiple triangles were solved by applying bending forces between each pair of triangles with a shared edge. If such edge represented a crease, the adjacent triangles were iteratively folded along the edge. The folding direction was determined by applying opposite forces to mountains and valleys. In case of two triangles forming one polygon, the algorithm avoided folding them together along the common edge in each iteration of the simulation.

After testing multiple schematics of folding, the students chose a solution and applied it to the final panel by engraving the creases and folding the panel manually along the grooves (Figure 3).
CONCLUSIONS AND DISCUSSION
Design worlds, as mentioned by Mitchell, and its tools developed with the advancement of science and technology. Architecture object’s means of representations evolved from Euclidean constructions to descriptive geometry, analytic geometry, until contemporary and computational geometry and other CAD environments. Currently it is common to see students limiting their concepts to the languages they already know or prefer, even if these languages do not necessarily satisfy their needs and despite the wide variety of available options. Moreover, it is equally often that students introduce designs created with algorithms available online without completely understanding them. In the development of the Digital Geometry Techniques course we addressed these issues directly.

In the showcased examples of students’ works we showed how the in-depth understanding of a task influenced the choice of techniques and tools used in the process. After a thorough analysis of a given problem the students were able to formulate a suitable definition of their idea, to algorithmize it and determine a desired scope of parametrization. Once the process was well understood and carefully planned, the selection of used tools proved to be a secondary decision. As a result, we found that the first edition of the DGT course reached its goals. In a survey conducted with 115 course participants in January 2017, six out of eight aspects concerning the course’s scientific and educational content were evaluated higher than 4.5/5 (very good), which confirmed our conclusion.

The digital paradigm can detach design from the limitations of traditional 2-dimensional representation techniques, however it does not limit the acquisition of spatial imagination skills. Simultaneously, the digital paradigm shifts the set of required skills towards analytical thinking instead of emphasizing manual drafting accuracy. The first edition of DGT was an attempt to help students adapt to the digital paradigm in descriptive geometry and to realize its importance in the architecture practice. Dominant opinions expressed by the students as responses to open questions in the survey indicate that the course is considered useful and interesting, and that it helped them to understand how digital tools can be used more efficiently and creatively.

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Figure 3
Simulation of stiff panel folding.
From Envelope to Layout

*Buildings Massing and Layout Generation for Solar Access in Urban Environments*

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The use of daylight for the inhabitants health and comfort purposes and for the energy efficiency of buildings influences significantly the shape and outlook of urban environments. The solar envelope and solar collection surface are methods to define the massing of buildings for direct solar access requirements. They have been recently improved to be used in the design of buildings in relation to the Estonian daylight standard. Nevertheless the solar collection method can be applied only to single buildings with simple shape. The present research investigates the direct solar access performance of building clusters with multiple layouts in different urban areas in the city of Tallinn. Result show that different patterns perform in significant different ways whereas the same cluster types have the best and the least performances in all the cases.

**Keywords:** Urban design, Direct solar access, Solar envelope, Environmental analysis, Computational design

**INTRODUCTION**

Daylight requirements are a significant factor for the growth of urban fabrics and for the image of cities. It is exemplary the case of the New York Zoning Resolution of 1916. The regulation stated that building floorplans could have had the same size as the footprint up to 30-40 meters, and after were required to recess gradually to 25% of it and were allowed to use that ratio for the rest of the height of the building (Willis 1995). The requirement was introduced because of the increasing heights of buildings, in order to allow the lowest floors of the neighboring premises to receive adequate quantity of daylight and it characterized the shape and image of New York in the first half of the past century (Figure 1).

Direct sun light and diffuse light scattered by the sky and the clouds and reflected by the environment are the components of daylight (Reinhart 2014). Daylight requirements are different from country to country and can be related to the direct or to the diffuse component of daylight.

Direct sun light is the most appreciated type of natural light for its properties, the intensity, the quality and the uniformity. The intensity is relative to the illuminance levels necessary to perform specific tasks, the quality refers to the capacity of natural light to render the colors of the surrounding environment without alteration and the uniformity limits the glare probability increasing the comfort of vision (Johnsen and Watkins 2010).
Therefore the availability of direct sun light inside the buildings is a crucial aspect for the physiological and psychological well-being of people (Altomonte 2008). However direct sun light requirements are more difficult to be fulfilled comparing other types of ordinances that take into account the diffuse and reflected components of daylight (DeKay 1992).

In Estonia direct solar access is regulated by the standard “Daylight in dwellings and offices” by mean of two requirements (Estonian Centre for Standardization 2010). The first states that new constructions cannot deprive existing premises of more than 50% of the direct solar access they have in the existing situation. The second requires that new dwellings receive minimum 2.5 hours of direct sun light in at least one room. This requirement does not apply to commercial and office spaces. Both the requirements have to be fulfilled on a daily basis in the period from 22nd of April to 22nd of August.

The solar envelope and solar collection surface methods are used in urban design for the prediction of direct solar access on existing facades surrounding new developments the first and on the facades of new buildings in urban environments the latter. The solar envelope is an efficient design tool, whereas the solar collection surface prediction capability is limited to single “shoe-box” buildings. The present work investigates the solar collection performance in relation to the Estonian daylight standard of clusters of buildings with different urban patterns, in distinct urban areas, the massing of which has been generated to allow the due direct solar access on neighboring facades.

**BACKGROUND**

The solar envelope determines the height and mass that new buildings cannot exceed to guarantee the due solar right on existing surrounding facades (Knowles 1981, 2003). It is generated translating the points of a grid that subdivides the plot and it is constituted by the three-dimensional volume between the translated points and the ground. It can be calculated using few inputs among which the new buildings plot layout and orientation, the distances from the existing surrounding buildings, the height of the shadow fence on the neighboring facades (the limit above which direct solar access has to be guaranteed) and the solar azimuth and altitude at the hours of the days during the required period of the year.

The solar collection surface, introduced as solar collection volume, is used to calculate the lowest height at which windows can be placed on new building facades so that they are not overshadowed by the surrounding environment in order to get the required direct solar access (Capeluto and Shaviv 1999, 2001). The input for the generation of the solar collection surface are the same as for the solar envelope and additionally the heights of the surrounding buildings are required. Also the solar collection surface is generated using the translated points of a grid that subdivides the plot, though in this case the por-
tion of space above the surface is the one that fulfill the requirement.

Both the solar envelope and solar collection surface can be calculated on paper though it is a tedious and error prone procedure. Tables are available for the maximum building volumes though they are limited for specific latitudes, hours and for simple plot and surroundings layout (Brown and DeKay 2001).

Computer applications to calculate solar envelopes and solar collection volumes such as SolVe-lepe, SolCAD and SustArc have been developed since decades (Yeh 1992; Juyal, Kensek and Knowles 2003; Capeluto et al. 2005). These were pioneering tools for basic or more complex design cases though not fully integrated into design software. Nowadays it is possible to generate solar envelopes and solar collection surfaces through environmental analysis tools integrated into computational and algorithmic design software (Marsh 2003; Niemasz, Sargent and Reinhart 2013; Sadeghipour and Pak 2013). The input that the actual tools require are the latitude of the location and the plot contour for both methods, the surrounding buildings shadow fences only for the solar envelope, the roof contours of the surrounding buildings only for the solar collection surface and the start and end time for every day of the required period during which direct solar access has to be guaranteed for both methods.

The actual environmental design tools based on the existing methods to generate solar envelopes and solar collection surfaces present limitations when used in dense urban environments and in relation to the direct solar access requirements of the Estonian daylight standard.

The solar envelope tools don’t permit to include the context in the calculations, whereas it is important to consider whether an existing façade receives direct sun light at specific hours or it is obstructed by the existing surrounding buildings. In the latter case new buildings are not required to allow direct solar access on that façade during those hours. Additionally the fixed daily start and end time is not compatible with the requirement of the minimum 50% of direct solar access hours that new buildings have to guarantee on existing surrounding facades. In urban environments building facades have multiple orientations and are differently obstructed hence they require distinctive quantities of direct sun light hours and during different portions of the days. The mentioned shortcomings have been tackled by the author developing an advanced method that consider the actual quantities of direct sun light hours for every façade and portion of it in urban environments (De Luca 2016, De Luca and Voll 2017a). In this way it is possible to generate larger and manifold solar envelopes, aware of the context and for required quantities of direct sun light hours every day. The advanced method has been applied for the generation of the solar envelopes of the present research.

The actual solar collection surface tools calculate the lowest points at which windows should be located to receive the required solar access considering the hours of direct sun light on the points of the horizontal grid subdividing the plot. Since a horizontal plane receives a significantly larger amount of sun light hours than a vertical plane with a specific orientation, the facades of buildings hosting the windows, the generated solar collection surfaces are not reliable. Additionally the fixed start and end time input constitutes as well a shortcoming in relation to the Estonian direct solar access demand of minimum 2.5 hours per day in the specified period. It is not possible to know a priori if and when during the day a point receive the required quantity of direct sun light and use the input for the solar collection tool. The author developed a method to generate solar collection surfaces based on the calculation of quantities of actual direct solar access hours on points located on vertical planes (De Luca and Voll 2017b). The evidence showed that the generated surfaces, one for every possible building façade orientation, are more reliable in predicting the portion of facades fulfilling the requirement than those calculated through the existing method and tools.

The advanced method to generate solar collection surfaces is applicable only to a single building...
with the shape of a parallelepiped (convex footprint). This limitation is due to the fact that the solar collection surfaces are generated a priori on the plot without the possibility to consider any building form, hence cannot take into account the self-shading of articulated buildings or the mutual obstructions of groups of buildings. Therefore the need to investigate solar collection potentialities in urban environments on different building types and pattern layouts.

**METHOD**

The present research investigates the direct solar access performance in relation to the Estonian requirement of minimum 2.5 hours per day in the period from 22nd of April to 22nd of August of different types of buildings the massing of which is derived from solar envelopes to guarantee the due solar rights on the neighboring facades. The buildings are organized in distinct patterns and located in three urban areas for the comparison of a large and representative number of cases. The work is developed in the 3D environment of Rhinoceros, through the integration of computational design and environmental analysis and simulations using Grasshopper and Ladybug Tools.

**Urban areas**

The method is applied to three plots in as much urban areas with different densities. The scope is to differentiate the size and shape of the generated solar envelopes so to obtain a larger variety of building clusters. At the same time the aim is to analyze the possible different influence of the surroundings on the direct solar access performance of multiple patterns. Each urban area constitutes a study case. All the areas are located in the city of Tallinn (Lat. 59°26’ N Lon. 24°45’ E).

Case 1: the plot on Maakri Street is located in the high density central district with different high-rise office, hotel and residential towers up to thirty floors.

Case 2: the area of Tammsaare Street is located in the Soviet era district of Mustamäe. The plot is located in a medium density neighborhood constituted by panel housing up to nine floors.

Case 3: the plot on Vähi Street is located in the low density suburb of Kakumäe, developed mostly from the 2000’s and populated by double-floor houses and small apartment buildings up to four floors (Figure 2).

**Pattern layouts**

The determination of the urban patterns to use in the research is a two steps process. In the first the building morphologies are selected and in the second these are aggregated in building clusters. The buildings selected are the most used urban typologies and relative sizes in the city of Tallinn throughout its history and from consolidated floor plan layout used in contemporary architectural design (Neufert E., Neufert P. and Kister 2012, Gausa et al. 2003).

Figure 2
The plots of the study cases 1, 2 and 3 from left to right. Image source: Estonian Geoportal 2016-17.
The building typologies selected are:

- **Point:** building characterized by a small footprint with mostly the same size on all the three dimensions or a prevalent vertical dimension depending on the solar envelope size.
- **Line:** building with one floor plan dimension prevalent on the other and on the height.
- **Block:** typology with a large footprint and a prevalent horizontal or vertical dimension depending on the size of the solar envelope.
- **Open block:** type of building with a large inner open space.
- **L-shape:** linear organization constituted by two line type united at their ends at 90°.
- **Court:** typology with a small inner open space.

Consequently every typology is aggregated through an algorithm in building clusters forming urban patterns. The point buildings have a square floor plan of the size of 18m and are dispersed with a random pattern on the plots (pattern P1).

The line buildings have a depth of 12m as most of the buildings in Tallinn of the same typology and are dispersed on the plots with alignments at 90° between each other (pattern P2).

The block typology has a square floor plan with variable size of 24m, 30m and 36m and is aggregated in regular grids (pattern P3).

The open block buildings have a depth of 12m as the line buildings and form cellular patterns aligned on the plot edge (pattern P4).

The L-shape type of buildings have a depth of 12m with shifted cross patterns forming two-sided open courtyard with the plots edges (pattern P5).

The court building presents one element 12m depth along the plot limit and inner elements of the same size forming patterns of enclosed courts (pattern P6).

All the facing buildings are at a minimum distance of 8m as required by fire regulations. All the six patterns have been used in the three areas. (Figure 3)
Solar envelopes

On each plot is generated a solar envelope using the mentioned advanced workflow to determine the maximum size and mass distribution of the buildings to guarantee 50% of the actual direct solar access on neighboring facades as required by the Estonian daylight standard. Three different heights are used as maximum height for the three cases based on a module of 3 meters. Each height is the same of that of nearby buildings: 63m for the plot of case 1 as the height of the nearby residential tower; 27m for the plot of case 2 as the 9 floors of the highest neighboring panel housing block; 12 meters for the plot of case 3 as the four floor small residential buildings nearby.

Due to the different urban density and morphology, distance and orientation of the facades surrounding the plot and maximum heights the solar envelopes present very different sizes and shapes. For case 1 it presents a manifold top surface with one pick on the open side of the plot. For case 2 it is a flat surface higher in the center and toward the open side of the plot and with sloping surfaces in correspondence of the surrounding building facades. For case 1 is a low flat volume except than for a very small portion of the plot (Figure 4).

Algorithm design

The algorithm created for the implementation of the method is based on the integration of standard Grasshopper and Ladybug Tools components and computation and selection tools developed by the author, and is divided in multiple stages.

In the first stage the algorithm generates the footprint of each of the six building types and aggregate multiple footprints creating variations of the same urban pattern. Each of the 6 patterns have been generated with three orientations, 0°, +45° and -45°, creating 45 variations per pattern for each of the 3 plots for a total of 810 layout variations. A developed algorithm selects the patterns that fulfill specific design requirements such as sizes and distances of buildings.

Consequently for the single variation the footprints are extruded and the intersections with the solar envelopes computed. In this way the masses of the clusters of buildings allow the due solar rights on the neighboring facades.

In the following stage contours are generated through horizontal sections of each building mass every 3 meters. A developed tool selects the contours with an area equal or larger than a specific ratio of the building footprint. The contour polylines that constitute the schematic building floor plans are extruded of 3 meters generating the floors thickness. The terracing profile of many building clusters reproduces the morphology of the upper solar envelopes surfaces. Every façade floor surface is subdivided in multiple samples each of the size of approximately 3 meters.

Figure 4
The solar envelopes generated on the plots of the three different urban areas of case 1 (left), case 2 (center), case 3 (right).
Consequently, the sun path for the latitude of Tallinn is generated and the positions of the sun for every hour and day are computed. These are the input of the component that calculates the total number of direct sun light hours received by each façade sample during the required period.

A developed portion of the algorithm computes the minimum quantity of direct solar access hours for each sample during every day of the required period and returns the statement true or false if the requirement of the minimum 2.5 hours is fulfilled or not (Figure 5). After, the ratio of the façade area (number of samples) fulfilling the requirement and the total floor area of the building cluster are computed.

Finally, for each case and for each building cluster a recursion tool iterates the described algorithm for every variation of the urban pattern.

**RESULTS AND DISCUSSION**

The direct solar access performance of every building cluster variation and for each case is analyzed through computation of the ratio of the façades area fulfilling the requirement. At the same time, the total floor area is calculated to determine the most performative pattern for each urban area.

The optimal pattern of each type of cluster is the one with the larger performance result obtained through the unweighted product of the deviations computed as ratios between the mean direct solar access performance of all the same pattern variations and the average among all the patterns types for every case, multiplied by the deviations of the mean total floor area of all the same pattern variations and the average total floor area among all the patterns for every case.

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*Figure 5*
Analysis of the minimum quantity of direct sun light per day during the required period on the building clusters with the six pattern layouts on the three plots.
In all the three cases the urban patterns constituted by buildings of the line and point typologies have the best direct solar access with a mean performance among all the pattern variations of about 70% for case 1, 80% for case 2 and 95% for case 3 for the line building clusters and of about 65% for case 1, 73% for case 2 and 91% for case 3 for the point patterns. The block pattern typology is the one that receive the least quantity of direct sun light hours in the required period for all the three cases with a mean performance among all the pattern variations of about 44%, 55% and 77% for case 1, case 2 and case 3 respectively.

The urban pattern that permit to realize the largest quantity of total floor area is as well the same for all the three cases. The courts cluster type total floor area is 62068m³ for case 1, 50659m³ for case 2 and 43137 for case 3. The least size of total floor area is realized through the line typology that permit to build 19838m³, 10680m³ and 8412m³ for case 1, case 2 and case 3 respectively.

The optimal pattern for all the three cases is the courts building cluster. It permits to realize the larger size of total floor area for all the cases and at the same time it is not the least performative for direct solar access in any of the three cases scoring the 5th grade (out of 6) for cases 1 and 2 and the 4th for case 3 (Figure 6).

The main findings of the study are:

- The fact that the same two cluster typologies are the most performative and the same pattern is the least performative in all the cases underlines that direct solar access performance in the first place is influenced by the pattern layout and building size.
- The analysis of the deviations of the best and worst urban pattern performance in relation to the average direct solar access for each of the three cases shows that in higher density and fragmented urban areas the difference is larger than in medium and low density area. This underline also the importance of the surrounding buildings on the direct solar access of new developments.
- As expected the open and dispersed pattern typologies have better direct solar access performance but permit to realize smaller total floor areas.
- The larger size cluster typologies permit to increase the quantities of total floor area comparing the small size cluster types with a larger ratio comparing the decrease of direct solar access performance they suffer of.

The primary importance of the pattern layout and secondly of the surroundings for the direct solar access performance is due to the fact that the Estonian daylight standard has to be fulfilled in a period of the year in which the sun paths have considerable altitudes and the quantity of hours, 2.5 every day, is a limited period of time.

In the low and medium density residential areas of case 2 and case 3 large portions of the façades fulfill the requirement of direct solar access in all the cases, hence all the building parts of every cluster type can

Figure 6
Charts for direct solar access performance (light blue bars), total floor area (dark blue bars) and optimal pattern (horizontal mark).
be used for residential dwellings. In the high density district of case 1, for the cluster types analyzed with small portions of façades fulfilling the requirement, the dwellings can be designed in a way that at least one room is located in correspondence of the façade that receive the required direct solar access or the buildings can be considered for mixed use allocating the portions with less direct solar access for offices and commercial activities.

CONCLUSIONS

The present research investigates the direct solar access potentialities of building clusters with different patterns in urban areas in relation to the Estonian daylight standard. The regulation requires that in new residential buildings at least one room in each premises receive 2.5 hours of direct sun light every day during the period from 22nd of April to 22nd of August. The study emerges from the limitation of the solar collection surface method that can efficiently predict solar access only for single buildings characterized by a simple shape.

The buildings of the clusters have a mass that allow the neighboring existing façades to receive minimum 50% of the direct sun light comparing the situation without the new development as required by the solar rights regulation of the Estonian daylight standard. The shape of the clusters is determined by the use of solar envelopes generated through the advanced method developed by the author.

The study is conducted on three plots in different urban areas. Evidence show that the patterns with the best and worst direct solar access performance are the same in all the cases, and that the difference of performance among patterns is larger in denser urban environment. This underline that the pattern layout is the primary factor for the direct solar access of building clusters and that the urban environment has a significant influence.

Results underline as well that the pattern that permit to realize the largest floor area in all the cases is not the one with the worst direct sun light performance. It is possible to deduct that a proper design can find optimal solutions that fulfill required daylight standards and buildings size.

The future work of this research is to develop computational methods for the floor plan layout design that take into account the portions of building facades that fulfill or not the direct solar access requirement. At the same time it will be investigated urban patterns performance for multiple requirements together with direct solar access, i.e. daylight (diffuse light), sky view and energy efficiency.

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SHAPE GRAMMARS
The complexity of formulating design(ing) grammars

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We are concerned with the complexity of formulating rules within a design grammar, i.e., a grammar for designing. Our motivation comes from an active development of a design grammar using railway station design as a demonstration study. In this paper, we identify a number of difficulties that may arise when developing shape rules and present approaches for graphical rule specification that can serve to overcome these difficulties. Specifically, we present examples where drawing shape rules and augmenting these with control conditions or rule constraints offer insufficient support for the rules' intricacies, and propose conventions for drawing and specification that support the explication of these exemplar shape rules, aiming not to overly complicate the drawing and specification process. We borrow from other authors where appropriate, and do not concern ourselves with implementation issues, at this point.

Keywords: Design grammar, shape grammar, shape rule, graphical depiction

INTRODUCTION

Shape grammars are a formal rewriting system for producing languages of shapes (Stiny 1980). Although conceived for producing both existing languages and new languages (Stiny and Gips 1972), they have been used mainly for analytical purposes as a means to understand the rules underlying given design styles (e.g., Stiny and Mitchell 1978; Downing and Flemming 1981; Çagdas 1996). Only in a few cases have they been used as an exploratory tool in the design process (e.g., Stiny 1980; Knight 1999; Beirão and Duarte 2009). Beirão et al. (2009) suggest distinguishing between ‘grammars of designs’, being analytical grammars, and ‘grammars for designing’, to denote the progressive development of a new grammar for a new design context. We will adopt the term design grammars to denote ‘grammars for designing’.

Design grammars present additional difficulties compared to analytical grammars. Developing an analytical grammar involves systematically determining all possible rule variations and encoding these into a grammar. Rule variations are necessarily finite and the encoding is done by the developer of the grammar, not by the user. The complexity of the rule is therefore less important. For design grammars, however, the designer is both the developer and the user of the rules. Rules may be defined from scratch or as alterations of existing rules. Therefore, complex rules stand less of a chance to be defined or altered.
Simplifying the rule development process becomes as important, if not more, than providing an easy interface for rule selection and application.

Non-parametric shape rules tend to be fairly straightforward to specify, at least when the shape rules are mainly geometrically with limited attributes. The user can simply draw the left-hand side and right-hand side of the rule as shapes on a canvas. Labels may need to be assigned to points or other geometric elements through selection and assignment, and similarly for other attributes such as weights and colours. However, the process becomes more cumbersome when considering parametric shape rules. Stiny (1977) demonstrates parametric shape rules for the Chinese ice-ray lattice grammar. Vertex points of a triangle, quadrilateral or pentagon are expressed using fixed and parametric coordinates. Additional constraints on these parametric coordinates are also identified (Figure 1). Specifying both parameters and constraints complicates the process of specifying parametric shape rules.

Fortunately, most implementations of parametric shape grammar interpreters (PSGs) rely on a graph-based representation (Grasl and Economou 2013; Wortmann 2013; Strobbe et al. 2015) which avoids the necessity to explicate coordinate parameters. Instead, constraints can be specified by drawing segments in parallel or of equal length (Grasl and Economou 2013). For example, a square has four sides, with parallel opposing sides, of equal length and, additionally, two diagonals of equal length. However, using a graph-based PSGI for Stiny’s Chinese ice-ray lattice rules does not pre-empt all constraint explications. As another example, Figure 2 shows a parametric shape rule from Duarte’s (2005) Malagueira grammar. Parametric coordinates are omitted, nevertheless, numerous control conditions are identified.

Note that procedural grammars (Müller et al. 2006) offer relatively straightforward support for such rules but, instead, complicate the rule development process for designers as they are required to possess programming skills and painstakingly script and edit the procedural rules, thereby fracturing the design process and graphical interaction. As such, we do not consider procedural grammars as a solution to the problem and instead are interested in an approach that is more graphically interactive. Nevertheless, we recognise that not everything can be graphically depicted and that additional expressions, such as simple control conditions (e.g., Duarte 2005) or rule constraints, mainly expressed as (in)equalities, may remain necessary.

In this paper, we aim to, on the one hand, identify a number difficulties that may arise when developing rules and, on the other hand, present solutions for graphical rule specification that can serve to overcome these difficulties. Our motivation comes from an active development of a design grammar using railway station design as a demonstration study. We present examples where drawing shape rules and augmenting these with control conditions or rule constraints offer insufficient support for the rules’ intricacies. We propose conventions for drawing and specification that support the explication of these exemplar shape rules, aiming not to overly complicate the drawing and specification process. We borrow from other authors where appropriate, for example, Duarte (2005) includes specifications of lengths of line segments in shape rules simply adopting normal dimensioning conventions in architectural drawings (Figure 2).
Figure 2
Rule dissecting an outside zone into yard and sleeping zones (after Duarte 2005, p. 359). The rule drawing illustrates the (parametric) specification of lengths of line segments. Control conditions referring to these lengths are also specified.

**PARAMETER CONSTRAINTS**

Let us reconsider Stiny’s (1977) Chinese ice-ray lattice grammar. Each rule allows for a convex polygon, whether a triangle, quadrilateral or pentagon, to be split into two new convex polygons by placing a single line between two of the original polygon’s edges. In the case of the pentagon, these polygon’s edges may not be adjacent, in order to avoid the creation of a hexagon. Stiny (1977) expresses the polygonal vertex points using fixed and parametric coordinates and identifies a few additional constraints:

1. A rule only applies if the polygonal area is greater than some specified minimum value.
2. Each polygon includes a point near the centroid of the polygon, specifically, at a distance equal to the radius of the greatest circle contained in the polygon and centred on the centroid, and multiplied (scaled) by the area of this circle over the area of the polygon.
3. The absolute difference between the areas of the two polygons arising from the splitting rule is less than some specified minimum value.

The first condition ensures a minimum size (area) for a polygon to be split, while the second condition aims to prevent any rule from applying to a polygon that has already been split by the same or another rule. It is unclear why the second condition does not simply constrain the location of the point to coincide with the centroid of the triangle, rather than at a specific distance that is, on the one hand, proportional to the radius and area of the greatest circle contained in the polygon and centred on the centroid and, on the other hand, inverse proportional to the area of the polygon. The third condition ensures that the resulting polygons have more or less the same size (area).
These and other constraints are explicated in Figure 1: The first line of constraints aids in simplifying the final constraint, these may otherwise be omitted. The second line ensures the area of the triangle is greater than \( c \). The third line simplifies the specification of the point as coinciding with the centroid, rather than at a specific distance of this centroid. The fourth and fifth line constrain the endpoints of the splitting line to coincide with two edges, though not with the vertices of these edges. The sixth and seventh line explain the location of points within the new polygons. Finally, the last line limits the absolute difference between the two polygonal areas below a value \( d \).

We already stated that a graph-based PSGI may pre-empt the parametric specification of the coordinates of the polygon vertices. In addition, Stouffs (2017) demonstrates that the near-centroid point can be omitted in favour of labelling the polygon’s edges. Using descriptions (Stiny 1991; Stouffs 2016) instead of labels, the polygon’s edges can be identified using a parametric description (Figure 3). As such, except for the area condition, only a single parameter is needed within the left-hand-side of the shape rule. We will return to the area condition below. However, the same does not apply for the right-hand-side of the shape rule, as the endpoints of the splitting line are specified in terms of parameters \( t_3 \) and \( t_4 \), each constrained between 0 and 1 (excluding 0 and 1) with respect to the endpoints of the respective edges.

Stouffs and Wieringa’s (2006) implementation distinguishes the polygon boundaries (line segments) as well as the polygon surfaces (plane segments). In fact, as they adopt an object-oriented approach in which subshape detection is of no concern, rule application only requires the identification of the polygon (surface). The boundary elements are maintained solely for the purpose of dimensioning and structurally analysing the design. For our purpose, the identification of the plane segments serve the area constraints (Figure 3), though, in principle, having the description assigned only to the plane segment, and not the boundary segments, is sufficient, though not efficient from an implementation point of view (Stouffs 2017).

Figure 3
The shape rule of Figure 1 redrawn for a graph-based PSGI including (parametric) descriptions. The rule illustrates how both endpoints of the splitting line are constrained within a bounded section of the respective polygon’s edge.

Figure 4
Variations on the shape rule of Figure 3 using the void predicate and limiting the splitting line to connect only the two longest edges: (above) the lengths of the line segments are compared; (below) the shortest line predicate is adopted. Note that the constraint comparing both areas is omitted.
Certainly, the approach illustrated in Figure 3 is far from the only one to reduce the complexity of the rule specification and its parametric constraints. Liew (2004) offers an alternative approach using a zone descriptor specifying a void predicate function prescribing the area to be devoid of any shape elements. Unfortunately, while it avoids a description to be required in the left-hand-side of the rule, labels or descriptions may still be necessary in the right-hand-side of the rule in order to implement the area constraint, unless such constraint would be omitted.

However, there are other situations where a predicate may be useful. Consider we want to constrain the triangle splitting rule such that the splitting line splits the two longest boundary lines, avoiding the shortest edge. We could indicate the length of all three boundary lines and specify constraints identifying the shortest line (Figure 4 above). Alternatively, we could adopt a shortest line predicate identifying the shortest edge (Figure 4 below). Beirão (2012) similarly considers a rule (or pattern) that identifies the longest line among a set of lines.

In our railway station design case study, we’ve encountered similar situations requiring for parameter constraints and predicates. In the context of an axial layout, we’ve considered a rule that adds a perpendicular line segment to an existing line. Figure 5 shows two variations of a same rule with quite different results. Both rules specify a single maximal line using the maxline predicate as the left-hand-side shape. In the first rule (Figure 5 above), the perpendicular line segment is only geometrically defined with its length proportional to the matching line segment. In the second rule, the length of the perpendicular line segment is differently defined, in Figure 5 (below) as a fixed length, but it can also be defined as a function of other information provided.

Other practical predicates may be no_label and no_line. The latter is conceived as a variant of void that applies only to line segments, not plane segments. The former can be considered to imply no description as well, as descriptions can be deemed parametric labels. Figure 6 illustrates the use of both predicates in a very simple grid and rule-based room layout procedure. The first rule (Figure 6 above) considers a rectangular space defined both by a plane segment without label and boundary line segments and defines it as a room with label “R_i” (i being the room index). The second rule (Figure 6 below) considers a previously defined room and an adjacent, unassigned space and assigns the space to the room, adding the room label to the space and removing the boundary line segment between both spaces. The use of the no_line predicate ensures that a rule only applies to a single grid cell, not a combination of two or more grid cells. Note that the two rules in Figure 6 only allow for combining cells in either a horizontal or vertical sequence, not both.

Stouffs and Janssen (2017) suggest the use of shape grammars to generate relevant 3D building data from 2D urban plans that can serve to analyse and assess such urban plans with respect to different criteria, requirements and targets. Proposed rules include subdividing plots based on a targeted plot-size range, and generating towers whose height and number of floors is guided by a specified Gross Plot Ratio or Floor Area Ratio (Janssen et al. 2016). This means that the number of subdivisions or the number of floors is initially unknown and thus cannot be incorporated or drawn into the shape rule. While constructing alternative shape rules for different numbers of floors would be undesirable, it is possible to iteratively add any number of floors using just
a few (three) rules: an initialisation rule, an iteration rule, and a termination rule (Figure 7).

The initialisation rule (Figure 7 top) determines the number of parts, \( n \), by comparing the average length of the opposite sides of the quadrilateral, \( \frac{l_1 + l_2}{2} \), to a target length \( l_t \): \( n = \left\lfloor \frac{l_1 + l_2}{2l_t} + 0.5 \right\rfloor \). Additionally, it creates the first quadrilateral part by adding a single line segment at the appropriate distance(s) from the starting segment. The descriptions “repeat” and “\( n - 2 \) times” are added to the starting and new segment, respectively. \( n - 2 \) reflects on the fact that the last line segment creates two quadrilateral parts at once. The iteration rule (Figure 7 middle) reads the required distance(s) from the previous quadrilateral part in order to create one more part, adding a new line segment and moving the descriptions one segment over while, at the same time, reducing the number by one. Finally, the termination rule (Figure 7 bottom) only applies when \( n \) has become zero and removes the descriptions.

While perfectly practical, it may be far from efficient. Generating a simple massing with floors, of a high-rise building, would require at least one rule application per floor. Speeding up the process could be achieved by adding a fourth rule to create a particular number of floors at once. For example, as long as the number of floors still to be created is larger than 10, a single rule could apply that adds 10 floors and reduces the number of floors to be created by 10. Once below 10, each remaining floor could be created individually by the existing rule. Additional rules could be added to create other, smaller or larger, numbers of floors, further reducing the number of rule applications needed to generate a single building.

Instead, we can conceive of a single rule, and its graphical depiction, that can generate any number of floors in a single application (Figure 8). Only the first and last quadrilateral parts are fully drawn. They are tagged, respectively, \#1 and \#n, with their lengths also specified. In between the first and last segment tags, three dots stand for any number of segments to complete the segmentation into \( n \) parts. We use the \# symbol to indicate the tagging in order to distinguish the tags from labels or descriptions. Obviously, the actual representation of the right-hand-side of the shape rule would require some form of a shape schema. However, here we are only concerned with the graphical depiction of such a rule and with the ease of use to conceive and elaborate such a rule. We are not concerned with the actual implementation, though we argue that devising the necessary shape schema should not be overly complicated.

**Discussion**

Considering this ability to identify any number of parts in one rule, one may be eager to extend this approach to other contexts, such as the number of sides of a polygon. As in Stiny’s Chinese ice-ray lattice grammar, rules may apply to a number of different kinds of polygons, e.g., triangles, quadrilaterals and pentagons. If we can conceive of a way to graphically identify a polygon with any number of sides (with restrictions), we could simplify the rule set. Let us consider an example from the railway station case study.

When designing an end station, we may have a number of parallel rail tracks ending at the station, though, while some tracks may end at the same linear point, other tracks may end earlier (or later). The shape of the end platform is then strongly defined by the linear end points of the various tracks with
access to the various side and/or island platforms, while the station building itself may define a single linear boundary (Figure 9). Considering that we can always define the end platform as a polygon, however complex, it would be advantageous if we could have a rule that takes any polygon as the left-hand-side shape to operate on it. However, it would be nearly impossible to graphically represent the rule or its left-hand-side. Instead, a symbolic rule would be more appropriate representing the polygon as a symbol or object, irrespective of its actual shape.
While a combination of (graphical) shape rules and symbolic rules may come in handy, here, we argue strictly for shape rules that can be graphically represented, even if we allow for simple topological variations. Specifically, we would like to argue that graphically identifying a polygon with any number of sides may complicate rather than simplify the rules, as it would become much harder to identify to which kind of polygons the rule applies and what the result of rule application would be. Stiny's rules are actually very simple and clear. One can immediately understand these apply to triangles, quadrilaterals and pentagons and also what the effect of rule application is on the respective polygon. Such would not be the case for a single rule applying to different kinds of polygons, as the user would need to carefully check the constraints and conditions in order to understand whether triangles, quadrilaterals or other polygons are included.

In the case of the potentially complex shape of an end platform, we would rather consider a small collection of rules that define partial end platforms, then join the partial end platforms together into one complete end platform, thereby identifying the platform boundaries, including with the island and side platforms. For example, in Figure 10, the top rule identifies the platform boundaries of any adjacent rail tracks with the same linear end points (using the maxline predicate) and the station boundary fronting the rail tracks, and defines a partial end platform between these two boundaries. The partial end platform is defined both as a polygon of line segments and as a coinciding plane segment with label “ep”.

The middle rule in Figure 10 is conceived as a general rule that takes two interlocking (partial) polygons of line segments, where both coincide with a labelled plane segment, e.g., with label “ep”, and replace it with a single (partial) polygon of line segments bounding the combined plane segment. Finally, the bottom rule in Figure 10 ensures that in case of an island platform that extends into a side platform, because one rail track extends beyond the other, the end platform area is reduced to allow for the full side platform width (indicated by $w_p$ from the centre of the rail track).

Note that in the middle rule of Figure 10, the label is parametrised as a description, even if the constraint currently limits the parameter only to the value “ep”. However, it would be very easy for the designer to generalise the rule and include other label/description values. Note as well that the middle and bottom rule assume that the width of an island platform is always smaller than twice the width of a side platform. If, however, the width of an island platform is exactly twice the width of a side platform, then, the bottom rule becomes obsolete, while a new rule would be needed to allow two (partial) polygons of line segments that touch (rather than overlap), where both coincide with a labelled plane segment sharing the same label, to be joined. In case the width of an island platform may exceed twice the width of a side platform, other rules may be additionally necessary. Finally, we would like to add that, following the same line of thought, we only conceive of rules allowing
for a one-dimensional topological variation, that is, for repeating elements, one-dimensionally, any number of times. In case we need to subdivide plots two-dimensionally, we suggest a first segmentation in one dimension, followed by segmenting each part in the other dimension. Obviously, there is some subjectivity involved in all these arguments and in our choice for what we allow for and what not. However, we would be happy to have this discussion and will further contribute with the continuous development and elaboration of the (limited) railway station grammar. Our ultimate aim is to achieve an implementation of the grammar, including all the solutions here presented.

CONCLUSION
We have identified different examples where drawing shape rules and only augmenting these with control conditions or constraints lead to overly complex rule formulations or offer insufficient support for the rules’ intricacies. We have presented examples of graphical constraints, e.g., indicating segment lengths or boundary intervals, and of predicate functions acting as constraints, as well as of topological variations expressed graphically. Some examples have been borrowed from other authors and extended where appropriate. As we acknowledge that others may have addressed similar issues, whether implicitly or explicitly, we also acknowledge that our investigation is far from complete. We consider this as an active discussion, one that we will continue to engage in and that we invite others to contribute to as well. We envision the discussion to include both the vocabulary of (graphical) conventions and techniques and the extents and limitations of these techniques. Specifically, with respect to topological variations, we have indicated where we would opt to limit this technique. While we have limited the discussion to graphical depictions, we do intend to implement most or all of the suggested techniques, at some point.

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Mapping the Architectural Genome

A Preliminary Study of Facade Syntax

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As its point of departure, this research contends that it must be theoretically possible to design a parametric urban design tool capable of simulating 90% of all conceivable site designs. The relevance of such a tool would be to quickly be able to simulate a large variety of site designs for any given context and location at a reasonable level of detail. The paper presents a preliminary study of facade syntax and its application to a prototype parametric design tool. The study finds that a combination of a compositional, geometrical and mathematical approach is promising to this end. From an empirical facade analysis, a taxonomy of three compositional levels is introduced and applied to the prototype. The paper concludes that the preliminary study is promising on a number of accounts. However, some issues must be investigated further, while other important issues have yet to even be examined. Yet while the task may seem insurmountable, there is potential to complete it, at least to a reasonable degree, and with a reasonable effort.

Keywords: Parametric urban design, Facade syntax, Composition, Geometry, Mathematics

INTRODUCTION

Urban design is often more concerned with building types than building artefacts. Operating on the typological level rather than the level of concrete design, principles for building design are of the essence, not the specificities of unique buildings. Therefore, parametric design lends itself perfectly well to urban design.

Being able to quickly and efficiently generate 3D models to illustrate design principles holds a great potential for many urban design tasks. From urban design competitions to urban design schemes within the framework of public planning, what is of relevance is to visualize ideas and principles for urban spaces to be.

While classical “white models” may be sufficient to convey an understanding of morphological and typological aspects of an urban design project, they lack sufficient detailing to be able to convey the architectural qualities of urban space. To compensate for this, urban design projects often feature perspective renderings which illustrate the architectural character without being based on actual architectural design of the buildings framing the perspective.
view. But even so, such illustrations are both expensive and time consuming to produce.

A parametric design tool capable of generating urban design models with architectural detailing would solve this problem. While of limited use when it comes to the actual design of concrete buildings, it would facilitate the communication of architectural principles in urban design, in addition to the morphological and typological principles which are typical at this level of design.

This paper presents some first steps in the process towards building such a tool.

Initial to this process is to consider the parametric logic which may be shared across different developments, buildings and facades. Traditional architectural analysis tends to operate by way of typologies and styles. Yet when performing a parametric analysis, buildings which may be typologically different or belong to different styles may share the same underlying parametric logic.

Such a parametric analysis may be applied to the levels of both site layout, building envelope and building facade. As an example, a row of terraced houses may be parametrically different from a housing block only in the sectioning of the block into individual units. And a strip of detached houses, in turn, may be parametrically different from a row of terraced houses only in the amount of open space between the units. The same is true for building facades, which is the focus of this paper.

In order for a parametric urban design tool to be useful in ideally any context, it should in principle be capable of generating any possible facade. However, mapping the parametric logic of any possible facade may seem an immense task. And truly, many facades are quite unique and may not share their parametric logic with very many other facades.

Yet a bold guess would be that 90% of all known facades have very similar parametric characteristics. Therefore, mapping what may figuratively be referred to as their “architectural genome” might not be such a vast undertaking after all. (see Figure 1)

Figure 1
A facade with a consistent glide reflection pattern of identical tiles, interrupted by a vertical and a horizontal variation (recessed tiles)

ANALYTICAL FRAMEWORK
The results section of the paper is structured into three parts. In the first part, a basic framework for the parametric logic - or syntax - of building facades is established on the basis of an empirical analysis of a large number of existing facades, based on photographs. The analysis is limited to planar facades, i.e. facades without protruding or recessed elements such as balconies, bay windows, or niches. In the ontology of the study, such elements may be considered qualities of the building envelope, not the facade.

The analytical framework is unfolded on three levels. The first level is the overall composition of facades. This encompasses vertical parts such as the base, the middle and the top sections of facades, as well as the parts that structure the facade horizontally. The second level is the composition of each of
these parts in terms of patterns of repetition - or tiling - of walls and openings, and other facade elements. The third level is that of the individual tiles and their possible parametric variation.

The second part of the section discusses the semantic organization of the control handles of the parametric tool. As the tool is aimed at architectural design professionals who should not have to understand its underlying parametric logic, a sort of reverse engineering must be made, in order to translate the parametric variables into architectural variables which are meaningful to the professional architect user.

This may seem to be an interface design problem. However, it ties directly back to the underlying parametric logic of the way the tool is built, as the variables which are operated upon in the interface ultimately are the underlying parametric variables deduced from the analytical framework. Postponing this part of the design might therefore render the tool useless and jeopardize the overall aim of the study.

The third part of the section presents a computational prototype for a select number of parametric variables for the generation of building facades. The computational prototype shows proof of concept on two levels. On the immediate level, it demonstrates the parametric versatility of the approach with regard to the selected variables. It does so, both with regard to the facade variations it is capable of generating. But it also does it with regard to the operability of the interface for the professional architect user.

As the prototype is work in progress, it is crucial that its architecture is expandable, in order to incorporate additional variables without cluttering up the code. Expanding the scope of the tool with additional variables is a potentially endless process. Therefore, this is an important issue. Otherwise, the expansion of the tool may too quickly become too cumbersome to be viable. Thus, on the meta level, the computational prototype also demonstrates the parametric expandability of the approach.

The presented work is part of a larger project which includes similar studies of site layouts and building envelopes. While these are different domains, the parametric logic applied to building facades, in principle, is similar to the one which may be applied to these other elements of the ontology of the study. However, there are variations. While site layouts and facades follow a planar logic, building envelopes are three-dimensional. Therefore, the parametric logic of building envelopes are partly different from that of site layouts and facades. (see Figure 2)

**Figure 2**
Facade with base and left wing parts. While the facade features only a limited number of different tiles, their distribution across the body part is too complex to be meaningfully described by means of variations. A stochastic distribution may be preferable though not exact in this case.

**RELATED WORKS**
On the general level of parametric urban modeling, different approaches have been applied to the solution of discrete problems such as designs for particular geographical sites (Godoi et al. 2008, Gürbüz et al. 2010, Hardy, Lundberg 2010) or for particular types of buildings (Matcha, Quasten 2009). Yet, these approaches only concentrate on a subset of parametric variables relevant to their respective domains. Yet other approaches target the level of urban planning (Beirão et al. 2011, Pellitteri et al. 2010), which typically deals with issues other than the layout and morphology of buildings. These studies also operate at a level of detail at which facade design is irrelevant.

On the specific level of facade modeling, several approaches exist to parametric facade generation, whether fully automated (Shen et al. 2011, Wan,
Sharf 2012, Weissenberg et al. 2013, Wu et al. 2014) or user assisted (Bao et al. 2013, Musialski et al. 2012). Some approaches focus on the parametric generation of existing facades from image (Weissenberg et al. 2013, Musialski et al. 2012, Teboul et al. 2010) or LIDAR (Shen et al. 2011, Wan, Sharf 2012) data. Other approaches focus on parametric variation of different facade schemas (Wu et al. 2014, Bao et al. 2013). And yet other approaches focus on computational efficiency through algorithm optimization (Weissenberg et al. 2013, Haegler et al. 2010). (see Figure 3)

Image or LIDAR data interpretation is highly relevant if the aim is to generate parametric models of existing urban environments. For large urban models, computational efficiency is relevant as CPU requirements for such models may strain even the best computers and require significant amounts of render time. And parametric variation of facade schemas can be relevant in the gaming industry, where the easy generation of plausible urban environments may precede over architectural quality and accuracy.

While Bao et al. (2013) have some concern for HCI in relation to user assisted parametric modeling, none of these approaches are entirely relevant to the aim of the research which is presented in this paper. Developing a parametric design tool for the easy generation and visualization of urban design schemes does not rely on image processing, as the focus is on new buildings rather than existing buildings. Computational efficiency is of lesser importance, as most such schemes are of overseeable size. And finally, most attempts at parametric variation of existing facade schemas either display modest architectural quality, offer variations of specific types, or rely on historic and well-established architectural paradigms which may not be relevant to current-day architectural design, let alone in any geographical region.

**METHODOLOGY**

This study is being carried out in a heuristic manner, based on architectural, geometrical, mathematical and parametric knowledge and experience. The empirical facade analysis is abductive in nature, drawing from a vast catalogue of building facades, which have been examined repeatedly with regard to different parametric strategies. Test facades have been selected for their architectural and compositional qualities and variation in order to test and corroborate different parametric approaches.

The tool prototype has been developed in a trial and error fashion, testing different approaches with regard to their computational clarity and openness, as well as their compatibility with architectural thinking, while compromising as little as possible, the versatility and flexibility of the tool as well as the level of detailing it can offer. Hence, architectural logic and compositional progression have guided the script development in order to make the algorithm meaningful and structured to work with for the professional architect user.
As the results represent work in progress, they have not yet been tested with live users, nor have they been applied to large models. Reservations therefore have to be made at this point, as to the actual user experience in live usage, as well as to the usability of the prototype in real-life urban design. Similarly, the computational efficiency of the algorithm has not been tested on larger models with lots of geometry. However, it is assumed that such potential shortcomings may be mitigated in later stages of the research. (see Figure 4)

Figure 4
Facade (partial) with padding between tiles. This facade inspired (though is not identical to) the facade in the prototype example below. Here, the padding was integrated into each tile.

RESULTS
In this section, the preliminary results of the study are presented. The first three sub-sections present an empirical facade analysis and its derivate taxonomy of to facade composition, facade symmetries and variations, and facade tiles and elements. The following sub-sections present the issues of control handles for a parametric urban design tool and a preliminary prototype of the tool respectively.

Facade Composition
The empirical facade analysis suggested that a geometric descriptive logic to the composition of facades, in combination with a few compositional elements, both lends itself well to parameterization and offers a comprehensible syntax to the professional architect user.

Most planar facades of multi-storey office and residential houses - which constitutes the domain of this study - regardless of their age, style, type or provenance, share a number of features which can be described generically. In their most simple form, facade schemas develop uniformly across the facade from left to right and from bottom to top, regardless of size and number of floors. However, most often, small variations occur at the ground floor, if nothing else, then at least in the form of an entrance door.

Vertically, from the ground floor to the top floor, facades are often divided into different compositional parts. Apart from minor variations at the ground floor, such as the entrance door or window formats, the absences of balconies, etc., facades may have a base which follows a different geometrical logic than subsequent floors. The base may span across one or more floors, and is a feature of many architectural styles. Similarly, facades may have a top which is different from the previous floors, which may also span across one or more floors.

Hence, the facade may be described as constituted of up to three horizontal compositional parts, an optional base, a body (which is always present), and an optional top. These features may be found in different combinations. Many modernist buildings have a uniform facade from the first floor up, and a base in a different design. Some buildings may develop uniformly from the ground up and have a variation at the top. And yet others may even feature all three compositional parts.

A similar logic can often be applied horizontally. From left to right, facades may have a left, a body and a right part, each of which feature different, sometimes reflective, geometrical logics. In historical facades, a center part may be flanked by symmetrical wings, and modernist facades often have a side part which is different from the rest of the facade, typically with a blank or nearly blank wall.

In combination, these three horizontal and vertical parts constitute a 3x3 matrix with 9 rectangles. The four corner rectangles sometimes - though not often - have unique geometry. But mostly they are
extensions of either the respective row or column part (base, top, left wing, right wing) to which they belong. Described in this fashion, each of the nine rectangles may hold facade parts with different geometrical logics. While unique corner conditions are rare, however, only the five main parts, base, body, top, left wing, right wing, have been implemented at this stage. (see Figures 5 and 6)

![Facade composition](image1)

![A glide reflection overlay](image2)

**Symmetries and variations**

Across the facade, different symmetries may occur, in the form of translations, and horizontal reflections and glide reflections. Rotations and vertical reflections are rare in facades, as their design relates to gravity and use. Symmetries are important in architectural as well as in parametric design, as they constitute both order and variation, as well as computational efficiency as they represent simple variations of the underlying grammar.

In terms of symmetry, many facades are composed from simple translations. Alternating reflections, both vertically and horizontally, as well as glide reflections (which by nature are both vertical and horizontal) often occur across the entire facade or parts of it. Translations, reflections and glide reflections may occur in combination. As such, the facade pattern may constitute a regular tessellation. Other more complex patterns of repetition may also occur.

In addition to symmetries, facades may feature one or more variations. Variations are regions in the facade where the primary geometrical patterns do not apply. Such variations may be constituted by single balconies or bay windows, or single doors and windows with different size, position and/or design from other doors and windows. Such variations may be used as architectural accents or tensions, or exist for practical reasons. The latter is typically the case at the ground floor level, where entrance doors, shop windows or gateways constitute variations to the general geometrical pattern of the facade.

Variations may occur in combination with symmetries, either as slight variations of the substituted part of the symmetry or in complete contrast to it. The more variations there are on a facade, the more complex it may be to detect them as something distinct from an otherwise underlying pattern. If too many variations occur, it may be more meaningful to conceive of the facade as stochastic. From a computational point of view, variations are less efficient than symmetries. Also for this reason, a stochastic description may be more desirable, even if it cannot generate an exact description.

**Tiles and Elements**

Once the facade has been classified with respect to its compositional parts, symmetries and variations, the next level of analysis is the different tiles which oc-
cur in the pattern of each part. Tiles are separated vertically by the floors of the building, typically flush with the floor decks. Horizontally, their separation is guided by the symmetries of the facade. Thus their widths are likely to vary more than their heights. Simple facade schemas may contain only one type of tile. If the tile does not have self-symmetry, reflections and glide reflections may produce highly varied facades, even from a single tile. However, many facades are composed from two or more different tiles, with or without reflections. (see Figures 7 and 8)

Figure 7
A variation (petroleum) is added for every third floor at shifting heights

Figure 8
For remaining tiles, an additional variation is added for every third floor stating at the ground floor

In their simplest form, tiles consist of only a wall segment or an opening (door or window). More complex tiles may contain sub-symmetries and different combinations of walls and openings. Wall segments and openings are elements. Depending on the level of detail of the analysis as well as in the parametric model they may have colors or textures. Walls may be made from different materials such as brick or concrete, and have minor recessions or protrusions such as lesenes and ledges. Apart from doors and windows, openings may be French balconies, have shutters, blinds and louvers, brise soleils, and more. While the catalogue of architectural elements is extensive, only elements with a reasonable effect on the morphology and character of the building should be considered.

Elements, in other words, constitute the smallest level of analysis. This is the level of texture and materiality. They also contain the final shapes of the parametric algorithm, also referred to as terminal shapes or leaf shapes in the terminology of computational grammars. Although every previous level of analysis (and computation) are important in terms of defining the overall and detailed composition of the facade, everything before the elements are just intermediary steps.

In total, overall composition and parts, symmetries and variations, and tiles and elements constitute the taxonomy which has been deduced from the empirical facade study. The different levels of the taxonomy have been applied, both to the considerations about HCI and user control in the parametric design process, and to the parametric algorithm design.

**Control Handles**

In order for a parametric urban design tool to be useful to the professional architect user, its user interface must be intelligible and meaningful. Many parameters go into the full definition of 90% of all site designs with building envelopes and facades. The design of the interface to control all the parameters could easily develop into a gigantic mixer panel with control handles for all the different parameters. And even if it would be possible to add meaningful labels to all the handles and possibly even tooltips and help sections, control handles which do not give any visual...
hints about their effects are likely to not appeal even to the most devoted user.

Therefore, the approach to designing the HCI has been dual. On the one hand, a hierarchy has been attempted which ultimately breaks all the different parameters down into logical sections following the gradual refinement of a site design from the bare site to elements and textures. On the other hand, the idea is to have the algorithm guide the different design steps, through different render scapes, similar, in principle, to different levels of detail (LOD) in model representation.

Prototype

In order to be able to address each tile of the facade with respect to different aspects of its composition, each tile (cell) was parameterized with symbols indicating its x and y indexes in the matrix. In this way, any cell or series of cells may be evoked in the script at any time by calling its/their coordinates through mathematical functions.

The prototype facade design part of the parametric urban design tool is demonstrated in an example for a contemporary facade (Figure 11). At the level of overall composition, the facade has the following features (Figure 5):

- A base part spanning one floor at the entire width of the facade
- A left wing part spanning all the upper floors and 1 narrow panel (column of tiles)
- A body part spanning 5 floors and 4 wide tiles

In this example, the right wing part is used as a very narrow padding in order to add extra wall thickness to the right of the right edge (symmetry line) of the rightmost panel in the body part.

At the level of symmetries and variations, three overlays were applied:

- A symmetry overlay in the form of an overall glide reflection of tiles across the base and the body parts of the facade (Figure 6)
- A variation overlay spanning every third floor, counting from the ground floor (floor 0 and 4) (Figure 7)
- A variation overlay spanning the fourth vertical panel of the facade (row 3 of the 0-based matrix) (Figure 8)

While the symmetry overlay only mirrors the tile without changing its description, the variation overlay substitutes the description, i.e. points it to a different tile description.

At the level of tiles and elements, the following features were applied:

- A tile consisting of a wall element, three tall opening elements and one short opening el-
element, padded with a narrow wall element on either side in the sequence aABBBCa.

- A tile consisting of two double opening elements separated by a wall element, also with wall paddings on either side in the sequence aBCABBa.
- A dark color wall element (A) with a ground floor variation which renders in a bright color apart from a top part which renders dark.
- A tall opening element (B) with a top dark color wall part.
- A short opening element (C) with dark color wall parts below and above the opening with a ground floor variation which renders is like the tall opening element (B).

In sum, this grammar results in five possible terminal elements, 3 main elements (wall, tall opening, short opening) and two ground floor variations (bright wall, tall opening), one of which, however, is identical to one of the main elements, adding to four visibly distinct elements. The resulting facade is shown in Figure 11.

**DISCUSSION**

While the presented work is still preliminary, it does lend itself to discussion on a number of points. The empirical approach to facade (de-)composition has allowed for the development of a parametric design approach which spans facades of different age, style, type and provenance. As the ultimate goal of the research is to develop a generic parametric urban design tool, this is important. However, as the facades have been abductively selected rather than based on a systematic, quantitative survey (which would have been unfeasible), there is a potential risk, that the sample is biased. Further testing should therefore take place.

The user interface design has proven to be a significant challenge. While careful thought has been put into the structure and semantics of the user interface, the number of foreseeable handles is substantial. The visual aid through intermediary renderings potentially provides important clues during the design process. There is still room for improvement, however, both as to the visualization and the implementation of different render stages in the user interface.

The three-level taxonomy of composition and parts, symmetries and variations, and tiles and elements is promising and meaningful, and seems to be able to embrace all necessary design steps in basic facade design. The number of overlays (symmetries and variations) which must be available in order to offer sufficient variation is yet to be determined and their implementation may represent a challenge.

The composition of tiles is still underdeveloped and should be subject to further development, both with regard to their number and their sub-symmetries. Similar to variations, tiles are not computationally efficient as every tile must be uniquely defined (although potentially by means of re-usuable...
sub-components which may represent an additional level in the taxonomy).

Finally, as the algorithm has not been subject to large-scale testing, it may potentially be slow due to the lack of focus on computational optimization.

**CONCLUSION AND PERSPECTIVES**

The presented work on a parametric facade design algorithm is only a small part of a larger plan of building a parametric urban design tool capable of modeling 90% of all site designs with building envelopes and facades at a reasonable level of detail. Yet while the task may seem insurmountable, it shows that there is potential to reach it in part with a reasonable effort.

Nonetheless, a lot of work still needs to be done. Notwithstanding the levels of site layouts and building envelopes, at the level of facade design, a number of aspects call for further exploration and development, apart from the ones listed in the discussion above. The issue of padding was briefly mentioned in this paper. However it may represent an important issue, both at the level of the overall composition of the facade, as well as at the tile level, Symmetry is a delicate matter and is easily broken due to missing padding (narrow elements in the facade schema) which may not be implemented within the matrix structure of the presented approach.

Another important issue is the question of when to use relative or absolute measures at the different levels of composition. By nature, parametric design must be flexible and adaptable to many different situations. The capacity to stretch various elements in the design is therefore indispensable. Yet, it is not always clear which elements in the design should be flexible and which should have fixed dimensions, and the grammar should be able to handle this.

Finally, the issue of randomization which has been only briefly addressed in this paper may hold some potential. Certain elements lend themselves perfectly well to randomization, such as curtains, shutters and other moving parts which in real life may be controlled by the users of buildings. However, given the fact that the ambition of this research is to generate a tool for urban design, capable of simulating distinct morphologies and characters rather than architectural accuracy and detail, randomization may represent an interesting shortcut to variation for some aspects of design.

**REFERENCES**


This article focuses on the use of both shape grammar and space syntax as tools to identify and encode the principles and rules behind the design of low-income housing in Brazilian context. The idea is to use such rules as part of a methodology for analyzing quality space in social housing plans and aims to understand to which attributes of contemporary society redefine certain patterns of familial social conduct, particularly their ways of living and how these attributes impact housing spatial patterns.

**Keywords:** shape grammar, space syntax, design methodology

**INTRODUCTION**

The problem of housing in Brazil was accentuated from the second half of the twentieth century due to the territorial explosion of cities and the deterioration of urban and social conditions. The intensification of the Brazilian housing problem made it urgent to debate the need for new solutions for social housing (SH), with focus on increasing quality at affordable costs.

The Brazilian housing deficit is estimated in 6,068 million households in 2014, of which 83.9% are located in the urban area, according to the Ministry of Cities (Brazil, 2014). The ‘My House, My Life’ Program (PMCMV) was created in March 2009 as one of the initiatives of the Brazilian government to supply the search for housing, stimulate civil construction, generate jobs and combat the economic crisis. Although widely disseminated throughout the country, the PMCMV presents several problems such as standardization, lack of service to the needs of the residents, and not completely solving the demand for quality SH in Brazil.

Facing this reality, it is possible to perceive that the production of national SH reveals a link to the modernist logic of standardization of typologies, defined for the “medium” Corbusian man, thus determining the way of designing and constructing housing from the twentieth century to the present days. The architects of the industrial era were faced with the problem of responding to the demands of the masses, made up of different users with different needs. However, the modernist strategy for this issue was to use an “ideal” or “medium” user model as the basis for designing home appliances from dwellings.
Thus, one of the advantages proclaimed by standardization and repetition indefinitely referred to the economy of time and intellectual work, since designing all possibilities individually, in response to the real differences of the users, demanded tome and bigger budget for development and execution of the projects (Mitchell in Duarte JP, 2007).

The contest “Houses for everybody - National Public Contest of Architecture Project of New Typologies for Housing of Sustainable Social Housing” was launched in March 2010 by the Housing and Urban Development Company of the State of São Paulo - CDHU and organized by the Institute of Architects of Brazil - IAB, Department of São Paulo. The objective of the contest was to present new solutions to the Brazilian housing problem, seeking to increase the quality of housing developments of social housing in Brazil, the contribution to improve the typologies for SH, especially considering diversity, flexibility, sustainability and adaptability, in addition to seeking new conceptions of market professionals, typological patterns to enrich the technical company aiming at a more human and multiple city in its urban form and content. (CDHU 2010).

The criteria used to evaluate the projects, as published on the IAB-SP website were as follows (IAB 2010):

1. Implementation in the field - verification of the possibilities of field implementation of the proposal, considering: morphology (accommodation to the natural profile of the terrain), geographic orientation and climate;
2. Needs Program - creativity, objectivity and clarity in its service; attention to the areas required for the various environments and recommended volumes;
3. Building Legislation and General Standards - attention and compliance with building legislation in effect in the city of São Paulo;
4. Accessibility - compliance with general legislation providing for facilities for people with various physical disabilities; integrated solutions and harmonics with those used by other users;
5. Constructive technique - structural system; building and special building systems; buildings system; between the systems and technical elements of the architectural complex; criterion and logic in the choice of general specifications; effectively necessary and justifiable finishing materials; fire design and facilitation of scape in the event of an accident; economy and feasibility.
6. Environmental Comfort - natural ventilation lighting, thermal load reduction and acoustic protection systems; artificial lighting systems;
7. Harmony and proportion of the architectural ensemble;
8. Contribution to technology, sustainability and ecology.

The housing typologies were organized into six categories: “ground houses”, “terrace houses”, “two floors houses”, “three floors buildings”, “four floors buildings” and “six and seven floors buildings”.

In view of the foregoing, the projects awarded 1st and 2nd in each category represent, in theory, good design solutions for SH, thus constituting a rich object of study for the development of better design solutions for Brazilian SH (Mendes 2014). Thus, an Analytical Shape Grammar was developed as a methodology to understand the social housing’s compositional logic, using those projects as a corpus.

OBJECTIVES
Adopting a structuralist perspective, this research aims to develop a methodology for the analysis of SH.
projects for the generation of parameters that guide new design solutions with varied typologies. For this, the theories of Shape Grammar (Stiny and Gips 1970) and the Social Logic of Space (Hillier & Hanson 1984) were used as theoretical references.

Grammar, in turn, was developed as a methodology to understand the compositional logic of social housing. And its formalism was employed aiming the analysis.

**PROCEDENTS**

The Shape Grammar (SG), developed in the early 1970s by George Stiny and James Gips, consists of a rule-based form generation system that originated in the generative grammar of the linguist Noam Chomsky (1957) and the system of Production of the mathematician Emil Post (1943) (Celani et al. 2006).

Shape grammars are a system of algorithms developed to generate and understand graphical compositions through direct computation, with makes use of forms, replacing indirect computation that uses texts or symbols, and can be defined as both generative and descriptive. This methodology of composition elaboration is formed by a set of rules that, step-by-step, give rise to a set of compositions that belong to the same language or style (Knight 2000).

In architecture, analytical grammars have been elaborated primarily to describe or analyze historical styles or language used by architects, for it starts from something already ready for rule-making. Synthetic grammars, in turn, depart from the rules inferred in analytical grammar for the generation of a set of objects, in this case dwellings, with similar configurations. Among other applications of synthetic grammar, they are used to generate spatial arrangements of residential plans which has resulted in more variety of alternatives (Mendes, Celani and Beirão 2015).

Duarte (2007), for example, used the grammar initially for analytical purposes, in order to describe the projects of the patio houses in the social housing of the Malagueira in Évora, Portugal - project developed in the 1970s by the Pritzker-prize architect Álvaro Siza. This is an important reference for the present research because it allowed to define a generative system to create custom houses that belong to the same language. Different combinations of the inferred rules allow to generate the existing houses and the new projects, that even different from the originals maintains the quality established by the criteria of the contest (Mendes, Celani and Beirão 2015).

**DESIGN METHODOLOGY**

The present work was made using the shape grammar as method of analysis of the corpus (winning projects of the contest) and space syntax (Hillier & Hanson 1984) as a method of evaluation of both the corpus analyzed and the projects generated by the grammar.

The analytical shape grammar was developed to understand the logic of the awarded projects in the contest, to recognize and infer rules or design patterns (Alexander 1969), and to generate, in an original way through synthetic grammar, new projects that present characteristics of design quality of the analyzed houses (corpus). Rules inference is intended to grasp the logic underlaying the project, in other words, to describe in rules the reform patterns identified in the projects.

Space syntax shows that social organization presents spatial content and vice versa, and in this spatial organization is possible to find patterns that determine a spatial configuration of the plant noticed through relational attributes. From this configuration, it is possible to understand the impact of the same in the human behavior and are generated accessibility conditions that give rise to a hierarchical spatial differentiation.

The theory of Social Logic Space is used to evaluate and verify if the new projects generated from the grammar present similar characteristics to the competition.

Through the space syntax methodology, the projects warded in 1st and 2nd, and the projects generates by the grammar were analyzed using the Jass.jar program as a tool through the convex maps
generated through the plants. These were analyzed for integration measures calculated by Real Relative Asymmetry (RRA). In this way, justified graphs were generated from the distribution of labels on the convex spaces of the same socio-spatial sector and linked according to the flow and connection of each environment, determined by the modern domestic sectorization based on Amorim (1997, 1999) that are: social, intimate, and service spaces, as well as the mediating space.

Based on the analysis of the projects of the “Housing for Everybody” contest, a methodology was defined to define the rules of composition of the plants. First of all, we sought to define the vocabulary of forms, that is, to identify a finite set of primitive forms that made up each project. Thus, it was sought to work with two-dimensional forms, since what was interesting was to analyze the categories of the contest mentioned. From the definition of the vocabulary of forms, the compositional rules were defined for each case study.

The main operations used to determine the rules used in the composition of the analyzed dwellings were: rotation, mirroring and addition of forms. Based on the organization of the information and the design of rules, it was noted that the projects suggest proposals that prioritize the flexibility of spaces, rationalization of the construction and typological diversity. [figure 2]

For the development of the rules, it was based on the analysis of each plans of the winning projects of the competition, simplifying the environments of the houses to a closed polygon, without thicknesses of walls, doors or windows. From this, the SG rules were inferred based on the winning houses of the contest, that is, the SG rules have the property of generating the own plans of the winning projects.

From the inference of the rules, it was possible to understand which rules were most used for the corpus generation. Some of the most frequent rules, being these rules of type A -> B (finding A, replaced by B), were the rules that when finding a bedroom, add circulation; when finding a bedroom, add a bathroom; when finding a circulation, add a living/dining room; when finding a circulation, add a bedroom; when finding a living/dinning room, add a kitchen; among others.

The spatial syntax is of extreme importance in

![Figure 2](image-url)

3 of the awarded projects analyzed. House 1, ground house; house 6, terrace house; and house 9, two floors house.
this step, since it evaluates with greater property
the relation between the corpus and the generated
houses. With the rules ready, it was verified that they
had the capacity to form the corpus and it was possible
to start the derivations, thus generating four new
houses. For the generation of the new houses, the
most frequent rules were used in corpus generation,
since these rules are the most comprehensive and
objective for the creation of new plans.

The similarity between the corpus and the gen-
erated houses is present in the configuration of the
plans, in the design language and in the intention of
the project. The configuration of the plans is simi-
lar in the houses of the corpus and in the houses of
the derivations in terms of the positioning, connec-
tivity and quantity of the SH environments. In most
corpus houses and in all the generated houses the
access is through the living/dining room and this
environment connects with the kitchen and circula-
tion; the circulation connects to the bedrooms and
the bathroom, and in some cases the bedroom and
bathroom are directly connected to the living room;
the kitchen connects to the service area. Both the
corpus and the houses generated by the SG have a
living/dining room, a kitchen, a service area, a bath-
room, 2 or 3 bedrooms, and some have a balcony or
courtyard and area that allow future extensions. [fig-
ure 3,4,5]

DISCUSSION
The accessibility analysis, which is done by making
the connectivity between the adjacent spaces in the
plant and seeing the relationship between them,
showed that in 3 of the 4 derivations (75%), the most
integrated spaces are spaces belonging to the so-
cial sector, and 1 of the cases (25%) is a circulation
that is considered a mediating space between sec-
tors. However, in 100% they are free circulation en-
vvironments. While the more segregated spaces, the
service area is shown as 1 of the results obtained
(25%) and another was a courtyard of derivation 2
(see graph 11 - figure 6) that is an even more reclusive
space because its access is made exclusively by
the service area, which is one of the most segregated
spaces of a house.

By making an analysis of the visibility, which is
done through the connectivity of the environments
that are seen from a certain room, and comparing it
with the analysis made regarding accessibility, a cer-
tain degree of difference is noted. This difference
means that the ‘depth’ - the measure that determines
the depth of the spaces in the houses - generates
more compact graphs for visibility than for accessi-
ibility in 100% of cases.

This difference in accessibility and visibility anal-
ysis exists because most of the time the field of vision
easily encompasses multiple spaces - it comprises the
area where a person is able to capture visual stimuli
without moving the head, that is, the area covered by
the vision (Leme 2003), while to get access to certain
places it is necessary to overcome obstacles and to
go through other rooms.

After all the analysis of the houses generated by
the grammar, the 9 samples of the winning projects
were resumed. It is noteworthy that although the
plants of the derived houses are different, the results
obtained were similar among themselves and to the
awarded projects.

The spatial configuration was also studied graph-
ically through sector justified graphs. It is possible to
verify that in 11 cases (84.62%) there is possibility of
having access to the house through the social sector,

Figure 3
Example of
derivation of a new
housing generated
by inferred rules.
Derivation of one winning project in the contest, which composes the corpus. Being house 1, example of the ground houses.

4 projects created from the generated SG.

Graphs generated from the houses studied.
and topologically, the intimate sector is the furthest in 84.62% of the houses. [figure 6]

When looking at the image above, it is verified that there is also no pattern among the graphs and that in most cases the sectors are not well spatialized which generates graphs with several labels of the same sector scattered and with greater topological distance.

It is possible to verify this argument when comparing graph 5 of the original projects with the 10 and 11 of the derivations, for example, in the latter the sectors are better distributed because they are more united and each area of the house is well defined. Because it was a contest, and probably did not require any standard room layout, participants were supposed to use the freedom they had to devote more to exploring plasticity than functionality, so we find houses with no well-defined areas with regard to sectorization.

CONCLUSION
This research arose from the problematic of the Brazilian housing deficit and the criticism of the main characteristics of housing developments built in Brazil. The proposals of the CDHU/IAB competition stimulated the research, since they are considered by experts as good solutions for SH. The personalization of the housing unit is the objective of this research, contributing to the development of housing projects, in response to standardization of types, monotony and repetition of existing housing developments.

The shape grammar created allows the generation of new projects of social housing more diversified, personalized and that incorporate the characteristics of the winning projects of the contest analyzed. The SG created has great potential to generate different housing plans, with principles of flexibility and adequacy to the needs of its inhabitants.

After using grammar and syntax as tools to identify and codify the principles and rules behind social housing projects in the Brazilian context, it was possible to analyze qualitatively the space. In addition to understanding what the attributes of contemporary society redefine some patterns of family social behavior, their ways of life and how these attributes impact a dwelling.

It is noticed that there is a repetition of the results in the analyzed measures of the integration and the graphs. The typical Brazilian way of living segregates the sectors in the housing. The private and service sectors are restricted to dwellers; visitor, commonly, are restricted only to social environments, because they are more controllable. By means of space syntax and perceptible how social relations can be expressed through the spatial formation of housing.

Daily activities are linked directly to his segregation and habits often determine what each environment is. For example, resting does not require as much privacy as sleeping, so it is more common to sleep in the bedroom and rest in the living room; and in many homes, it is possible to see great integration of spaces because of the varied functions performed. Thus, is seen that the traditional way of living defines the distribution of space.

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A shape-grammar for double skin facades

A basis for generating context sensitive facades solution

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Double skin façade (DSF) is considered one of the best envelope systems in terms of energy efficiency. However, designing an energy efficient DSF system depends on different factors, such as climate, DSF shape and how the air flows in that system. This study presents a methodology to assist design decisions regarding the DSFs shapes. For this purpose, shape grammars was used as a generative design system to generate alternative DSF shape designs. Results of this study can be integrated with an energy simulation tools to calculate the energy demand of each design and consequently design the most efficient DSF system for each context.

Keywords: building envelope design, double skin façade, generative design system, shape grammars

INTRODUCTION

In developed countries, energy saving is a high-priority concern. Therefore, an extensive set of energy-efficient measures and features are being increasingly implemented in all areas. The building sector is not exempt from this concern as it is responsible for an important part of the overall energy consumption in the world. One of the most important methods of energy saving in a building is to carefully design its façade. A ‘double skin façade’ (DSF) is considered one of the best options in managing the interface between the outdoors and the indoor spaces. It also provides some architectural flexibility to the design. Recently, it has attracted more attention as an alternative solution to the more traditional glazed curtain wall. This is due to its ability to efficiently reduce energy consumption, which decreases building operation costs. The amount of energy saved depends on the climate and on the selected design. The specific configuration of DSF systems can vary, but generically these systems consist of few basic parts, including exterior glazing, interior glazing, and the airflow cavity between them, where shading devices are usually placed (Uuttu 2001). The design of the DSF involves decisions regarding on different parameters such as geometric parameters, glass selection, ventilation strategy, shading, daylighting, aesthetics, wind loads, and maintenance and cleaning cost expectations (Kim et al. 2013). Combination of these different parameters may result in the creation of multiple types of DSF. The motivation for this research is the need for a system that can present all of the design alternatives, so that it can be used in dif-
different analytical studies (e.g., energy analysis or cost analysis).

This paper aims to use shape grammar as a methodology to assist designers in the design of DSFs. In this study, two of the most common ways of classification of DSFs (i.e., based on geometry of the air cavity and on ventilation mode) are used as a basis to develop a shape grammar, capable of generating alternative DSF designs. The results can be integrated with energy simulation to calculate the energy demand of each design and ultimately results in selecting the most efficient DSF system for each context.

PRECEDENTS

Double skin façades

The term double skin façade (DSF) covers a wide range of façade systems and types from narrow fully sealed assemblies to systems with fully operable external louvers or shading devices (Arons 2000). Although different definitions of DSFs exist, the basic concept is a façade system that is comprised of an external and internal glazing system separated by a ventilated cavity hosting an operable blind or shade. The main advantage of DSFs is the greater control that they provide over the thermal/fluid exchange between the perimeter zone and the outside environment (Doebber and McClintock 2006).

According to Author and Pollard (2000), there is no accepted standard for grouping or defining the different types of DSF. The literature reviewed in their report found multitude ways to classify them. Some of the most popular methods for classifying DSFs are based on the geometry of the air cavity, as well as on the ventilation mode. For instance, Compagno (1999) provided a comprehensive review of
DSF and stated that double-skin façades can be divided into four categories based on the geometry of the air cavity: building high double-skin façade (multi-story window), story-high double-skin façade (corridor window), box double-skin façade, and shaft façade, as shown in Figure 1.

Loncour et al. (2004) added an additional type of DSF to the above typology called the louvers façade. Recognizing the advancements made in the industry over the years, Knaack et al. (2014) further developed this typology with two additional types: alternating façade and integrated façade. It is notable that some of the types of DSFs mentioned are quite similar with small differences, which was not in the scope of this study, so they were considered to be in the same category. There are also some other classifications based on the ventilation mode of the DSFs and the airflow pattern, as shown in Figure 2. Airflow pattern describes the air movement into and out of the cavity, which is considered the main difference between double-skin façade and single-skin façade. The three modes of airflow include outside-ventilated, inside ventilated, and hybrid ventilated (Arons 2000).

**Performance-driven generative design**
Shape grammars and other generative and parametric design tools can affect architectural design in early stages of the design process. These tools can predict the design solutions by analyzing and optimizing early design alternatives through parameter control.
There are several examples of using generative/parametric design tools in order to assist design decisions that have been made with different purposes. Monks et al. (2000) applied optimization techniques to a generative acoustics simulation system through an interactive approach of acoustic design. Shea et al. (2005) used a preliminary integration of a generative structural design system (eifForm) and Generative Components through the use of XML models. Caldas (2008) used GENE_ARCH, which is an evolutionary-based generative design system assisting designers to achieve energy-efficient and sustainable architectural solutions. For this purpose, she combined a genetic algorithm (GA) as the search engine with the DOE2.1E building energy simulation software as the evaluation module. Moreover, Granadeiro et al. (2013) integrated shape grammars as a generative envelope shape design, parametric design, and energy simulation to calculate the energy demand of each design solution, hence, assisting designers in decision making in early design stages.

**METHODOLOGY**

In this study, shape grammars was used for encoding and developing a generative design system. According to George Stiny who co-created the concept of shape grammars, shape grammars are systems containing an initial shape and transformational shape rules. By applying shape rules to the initial shape recursively, a set of shapes that are part of the same family or belong to a certain style can be generated.
Therefore, in this study it was attempted to develop a grammar for DSFs by:

- Analyzing the selected classification of DSFs (based on the geometry of the air cavity as well as the ventilation mode);
- Extracting the rules that are embedded in the structure of DSFs based on the aforementioned classifications;
- Applying those rules to the initial shape (in this study the initial shape is a single pane window that is considered as a baseline) to generate all design possibilities.

The grammar
As already mentioned, there are four main types of DSF based on the geometry of the air cavity: box windows, shaft windows, corridor windows, and multi-story windows. Moreover, in this study three main air flow patterns (i.e., Outside-ventilated, inside ventilated, and hybrid ventilated) were combined with different types of air cavity geometry to produce twelve different types of DSF system. These different classifications of DSFs are depicted in Figure 2.

In generic terms, a grammar is a production system that consists of “if-then” rules. Geometric operations-translation, such as rotation, reflection, and scale can be applied to match the “if shape” of the rule to a shape in the evolving design, and substitute it for the “then shape”. In shape grammars, rules can be potentially applied an infinite number of times (Granadeiro et al. 2013).

In order to extract the rules from available DSFs, we started with a single pane window as the initial shape (from which all DSFs were generated) and tried to re-create all possible air cavity geometries, step by step. It should be noted that, as the section of the DSF system is the best view to describe the details and differences of the various DSF configurations, the extracted rules were defined in this view. Figure 3 presents the extracted grammar rules base on the geometry of the air cavity and different air flow patterns.

In the first step, the air cavity boundaries are created by applying rules 1 to 6, thereby creating the geometry of the air cavity. These rules recreate different types of interior and exterior glazing system (single pane or double pane), the vertical partitions position, and the pivot point of the interior window. Rules 7 to 31 define different configuration for the openings in the interior and exterior glazing systems. Rules 32 to 50 describe the possible direction of the air flow in each of the created air cavity geometries. Figure 4 shows some of the derivations of DSF designs using the proposed grammar rules.

In the next stage of our research, to explore the potential of the proposed shape grammar-based methodology for designing DSFs, we considered a case study. As shown in Figure 5, this case study was a DSF system formed by 4 by 5 modules, totaling 20 modules. Each of these modules, has two different
sections (section A-A, and section B-B) and the proposed shape grammar rules can be applied to each of these sections, independently. Different design variations for one module were generated as discussed in the next section.

RESULTS
The results of the study indicated that, based on the rules extracted from existing DSF designs, there are 20 different design variations for section A-A and 27 design variations for section B-B. Some of the design variation of section A-A and B-B are illustrated in Figure 6. As a result, there are 540 (20 x 27) different design possibilities for each module in the DSF.

Considering that each of these 20 modules could approximately have the same number of design possibilities, the potential of using this methodology in the design of appropriate DSF designs for different contexts is clear.

SUMMARY AND FUTURE WORK
In this paper, we propose a shape grammar-based methodology to assist designers in the design of DSFs. The development and application of the shape grammar is based on two of the most common ways of classification of DSFs (i.e., based on geometry of the air cavity as well as ventilation mode).

For future work, this design system can be implemented as a parametric design system, and coupled with other analytical tools to search for the design solution with best performance for a given context. For instance, it can be coupled with Ecotect and SAP SE to find the solution with the least energy consumption. In this scenario, different design solutions produced by the shape grammars can be analyzed in different contexts with regard to their energy consumption. The outcome of this study, provides a framework for decision making in early façade design stages.

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Santa Marta Urban Grammar

Towards an understanding of the genesis of form

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The research presented here aims to understand how spontaneous occupation in informal settlements evolves, how to develop guidelines for the requalification of these settlements, and how to plan new settlements in similar conditions. This paper focuses on the use of a parametric urban grammar as a methodology to describe the complex urban form of informal settlements, explaining how buildings and pathways create the maze-like urban structure, how different building typologies are located according to internal and external forces like topography, and urban context and functional organization of these buildings.

Keywords: Santa Marta, informal settlement, shape grammar, urban grammar

INTRODUCTION

Informal settlements are present all around the world and it is estimated that nearly one billion people are living in such settlements, (United National Human Settlements Program, 2015) characterized by spontaneous urban occupations as a result of fast urban growth (Davis, 2006) and lack of resources. Although the relative number of people living in informal settlements decreased between 1990 and 2010, the absolute number during the same period increased from 650 to 800 million. Addressing how to improve the living conditions of these people is an important Millennium goal set by the United Nations to be reached by 2020. (United National Human Settlements Program, 2015) Informal settlements have problems related to poor housing quality, overcrowding, inadequate access to safe water, inadequate access to sanitation and other infrastructure and insecure residential status (United National Human Settlements Program, 2015) but they are a fast and economic answer for the lack of housing.

The goal of the research is to understand how informal settlements occupy the urban space, spontaneously evolving over the territory, define guidelines and a methodology to requalify informal settlements and plan new settlement in similar conditions. As a prior step to define a general methodology applicable to all informal settlements, the study focuses on a specific case study located in the south area of Rio de Janeiro and called Santa Marta, which evolved over a steep topography and near a prime area of the city.

The research encompasses the following five stages: (1) Creating a digital model of the case study based on a photo site survey (Verniz et al, 2016); (2) Creating a virtual model that allows remote access to the case study; (3) Creating a computational model that explains the existing urban occupation (analytical grammar); (4) Development of a shape grammar to requalify the case study (requalifying grammar); (5) Development of a shape grammar to design new settlements on sites with similar spatial properties (design grammar).
The work described in this paper focuses on the development of the analytical grammar with the aim to explain how the maze-like structure of Santa Marta evolved, creating a complex urban morphology out of buildings and pathways.

STATE OF ART
Santa Marta is located on Dona Marta hill and it can be considered an example of how informal settlements coexist with formal cities in Brazil, providing the workforce with housing near the workplace. The hill’s occupation started in 1924 when a priest built some houses to shelter workers from the construction site of Santo Ignacio’s High School. The place grew fast after the American Great Depression in 1929, which affected the Brazilian coffee economy and induced an intense urban exodus. Many farm workers then migrated to the city, becoming security guards, factory workers and housekeepers. (Meirelles and Athayde, 2014).

This research is based on previous work on the development of housing and urban grammars that addressed the problem of creating a grid to generate housing layouts and urban plans following grammar rules (Stiny and Mitchel, 1978; Andrew Li, 2001; Beirão and Duarte, 2005). As informal settlements are not planned, the agglomeration of building into a grid is not easily identifiable, although it does exist. As such, we considered that a bottom up approach would deliver a better result.

Duarte et al., (2007) presented an urban grammar for the Marrakesh Medina, an ancient fabric that grew spontaneously over time, resulting in a complex urban form that express social conventions and physical conditions. Subsequently, Barros et al. (2013) described the structure of Mozambican slums and Dias (2014) explained how buildings expanded over the time in Rocinha, the biggest Brazilian slum. The steep topography of Santa Marta makes it a unique and innovative case. Figure 1 shows the Santa Marta’s plan and indicates the three entrances, where the informal settlement communicates with the formal city.

METHODOLOGY
The methodology used to infer the analytical grammar was divided into three steps. The first step was the identification and classification of the different polygonal shapes that represented the buildings. This work was based on a map of Santa Marta provided by the municipality, complemented by the results of the photo survey. The second step was the analysis of the urban topology, identifying building clusters and pathways between them and inferring the rules to locate buildings. The third step was to find the relation between the shape of the buildings and external and internal forces, understanding the factors behind the complexity of such shapes. In this last step, it was inferred rules to distort basic quadrilateral building shapes and the sequence in which the grammar rules should be applied.

In the first step, buildings were separated according to use into two groups. The first group included housing and commerce and the second one, temples, planned social housing, public squares and sport fields. The first group represents the informal building production and it was used to develop the grammar. It included 1011 buildings, which were further classified according to n, the number of sides in their polygonal shapes with $4 \leq n \leq 11$, and the type of shape, convex or concave.

In the second step, urban topology was identified and seven rules were inferred. They define the location of a new building, considering a previous one as a reference.

In the third step, the urban structure and the building configuration were analyzed to understand the internal and external forces that influenced the building shapes. The maze-like formal structure of Santa Marta is a result of these forces:

- Topography, which is an important feature in the majority of informal settlements in Rio de Janeiro. The rough terrain in the region works as a barrier to the growth of the formal city, which tends to occupy flat or slightly sloped surfaces, preferable for construction than steep ones, leaving these areas empty for
Figure 1
Santa Marta’s chart.
Figure 2
Decision-making flow chart.
occupation by the informal city. Although informal buildings are not planned, they tend to follow the topographic contour.

- Urban context, as the placement of buildings is influenced by existing buildings, formal and informal, as they constrain accessibility, the ease of construction, and the perception of safety.
- Functional organization, as it constrains how buildings are shaped and sized.

These forces are the reason why buildings in Santa Marta have a potentially complex polygonal shape. In addition, the complex network of pedestrian pathways is not planed but a result of circulation needs. On the east side of the settlement there is a cable train that provides for public transportation to the upper parts of the hill, but this was introduced much later and has not influenced the existing urban morphology.

The growth of informal settlements is spontaneous and the goal is for buildings to occupy all the available space, taking into account the scarcity of resources and security issues. (Alexander, 1973, David Gouverneur, 2015) Santa Marta’s building aggregation was analyzed and rules were inferred to explain its emergence and growth. Our work followed a bottom-up approach similar to the work on the Marrakesh Medina (Duarte et al, 2007) where buildings and circulation emerge as a result of the process to occupy available space. However, while in the Marrakesh grammar circulation is defined first and buildings are placed afterwards, the Santa Marta grammar works the other way around, with buildings defining sinuous pathways.

Santa Marta has a specific urban configuration that is delimited on the South by the formal city, on north by the top of the hill, on east by a private property, and on west by a national park. This characteristic creates a dense, steep and confined urban space. To solve the complex configuration of Santa Marta, Figure 2 shows the decision-making flow to define the order in which contextual forces should be taken into account. The first, Topological context indicates the way buildings inside the informal city relate to each other, in terms of location and circulation between them. Topographic context indicates the way that buildings inside the informal city relate to the terrain. Urban context indicates the way buildings inside the informal city are shaped based on what is already built in the formal or informal city. Topological context expresses the way a building’s internal functional logic influences its shape.

Topographic and urban contexts are the main forces and the order in which each is applied depends on the location of the building. As Santa Marta has well defined bounds the urban context predefines the alignment of buildings that are closer to its limits. As occupation expands, moving away from the limits, topography becomes more influential in the alignment of buildings. As buildings are not predesigned, in the process of locating, it is first assumed that they have a quadrilateral shape and then, functional organization plays its roles, giving the building its final shape.

**Urban Grammar**

The initial shape is a polyline representing the side borders of an existing street. Existing buildings represent the limits of the formal city and are placed on each side of the street, represented by polygons. Topography is depicted by contour lines, represented by gray polylines.

The vocabulary of shapes includes: the initial shape; quadrilateral polygons representing buildings; dashed lines that represent the circulation midline (streets or pathways); and circular labels that emphasize the nodes of building polygons.

Figure 3 shows the set of rules proposed for locating buildings. The Santa Marta urban grammar encompasses eight parametric rules. The first seven of these rules define the location of a new building. Each rule addresses a different urban topology and in all the building is as a quadrilateral polygon. The eighth rule adds sides to the initial quadrilateral polygon and at this point the building being located has its basic shape defined.
Figure 3
The set of rules for locating and modifying houses.
Figure 4
Generation of a six-sided polygon from a quadrilateral by recursive application of Rule 8.

Figure 5
The partial derivation of the south-west entrance of Santa Marta.
Figure 4 illustrates how a six-sided polygon can be generated following the application of Rule 8. To generate a n-side polygon, Rule 8 should be applied n-4 times.

The growth of the informal city starts close to the formal city, utilizing resources that are already available, such as existing access pathways and walls, minimizing the use of resources, particularly space and materials, thereby generating a very dense urban fabric. The growth of Santa Marta started from three different places, all located at the border of the formal city where three streets end and from where it is possible to access the place: two at the bottom and another at the top (Figure 1). Figure 5 shows the growth of zone of Santa Marta from its Southwest entrance by recursive application of shape grammars rules (Figure 3).

CONCLUSION
This work presents the preliminary version of a shape grammar to describe the complex urban form of informal settlements in steep locations, using a particular settlement in Rio as a case study. So far, we have inferred rules to explain the buildings’ locating and shaping processes. Key to the definition of the grammar was identifying the topological relations between buildings and pathways, and between adjacent buildings, as well as recognizing the influence that factors like topography, urban context, and functional organization have on site occupation. Proposing an adequate decision-making flow was an important step to explain the existing complex urban form urban as a result of the interplay between such factors, which are depend the specific location of the buildings. The option to use a parametric quadrilateral polygon representing buildings, that is positioned and then shaped was crucial to avoid the need for a set of rules for each n-sided polygonal building. Future steps in the development of the grammars are concerned with the inferring of new rules to explain the generation of other public spaces, such as squares and stairways.

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A Shape Grammar of Emotional Postures

An approach towards encoding the analogue qualities of bodily expressions of emotions

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This paper is concerned with the translation of analogue qualities of human emotions into digital readings. Human body postures are considered as one of the main behavioral conduits for non-verbal communication and emotional expressions (Shan et.al., 2007). This research is the first step towards identifying and detecting emotions through posture analysis of users moving through space; leading towards generating real time responses in the form of spatial configurations to users’ emotions. Such spatial configurations would then help inhabitants reach certain emotional states that would enhance their life quality. In order to achieve this goal, we propose a methodology for developing a comprehensive shape grammar algorithm that could evaluate and predict bodily expressions of emotions. The importance of this study lies under the embodied interactions (Streech et.al., 2011) in space. As the circumfixed space impacts the embodied mind, the body impacts its surrounding including the architectural space.

Keywords: Shape Grammar, Computation, Emotion, Posture, Interactive Architecture

BACKGROUND

In their paper Abreu et. al. (2009) discuss architecture as a composer for melodic behavior; an arranged sequence of movements and feelings called a gesture. “The subject-person is induced to a sort of slow dance movement by the melody architecture plays [...]. A place produces a complex of motions and emotions in the subject” (Abreu and Esteves, 2009). Abreu calls this complex of motions and emotions “gesture”. A gesture caused by architecture could be comprehended for its meaning- emotions. Gestures then become a universal and shared basis for further interpretation: not only to understand the meaning of a work of architecture, but architecture’s impact on human psychology and emotions.

In an empirical study by Abreu (Abreu, 2017) the impact of architecture, specifically a church, on the gestures of its visitors has been experimented. Focused on a sequence of walking and gazing, they use multiple strategies such as eye-tracking glasses, heart beat trackers, and semi-manual GPS trackers to trace the visitor’s gestural response as they face
the church’s environment. However, their work does not exceed beyond the understanding of shared patterns among visitors and individual expressions have not been studied beyond walking patterns in space. In this case, bodily expressions of individual visitors could have been studied through postural behavior in order to evaluate emotional responses of each individual, subject to experiencing space. In other words, postures are representations of certain emotions that if studied, they could have been implemented in the evaluation of each inhabitant’s perception of space.

In another work, Heinrich et al., propose a methodology in order to measure people’s responses to the qualities of certain buildings (Heinrich and Wurzer, 2016). This method however, is limited to surveys and indirect evaluation of architectural qualities. The direct interpretation of bodily expressions in the architectural space and the evaluation of postural behavior could be a method that would complete, or rather, validate their measurement of the perceived architectural quality.

Stepping beyond architectural evaluation, bodily expressions of emotions can help architects to design spaces that would change their properties in accord to the psychological needs of the individual inhabitant. In the work done by Motalebi (Motalebi, 2017), a computationally actuated sitting area has been designed that changes shape in response to the gestural behaviors of those sitting on it (Figure 1). At this point however, this design has yet to appropriate its actuation based on the variety of postures and the psychology of gestural behavior of the inhabitants. Today on one hand, the technology exists to design and manufacture actuated environments, while on the other hand, the gestural behaviors of the inhabitants have been merely studied and implemented in defining such actuations. There still remains space to apply the psychology of gestural behavior into the design of actuated environments in order to achieve what is known as “interactive architecture” (Fox and Kemp, 2009).

As the first step to fill this gap, we propose the use of shape grammars as a tool that goes beyond the design of architectural elements towards incorporating behavioral factors into the design process. Shape grammars can help us identify the characteristics of the bodily postures and expressions that compose the properties of the architectural space. As architecture shapes movements, and movements shape architecture, the postural understating of human behavior could lead to appropriating the architectural space for those behaviors.

Postural studies relate to the semiotics of human behavior (Eco, 1976), (Radford, 2003). Thus meanings cannot be generalized to postures across cultures. However, there are certain postural habits that have been studied and identified as universal (Hewes, 1955). The postural behavior of each person in different architectural contexts, while it can be based on personal and contextual preferences, could...
indicate an emotional behavior (Wallbott, 1998). A vast number of researches have used worked on using computational devices for postural analysis and emotion evaluation such as (Clavel et al., 2009), (Coulson, 2004) providing proof to this claim. However not many have integrated design and design processes into their technology for emotion detection. Knowing such technology exists, it is time to integrate user behavioral analysis with the design of architectural spaces that could adjust their qualities to users’ emotional state. Next section is dedicated to presenting a methodology for incorporating bodily expressions of emotions with a descriptive shape grammar that could be used as a computational tool for the design of architectural spaces.

METHODOLOGY

Today machine learning algorithms are developed towards image recognition and visual search (Pannaman, 2016). There are techniques that would train the computer on the user’s emotional gestures and behavior with a 98 percent accuracy (Behoora and Tucker, 2015). In their paper, Behoora et. al (2015) use skeletal joint data inferred from the user’s body language to read live time emotions. However, these techniques are mostly limited to a high level representation of raw data from the user’s body postures. Predicting, simulating, and generating responses to the collected data are usually condened. This research proposes shape grammars for their high level visual analytic and generative power as a tool to incorporate behavioral analysis of the users with architectural design as a creative process. As to demonstrate this power, this paper uses shape grammars to generate variations of bodily expressions; to not only detect emotions from body postures, but to simulate certain emotional postures and define descriptive responses for the analogue qualities carried by those emotions.

By generating a shape grammar of emotional postures, we can exceed beyond a quantified detection of emotions to a descriptive qualification of postural behavior. In the context of description grammars (Garcia, 2016) we will integrate posture recognition with a descriptive labeling system (Stiney, 1980) in order to simulate, predict, and generate emotional responses to the user’s emotions. In other words, we argue for implementing empathetic behavior in computer systems with such methodology. Followed by the implications of postural detection of emotions, the shape grammar of bodily expressions of emotions are presented and discussed.

Shape Grammars, as a visual calculating system are based on shapes and shape rules. Rules are repeatedly applied on any given shape to generate new forms and shapes based on specific transformations. Shape Grammars work closely to the eye and the visual qualities of any 3D shape (Stiney, 1980), suggesting that they can be used to calculate body movements, postures, or in other words motions and hence emotions. However, the use of shape grammars has been mostly limited to shape generation for arts, design, architecture, and so on. Shape grammars allow symbolic calculation of shapes, where shapes are infused with ambiguity (Stiney, 2006). Even though calculation is inherently in oppose to ambiguity, shape grammars leave the space for calculating qualities that were not originally thought of.

For this, shape grammars seem to be the appropriate tool for calculating the analogue qualities of human behavior; to not only analyze human behavior based on visual postures, but to predict, generate, and simulate the behavior of an embodied mind. The importance of such system lies in its integration with design where shape grammars have already proven to be useful. As soon as the analogue qualities of human behavior is translatable into digital readings, it will be possible to train digital systems that would directly interact with their human subjects in different scenarios. In the case of this paper, we focus on embodied emotions and the shape grammar of emotional postures. In order to design systems that interact with the emotional behavior of their users, we needed to start from understanding such behaviors using the shape grammar tool. Next, we will demonstrate how shape grammars were used to specify some emotions based on postural studies.
The Shape Grammar of Emotional Postures

In this paper, a shape grammar of emotional postures is proposed in which emotions are assigned to different layers of bodily movements based on a psychological study by Wallbott (1998). The grammar itself functions similarly to a human movement simulation tool previously investigated by Maria Piedade Ferreira (2011). Adding emotional qualities to certain postures, the rules and parameters that define the grammar are more confined. The initial shape represents the standing position of a human body. Based on the skeleton data, the body joints are numbered for the description and application of the rules of the grammar (Figure 2).

The rules extracted from Wallbott’s study are then developed to generate series of variations for different emotional postures and behaviors. Every stage of the grammar represents a set of emotions. By applying more rules to the outcome of each stage, the emotions become more specific. Figure 3 demonstrates the grammar for simulating Elated Joy in three different views in the Cartesian system: Frontal, side, and plan view. The applied rules and the description of each stage follows a specific structure. For instance, to achieve a position for Elated Joy, rules 1 to 4 must be applied as below:

- R1: Upper Body Erect / Possible Emotions: Cold Anger, Hot Anger, Elated Joy, Interest, Pride
- R2: Shoulders Up Center in 3: Rotate until joints make an angle between 0 and 90 with the X axis: 10, 10’ / Possible Emotions: Hot Anger, Elated Joy
- R3: Head Backward Center in 2: Rotate until joints make an angle between 0 and 90 with the Y axis: 1 / Possible Emotions: Elated Joy
- R4: Arms Outward Center in 10: Rotate until joints make an angle between 90 and 180 with their drop down position with the X axis: 11, 11’, 12, 12’, 13, 13’, 14, 14’, 15, 15’
- If: R1->R2->R3->R4 Then: Elated Joy

In this description, first the joint number as the center of rotation is identified. Consequently, the action is specified following the joint numbers which the rule will apply to them.

Figure 3 is part of a more complex system of posture generation and emotional evaluation. This grammar is capable of describing any number of pre-identified postures. Figure 4 demonstrates a bigger scale of posture generation that narrows down cer-
The postural grammar for “Elated Joy”. By applying four rules to the initial shape, we can achieve the posture that represents this emotion. In this example, elated joy, sadness, cold anger, hot anger, interest, pride, disgust, contempt, despair, fear, terror, shame, and boredom are the identified emotions. The rules can differ for different parts of the body which as a result concludes to specific emotions.

By focusing on the body joints, we have defined a clear representation of body movements which are understandable and can be used as high level representations to be implemented in visual search APIs and machine learning algorithms. As a first step towards achieving this goal, the code above has been used in a Processing code for Kinect using the built-in Skeleton Library (Figure 5). The same visual algorithm can be further developed for designing simulations of postural emotions and to be used for interactive systems. A very good example is the use of such visual algorithms for designing human-robot interactions. Nonetheless, architecture can use the same algorithms in different contexts for the design of actuated and interactive environments; capable of responding to human emotions based on their postural movements in space.

Developing such environments necessitates taking the first step towards translating analogue qualities of human behavior into digital readings. Posture recognition as a more convenient method for emotion analysis could then be integrated with other sensorial data inputs such as galvanic responses (Kurniawan et al., 2013), EEG readings (Soleymani et al., 2016), facial expression recognition, and so on for more accurate behavioral data. However, posture recognition has the advantage to allow the inhabitant to move freely in space, as the first medium for spatial perception. It is for the future steps to build up the way towards developing environments capable of understanding their inhabitants more accurately and adapting to their needs accordingly. One example of such developments is expanding the design for “The Ephemeral Dreamspace: (Re) Activating an Evocative Architecture through Computational Devices and Bodily Interaction” (Motalebi 2017) to not only react to positions, but adapt itself to detailed postural behaviors.
Figure 4
The Shape Grammar of Emotional Postures
CONCLUSIONS
A shape grammar of bodily expressions of emotions has been developed to be used as a high level representational tool for evaluating, predicting, and simulating different emotional states. Implementing the logic of shape grammars in visual search algorithms helps training systems that can not only detect emotions from gestures, but will help the system to simulate the emotional behavior and define appropriate responses for such emotions. The importance of this approach lies in developing technologies that would consider human psychological responses in different situations. These technologies can vary from robotics, web interfaces, and architectural spaces that detect and interact with their user’s emotional behavior. Today researchers are trying to study empathetic behavior and ways in which spaces can empathize with human emotions in order to help the inhabitants in overcoming emotional difficulties in times of stress, anger, and so on. We hope that this research can be further developed and implemented in the design of interactive environments in which physically actuated environments change their properties based on the emotional and psychological need of their inhabitants.

CONTRIBUTIONS
The generative abilities of shape grammars would help designers to not only predict, but to generate responses in accord to the inhabitant’s emotions. The implementation of shape grammars in computational algorithms can be used as a tool for architects and designers for implementing human emotions in their designs for interactive environments. In addition, shape grammars can be used for the study of human behavior and implementing them into the design process and education. Shape grammars can exceed beyond shape generation towards incorporating behavior analysis of the users of space and how it affects the design outcome.

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PhotoAR+DR2016

Integrating Automatic Estimation of Green View Index and Augmented and Diminished Reality for Architectural Design Simulation

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Urban vegetation has been used to tackle architectural and urban problems by reducing urban heat islands and improving the quality of urban landscapes and biodiversity. The green view index provides end users with a metric to intuitively understand the vegetation scenarios. This study integrates a green view index estimation method and augmented reality (AR) and diminished reality (DR) scenes of future architectural and urban design simulations. We developed the AR/DR system "PhotoAR+DR2016 (photogrammetry-based augmented and diminished reality)" that simultaneously measures the green view index and simulates building, urban, and planting designs with addition, demolition, and removal of the objects such as structures. The developed system enables real-time measurement of the green view index by appropriately reducing the image size and extracting the green area. Using the developed prototype system, the on-site verification can be conducted; in addition, the processing speed and the accuracy and inaccuracy rates can be measured, and the green view index can be sufficiently measured in real time.

Keywords: Green View Index, Landscape assessment, Design support system, Diminished Reality, Augmented Reality, Image analysis

INTRODUCTION

Urban vegetation has been used to tackle architectural and urban problems by reducing urban heat islands and improving the quality of urban landscapes and biodiversity. The quantification of urban vegetation using metrics such as the green coverage ratio and green view index is important for stakeholders in order to motivate increases in vegetation and to simulate the amount of vegetation required in a design process (Shafer and Brush 1977, Aoki 1987). Specifically, due to technological developments and the diffusion of green walls, the green view index has received increasing attention (Almazan et al. 2012). Local governments exists that set green view index as one of the landscape criteria for new construction and extension or reconstruction of buildings [1].
The green view index provides end-users with a metric with which to intuitively understand vegetation scenarios (Yang et al. 2009). One of the conventional measurement techniques is to determine the vegetation percentage per viewpoint using image processing software applications. In this technique, after taking photographs from representative viewpoints, the natural green areas in the images are manually selected. However, this technique is time consuming and is subject to large variations in the amount of time required to process different images. Therefore, researches on automatic measurement of the green view index has been reported. Komiya and Susaki (2015) proposed a methodology to estimate a green view index in urban areas using airborne LiDAR and aerial photographs. This method efficiently estimates a wide range of green view index; however, it is difficult to measure hedges and wall greening with low depth. A method to measure the green view index by analyzing landscape images acquired by Google street view (GSV) was proposed (Li et al. 2015, [2]). However, GSV images are captured at a certain point in time; therefore, it is difficult to obtain the green view index for other times. In addition, this technique is not practical for dynamic viewpoints, such as gathering continuous data on visible greenery while walking or driving. Ding et al. (2016) proposed an automatic estimation system that can exclude certain unwanted objects (such as the reflection of trees in windows) using Gaussian blur, mean shift, hue, and saturation filtering functions based on image processing technology. However, real-time processing was impossible.

This research tackles a method for real-time estimating the green view index using image processing. This research also integrates a green view index estimation method and augmented reality (AR) and diminished reality (DR) scenes of future architectural and urban design simulations. AR integrates the 3-D virtual objects of design proposals into an existing 3-D environment in real time (Milgram and Kishino 1994). Specifically, AR can help visualize full-scale design projects on a planned construction site (Gudrun et al. 2001). However, the use of only existing AR approaches cannot correctly simulate the view after the demolition and removal of the structures. If new structures are simulated while an old existing structure is still present, a 3D virtual model of the new structure will overlap the existing to-be-renewed structure. As a result, a portion, if not all, of it will still be visible and displayed. To solve this problem, DR removes the image of an existing object from a scene (Enomoto and Saito 2007, Inoue et al. 2016). In this way, possible future changes in vegetation can be visualized in an AR/DR environment by adding planting design models.

AUTOMATIC ESTIMATION OF GREEN VIEW INDEX USING IMAGE PROCESSING

Our proposed method aims to realize real-time processing for the automatic estimation of the green view index by extracting natural green pixels in landscape images (Figure 1). In this study, an algorithm with six steps is developed and implemented using OpenCV (ver. 3.0.0) on Microsoft Visual Studio 2013 (C/C++): (1) input target image; (2) reduce the image
size using bilinear interpolation; (3) apply Gaussian blur, mean shift (Cheng 1995), hue (40, 180), and saturation filtering (0.2, 1.0) (Ding et al. 2015); (4) calculate the number of pixels extracted by filtering; (5) calculate the green view index; and (6) restore the image size using bilinear interpolation.

In order to identify the optimal combination of these parameters, a parameter study was carried out as follows. First, a combination of arbitrary values for each parameter was studied for a representative image. Next, based on the results, the search ranges of each parameter value were further narrowed down and the optimum combination of the parameters was identified using a full search. The criteria for the optimum combination are an accuracy rate of more than 85%, a calculation time of less than 0.0667 seconds (15 fps), and a minimum inaccuracy rate.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set values (Test search)</th>
<th>Set values (Full search)</th>
<th>Optimum solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction ratio</td>
<td>5-100 (pitch: 5)</td>
<td>5-29 (pitch: 1)</td>
<td>20</td>
</tr>
<tr>
<td>Gaussian kernel size</td>
<td>1-103 (pitch: 8)</td>
<td>1-29 (pitch: 2)</td>
<td>5</td>
</tr>
<tr>
<td>Spatial window radius</td>
<td>1-61 (pitch: 10)</td>
<td>1-30 (pitch: 1)</td>
<td>4</td>
</tr>
<tr>
<td>Color window radius</td>
<td>1-201 (pitch: 10)</td>
<td>1-120 (pitch: 1)</td>
<td>20</td>
</tr>
</tbody>
</table>

In the parameter study, Figure 2 shows an example of the input image (1200 × 800 pixels) and the output image. With reference to Figure 2, both the accuracy and inaccuracy rates that are the setting conditions of the optimum solution search are explained. First, based on the original image (Figure 2 (a)), a correct image (Figure 2 (b)) was created via a conventional manual method using Adobe Photoshop. Second, an automatic measurement image (Figure 2 (c)) generated by combining certain parameter values and the correct image are synthesized (Figure 2 (d)). Third, pixels extracted in both the correct image and the automatic measurement image are regarded as correct pixels. Incorrect pixels obtained by combining pixels extracted only in the correct image (hereinafter referred to as unextracted pixels) and pixels extracted only in the automatic measurement image (hereinafter referred to as over-extracted pixels) are calculated. Finally, the accuracy and inaccuracy rates are calculated by dividing the correct and incorrect pixels by the correct pixels, respectively. In Figure 2 (d), the yellow pixels, the green pixels, and the red pixels correspond to the correct pixels, the unextracted pixels, and the over-extracted pixels, respectively.
Table 1 indicates the set values in test search and both set values and optimal solutions in full search. In the test search, when the reduction ratio was ≥30% or the space window radius was ≥31 pixels, the combination satisfying the calculation time setting condition (<0.0667 s) did not exist.

In addition, with the Gaussian kernel size of ≥31 pixels and the color space window radius of ≥121 pixels, the accuracy and inaccuracy rates markedly deteriorated.

Therefore, as shown in Table 1, the search range in the full search was set. As a result, the optimum combination was obtained as (reduction ratio, Gaussian kernel size, spatial window radius, color window radius) = (20, 5, 4, 20), respectively.

We applied the optimal combination to the developed automatic estimation system and measured the green view index of live video images. The image size reduction ratio was set such that the image width was 240 pixels. The experimental target was the change in green view index with respect to landscape changes during walking etc. As the important viewpoints, we selected the front of the Techno Alliance building and selected Keyakidori road to the entrance of US1 building in the Osaka University Suita Campus as a walking landscape. The measurement results are shown in Figures 3, 4 and 5 and in Tables 2 and 3.

As result of the experiment, the accuracy rate was 77 to 90% and the inaccuracy rate was 15 to 28%. The green view index by our proposed system was measured less than the green view index by manual operation using Adobe Photoshop. The reasons for these values were that (i) the extraction of thin components such as tree branches and leaves was incomplete and (ii) the shade of the crown could not be extracted due to low brightness. Compared with the results of Ding et al. (2016), the accuracy (85.6%-93.3%) and the inaccuracy rates (11.5%-21.4%) were almost similar. On the contrary, the proposed method has enabled real-time processing.

INTEGRATING THE AUTOMATIC ESTIMATION OF THE GREEN VIEW INDEX AND AR / DR

The PhotoAR+DR2016 (photogrammetry-based augmented and diminished reality) developed in this research is an AR/DR system installed in the real-time green view index measuring module developed in Chapter 2. This system enables simultaneous measurement of the green view index and simulation of building, urban, and planting designs (Figure 6).
The proposed system creates DR scenes from video images acquired by a camera for a post-demolition landscape simulation. As explained in Chapter 1, DR is a technique for removing unwanted objects from a scene by overlaying an appropriate background image on the objects. DR uses computational techniques for tasks, such as estimation of the video camera's position and orientation, computation of the background image, and recognition and tracking of the object. Our method estimates the video camera's position and orientation based on the photogrammetry method. Based on the estimated position and orientation, our method computes the background image of the target area and recognizes and tracks the target. Our method has two main phases: pre-processing and the real-time processing.

In the pre-processing phase, several photographs of the target structure to be diminished...
and background structures that are hidden behind the target structure are necessary as input data. Photographs of the target structure are used to reconstruct point cloud data and estimate the position and orientation of the web camera. Point cloud data of the target structure are reconstructed using the SfM (structure from motion) method (Tomasi and Kanade 1992, Agarwal et al. 2009). From the point cloud data, mask polygons are made, which are used to determine the removal region. The green mesh of the mask polygon allows for the removal region to be clearly distinguished. Additionally, the local features of each photograph of the target structure are extracted and used for image matching. Moreover, point cloud data and the polygon model of background structures are reconstructed from their photographs using the SfM.

In the real-time processing phase, local features, the mask polygon, and the background structures polygon, which are calculated and created in the preprocessing phase, are used as input data. First, local features of a live video image are extracted. The extracted features are compared with the features of stored images, which are calculated in the preprocessing phase. The automatic image matching method finds the most similar image and the position and orientation of the camera for that image are chosen as the current position and orientation of the web camera. By using the estimated position and orientation of the web camera, the mask polygon and back-

Figure 7
Design simulation using PhotoAR+DR2016
ground structures polygon are rendered. The rendered mask polygon determines the removal area. The area of the rendered background structures polygon is overlaid onto the live video image. As a result, the target structure on the live video image seems to be diminished. Then, 3D virtual models can be inserted using an AR function and the green view index can be measured in real time.

To verify the applicability of the developed PhototoAR+DR2016, a pseudo design project was conducted in an outdoor environment. We used a standard spec laptop PC, Panasonic Let’s NOTE CF-SX3TDLTC with Intel Core i7-4500U @ 2.40GHz of CPU, 4.0 GB RAM, and Microsoft Windows 7 Professional 64 bit. A Microsoft LifeCam Studio webcam for Notebooks with a resolution of 1280 x 720 pixels was used. We designed to dismantle the two-storey building of Welfare Hall on Poplar Avenue in Osaka University Suita Campus and plant vegetation around the new building. Then, the green view index of the existing building before the dismantlement and that of the new building and vegetation were compared. The arrangement of the current building and the new building is shown in Figure 7.

By applying AR/DR, it was confirmed that in landscape simulation, the existing structure is dismantled and removed, and that a newly designed structure including vegetation is possible. However, assuming cloudiness, the sky area without a hidden back-ground model is painted with (R, G, B) = (225, 225, 230). After adding a tree model, the visible greenery ratio is increased from 18.5% to 31.3% (Figure 8).

CONCLUSIONS
The contributions of this research are as follows:

- We developed the AR/DR system “PhotoAR+DR2016” which simultaneously measures the green view index and simulates building, urban, and planting designs with addition, demolition, and removal of the structures.
- The developed system enables real-time measurement of the green view index by appropriately reducing the image size and extracting the green area. Using the developed system, the on-site verification can be conducted; in addition, the processing speed and the accuracy and inaccuracy rates can be measured and the green view index in real time can be sufficiently measured.

In terms of future work, the extraction accuracy of the green region that was not properly extracted, e.g., tree branches and leaves and low brightness regions such as the shade of the crown, should be improved. It is also necessary to study the algorithm to automatically learn the optimum combination of many parameters such as AI (Artificial Intelligence). To provide a more user friendly development environment for users, who are not experts in computer science, it is necessary to port the development platform from Visual Studio onto a game engine such as Unity.

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A Parametric Approach To Simulating Use-Patterns in Buildings

The Case Of Movement

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We describe one of the three core use-pattern building blocks of a parametric approach to simulating use-patterns in buildings. Use-patterns are modeled as events which use specified descriptions of spaces, actors and activities which constitute them. The simulation system relies on three fundamental patterns of use - move, meet and do. The move pattern is considered in detail in this paper with specific reference to what we term the partial knowledge issue. Modeling decision making about how to move through the space (what path to take) depends on modeling the actor’s partial access to knowledge. Visibility is used as an example of partial knowledge. The parametric approach described in the paper enables the clear separation of syntactical and semantic conditions which inform decisions and the coordination of decisions made by agents in a simulation of use-patterns. This approach contributes to extending the analytical capability of Building Information Models from the point of view of evaluating how a proposed building design may be used, given complex, interrelated patterns of use.

Keywords: Agent-Based Systems, Simulation, Use-Patterns, Design Tools

INTRODUCTION

The role of computers in architectural practice has been imagined by scholars for at least fifty years. In the early seventies, Nicholas Negroponte imagined computing as revolutionary not just for architectural practice, but the built environment itself (Negroponte 1975). In a still earlier period, Herbert Simon and others took an optimistic view of the computability of human thought, and as a result, concluded that design problems were amenable to computational solutions (Simon 1973). This optimism was challenged from various standpoints such as Horst Rittel and Melwyn Webber’s conceptualization of design problems as ‘wicked problems’ (Rittel and Webber 1973) and the phenomenological arguments presented by Hubert Dreyfus (Dreyfus 1967, 1992).

By the 1980s, a consensus emerged against the computability of design and for the potential of computational process to inform the design process. Bruce Majkowski and Yehuda Kalay made the following distinction between the design process and computable processes. “Design is an ill-defined process
that relies on ill-understood practices such as learning, creativity, and intuition, as well as the judicious application of scientific principles, technical information, and experience. Computable processes, on the other hand, are by definition well-understood and subject to precise analysis and mathematical modeling, which qualify them for simulation by artificial computing devices” (Kalay, 1987, p. 349-350). The role of the computer came to be understood as one which assisted and augmented the designer in architectural design practice.

Building Information Modeling (BIM) has become a mainstream computing technology in architectural design practice over the last 25 years. From a data modeling point of view, the development of BIM can be understood as the design and implementations of new rules and data structures which enable new kinds of systematic analysis. These new rules and data structures are built on the basic building information model in which the building is described in terms of its built elements. These built elements in turn are described as a combination of their geometry (usually in three dimensions) and other attributes (Eastman 1999, Kalay 2004). The overwhelming majority of these systematic analyses involve the physical attributes of buildings such as energy efficiency, acoustic performance and daylighting. Compared to these areas, simulating the use of buildings have proved to be more difficult.

Buildings are typically both expensive and long lasting. Being able to estimate how suitable they will be for expected current and future uses could therefore be considered to be of significant advantage to architects. Currently, advances in modeling and simulating the use of buildings lag far behind advances in fields like energy, thermal comfort, acoustics or light simulation. Simulating how buildings might be used requires models to describe at least three constitutive aspects of use. First, a model of spaces in the building and their inter-connections is required. Second, a model of actors who are expected to use the building is required. Third, a model of the types of things these actors are likely to do in the building is required. Furthermore, these three models have to be developed with reference to one another. Achieving this involves extending existing BIM, which is best understood as a formal description of building elements and their relationships.

**DESCRIBING SPACES, ACTORS AND ACTIVITIES**

Buildings are made up of built elements and the spatial elements defined by those built elements. Orthogonal architectural drawings in a three dimensional isomorphic, infinite cartesian space describe these built and spatial elements non-redundantly. In BIM, both built and spatial elements need to be made explicit. Existing BIM tools do not contain sufficiently detailed models of the spatial elements of buildings. While such capability can be modeled in existing BIM tools, significant conceptual work is required to produce a general model which is capable of simulating complex use-patterns. The figure below (Figure 1) shows an overview of the current state of one attempt to develop such a model. (Schaumann, Date and Kalay 2017, Date Schaumann and Kalay 2017)

The central insight of the approach summarized in the figure above is the concept of an Event. An Event is a co-ordinating entity which defines how one or more actors conduct a complex activity in a set of spaces. The event specifies the conditions required for the complex activity to be possible, the actions involved in the complex activity, and the conditions required for the activities to be considered complete. The complex activity is best understood as some combination of the three elementary activities - move, meet and do - collected in a specific pattern. The complex activity can therefore be considered a use-pattern. At any given time the use of the space is made up of multiple use-patterns which utilize (and share) resources (mainly spaces and actors) (Simeone et al 2013, Schaumann et al 2016). Resource sharing is managed by an event manager (Schaumann et al 2017). The situations to be simulated do not always involve people acting individually. They can also involve people acting in groups from time to time. This
and other well established arguments described by O’Sullivan and Haklay (O’Sullivan and Haklay, 2000) motivate the event based approach.

The model imposes syntactic constraints on the simulation in addition to domain based semantic constraints which exist in the profiles of spaces, actors and events or use-patterns. Space is described as a two dimensional grid of square cells. The cell is the atomic unit of space. Zones, which are contiguous two-dimensional collections of cells, are the smallest logical unit of space. Thresholds, which are one-dimensional collections of cells, connect two zones. An actor occupies exactly one cell at any given point in time. An actor’s personal space can be described in varying degrees of detail in the form of a neighbourhood of the cell occupied by the actor.

The move activity defines the movement of one actor to a specific target location through a search space. The algorithm used to derive the path is a hierarchical adaptation of the A star algorithm (Hart, Nilsson and Raphael, 1968; Botea, Muller and Schaffer, 2004). In the rest of this paper, the move activity - one fundamental building block of the model outlined in this section - is discussed in greater detail in syntactical terms. This paper will not address the semantic aspects of the move activity which can only be discussed in the context of the specific real world use case such as a hospital ward or emergency room or some other example of a building type.

THE STRUCTURE OF THE MOVE ACTIVITY

The move activity defines the movement of an actor through a hierarchically defined discretized space constituted by cells, zones and thresholds. Consider a space consisting of six zones (Z0 TO Z5) interconnected by six thresholds (T1 to T6) as shown in Figure 2. The blue actor positioned in Z0, while the red actor is positioned in Z4.

The path is calculated at two levels. At the first stage, the threshold level path from blue to red is cal-
culated. This results in a sequence of cells, in this case, from the position of the blue actor to a cell in T1, to a cell in T3, to the position of the red actor. Once the location of the first threshold cell to be crossed is thus available, the current zone of the blue actor is searched for the path from the location of the blue actor to the appropriate cell in T1. The purpose of this calculation is to calculate the next available step for blue actor. This mechanism also allows for static and dynamic features of the space which are modeled as spatialized costs to be updated and considered by the search algorithm. The method for accounting for these costs along with the calculation outlined in this paragraph has been described in detail elsewhere. (Date, Schaumann and Kalay, 2017)

This approach raises several questions. For instance, suppose that zone Z2 is unavailable to the blue actor. When does the blue actor become ‘aware’ of the unavailability of Z2? If Z2 is unavailable, this would mean that thresholds T1 and T3 which are attached to Z2 would be unavailable at the level of the threshold search. An alternative path would be returned. This question can be reframed systematically in a problem of partial knowledge. The actor, or the event which is managing the actor’s actions, must contend with the fact that an actor in a given space does not always know everything about the space and makes decisions based on incomplete information. The model must be capable of describing different types of incompleteness in the information.

The logical steps involved in the core move action is as shown in Figure 3. The move action is initiated by the governing coordinating event which provides an actor with a target in a overall search space.
The overall search space is synonymous with the designed architectural space in which the simulation is being implemented. A relevant search space (which is a proper subset of the overall search space) is derived by the coordinating event after applying filters specific to the event. The space is evaluated in two steps within the move event. First, the search space is pruned by filtering it according to the preferences of the actor. Second, the search space is evaluated during the actual path-finding operation, which is hierarchical. As described above, the hierarchical path-finding operation enables evaluation of the search space at the zone as well as cell level. The coordinating event provides instructions to the move action about what to do in case a path is not available. The move action can either be repeated, or failure may be reported back to the event.

The move action is designed to allow an actor to make decisions based on what is known by this actor at this point in time. This partial knowledge in-
cludes elements from the actor’s profile which provide preferences and biases about different spaces in the overall search space. It also includes situational facts about the overall state of the world (as it is constituted in the simulation) at the time step in question.

When applied to the example described at the beginning of this section of the paper three possibilities arise. First, the blue actor could either know that Z2 is unavailable due to this fact being available in its profile. Second, it could become aware of it due to some instruction from the coordinating event. Third, it could become aware of it as a result of its current position and task.

The first case is not a case of partial knowledge, since the actor’s profile is an input to the simulation. In other words, the blue actor’s knowledge about the unavailability of Z2 is not due to any particular situation in the simulation involving either a specific state of the actor or a specific state of the zone or coordinating event. An example of this type of situation would be that the blue actor does not have permission to enter Z2 because Z2 is a private part of the space, while the blue actor is a visitor in the space and not a member of the staff of the space.

In the second case the partial knowledge is managed in the coordinating event, either directly, by providing the move action with filtered search space. Once the coordinating event provides the move action with a search space which does not include Z2, there is no way for Z2 to be considered by the move action without the involvement of the coordinating event. An example of this would be that the coordinating event has filtered out Z2 from the search space available to the blue actor to reach the red actor because there is a meeting going on in zone Z2 which cannot be interrupted or disturbed. In such an instance the blue actor will follow a path which does not require it to pass through Z2 in order to reach the red actor.

In the third case, the partial knowledge is managed by the actor on a timestep by timestep basis by virtue of it position in the world. There is no governing knowledge in the actor’s profile per se which enables clarity about the availability of Z2. For example, consider visibility as an example of partial knowledge. Suppose that visibility is modeled by zone in this simulation model. For any actor in Z0, the visible zones are Z1, Z2 and Z4. Further, suppose that T1 is a wooden door which can be either open or closed. The state of the door affects the visibility from Z0 to Z2. There is no reason to think that the door will remain closed throughout the duration of the blue actor’s quest to reach the red actor in Z4.

This third case creates a potentially intractable situation. Suppose that the door opens and closes periodically. Given that the move action has to reevaluate the path at every time step to check for changes to the world (movement of other people or other developments) which mean that the previously calculated path need not be valid any longer, when the door is open, the path returned by the move action would take the actor through Z2, while, when the door is closed, the path returned by the move action would provide a path which does not involve Z2. In the worst case, the door could open and close in every consecutive time steps, causing the blue actor to keep switching between the two paths (one involving Z2, one not involving Z2).

To avoid this problem, the partial knowledge availability to the blue actor by virtue of being in Z0, and ‘knowing’ that Z1, Z2 and Z4 are visible is used as the governing fact for the transaction irrespective of whether the door in threshold T1 is open or closed. If Z2 is available, then even if the T1 is closed, it is assumed that the blue actor is capable of opening the door when it is reached and the path is calculated as if the door in T1 were openable, if not open. Unless the state of Z2 changes fundamentally, making it unavailable the blue actor, partial knowledge (such as visibility in this case) ensures that the blue actor can evaluate visible zones and make decisions about the next move.

Visibility is one example of partial knowledge. In any reasonably complex simulation, there will be many different types of partial knowledge encoded.
and the evaluation function effectively acts on a composite description of the partial knowledge in given situation for an actor. A change in the state of Z2 while the blue actor is in the move action could result in Z2 no longer being available. This would create a situation in which, as far as visibility is concerned, Z1, Z2 and Z4 remain visible from Z0, but as far as, say social permissions (the idea that a certain class of zone is unavailable to a certain class of actor), Z2 may no longer be available. This composition of different types of partial knowledge is syntactically carried out as a set operation.

It is important to note that the description of the move action in this section is limited to a syntactical description of the action itself. The coordinating event has a syntactical role in the move action by determining the steps to be taken in case the move action does not return a path. Syntactically, the event can pass one of three types of instructions. It can either instruct the move action to keep trying until a path becomes available. Alternatively, it can instruct the move action to abandon the possibility. Thirdly, it can instruct the move action to attempt to complete the move action with a modified set of parameters.

In the move action itself, partial knowledge can be evaluated either in the evaluation function of the action or in the path-finding function. This provides flexibility for the codification and consideration of multiple types of partial knowledge as the examples of visibility and social permissions show. It also enables the codification of different types of partial knowledge.

**FUTURE WORK: THE LIMITS OF PARTIAL KNOWLEDGE**

The description in this section is a syntactical description of the move action. It describes the skeleton of the general action which can describe any instance of a move action which partially constitutes a complex event. Similar skeletal descriptions of the elementary meet and do actions are required. Additionally, syntactical rules for transition amongst these three elementary actions are also required.

However, these syntactical rules are not sufficient to describe use-pattern in a complex space consisting of multiple events, some of which occur according to a prescribed schedule, while others are initiated due to a particular state of the world. For instance, on the way to meeting the red actor, the blue actor could run into a green actor and have an impromptu meeting. This unscheduled event can also be defined using the same syntactical skeleton.

Modeling actors, spaces and partial knowledge requires semantic work which is dependent on the domain of the simulation. For instance, if the simulation involves a busy hospital ward, then semantics specific to hospital wards needs to be codified in the profiles of these elements. Currently, the study of the semantics of hospital wards (in the sense in which the term semantic is applied in this paper) is most advanced in the field of ethnographic post occupancy evaluations of built environments which were developed in the field of environmental design (Cranz 2016, Lindsay and Morhayim 2015). Significant conceptual work is required to derive codifiable domain specific semantics from this fieldwork.

**CONCLUSION**

In this paper we presented a parametric model of the elementary move action within a larger system for simulating use-patterns in buildings. This system can allow designers to estimate how a given design proposal will perform for a given set of use-patterns before the costly and often irreversible task of construction is undertaken. The examples described in this paper have been tested via implementation in a python based game engine known as pygame. The proposed syntactical skeleton of the elementary move action is designed to take advantage of a discretized, hierarchical description of space and a spatialized description of actors. This approach outlines an attempt to build an information model describing the syntax of how people use buildings which can be appended to existing BIM tools in order to extend their analytical capability.
ACKNOWLEDGMENTS
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Luna Moth
A Web-based Programming Environment for Generative Design

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Current Generative Design (GD) tools require installation and regular updates. On top of that, programs that are created using them are stored as files, which have to be moved and shared manually with others. On the other hand, web applications are accessible using just a web browser and they can also store information remotely, meaning that it does not need to be moved and is easily shared with others. Consequently, GD tools should also be available as web applications to get the same functionality. We present Luna Moth, an IDE for GD available from the web that shows the relationship between a program and its results and integrates into the architect's workflow. Then, we give examples where Luna Moth's features help the architect during the programming process. Finally, we compare Luna Moth's performance with other IDEs, namely, Grasshopper, OpenJSCAD, and Rosetta.

Keywords: Generative Design, Web application, Design tool integration,

INTRODUCTION
Generative Design (GD) is a design process that comes partially from the automation of modeling tasks in Computer-Aided Design (CAD) applications using programming. GD uses computers as a new medium for artistic expression (Maeda 2001) that can be used by architects, as shown by Terzidis in Expressive Form (Terzidis 2003). Having a faster and more flexible process for building 3D models allows the architect to explore more variations of a design.

Furthermore, using GD as a new design process promotes a simpler handling of changes coming from uncertain design intents and emergent requirements, which evolve as the understanding of the problem improves or as the project’s needs change (Fernandes et al. 2014). In fact, programs are unambiguous parameterized representations of designs, which only need small changes to parameters or functions to express changes.

Interactivity in GD IDEs
In order to improve the programming process, Integrated Development Environments (IDEs) and Programming Languages (PL) were developed, some of them directly addressing the needs of GD. For example, in Rhinoceros we have PLs like RhinoScript and RhinoPython, and in AutoCAD we have VisualLisp. They allow the architect to access the host CAD application’s functionalities, such as operations to create or transform geometry. These PLs are textual programming languages (TPLs) meaning that their programs are represented as text.
However, the mode of interaction with these PLs and their IDEs leaves much to be desired in the context of GD. The usual interaction with them follows a sequence that begins with the architect writing a portion of code, running the program, waiting for the program to finish running, looking at the generated model, and repeating the sequence until he is satisfied with the result. In this mode of interaction, the architect has no feedback regarding the changes he makes to the program while he is making it. It is not until he finally runs the program again that he gets the outcome. Given enough time between runs, he may start to miss the details that changed, which will make it harder to make sure the program does what is intended.

IDEs like Grasshopper for Rhinoceros and Dynamo for Revit tackle this problem by running programs continuously while changes are made. This allows the architect to immediately see their effects, which, in turn, allows him to make corrections as soon as he finds that the results are not what he intended. Moreover, while testing his programs, the architect can use tools like sliders to control input parameters and see the effects of changes almost immediately. Apart from this, these IDEs use visual programming languages (VPLs) where programs are represented graphically by connecting functions, represented by boxes, with wires that represent the flow of data from one function to another. As such, they can be seen as more intuitive for beginners.

Unfortunately, these IDEs quickly lose interactivity as programs grow. For bigger programs, sliders lose immediate feedback since the program takes too much time to run, which makes architects give up using sliders and, instead, change parameters textually. This performance problem comes both from the complexity of the GD program, which can make running times grow beyond the limit for immediate feedback, and from the way CAD applications are implemented, since they were designed to handle human interaction and not the volume of operations generated by GD programs. Solving the first cause might require the use of more efficient programming models and techniques to keep program complexity down, while the second can be alleviated by implementing dedicated visualizers to avoid using a CAD application entirely, e.g., an OpenGL viewer (Leitão et al. 2014).

Apart from improving performance to allow for better feedback, IDEs can make it easier for architects to understand programs. A program is a rather abstract representation of the design and it can be hard to understand what each part of it is intended to represent, even more so when it grows in complexity. One way to make programs easier to understand is to include documentation with them. As pointed out in Illustrated Programming (Leitão et al. 2014), architects already make sketches to help them formalize their design into a program which can serve as documentation. Therefore, the IDE should allow sketches to be part of programs. The work in (Ferreira 2016) went a little further by improving the perception of the relationship between sketch and program. In addition to documentation, it is also easier to understand programs with traceability as also pointed out in (Leitão et al. 2014), that is, being able to trace an element of the 3D model back to the parts of the program that created it. The opposite direction, from a part of the program to the parts of the 3D model, is also helpful. Unfortunately, GD IDEs that support traceability have limitations. Dynamo and Grasshopper only support it in one direction, from program to model, while Rosetta (Lopes and Leitão 2011) sup-
ports both directions but is too slow even for small programs.

Figure 2
An example of numeric parameter adjustment. Clicking and dragging changes the value of the parameter.

Web applications
The web has seen a big increase in popularity, which has become even stronger by the standardization of web technologies, such as HTML5 (Hickson and Hyatt 2011) and WebGL (Marrin 2011), which allowed web applications to achieve user experiences on par with desktop applications. In addition, as web applications run on remote computers, they are always accessible without installation or updates. This has led to the creation of many web application counterparts of common desktop applications. For example, office productivity tools, like Microsoft Word, Excel and PowerPoint, have seen the appearance of their web application counterparts such as Microsoft Office 365. Furthermore, 3D modeling web applications and CAD web applications have also appeared. One example of the first is Clara.io (Houston et al. 2013), for 3D modeling and animation, and one regarding the second is OnShape [1], for Product Design/Engineering. Moreover, these web applications can save information remotely, which removes the need to transfer files between computers, and they can also support collaboration over great distances.

Closer to GD, experimental web applications have also appeared. One example is OpenJSCAD [2], for 3D modeling with Boolean operations using a TPL, and another is Möbius (Janssen et al. 2016), for 3D modeling using node- and block-based VPL. However, they do not have functionality for remote storage nor for collaboration found in the previous web applications. In addition, they also lack features that help understanding programs found in the GD IDEs from the previous section.

Goals
As mentioned in the previous section, web IDEs for GD are still lacking features that make them suitable for practical use. A modern GD IDE that addresses the previous problems needs to: (1) have good accessibility, being available on any computer with internet access and without requiring installation and updates; (2) be interactive, letting architects explore GD easily, giving them feedback and showing the relationship between program and results; (3) integrate easily with the CAD applications already used by architects, so that they can combine their GD experiments into their normal workflow.

In this paper, we present an experimental IDE, Luna Moth, a HTML5/JavaScript-based web application that harnesses the performance and graphical capabilities of modern web browsers and that can connect to the other CAD applications used by architects. Using Luna Moth, architects can write their GD programs, visualize the results without being chained to a particular computer, and can easily integrate results into their normal workflow.

We can summarize the structure of the paper as follows:

- We describe Luna Moth’s interface for creating GD programs, which makes use of immediate feedback and traceability mechanisms.
- We describe the way Luna Moth integrates with other design tools used by the architect.
- We show how Luna Moth’s features can help the architect during the programming process.
- We compare Luna Moth with OpenJSCAD, Grasshopper, and Rosetta by measuring the times for running programs and displaying their results.
LUNA MOTH OVERVIEW

User interface

Luna Moth’s editing interface consists of a source code editor (A) and a 3D view (B), as can be seen in figure 1. Apart from the main editing area, the interface also includes panels for managing programs (creating, opening, and deleting)(C) and for connecting Luna Moth to CAD applications (D).

The 3D model displayed in the 3D view is kept in sync with the results of the program in the source code editor, providing immediate feedback to the architect. Whenever program changes, Luna Moth re-runs it and regenerates the 3D model. Moreover, Luna Moth also includes something akin to sliders to change numeric parameters. As such, instead of having to change the individual digits of the parameters, the architect can click and drag on parameters to change them. Figure 2 shows an example of use of this functionality.

The interface also makes it possible to understand which parts of the 3D model were created by an expression of the program by pointing at it. Like-
wise, it is also possible to go the other way, pointing at any part of the 3D model to know which expression created it. By letting the architect go both ways, the interface facilitates the understanding of the relationship between program and results – see figure 3.

Figure 6
Correction of protrusion from depending on the column to depending on the row.

Figure 7
Increasing the wall’s length by clicking and dragging.

Figure 8
Clicking on an apparently wrong 3D element shows the function that created it.

Programming Language
Regarding the programming language used to write programs, Luna Moth supports the JavaScript TPL. We chose a TPL since, as described in (Leitão et al. 2012), although VPLs are more intuitive, they do not scale well for big programs. When visual programs grow in complexity, they become big nets of inter-connected nodes that are hard to understand and modify. On the other hand, textual programming languages have mechanisms, like functions, that allow architects to create abstractions that hide how a certain task is performed from the rest of the program. As such, architects can create the rest of the program without worrying about all the details of each part, thus, focusing their attention on higher-level concepts. For example, creating a roof in a 3D model does not depend entirely on how the support below is created; both tasks share parameters, like the shape of the building, but they are otherwise independent from a 3D modeling perspective. Consequently, these can be packed in different functions. Afterward, they can be used in another part of the program without knowing their details.

We assume that someone using Luna Moth is at least comfortable with using TPLs, which can require more study upfront when compared to VPLs. Nonetheless, the initial investment quickly pays off since it is easier to adapt programs to accommodate more changes, given the increased flexibility of TPLs.

Workflow Integration
A GD IDE can only have a significant impact in the design process if it can integrate into the architect’s workflow. This is typically supported in GD IDEs by exporting to a common file format which is recognized and/or required by other tools. Instead of exporting, Luna Moth connects to the CAD application and, then, generates the model from scratch there. To achieve the connection with other design tools, Luna Moth uses the software architecture shown in figure 4.

To use this functionality, architects have to run the Rosetta Remote Service on their computer, which lets Luna Moth know which design tools exist on that computer. Afterward, they select the desired design tool in Luna Moth and start the connection. Then, Luna Moth uses Rosetta Remote Service to generate the results of their program directly in the design tool. As such, when they reach the desired solution, they can then connect to a design tool, such as Au-
toCAD, to generate drawings or render the solution with higher detail – see figure 5.

This intermediary step is necessary since there are no other means for web applications to know which applications exist in a computer. However, it does require the architect to run something on his computer in addition to the web browser, which goes against the principle that the web browser is the only software needed to use Luna Moth. Still, this is only true when the architect wants to connect Luna Moth to his design tools. The rest of the time, he can use Luna Moth without a problem with just a web browser.

As the Rosetta Remote Service uses Rosetta (Lopes and Leitão 2011) to connect to design tools, Luna Moth can connect to design tools other than AutoCAD. Due to recent extensions to Rosetta (Feist et al. 2016)(Leitão et al. 2017), Luna Moth can also connect to BIM and analysis tools, such as Revit and Radiance.

RESULTS AND REFLECTIONS

Programming Experience

As mentioned earlier, Luna Moth supports a TPL and keeps the view of results in sync with the current version of the program. In this section, we give examples of how Luna Moth can help with the development of a program.

Suppose an architect wants to create a façade composed of bricks. He created functions to make a straight grid of bricks and wants to control how much each brick is protruded. He decides that the protrusion should depend on the brick’s position in the façade, i.e. its row and column. As Luna Moth has immediate feedback, he sees how each change affects the resulting façade. As such, if he wants the protrusion to increase as the row increases and starts changing the program to make it happen but, instead, makes it depend on the column, he will see that the result is wrong immediately. In this case, he can just as quickly correct the bug, as seen in figure 6.
After correcting this bug, he may want to tweak the code’s numerical parameters to make the wall more or less steep. He can adjust those parameters by clicking and dragging them. The same goes for the number of bricks horizontally and vertically, in which case, the architect may want to see the effect on a bigger or lengthier wall (Figure 7).

In another situation, consider that an architect is developing a program that creates a model in separate parts, for example, a building skeleton with columns, slabs, and stairs. In this situation, he may notice that some columns are not appearing in the right locations, therefore, he can use Luna Moth’s traceability, pointing at one of them to be directed to the function that creates it (Figure 8). From there, he can start to examine the function to understand why it is creating columns in the wrong location. Furthermore, the architect can also use traceability to find the remaining columns created by that function and check whether they are also incorrect. This time, he uses traceability in the reverse direction, from program to results.

In the same way the architect clicks on the model to get to a function that is not producing the right results, he can also do this to find a function that he wants to experiment on.

**Examples**

In addition to the previous examples, we also implemented other examples that can be seen in figure 9.

**Performance**

As part of the evaluation of Luna Moth, we also compared the running times of programs in Luna Moth with the running times in other IDEs, namely Grasshopper, OpenJSCAD, and Rosetta.

For each program, we measured the running times in Luna Moth not connected to design tools, in Luna Moth connected to AutoCAD, in Rosetta connected to AutoCAD, in OpenJSCAD, and in Grasshopper connected to Rhinoceros. Each IDE has a different programming language. Like so, we implemented each program using each IDE’s programming language. These times can be seen in the chart from figure 10.

These measurements show that, when disconnected from other design tools, Luna Moth can run programs faster than Rosetta, OpenJSCAD, and Grasshopper, sometimes by one or more orders of magnitude. This tells us that Luna Moth can provide faster feedback to changes to programs compared to the other IDEs.

On the other hand, the measurements also show that, when connected to AutoCAD, Luna Moth is slower than the other IDEs. Nonetheless, this is explained by taking into account the communication time between Luna Moth, Rosetta Remote Service, and the connected design tool, and the time that the design tool takes to execute the desired commands. Nevertheless, this functionality is aimed to be used when the architect has already developed a program, in which case, it is used only once, therefore, fast feedback is not as important. This also means that Luna Moth is not connected to other design tools most of the time spent during the development of programs, consequently, it can be considered faster than the other IDEs.

**CONCLUSION**

As collaboration in architecture projects occurs between further and further apart teams, they have to use better ways of collaborating remotely. Web applications provide a possible path for supporting that collaboration. As such, design tools also have to make such collaboration possible. However, current GD IDEs were not designed with this collaboration in mind. Apart from that, a GD IDE also needs to
be adapted to architects so that they can understand and modify programs quickly. Moreover, the GD IDE must integrate into the architectural workflow, embracing the tools that are typically used in it.

With this in mind, we created Luna Moth – a web application that supports the programming task by providing immediate feedback to changes, a way to change parameters intuitively, traceability between a program and its results, and that also integrates into the workflow of the architect. In the paper, we showed an example of use of Luna Moth where we explained how the included features included help in the programming process. Lastly, we compared Luna Moth with other GD IDEs in terms of running times. Luna Moth performed better than the others when running programs by itself. On the other hand, when connected to other design tools, Luna Moth got slower than the others. In spite of this, Luna Moth is only expected to be connected to other design tools when the architect has already developed a program, meaning that it is faster than the other IDEs throughout most of the programming process.

Future work will focus on improving editing experience with features such as illustrated programming, code completion (and help in knowing the library of available functions), better code navigation, and further exploration of traceability. In addition, we plan to improve the performance of running programs when connected to other design tools and to add support for remote collaboration.

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[1] https://www.onshape.com
A Simulation Model for Logical and Operative Clash Detection

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The introduction of the Building Information Modeling (BIM) approach has facilitated the management process of documents produced by different kinds of professionals involved in the design and/or renovation of a building, through identification and subsequent management of geometrical interferences (Clash Detection). The methodology of this research proposes a tool to support Clash Detection, introducing the logical-operative dimension, that may occur with the presence of a construction site within a hospital structure, through the integration of a BIM model within a Game Engine environment, to preserve the continuity of daily hospital activities and trying to reduce negative impacts, times and costs due to construction activities.

Keywords: Construction site, Hospital, Game Engine, Gaming, Building Information Modeling (BIM), Simulation

INTRODUCTION

The aim of this research is to propose a tool to support Clash Detection, introducing the logical-operative dimension, through the integration of a BIM model (Building Information Modeling) within a GE (Game Engine) environment.

Prior to the introduction of the BIM approach into the design and/or renovation of a building, a considerable amount of imperative documents was drawn up, checked and validated separately for each sector, by one or more specialists, without any strict implementation of sector-wide cross-checking revision, and then sent directly to site for execution.

The spread of BIM has facilitated multidisciplinary project model management by enabling identification and subsequent management of interferences (Clash Detection) (Eastman 1992). Through Clash Detection 3 kinds of geometrical interference can be determined:

- **Hard clash:** clashes between 2 or more elements;
- **Clearance clash:** element A may/may not intersect element B, occurring at a lower distance than the tolerance (e.g. Due to overheating two elements must be placed at a determined safety distance);
- **Duplicate clash:** two elements have the same geometry and are placed within range of tolerance. If the tolerance is zero, they occupy the same position.
Management of detected interferences is usually simplified through chrome-classification as such:

- **New**(RED): interference identified for the first time through a new test;
- **Active**(ORANGE): interference identified in a previous test, not yet resolved;
- **Reviewed**(BLUE): previously identified interference, manually tagged as detected;
- **Approved**(GREEN): previously identified interference, manually approved;
- **Resolved**(YELLOW): previously identified interference now resolved.

Analysing the building context of renovations and/or maintenance of complex structures and directing more focus towards those obliged to maintain different daily activities functional e.g. hospitals, greater care must be taken with interferences that are not strictly tied to the geometry, or rather those that are not detectable via Clash Detection carried out by today’s BIM software.

In fact, in this case, not being solely limited to detection of interference between technical elements lends an operational-logical dimension to Clash Detection, through identification of interferences between technological elements and localised activities.

The presence of construction sites inside these structures adds different elements of complexity, such as noise, vibrations and dust, generating interference for daily activities due to negative impacting determined by the surrounding environment and actors involved (Zhang 2013).

**STATE OF ART**

Noise risk evaluation is a technical process that, through knowledge of known noise levels present affecting the production process object to evaluation, accomplishes risk reduction/control by adopting specific organisational and procedural technical measures.

European regulatory approach (UNI EN ISO11690-1:1998), within healthcare structures, defines the environment’s soundproof characteristics, the background noise and the exposure levels. Establishing how long the noisiest equipment will be in use is essential considering it may only take a few minutes to exceed acceptable levels of exposure (LEX) to 80dB(A).

Healthcare site environments, depending on their intended use (e.g. A&E, operating theatres, laboratories), necessitate specific acoustic requirements; therefore, relative noise-exposure problems mainly concern healthcare staff and patients, compromising quality and efficacy of healthcare services offered more so than the actual risk of auditory damage.

For each hospital environment, an internal noise limit is provided, as proposed by Professor J. Van den Eijk in the early 1970’s. In 1986, the Italian Ministry of Health supplied the following internal noise limits: 35dB hospital rooms, 40dB connection zones, 45dB nurses room and physician offices, 50dB operating theatres and delivery room, and external outpatient clinics or general service areas 55dB. These values refer to noise limits, expressed in dBA, allowed only from 7:00 to 19:00, the time span during which construction works are carried out. UNI 8199-1998, then replaced by UNI 8199-2016, provides for a more detailed classification and a reduction of about 5dB, as shown in Table 1. (G. Uguccione 2005)

<table>
<thead>
<tr>
<th>Environment</th>
<th>Noise limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>hospital rooms</td>
<td>30 dB(A)</td>
</tr>
<tr>
<td>wards</td>
<td>40 dB(A)</td>
</tr>
<tr>
<td>operating theatres</td>
<td>35 dB(A)</td>
</tr>
<tr>
<td>connection zones</td>
<td>40 dB(A)</td>
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<tr>
<td>visitors area</td>
<td>40 dB(A)</td>
</tr>
<tr>
<td>general service areas</td>
<td>40 dB(A)</td>
</tr>
</tbody>
</table>

Concerning dust particle risk, however, it is internationally agreed to adhere to a proactive approach in accordance with the proposed classification system by the Canadian Center for Infectious Disease Prevention and Control, which frames site activities -both
maintenance and ex-novo construction—within hospitals, according to these categories (D'Alessandro et al. 2007):

- Type-A: Non-invasive activities and inspections which will not generate dust or construction work on walls and ceilings (e.g. on water and electric systems, suspending operation less than 15 minutes)
- Type-B: Brief activities generating low dust emissions (e.g. on wall and water systems, suspending operation less than 30 minutes)
- Type-C: Partial demolition/removal activities (e.g. false ceilings, electrical wiring chases, water systems, suspending operation more than 30 minutes but less than 60 minutes)
- Type-D: Significant demolition/reconstruction (e.g. new construction, water systems, suspending operation longer than 60 minutes).

This classification has been revised to enable site activity development without suspending hospital services.

In recent years research has been geared evermore towards the possibility of integrating BIM models and simulation environments (Game Engine) as support for architects, engineers and social educators, making an interactive and 360° immersive experience within the model possible, to the point of including accessibility tests and fire evacuation drill simulations (Yan et al. 2011).

The use and relative development of BIM technology have made possible the exemplification of continual maintenance and refurbishment management in a hospital keeping with an accurate monitoring of financial resources aimed to lower costs.

For this reason, healthcare owners and industry partners created the Healthcare BIM Consortium (HBC) in order to favour interindustry cooperation between software vendors, designers, builders and consultants to support the increase in data interoperability for the Facility Life Cycle Management.

Utilising a BIM 6D model, other than taking into consideration time and costs, the entire lifecycle of the hospital can be monitored. Currently, the BIM model can be integrated with real-time infrared localisation in order to allow medical instrumentation tracking directly within the 3D model, therefore facilitating its successive outplacement (Linehan and Andress 2013).

**METHODOLOGY**

As previously mentioned, cost reduction in both trial and management for the refurbishment of complex structures such as Hospitals is crucial.

Forecasting potential risk factors in the preliminary planning stage allows for negative-impact reduction, on present actors and environment, and avoidance of resource waste and/or additional costs incurred. Regarding noise issues, for example, many feasible though often overlooked interventions are low cost when done in the planning stage.

Given this premise, the proposed methodology of this research is founded on one hand on the BIM, aiming to identify in the initial site planning stages the spatial and environmental units involved in the refurbishing and/or maintenance activities, and on the other on the GE, in this case Unity3D, which utilises the BIM model to generate an environment to reproduce and verify physical phenomena and user behaviour simulations.

Contextual analysis and Logical and Operative Clash Detection is defined by 6 stages:

**Identification and modeling of the environment and technological components of the building in BIM**

The large quantity of information characterising a complex building, in this case a hospital, is made available because BIM facilitates their exchange and interoperability. These characteristics, geometric or not, all collected and managed by a database (e.g. Excel, MS Access) represent the information structure of the scenario at the base of the final stage of simulation.
Starting from the premise that the BIM model of the hospital, in this case modelled with Autodesk Revit, refers to an existing and functioning hospital, each parameter, characteristic of the architectural elements (e.g. Sound Insulation Capacity, see Table 2) or the space constructed by these (for example, the Rooms label, or rather the differentiation of environments within a ward) can be managed by defining and modifying categories and families directly within the aforementioned model.

This information is extracted through Autodesk’s Dynamo software (see Figure 1) that allows to collect them in a comma-separated values (CSV) database, in this case in Excel. The hospital or department, or rather the simulation scenario, is modelled directly into Revit assuming it has been constructed in accordance with best practice and that problems had been resolved, at the design stage, for example those related to lateral or structural noise transmission.

**Definition of Work and associated quantitative risk analysis**

The data inherent each construction site activities are managed via either database implemented by other validated database, measurements or technical literature data. This research the attention has been focused on 3 specific parameters: Noise quantification, Dust dispersion and Vibration quantification. The first parameter refers to the amount of noise produced by each single construction site activity (e.g. Concrete mixer LAeq 80,3dB(A), Rotary hammer-drill LAeq 97,7dB(A)). The second parameter, on the other hand, concerns the dispersion of the dust produced by different construction site activities relating to the...
level of risk where they are classified, as reported in the Qualitative Risk Matrix (see Table 3) (Moscato et al. 2007). The last parameter taken into consideration in this research is the amount of vibration produced by the equipment used to carry out some work activities.

**Identification and classification of the type of risk factors based on required project maintenance operations**

For example, noise risk factors are attributable to:

- **External Sources:** transmission occurs through building perimeter walls or the concerned internal environment;
- **Technical Systems within the building:** noise can travel through the structure;
- **Functional activity equipment:** either construction site or hospital related;
- **Anthropics:** from human voices to impacting noises related to human behaviour.

Environments exposed to excessive noise could induce fatigue and consequently cause distractions and errors in daily activities, whilst sudden noise in work situations requiring extreme concentration could cause involuntary reactions. The identification within the Revit model of the different typologies of hospital environments and the subsequent cataloguing in an Excel database allows us to classify these environments according to, for example, the maximum noise levels allowed. These values allow a qualitative simulation of environments exposed to acoustic impact.

**BIM model integration within the GE environment**

The decision to import the BIM model (Revit) within the GE environment (Unity3D) is dictated by them compatibility and easiness of reading in FBX format. Additionally, once integrated, the model can be added directly to the virtual environment, extending the BIM representation from its Static level (Revit) to Dynamic (Unity3D). Through this stage the Model becomes the scenario of simulation, or rather the environment within which it’s possible to link the law of physics phenomena with the corresponding construction site activities.

**Inserting and settings of the sources and receptors within the GE environment**

The model of simulation have to be populated and set of sources and receptors depending on the expected work activities, their characteristics and risk factors. All the values that have been collected so far in the database (e.g. Sound Insulation Capacity, Internal Noise Limits, Risk Factors, Dust Dispersion, Vibration quantification) are imported into the Unity environment through scripts that allow them to connect to objects (e.g. walls, doors, floors) that make up the model of the hospital, or rather the scenario of the simulation. The graphical interface developed in the Unity model to characterise and facilitate interaction with the end user (e.g. engineer, architect, hospital manager) allows, once the construction site activity is selected, to populate the model.

**Simulation by using algorithms and particle systems**

The management of Noise, Dust and Vibration within the GE environment is eased through the use of simplified entities which enables creation, management and animation of many more particles than using a single object for each one. Unity3D’s particle system can generate hundreds of particles and move them around, varying their colour and dimension. These characteristics are tied to the time variable beginning the instant in which the particle is created, or randomisation. In this case, we had to use a customised particle system to solve the problem of particle collisions with architectural elements, which can’t be handled using one of the standard particle system provided by Unity. Thanks to the customised scripts it is possible to see, relatively to the construction site activity selected and located within the Unity model, the propagation in real time of noise within the ward/hospital and, moreover, the change of colour due to the noise attenuation caused by
the collision with, for example, a wall (see figure 2, where noise propagation is reported by comparing the case where the door is open or closed). In addition to the propagation of sound and its classification through the chromium scale (very high-red, high-orange, middle-yellow, low-cyan, ok-green), thanks to these scripts are highlighted, according to a qualitative simulation, the hospital environments subject to the impact of construction activity.

**CONCLUSIONS**

Statistical data reports roughly 85% of hospitals in Italy were built in the early 1900s and roughly 80% of operating theatres do not fulfill suitability requirements (Moscato et al. 2007), thus predicting steep increases of requalification and refurbishing of existing hospital structures.

Through the tool offered in this research, it is possible to visualise, in real time, the impact of the con-
construction site activity on the specific hospital environment where they are carried out and on the surrounding environments.

The methodology elaborated in this research aims to support the detection of logical-operational interferences by BIM model integration within a Game Engine environment, aimed to reduce impact that maintenance, within a healthcare structure, can generate on the actors' health and safety, preserving as much as possible the continuity of daily hospital
activities, as well as determining cost reduction and time optimisation of the activity stages that characterised the site.

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WP-BIM: Web-based Parametric BIM Towards Online Collaborative Design and Optimization

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We present initial experiments of Web-based Parametric Building Information Modeling (WP-BIM) towards collaborative design, modeling, simulation, and optimization. A new framework that integrates Web-based information technology (WebGL graphics, networking, and Web browsers), and design computing technology (visual programming) into parametric BIM is prototyped for the experiments. The integration of Web technology is going to enable online collaborative and user participatory design. Connected through the Web platform, a BIM model, visual programming-based user interfaces for parametric changes, and an optimization algorithm, which may reside in different servers or local computers in different geographical locations, have the potential to be integrated and working together to resolve design optimization problems, especially if combined with cloud-based performance simulation tools. After future development, this may allow architects, engineers, clients, etc. to collaboratively work on a project with up-to-date building data and different design and simulation tools.

Keywords: Web-based, Parametric Modeling, BIM, Collaborative Design, Optimization

INTRODUCTION
In this paper, we present initial experiments of Web-based Parametric Building Information Modeling (WP-BIM) towards collaborative design, modeling, simulation, and optimization. A new prototypical framework is created based on Building Information Modeling (BIM), parametric modeling, and Web technologies. The framework integrates Web-based information technology (WebGL graphics, networking, and Web browsers), and design computing technology (visual programming) into parametric BIM. The important addition of Web technology is going to enable designers’ collaboration online and allow user participatory design. Visual programming uses a graph structure of data flow for creating computer programs to conduct parametric design, simulation, and optimization. Visual programming is being used more and more widely in contemporary architectural design projects. Connected through the Web platform, a BIM model, visual programming-based user interfaces for parametric changes, and an optimization algorithm, which may reside in different servers or local computers in different geographical locations, have the potential to be integrated
and working together to resolve design optimization problems, especially if combined with cloud-based performance simulation tools. After future development, this may allow architects, engineers, clients, etc. to collaboratively work on a project with up-to-date building data and different design and simulation tools of the users’ choices. The integration of these different computing technologies also provides a case study of solving the challenging software interoperability problems.

**BACKGROUNDs**

BIM is a digital representation of a process to facilitate the exchange and interoperability of building information (Eastman et al. 2011) and a digital representation of a product of physical and functional characteristics of a building (NIBS 2008). Semantically rich and object-based, BIM facilitates the creation and management of comprehensive building data, including objects and their properties used in design, simulation, cost estimation, construction, and operation, increasing the AEC process efficiency. In addition, BIM’s parametric modeling capability enables quick, interactive, and real-time design changes (Lee et al. 2006). The relationship between BIM and parametric modeling lies in that BIM contains building objects and their relationships, which can be used to express design intent, while the parametric modeling method helps establish and manage these relationships (Yan 2014). In a BIM project, objects are defined by built-in or user-specified parameters, and external data such as physical and functional data accessed through databases or entered in Graphical User Interfaces (GUI). Parametric modeling enables parameters to be processed by mathematical formulas and computational algorithms before being passed among objects. The formulas and algorithms can be designed based on research and creative design thinking. Integrated together, parametric BIM becomes a powerful design tool for architects.

As a contemporary architectural design method, parametric modeling is important in the design process for creating parametric design models that can generate multiple design options, whose performance (such as energy, daylighting, and functions) can be simulated and optimized. Existing systems, such as Flux (https://flux.io), are able to translate model data among BIM, databases (e.g. Excel), and geometry modeling tools (Rhino/Grasshopper or Revit/Dynamo) and display the models on the Web. However, establishing parametric relationships or constraints of design objects using different modeling tools working with the Web has not been experimented, but is necessary for multidisciplinary collaboration and software interoperability. Therefore, one of the major research aims of this study is the creation of parametric relationships between building objects in the Web-based building information models with various design tools. Unlike existing systems that attempt to display isolated parameters and their static values online, this proposed project is going to establish parametric relationships in the building models that may be displayed and changed online in the design process by designers, engineers, and building users. The purpose of establishing the parametric relationships in the building models is to maintain design intents for parametric studies and design optimization.

**METHODOLOGY**

The methodology used in this research consists of prototyping and experiments with case studies. Previously, a plugin (Autodesk Design Review) of Internet Explorer was used to allow BIM model geometry and database to be viewed online for a case study (Jeong and Yan 2013). The requirement of a plugin in a specific Web browser limited the application and development of the system significantly. This present research has created a new integrated system that utilizes Autodesk Forge Viewer, which can work on most of the modern Web browsers without any plugin (Figure 1), allowing BIM models and their parameters to be displayed in a Web browser directly, and further enabling the interaction between visual programming tools and BIM online. Using Autodesk Forge Viewer API and Model Derivative API, the BIM
model (made in Revit) was uploaded to Autodesk Forge cloud, translated into the SVF format, and displayed in Forge Viewer. BIM 3D models, 2D drawings, and parameters can be displayed in a Web browser using Forge Viewer (Figure 1 left). A user can interactively examine the design model (Figure 1 right). All major current Web-browsers support the model display due to the use of JavaScript-based WebGL technology by the Forge Viewer. This system supports our new research and development to enable parametric relationships between building objects for the Web-based models.

We investigated the use of Flux to facilitate the integration of major visual programming tools for design, including Dynamo and Grasshopper, with Forge Viewer, and developed a prototype for demonstrating the Web-based parametric modeling method using visual programming and Forge Viewer. The prototype is created using JavaScript and Forge Viewer API/Extension. A sample of running the prototype for the communication of Dynamo and Flux is shown in Figure 2. In Figure 3, Flux is working on the background and help the communication between Dynamo and Forge Viewer, through our developed JavaScript program. When the slider of the Translate parameter is changed in Dynamo, the translation data is sent to Flux, and Viewer receives the data from Flux and makes the translation of the building roof in real time. Similarly, the slider of Scale is used to control the scaling of the roof.

After the integration between Viewer and Dynamo through Flux, it’s similar to integrate Grasshopper with Viewer through Flux (Figure 4). Compared to current developments combining Web-based 3D models and simple graph-based programming tools for editing the models, such as Autodesk Project Fractal (https://home.fractal.live) and Flux Flow (https://flux.io), the present prototype utilizes full-fledged visual programming tools: Dynamo and Grasshopper, which support complex parametric, generative design through their comprehensive built-in function and algorithm libraries and a large number of third-party plugins.

Based on the integration of Viewer, Dynamo, Grasshopper, and Flux, we developed a simulation of two users working on the same building model in Viewers: (1) User 1 controls the Dynamo program for the roof translation and scaling with Viewer on Google Chrome; and (2) User 2 controls the Grasshopper program for the roof rotation with
Viewer on Microsoft Edge. The actual use of two computers to test the collaborative parametric modeling between two (simulated) users was conducted (Figure 5). In the test, one computer runs Viewer and Dynamo to change the translation and scaling, and the other computer runs Viewer and Grasshopper to change the rotation. The transformations are synchronized on the two computers.

EXPERIMENTS WITH WP-BIM IN DESIGN OPTIMIZATION

In the present research, we have experimented Web-based parametric modeling supporting design optimization for a simple example. The experiment utilizes a Genetic Algorithm tool (Galapagos) in a visual programming environment (Grasshopper) to automatically generate design options and improve the options for sample design objectives. During the optimization process, Web-based Viewer is able to display the varying design options. A scenario of two designers using different visual programming tools - Dynamo and Grasshopper - to experiment with a preliminary design optimization through the Web is simulated.

In the example as shown in Figure 6, the design objectives are: through changing the rotation and scale of the roof, make the roof:

1. cover the whole building floorplan (50ft x 25ft)
2. cover the front area of the door (i.e. a location point that is 2.5ft in front of the door needs to be covered by the roof.)
3. have minimal area (i.e. the scale factor of the roof should be as small as possible).

While the Dynamo program can still be used to change the translation and scaling of the roof by a user manually (Figure 6 upper left), the Grasshopper program now contains a Galapagos (Genetic Algorithm) node, which uses the rotation angle and the scaling factor of the roof as parameters, and a fitness function that combines the above design objectives for optimization (Figure 6 lower left).

Running the Genetic Algorithm, multiple generations of design options are created automatically and evaluated with the fitness function. In the process, Galapagos inside Grasshopper displays the running of the Genetic Algorithm (Figure 7 lower left), and Viewer displays the multiple design options automatically (Figure 7 right). Figure 7 (right) also displays the resulting optimal design solution after running the process for 41 generations. From the bot-
Two computers representing two users collaborating on parametric modeling.

tom perspective, Viewer shows the resulting rotation angle and scale of the roof. The building is covered by the roof, the door’s front area is also covered by the roof, and the roof area (scale) is the smallest among all the solutions found in the specific optimization run of 41 generations. For parameter, constraint, or objective changes, re-running the optimization process can produce new design solutions. For example, the door front point is set 5 ft farther away from the door (the distance is 7.5 ft now), the results of the new optimization are shown in Figure 8, which also displays the Grasshopper-generated geometry model in the modeling tool Rhino. Note that the building model was originally created as building information model in Revit, and uploaded to Autodesk Forge cloud, translated into the SVF format, and displayed in Forge Viewer in a Web browser.

The changing of the building’s design options can be seen on the Web in real time by multiple users, who will be informed about the optimization process and may eventually contribute to the optimization process from different perspectives.

DISCUSSIONS
The case study was an example of a simplified single objective optimization problem (combining the multiple objectives into a single objective through weighted sum). Architectural design can be regarded as a multi-objective optimization process, where multiple design objectives need to be satisfied or optimized. For example, a project will optimize space layouts, building structure, energy consumption, daylight performance, costs, etc. Each of these building performances can be formulated into a separate design optimization objective, and all together, comprehensive optimal design solutions are sought in the design process. For a complex design project, the search space (the set of all possible solutions) can be very large, due to the large number of variable parameters and their constraints in multi-disciplines. Dividing the search space into subspaces and using concurrent subspace optimization algorithms are good strategies for effective optimization (Lu et al. 2014). However, the studies of concurrent subspace optimization on how to define the subspaces, parameters and constraints inside each subspace, and common or shared parameters and constraints between subspaces, and how to use efficient optimization algorithms, have been conducted mostly in engineering design, such as aerospace, automobile, etc., but not in architectural design. Further development of the WP-BIM system may help provide such a tool for the study of concurrent subspace optimization to facilitate architectural design collaboration.
Figure 6
Sample Web-based parametric modeling and design optimization.

Figure 7
The optimization workflow and results.
CONCLUSIONS AND FUTURE WORK

The prototype integrating Forge Viewer, visual programming tools Dynamo and Grasshopper, the data interoperability platform Flux, and Genetic Algorithm, was developed using JavaScript programming with Viewer API and Extension as well as other mentioned tools. The prototype can run successfully demonstrating the capability of Web-based collaborative parametric design and optimization with visual programming and BIM models. The source code of the prototype is hosted on the online software repository GitHub: (https://github.com/wyanTAMU/parametricdesign).

Future work includes: (1) extending the Viewer’s model editing functions to enable more comprehensive parametric modeling capability; (2) testing the applications of Web-based collaborative parametric design and optimization with more complex case studies; (3) investigating distributed and concurrent subspace optimization processes utilizing an enhanced framework. Future WP-BIM system will also include different optimization algorithms for solving different problems within subspaces of optimization, e.g. classical calculus for solving optimization problems that can be formulated as continuous and differentiable equations, linear programming for problems that can be modeled by linear relationships between variables, and dynamic programming for those with discrete and stochastic variables. In addition, different Genetic Algorithm tools, including BIM- and visual programming-based Optimo (Rahmani Asl et al. 2014, 2015a, and 2015b) can be included in the framework. It is expected that the Web-based, collaborative parametric design method utilizing different modeling and visual programming tools will enhance the multi-disciplinary and multi-objective design optimization process for architecture.

Figure 8
New optimization results after the door front point is changed to 7.5 ft away from the door.
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pneuSENSE

Transcoding social ecologies

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Cities are continuously produced through entropic processes that mediate between complex networked systems and the immediacy urban life. Emergent media technologies inform new relationships between information and matter, code and space to redefine new urban ecosystems. Modes of perceiving, experiencing and inhabiting cities are radically changing along with a radical transformation of the tools that we use to design. Cities as complex and systemic organisms require approaches that engage new multi-scalar strategies to connect the physical layer with the system of networked ecologies. This paper aims at investigating emerging and novel forms of reading and producing urban spaces reimagining the physical city through intelligent and mediated processes. Through data agency and responsive urban processes, the design methodology explored the materialization of a temporary pneumatic structure and membrane that tested material performance through fabrication and sensing practices through the pneuSENSE project developed in July 2016 in New York at the Brooklyn Navy Yard during the `HyperCities' IaaC- Institute for Advanced Architecture of Catalonia - Global Summer School.

Keywords: responsive urban processes, data agency, reciprocity between micro (body) and macro (environment), dynamics of social ecologies, mapped-environment

INTRODUCTION

PneuSENSE is collaborative project that takes the form of a responsive, interactive and inhabitable pavilion space (see Figure 1) The pavilion embodies the dynamic relationships of interdependence and reciprocity, between micro (body) and macro (environment) systems, within a diverse range of urban conditions found within New York City. Through the use of sensing and actuation technologies, biometric and environmental data was collected from individuals within a range of specific urban sites, and was translated into a responsive inhabitable space, a ‘mapped-environment’ that renders the dynamics of social ecologies. The design methodology of this project disrupts conventional digital design processes by using computational tools, GPS, and sensing technologies to rethink the complex relationships and interdependencies between bodies, build-
ings, urban spaces, and environments, as interconnected, multi-scalar, ecological systems.

CONCEPTUAL FRAMEWORK: INTERDEPENDENCE AND RECIPROCITY THROUGH SYNTHETIC MACHINIC SYSTEMS

The notion of social ecologies intended as the interaction between social and environmental systems and adaptations triggered by their co-evolution is the overarching project framework. As Henri Lefebvcre’s already suggested in his book ‘The Production of Space’, social space is a dynamic space in which interaction and exchange at multiple levels produce the urban space itself. The production of such a space can therefore be understood as a collective experience in a broader context and in continuous tension between the collective and the individual, the imagination of shared scenarios between the macro and micro scales. The project aims at investigating dynamic relationships of interdependence and reciprocity between the macro (environment) and micro (body) scale through prototypical macro-contexts in New York. In particular, the notion of ‘Urban Machines’ represents the underlying conceptual scaffolding of the pneuSENSE project.

As emergent technologies have brought into question the role of the material city in representing the public and the collective experience of urban space, Information and matter, code and space collapse into a new system, and mediated spaces become an architectural problem. In this new scenario, the role of machines is intended as a set of devices that become relevant to the experience of urban space and the public realm.
A device can be defined as an apparatus, instrument or tool designed for a specific purpose. Devices perform, inform and continually transform the environment and our perception. They can manipulate data by seeking performative spatial relationships. Accordingly a machine can be defined for its inherent meaning of being a system of devices able to communicate and perform within a certain environment. A machine implies the notion of “something that has been constructed” and “function with a specific purpose” while being composed by parts that respond to a “functioning whole.” The notion of assemblage developed by Deleuze and Guattari is intended as a composition of heterogeneous elements that give rise to a new system. In Deleuze's book A Thousand Plateaus the concept of machine can be understood as a more complex formulation of the concept of assemblage. In Guattari’s terms, a machine is a composition of heterogeneous elements-subjective, social, technical, spatial, physical and process-related—that delimits a series of conditions for the production of the real. This entails that the notion of machine is directly connected to the concept of agency as it has the capacity or potential for an action within an environment. Rather than seeing those interventions only as objects or installations, they are seen as assemblages whose spatial parameters merge with information, networks, devices, media and users to create a public space that is more responsive, participatory and collective. The inhabitants are a dynamic part of the assemblage and become active producers of the public space. Space in this scenario emerges as a social product, and citizens are empowered in the production of it. Those interventions can be seen as tools to produce hybrid public spaces that in the temporary, interim or permanent phase are active, networked and responsive. Urban Machines in that way provide an alternative scenario to the production of physical public space.

From this conceptual context, Urban Machines are interventions in the physical urban public space that function as a system or set of devices, and through information technology, mediate the relationship between the urban environment and the user. In this framework the spatial practitioner is designing and programming these machines to promote, test and prototype the relation between city, technology and the human scale. The machines have the potential to generate a new type of either permanent or temporal urban geography operating as large-scale plug-in systems. CJ Lim, in his book Devices, argues that a technological or abstract understanding of such machines and their construction can influence and redefine the potential for architecture and spatial thinking. Urban Machines are a family of projects designed and developed to mutually enrich relationships between people, the space they inhabit and the urban environment. As the city is more and more produced through entropic processes, Urban Machines could operate as synthetic systems determined by the recombination of multiple parameters into one performative spatial form. Those systems perform differently based on how and where they are situated, their scale and their relationship to the environment. Urban Machines could help to intensify the interaction between urban space, people, objects, architecture and media devices. They have the potential to test and prototype models for future urban scenarios.

**CONTEXT: BODIES AND CITIES**

Within the systemic machinic system framework, the dynamic conditions of the users and their body in space/environment reflect constantly on the reciprocal approach to the production of space itself. Hybrid public space refers to collectively inhabited urban space that is traversed by digital flows of data and images that enhance and alter the traditional interaction between the body and its physical, social and symbolic environment. In the mix of people, flows, networks, data and electronics, new relationships between humans and machines, time and space can be found. An urban space that embraces technologies changes everyday rituals and how social interactions are mediated. At the same time, the importance of the physical encounter must be rec-
ognized. Those interventions embody the capacity of bridging the physical and non-physical into a hybrid condition. They merge the hardware (space, tectonics, materials) and software (information, systems, networks). Synthetic machinic systems produce new ecologies in the way Guattari theorizes: environmental or technical ecology, social ecology and mental ecology. Urban Machines are an urban heterotopia, a public space that emerges between environmental conditions, ambient conditions and situations, an urban manifestation of event and memory, a space that is temporary but leaves a permanent transformation in its urban context. Experimenting at the intersection of information technology, urban space and architecture, Urban Machines emphasize hybridity over mono-functionality. Environment, space, technology and different forms of use are intertwined to produce a space that encourages new modes of urbanity and the emergence of new forms of public life. As a space-environment Urban Machines allow for multiple conditions to exist simultaneously. Urban Machines promote a continuous hybridization and exchange between the city and its citizens, place and technology.

To test the dynamic relationships between bodies and cities through the lens of Urban Machinic approach, four prototypical macro-contexts in New York City are the extended sites of investigation, sampling a variety of urban characteristics, including green spaces, dense urban conditions, public transportation systems, and spaces of extreme verticality. They are experienced through the simultaneous overlap of micro-condition (body) and macro-condition (environment) in order to understand the

Figure 2
Customized sensing device that incorporates biometric and environmental sensors, and a map of the various sites where data was collected.
multi-scalar, temporal, and dynamic complexities that form urban spaces. Through sensing platforms, agents are able to record both biometric and environmental data, in order to evaluate and translate collected information and metrics into data-driven design strategies.

DATA SETS: BIOMETRIC AND ENVIRONMENTAL
The project engages simultaneously two sets of data and sensing devices: environmental sensors (sound, light, temperature, humidity, and CO2) and body sensors (heart rate, stress sensor, skin conductivity). The data is collected from sensing platforms, stored, and organized into quantifiable sets, which are translated and parsed using computational processes to visualize information and relationships, into patterns and geometry.

The first step of this phase was to build the ‘Data Acquisition Unit’ (see Figure 2) as a portable device able to be attached to the body to record and store in real time to data-set at each of the four macro-contexts. The customized sensing device incorporated simultaneously biometric and environmental sensors to understand the level and degree of co-dependence of the data sets and how they affect each other in relation to context.

After the collection of data, the subsequent step required a system to interpret and select data able to reveal the interdependence between the environment and body. Through evaluation and direct comparative translation, patterns of reciprocal data behaviors started to emerge and guide the data parsing phase.

Visualization of Data into quantifiable sets provided a platform for testing strategies for form-finding and geometric recurrence. Through grasshopper and generative processes, the inter-dependent data sets were mapped through geometries that visualized tri-dimensionally the dynamic and relational fluctuation of the environment and biometric data sets. In particular, three inhabitable units were mapped and geometrically translated; each unit represented one specific prototypical site in New York City: The Brooklyn bridge, Grand Central Station and Top of the Rock (see Figure 3).

MATERIAL FABRICATION: CODING AND PROTOTYPING
The patterns and geometry derived through the data were used to design a physical construct. A pneumatic structure made out of a reflective mylar material, was used to express the dynamic and temporal qualities of the body and environmental phenomena. The project explored the potential for pneumatic structures, through the generation of inflatable components, assembly methods, and the performance of aggregate systems.

Geometry was first tested into small prototyped units to understand the inflation capacity relative to structural performance. From small components, the macro-modules were developed acting as independent and self-stable unit to then be aggregated into the larger map/spatial system. A series of non-linear testing were performed to evaluate the relationship between air supply, the system of interconnected inflation tubes and the form-finding process in relation to structural stability. Once stable form was achieved, the system was aggregated in its final configuration.
FEEDBACK: RESPONSE AND INTERACTION

As the nature of the public environment has changed dramatically, responsive and systemic machinic systems seek to create atmospheres that embody this negotiated status, engaging the public in constructed agencies. The same perspective was theorized by Henri Lefebvre who pointed out that the city is both a product and a medium created by social praxis and socio-spatial processes. Lefebvre decodes the urban space in three dimensions: 1) the perceived space: space produced by the collective activities in the urban space; 2) the imagined space: space constructed by urban planners and architects as a “representational space” projected onto the reality; 3) the experienced and suffered space: space experienced by users and mediated through images and symbols of everyday life. Urban Machines are systems able to extend material space into space for action. Action is a generating mechanism to express form and space. Those interventions have an inherent relational nature and the ability to set up a public system for interactions and events to occur. Urban Machines construct scenarios in which the public is invited to enter a manifold space where the experience is multilayered and set in motion by a series of spatial, ephemeral and technological mediated devices. They intervene in the public realm as systems that are socially, technologically and physically integrated. (see Figure 4)

The machinic responsive condition of PneuSENSE is performed through feedback loops of input-processing-output (see Figure 5). Each individual spatial responsive unit assembled in a continuous macro-spatial map was layered with embedded biometric sensors to provide real-time responses and feedback: the first unit (Grand Central Station) sensed in real-time the heart rate, the second (Top of the Rock) CO2 in the breath and the third (Brooklyn Bridge) the skin conductance.

This provides new opportunities for body/architecture and individual/social interactions. Users can ‘plug-in’ to the physical prototype, which reads various biometric data and provides actuated feedback through breathing (inflating/deflating) and pulsating (lighting) effects (see Figures 6 and 7).
Figure 6
User interacting with the architecture to receive a real-time response. Carbon dioxide sensors were used to measure air quality to actuate lighting.

Figure 7
LCD screens that communicate information to users in text format, in this image, instructing the user to ‘see your heart beat’.
The testing of those interdependent actuated conditions can be the accelerator of ways in which we understand urban space and its multiple forms of operations. They provide agencies that could potentially influence urban configurations and narratives yet to come. The generative potential of these interventions is the capacity to catalyze processes of creation of the “open city,” a city that is in constant evolution and that can be transformed through bottom-up and overlapping of functions, while initiating processes that start the dialogue about urban scenarios.

CONCLUSIONS
This paper aims at providing a trajectory and a step-by-step design methodology to understand dynamic relationships of interdependence and reciprocity between micro (body) and macro (environment) systems and how they could inform forms of projecting design scenario in public spaces. The pavilion (see Figure 8) developed within the two-weeks of the IaaC Global Summer School represent a prototype that negotiates between “process” and “product” to test a system of relationships. Functioning in this case as a prototype, it seeks to engage the public or a specific urban condition. Once a strategy has been proven successful the prototype might inform long-term implementations. This has a strong potential to replicate the same intervention in other urban contexts as a testing device. The process of prototyping, replicating and adopting can promote urban innovation. Urban prototyping as a movement is exploring those processes demonstrating that participatory design, art, and technology can improve cities.

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Informed Design Platform

Multi-modal Data to Support Urban Design Decision Making

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Evidence based urban design and planning support benefits from providing designers with multi-source, multi-scale and multi-time information, which is both 'big' and 'small', and quantitative and qualitative. We are developing a platform, namely Informed Design Platform, that adopts a (big) data driven approach to derive insights and principles in order to adaptively design or re-design various forms of urban public spaces based on usage patterns and perceptions of the public. This platform is designed using a four step methodology of data collection, integration, analysis, and visualization. Multi-source data is integrated based on three analysis dimensions: place, time and people; and four analysis pillars: utilization, activity, opinion and sensing. This paper describes the aims, the design principles, and partial results of development of this platform.

Keywords: Evidence based urban design, Multi-modal data, Information modeling, Information visualization

INTRODUCTION

This paper presents the design of a digital platform, namely Informed Design Platform (IDP), for offering designers and planners a deep understanding of use and usage patterns of pedestrian public spaces in a dense urban environment.

The use of data in the building and urban design processes is not new, as design is a highly data and information driven and complex process, where the data entails many relationships and interdependencies. Furthermore, many actors and disciplines contribute their specific knowledge and information in these processes. Designers must consider a large number of issues belonging to a wide spectrum.

Technology is more than ever available for providing designers with real-time data and information about many aspects of our environment, with the potential of being used in design processes to improve our built environment (Batty, 2013). The term 'smart cities' has become widely familiar in the last years among designers, planners, engineers, and policy makers (Albino et al., 2015; Kitchin, 2014). Some literature portrays a cheerful vision of a city that employs wireless and internet-enabled technologies to promise good performance and effective use of resources. In this view, smart cities are considered to foster new knowledge-based economies that are en-
vironmentally and socially sustainable, well gov-
erned, and resilient. However, technology itself can’t
automatically transform and improve cities and the
lives of their inhabitants.

The use of ‘big data’ as an enabler of the smart
city vision is a reality in our cities. Some of the char-
acteristics of big data are volume (a huge amount of
data), variability (heterogeneous and often unstruc-
tured formats of data), and velocity (an almost real-
time processing of incoming data) (Laney, 2001). We
claim that the most important characteristic of big
data in the context of design support is variability, as
designers switch between various scales, frame and
solve various problems consecutively, and even si-
multaneously. Therefore providing designers with
multi-source, multi-scale and multi-time information,
or evidence, is an important contribution of big data
to design support.

When designers make design decisions, apart
from their knowledge and experience, they rely on
assumptions about users and use cases. Evidence
based design support is a field that is often used in
urban design (Faludi and Waterhout, 2006; Chong
et al., 2010; Khan and Kiani, 2012). Designers use
evidence from existing situations in projects in or-
der to gain insights to improve these projects and
gain insights for new designs. However, having an
access to evidence related to certain design needs
and requirements does not lead to a linear transla-
tion of evidence to design solutions, as design is an
open ended endeavor with many unrelated inputs
and many preconceptions. Evidence based design
support can, however, replace some of the assump-
tions made during design by grounded evidence. For
instance, having an access to multimodal data on an
analysis of user, usage, and perception information
of public places in dense urban environments can
provide designers with valuable evidence. Rather
than considering a typical user, we can have evidence
about a whole number of users with their own pref-
erences, desires and behavioral patterns, such that a
public space design can be responsive to each and
every one of these users, at the same time or over
time. The research challenge lies in finding out which
behavioral hypotheses can be drawn from specific
urban data sets and their combination, and under-
standing the relationship of these hypotheses with
spatial and organizational aspects of urban spaces.

Urban big data encompasses various sources for
data, including sensor data for all types of urban in-
frastructures, real-time transport tracking data, social
network data containing information about events or
opinions, public app data, phone data, and open data
provided by government agencies, such as air pollu-
tion data, crime data, meteorological data, and land
usage data. Additionally, user volunteered data, in-
cluding geographic data, contributes to the bottom-
up formation of publicly available data sets (Mark,
2013). Such new data sources enable new and in-
novative ways of urban analysis and design support,
complementing conventional sources such as behav-
ioral surveys (Balaban and Tunçer, 2016; Tomarchio et
al., 2016; You and Tunçer, 2016).

Our approach is to use these technologies to
foster evidence-based design, and translate the rich
and varied information sources into design support
means. Another goal is to use these technologies to
increase public participation in decision making in a
meaningful way, taking subjective perceptions and
opinions of users into account, together with mea-
sured and objective facts (Mark, 2013). We aim to
take advantage of new and abundant forms of data,
sensing technologies, and possibilities for interaction
among people, communities and their physical envi-
ronments.

This research project is carried out by a multi-
disciplinary group consisting of architects, engineers,
data scientists, and social scientists. The project has
a site that consists of residential, transport and com-
mercial zones, that we use as a test-bed area for this
research.

INFORMED DESIGN PLATFORM
This section describes IDP, which presents 2D Maps
and 3D models, information visualizations, and is
supported by an information model that integrates
multi-source, multi-scale, multi-time data, that is both ‘big’ and ‘small’, and both qualitative and quantitative. The project as part of which IDP is developed adopts a (big) data driven approach to derive insights and principles in order to adaptively design or re-design various forms of urban public spaces based on usage patterns and perceptions of the public. The ultimate goal is to improve the quality of public space by improving the current and future use, function and usability of spaces. Therefore, we have defined three sub-goals:

1. Create support for designers: We collect multi-modal data about people’s use of spaces, people’s perception and opinion of spaces, and physical conditions of spaces. We integrate this data, and derive insights relevant for designers related to these spaces, and visualize these in the Informed Design Platform (IDP) prototype that we are developing.

2. Develop methods and techniques: Multi-source, multi-scale and multi-time data collection and analysis for design support and deriving design related insights is a field that is little explored. Many research efforts focus on a single or a few data sources in support of design. In this project we are exploring how various rich data sources can serve designers in a meaningful way.

3. Contribute to scientific knowledge: We are contributing knowledge in the field of evidence based design support, specifically related to the relationships between use of space, users’ opinions about space, and physical conditions of space.

When designers design urban spaces, they build on a number of factors, such as site, brief for the project, existing space network, characteristics of potential users, climate patterns, landscaping options, etc. We have conducted in depth interviews with experienced designers of public spaces, and these have revealed that designers take a number of factors into account when adaptively (re)designing public spaces, such as climate and weather, cultural factors, demographic factors, physical characteristics of the space, environmental/situational characteristics, and users’ impressions of the space.

IDP integrates data collected from a variety of sources and presents 2D maps, 3D models and a number of information visualizations (Figure 1), addressing questions that designers are likely to ask, such as:

- Which spaces are being used, how, how much, by whom (demographics)?
- Do the spaces contribute to their users’ perception of livability?
- Are any spaces over- or under-utilized?
- What can be additional/alternative uses for spaces that increase liveliness and user appreciation?

In this context, the methodology that we follow in this research project concerns four main steps.

Step 1 is data collection. We mainly focus on three categories of data. The first one is user behaviour and opinion data. We use big and small data to understand how users utilize and behave in urban public places, using social media data, mobile phone data, sensor data, app data, observations, workshops, and interviews. The second one is data on physical comfort of users of urban public places. This relates to thermal comfort and environmental comfort. This is measured using specifically collected data sets of climate and environmental parameters, obtained by a variety of sensors, in addition to questionnaires and workshops. The third and final data category is urban analysis and mapping of functions and physical characteristics of spaces. This involves conducting spatial analysis and mapping, and examining the typologies of urban public spaces, using analysis methodologies such as space syntax, catchment area analysis, and functional analysis. Additionally, we analyse individual properties of places, such as the placement of urban greenery, furniture, shadow studies, etc.
Specifically, IDP uses the following data:

1. We have conducted questionnaires, interviews and workshops with users on site.
2. We have established a sensor network on various points of interest on the site. The sensors are weather, environmental, and people counting sensors.
3. We have developed a smartphone app, which tracks the mobility and activities of its users. This app also has an active data collection portion, where users are able to rate spaces according to various dimensions of our inquiry into livability, in order to receive a subjective perceptual evaluation of public spaces that users visit.
4. We have access to mobile phone data, in order to detect coarse population level human flow patterns on site, footfall in selected areas, and associated demographic attributes.
5. We collected social media data (currently Twitter and Instagram) and perform sentiment analysis (positive, neutral, negative) on the geo-tagged feeds.

Step 2 is data integration. Multi-source data are integrated based on three analysis dimensions, namely Place, Time and People.

Step 3 is data analysis. We defined four analysis measures, namely Utilization, Activity, Opinion and Sensing. Based on the three analysis dimensions, related analysis is made to mine insights from the data for informed design.
This structure enables users of IDP to explore the site and the body of evidence derived on the site in various ways (Figure 2). Users may start from any of the analysis dimensions, place, time, or people. Place can be a specific location (e.g., a covered pavilion) or place type (e.g., all covered pavilions). Time can be a specific day and time range (e.g., June 6 2017, 2-4pm) or a predefined time range (e.g., weekends). People refer to demographic attributes, such as age ranges, gender, and ethnicity. Users may also select any combination of these three dimensions, such as places and time (e.g., playgrounds during weekday afternoons between 3-5pm), places and people (e.g., covered pavilions, people above 50 years old), time and people (e.g., women, Mondays), or place, time, and people (e.g., a specific playground, children under 15 and elderly above 50, and weekday afternoons between 3-6pm).

After this selection, users may combine this selection with one or more analysis pillars. The specific selection made above will determine the filtering of data for each analysis pillar selected. Utilization selects data related to the utilization patterns. Activity selects data about activities of users. Opinion data selects user opinions. Sensing data selects environmental and weather related information. The only combination that will not generate results is people and sensing, as demographic data of users about sensor data is not available.

Figure 3 presents the various data sets that contribute data for the analysis pillars, and a subset of available information categories. App, survey, social media, and workshops contribute to activity. Sensor, app, survey, workshop, phone, and social network data contribute to utilization. App, survey, workshop, and social network data contribute to opinion. Sensor data contributes to sensing.

Insights related to places and place types are integrated in IDP. We derive these from the individual insights from various data sets, as well as a combination of data sets using the above model. These insights are produced using multi-dimension and multi-measure analysis methods.

For example, a combination of People, Places, and Utilization produces insights related to which places (or place types) are utilized by which demographics (age, gender, ethnicity), and the derived insights include additional information regarding family structures associated with such demographics. A design insight from this is the comparison of presumed design intent of a specific place or place type in terms of target users compared to actual use by demographics.

We have demonstrated analyzed data and derived insights from various data sets regarding the place type “coffeeshop”. As described above, in IDP we integrate all data and insights using the analysis data model presented in Figure 4. For the coffeeshop, we present all opinion data (survey, workshop, app, social network) together with the utilization data (sensor, app, social network, telco) through the configuration of time and people analysis dimensions. We derive insights about coffeeshops related to:

- their proximity to other amenities (e.g., grocery store, playground, clinic) related to their utilization volume and frequency
- usage patterns related to insights about social behavior occurring there derived from group configurations and activities, and demographics
- design and maintenance recommendations derived from opinion data related to temporal utilization distributions
Figure 3
Various data sets that contribute data for the analysis pillars, and a subset of available information categories.
Step 4 is data visualization. Insights are visualized through intuitive analysis charts and analysis maps implemented by IDP. The IDP interface consists of 3 parts, 1) on the left, there is a list of analysis measures for users to select; 2) on the top, there are three configurators for users to set values of “Place”, “Time” and “People” analysis dimensions; and 3) in the middle, there is an analysis chart on the right and an analysis map or model on the left to present extracted knowledge intuitively (Figure 4).

The visualizations that we use to represent all this information and insights are at the moment being implemented. In addition to charts and dashboard type panels, we are using various data visualization techniques: heat maps, 3D surface plots, animated visualizations for trajectories and many other time sequence related information.

CONCLUSION
This paper advocates the view that urban design support benefits from providing designers with multi-source, multi-scale and multi-time information, which is both ‘big’ and ‘small’, and quantitative and qualitative. IDP is currently under development, and aims to provide designers with evidence in order to adaptively (re)design public spaces. A description and evaluation of the use of IDP in a real design context will be provided in a future paper.

This approach has many limitations. The data collected may not represent all users of the selected site. Additionally, the evidence and insights derived don’t shed light on many design parameters that are very important for design. However, in order to have a deep understanding of both real and perceived utilization and appreciation of existing public spaces, and starting to relate these to physical attributes of places is a promising direction, and developing the methodology and technical infrastructure for this is an important contribution.

A future research direction is the formalization and encoding of a part of the insights and evidence derived from the data collection, integration and
analysis process into a design environment, where designers can use this evidence in the design of new public places within similar contexts.

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Participatory Evaluation of the Walkability of two Neighborhoods in Brussels

Human Sensors versus Space Syntax

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In this paper, we further develop and test a walkability evaluation method developed by the first author to understand two neighborhoods in Brussels. This method introduced alternative strategies and tools for enabling the evaluation of walkability and discussed how a structured collection of human experiences could lead to a social construct of walkability. In this study, following this method, we made a field survey with architecture students to measure the walkability of the two referenced neighborhoods. In addition, considering the close links of walkability with the physical layout and configuration, we made a Space Syntax analysis (visual integration and axial connectivity) and compared this with the walkability ratings made by the students. As a result, we found moderate to high correlations between the experiential evaluation of the students and the Space Syntax results. Besides establishing links between subjective and computational surveys, this study led to the conception of a web-based platform with a mobile app which integrates location-based experiential and computational evaluations of walkability.

Keywords: Walkability, Human sensors, Experiential Knowledge, Field Survey, Space Syntax

INTRODUCTION

This research is the follow-up of a former study (Pak and Verbeke, 2013)(Pak and Verbeke, 2014) which explored the potential of walkability as a performance indicator for urban spaces and revealed a method for crowdsourcing walkability. This method introduced alternative strategies and tools for enabling the collective evaluation of walkability and discussed how a structured collection of human experiences could possibly lead to a social construct of walkability. For the readers who have not read the referenced paper yet, we want to clarify what we mean by the term Walkability. Walkability is a measure of how walking-friendly a specific place is (Pak and Verbeke 2013). Walking-oriented design idea was first introduced in design and planning theory by Perry (1929) through the “Five-Minute Walk” neighborhood concept, the average distance that a pedestrian would desire to walk. Lynch (1961) revealed the importance to the user-walker experience and offered mental maps of
paths, edges, districts, nodes and landmarks for analysis. Jacobs (1961) stressed the uses of sidewalks and described the benefits of safe, diverse and lively streets.

Walkability is an essential urban quality closely related to the experience of a sense of place, social cohesion as well as resilience (CNU, 2017). Walkability is considered to be a predictor of public health (Frank et al., 2009), house values (Cortright 2009) and pursued as a top prerequisite for environmental sustainability (LEED ND 2015) and neighborhood vitality (CNU 2017). Several studies attempted to link walkability with spatial configuration methods such as Space Syntax. In “New methods in Space Syntax”, Bill Hillier and Chris Stutz (2005) introduced Walkability Index as a complex construct of several factors such as transport nodes, land use, building frontage, infrastructural elements, major attractors or generators, and aesthetic features. Furthermore, Koohsari et al. (2016) found that the concept and methods of space syntax can provide an understanding how urban design influences walking behavior.

In addition to these, the empirical field research of the first author (Pak and Verbeke 2013) observed and revealed a set of qualities which were found to be associated with the perception of walkability. Among those, the experiential qualities were: aesthetic appeal, sense of place, sense of identity, particular and somatic sensory experiences (odor, noise, wind etc.) and perception of safety (Table 1). Furthermore associated quantifiable qualities were: the number and variety of amenities and attraction points, linkage to public/bike transport, physical layout (block length, intersection density, street width etc.), land use mix, linkage to other parts of the city, the physical qualities of the sidewalks (width, height, surface etc.), the physical qualities and placement of the urban furniture and policy enforcement tools (benches, parking meters, signs etc.), level of pollution (collection of trash, air quality etc.), number of pedestrians on the street, density of the car traffic, weather conditions and natural elements.

Based on the studies reviewed above we can identify at least two different approaches to walkability. The first is a positivist approach to walkability, an absolute measure, which can be measured and verified by repeatable surveys, experiments or other possible means.

The second view of walkability is a constructivist one which approaches this concept as a relative measure, a social construct which emerge as a result of human experience. We are not going to make an epistemological inquiry and stress the differences in this study. In contrast, we believe that these two views of the world have merits on their own and they can provide different types of data, information and knowledge to the researchers.

This discussion evokes two research questions which motivated our current research study:

- Can we measure walkability of a neighborhood using the associated experiential qualities by using a group of human sensors?
- Considering the close links with the physical layout, configuration and linkage detected in the former study, is it possible to make an estimation of walkability using Space Syntax methods such as visual integration and axial connectivity?
- What are the possible relations between these two evaluations?

In order to test these research questions and understand the walkability of two historic urban neighborhoods in Brussels, we initiated two observation studies. In the second part of our research, we compared the collected data with space syntax analysis results (visual integration and axial connectivity).

As a result, we found moderate to high correlations between the experiential evaluation of the students and space syntax results. In the following section we will elaborate on these and discuss the significance of our findings. After elaborating on these, in the last part of this section, we will introduce the idea of a novel ICT-enabled location-based method which integrates experiential and computational evaluation of walkability.
Table 1  
Dimensions of walkability: spatial qualities revealed (Pak and Verbeke 2013)

<table>
<thead>
<tr>
<th>Qualities Extracted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiential</strong></td>
</tr>
<tr>
<td>- Aesthetical appeal</td>
</tr>
<tr>
<td>- Sense of place</td>
</tr>
<tr>
<td>- Sense of identity</td>
</tr>
<tr>
<td>- Special and Somatic Sensory Experiences (<em>odor</em>, <em>noise</em>, <em>wind</em>, <em>vibration</em>, <em>temperature</em>, <em>kinesthetic</em>, <em>balance</em> etc.)</td>
</tr>
<tr>
<td>- Recreational capacity</td>
</tr>
<tr>
<td>- Explorability</td>
</tr>
<tr>
<td>- Perception of safety</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
</tr>
<tr>
<td>- Number and variety of amenities and attraction points</td>
</tr>
<tr>
<td>- Linkage to public/bike transport</td>
</tr>
<tr>
<td>- Physical layout (block length, intersection density, street width etc.)</td>
</tr>
<tr>
<td>- Land use mixity</td>
</tr>
<tr>
<td>- Linkage to other parts of the city</td>
</tr>
<tr>
<td>- The physical qualities of the sidewalks (<em>width</em>, <em>height</em>, <em>surface</em> etc.)</td>
</tr>
<tr>
<td>- The physical qualities and placement of the urban furniture and policy enforcement tools (<em>benches</em>, <em>parking meters</em>, <em>signs</em> etc.)</td>
</tr>
<tr>
<td>- Level of pollution (<em>collection of trash</em>, <em>air quality</em> etc.)</td>
</tr>
<tr>
<td>- Number of pedestrians on the street</td>
</tr>
<tr>
<td>- Density of the car traffic</td>
</tr>
<tr>
<td>- Weather conditions</td>
</tr>
<tr>
<td>- Natural elements</td>
</tr>
</tbody>
</table>

Figure 1  
The walkability survey made with the students from the KU Leuven Faculty of Architecture and Tunghai University Department of Architecture. Workshop leaders: Burak Pak, Chotima Ag-ukrikul and Simon Shu.
HUMAN SENSORS VERSUS SPACE SYNTAX

In the first part of our study, we organized a workshop at the KU Leuven Faculty of Architecture with the contribution of Prof. Dr. Simon Shu and his students at the Tunghai University Department of Architecture.

We employed 40 students as human sensors to rate a selection of the walkability-associated qualities in a structured manner. The students walked in two small neighborhoods and made rated in all streets in each neighborhood (Figure 1). They rated:

1. A selection of 10 different criteria for Walkability (Table 1) (Pak and Verbeke 2013) (Pak and Verbeke 2014): Aesthetical Appeal, Sense of Place, Sense of Identity, Physical Quality of the Sidewalk, Urban Furniture, Natural elements, Pollution, Smell, Noise, Wind.
2. An overall perception of walkability

The ratings have been made through a location-based Likert scale form, at the predesignated specific locations distributed with 20-meter distance in between and covered all of the streets in the relevant neighborhoods. These ratings have been codified to make collective maps of walkability and associated qualities as a social construct (Figure 2).

In the second part of our study, we have been inspired by the research by Bill Hillier, which revealed that the distribution of spatial integration values in the axial map can predict the actual and the potential number of pedestrians (Campos et al 2003). The space syntax pedestrian analysis project in London (Hillier et al 1992) showed the correlation between spatial integration and pedestrian flow (R-squared 0.75).

Since the link with the number of pedestrians on the street and walkability is quite evident (if a place is walkable, there should be more people walking), we hypothesized that the ratings made in our study should have a relation with Space Syntax analysis. Prof. Dr. Simon Shu and his assistants ran a Space Syntax analysis to test this hypothesis. Then we compared the results of Space Syntax and the student ratings. This correlation analysis revealed interesting findings.

In the neighborhood of Rue de Bouchers:

- There is moderate correlation (0.61) between Rn Global Visual Integration and the walkability evaluation of the students (their conclusive judgment, not average)
- There is moderate correlation (0.59) between R3 Local Visual Integration and the walkability evaluation of the students (their conclusive judgment, not average)
- There is a moderate correlation (0.64) between axial connectivity and the walkability evaluation of the students (their conclusive judgment, not average)
- There are moderate-low (0.4-0.61) correlations between Rn Global Visual Integration and the first 5 walkability factors (individually).
- There is a high correlation (0.73) between axial connectivity and the Average of 5 walkability factors: Aesthetical, physical quality of the sidewalk, urban furniture, natural elements, noise.

In the neighborhood of Saint-Catherine:

- There is moderate correlation (0.65) between the Average of 5 walkability factors: Aesthetical, physical quality of the sidewalk, urban furniture, natural elements, noise and R3 Local Visual Integration
- There is moderate correlation (0.63) between the Average of 5 walkability factors: Aesthetical, physical quality of the sidewalk, urban furniture, natural elements, noise and Rn Global Visual Integration
- There are moderate-low (0.38-0.63) correlations between Rn Local Visual Integration and the first 5 walkability factors (individually).
- There are moderate-low (0.32-0.63) correlations between Rn Global Visual Integration and the first 5 walkability factors (individually).
Figure 2
The results of the walkability survey derived from the ratings of the students (averages of the rating of 10 variables of 40 students).
As evident in Table 2, strong autocorrelations between the Walkability indicators are evident in the correlation chart and an evident expected result.

**CONCLUSIONS**

In this study, we evaluated the walkability of two neighborhoods focusing on ten different experiential qualities with a group of human sensors, particularly architecture students. In addition to this research, we made a Space Syntax study including visual integration and axial connectivity, compared the results and searched for possible relations between these two evaluations.

We found moderate to high correlations between the experiential evaluation of the students and the Space Syntax results. These findings confirm the research of Hillier (1992), Hillier and Stutz (2005), Campos et al. (2003), Koohsari et al. (2016) and numerous other studies not covered in this paper.

In this sense, this study is a partial proof that two different approaches to walkability coincide and correlate: a positivist one interpreting walkability as an absolute measure and a constructivist one which approaches this concept as a relative measure.

Furthermore, strong autocorrelations between four Walkability indicators were evident in the correlation table 2 (Aesthetical Appeal, Sense of Place, Sense of Identity, Physical Quality of the Sidewalk). This is a confirmation of our former findings (Pak and Verbeke, 2013). In contrast, some of the variables were not capable of predicting walkability, specifically the inter-subjective ones relating to the human senses such as smell, noise, and wind. These variables did not relate to Space Syntax analysis too.

We found that average of five variables (aesthetical appeal, physical quality of the sidewalk, urban furniture, natural elements, noise) is strongly correlated to axial connectivity ($R= 0.73$) as well as with overall walkability ($R=0.94$). This finding suggests that these specific variables could be used as core indicators for a future experiential analysis.

The study is limited in several aspects. The experiential evaluation was conducted by 40 international architecture students with different backgrounds. This evokes questions on expertise, as well
as on how a smaller group could also provide similar results.

In addition, parallel to our previous study, our comparative research triggered a discussion on possible solutions to the local walkability problems. During the reflection moments, the students were able to come up with a significant number of ideas which revealed the sources of poor walkability and possible design approaches to avoid these.

Besides these aspects we would like to quote an important point brought out by one of the reviewers of this paper: “Limiting the study to the students of architecture introduces a significant bias, most likely because the conceptual frameworks of the students are similar to those who were designing the Space Syntax. In this sense it’s not a coincidence that the correlations are high. There should be a new study with a control group of lay people that would evaluate walkability in an unstructured way.”

After elaborating on our findings, and considering the input of the conference reviewers, the authors conceived the idea of a web platform which integrates location-based experiential and computational evaluations of walkability. This method involves a mobile app that suggests a walkability rating for human observers (lay-people) to reflect on and collect feedback, incorporate this feedback in real-time and create an ongoing evaluation of walkability.

The future aim is to develop and test a tool which can help us understand the change of walkability in time and its relation to social and spatial interventions. A research project proposal concerning this platform and the suggested method is under evaluation, therefore, we are not allowed to share images in this paper (further details will be revealed during the conference presentation).

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A Multiscale Model of Morphological Complexity in Cities

Characterising Emergent Homogeneity and Heterogeneity

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Approaches from complex systems science can support design decision-making by extracting important information about key dependencies from large, unstructured data sources. This paper presents an initial case study applying such approaches to city structure, by characterising low-level features and aggregate properties of artifact morphology in urban areas. First, shape analysis is used to describe microscale artifact clusters, analysed in aggregate to characterise macroscale homogeneity and heterogeneity. The characterisation is used to analyse real-world example cities, from both historic maps and present-day crowdsourced data, testing against two performance evaluation criteria. Next, the characterisation is used to generate simple artificial morphologies, suggesting directions for future development. Finally, results and extensions are discussed, including real-world applications for decision support.

Keywords: Complex systems, morphology, shape analysis, urban planning

INTRODUCTION

In complex systems science, the ‘complexity’ of a system can be defined by the length of mathematical description required to fully encompass the system without redundancy. If all data in the system is entirely uncorrelated, it is highly complex, but only at the finest scale. At a larger scale, like that we are likely to be concerned with when looking at cities, it can be described very simply because the independence of elements implies no larger scale behaviours. The variables can be mathematically described as random. By contrast, if the system contains patterns and dependencies distributed through the data, the mathematical description required includes behaviour at multiple scales. Such ‘complex’ systems are the types of systems that generally exist in the natural world.

Big data is becoming increasingly common, providing incredibly detailed mappings of real-world systems. These massive quantities of data are typically unstructured, and it is often unclear which properties are important for projecting the impact that new interventions will have upon the existing system. Complex systems science provides frameworks from which a system’s intricate multiscale cause and effect relationships can begin to be analysed and understood, when looking at new unstructured data.

Complex systems approaches have been used in studying spatial networks of occupant-centric properties of cities (e.g., land-use, economics, settlement,
transportation), leading to analytic and generative models (e.g., Batty 2005; Barthelemy 2011;2016). Architecture and planning research in this science of cities has been pioneered by Batty, who calls the complex systems understanding of cities a key scientific open challenge (Batty 2008;2013). Complementarily, shape or morphology of urban artifacts and spaces is often studied in architecture and planning (e.g., Beirao et al. 2014), but such analyses are typically not tied to aggregate properties at larger scales.

The dynamics of cities can be understood as the interdependence between the short time scales at which socio-economic characteristics change and the much longer time scales at which morphological structure changes. The large time scale historical process is one aspect of the fundamental way physical structures engage with social and economic dynamics. Complex systems approaches to cities typically model socio-economic forces, and have infrequently been used to understand, model, or characterise morphological properties of urban artifacts (see Figure 1). Here we present an approach to identify the morphological complexity of artifacts, building on existing shape analysis work (see Loncaric 1998; Yang et al. 2008) to characterise important low-level features and their aggregate properties. The characterisation of multiscale attributes of morphology is necessary as a step toward understanding the interplay of physical build with cities’ socio-economic dynamics. Combining such form-centric quantification with studies of occupant-centric dynamics across different urban areas (e.g., data from mobile phones, De Nadai et al. 2016; social media, França et al. 2015; utility use, Morales et al. 2017) can provide opportunities for further advances.

**BACKGROUND AND APPROACH**

Our approach to representing urban morphology follows a method from complex systems science that enables extracting from massive quantities of detailed source data the key high-level characterisations of the system (Bar-Yam 2016). This multiscale method focuses on macroscale patterns that arise from dependencies in the system. In complex systems science, ‘dependencies’ include all properties of a system that allow one to infer one observation of a system from another. This includes the effects of both direct interactions and common origins. The latter is manifest, for example, in the replication of features of a system across multiple parts. The important aggregate properties of the system include cases that can be characterised directly as repetitive structures or behaviours. More elaborate fine scale details that recur across a system are also relevant. This framework replaces the infeasible task of using big data to exhaustively map every detail of a system, with the actionable task of characterising the large-scale information that is required for informed intervention with similarly large impact in an existing real-world system. In this way, morphological interventions in cities can be informed by projections of their impacts, not only on surrounding morphological structure, but on socio-economic characteristics that can be represented with data-driven mathematical models.

Existing approaches that utilise a complex systems understanding of cities to inform new morphological interventions focus on proposing new design solutions or rules of thumb and are termed ‘pattern language’ approaches (e.g., Alexander 1977). These rules of thumb seek to recommend specific design templates for buildings and artifacts, positing that successful artifacts belong to a “pattern language” and unsuccessful artifacts are “anti-patterns.” By contrast, our approach seeks to develop a unified multiscale mathematical model that describes any urban morphological condition, irrespective of design or value set. In a successful unified model of this type, a designer can utilise the mathematical model to un-

Figure 1
Morphologically diverse examples of urban artifact clusters.
understand projections of their design’s impact on existing systems, regardless of the morphological intervention they propose, as the model contains no internalised bias toward certain design solutions. The purpose of the mathematical model is to formalise dependencies between singular design proposals and the collective characteristics impacted by the proposed intervention.

Prior studies have been done analysing morphological characteristics of cities, but typically do so by establishing spatial metrics that summarise an urban area as a whole (e.g., Huang et al. 2007). When making decisions about new urban developments, such an approach is most useful when planning an entire new urban neighborhood. By approaching morphological characterisation of existing and proposed urban systems through a multiscale complex systems science method, we hope to gain new insights into successful urban interventions. New types of insights enabled by this approach are understanding how 1) small local changes might impact the urban area as a whole due to dependencies, and 2) decentralised low-level decisions by occupants might affect centralised planning agendas.

TOWARDS A UNIFIED MULTISCALE MODEL OF MORPHOLOGY

As a step towards a unified model of morphological complexity, we consider a set of historic example cities representing a range of planning paradigms, and a set of present-day cities for which detailed open-source data is available (through the OpenStreetMap (OSM) Foundation’s crowdsourced data [1], Haklay and Weber 2008). We identify a set of morphological traits and characterise the spatial distribution of those traits across cities, through both spatial mapping and mathematical distribution of their values. The microscale representation that we define to mathematically describe the shape of urban artifacts seeks to create a “faithful representation” (i.e. a representation with states that map one-to-one onto the respective real-world system, as described in Bar-Yam 2016). That is, we seek to define a set of variables that describes the repeating microscale attributes of city morphology. Mathematical analysis of the mapping and distribution of component variables is used in building a novel characterisation of homogeneity and heterogeneity in the aggregate morphological properties of the cities, capturing dependencies and important macroscale information. The component variables are then used in generating artificial morphologies, discussed and compared to the real-world cities. We conclude by suggesting future work and extensions for real-world applications.

Method for analysis of real-world cities

Shape description at the microscale. We characterise microscale morphological traits, examining their aggregate properties at the macroscale. The microscale traits are derived from the shape of individual artifact clusters (for instance, city blocks), which we refer to as components. Though in this implementation we limit ourselves to these microscale traits, future development may also include mesoscale traits to characterise the local relationships between neighboring artifact clusters, as well as macroscale traits characterising city neighborhoods.

We conduct several simple shape analyses to build the set of characteristics of components (see Figure 2). The overall description we build of each artifact cluster is contour-based (i.e., based on the xy-points that comprise its boundary, rather than interior points) and is based both on the shape as a whole, and on separated segments (terms refer to the survey of Yang et al. 2008). Our component variables are based on shape description techniques that are as simple as possible. Some are approximated from more complicated techniques in the literature, simplified to extract the minimum information necessary for our purpose. The component variables, each mapped to the domain \([0, 1]\), are as follows:

1. average angle at contour point \((BE)\), approximating “average bending energy” (Yang et al. 2008);
2. quantity of contour points normalised to the maximum present \((QP)\);
3. average normalised segment length (CL), approximating “chord lengths” (Yang et al. 2008);
4. standard area ratio (AR), i.e., perimeter per unit area, normalised to the maximum present;
5. standard normalised area (SA); and
6. average angle of inclination of segment (PA), approximating the major axis of the “principal axes” (Yang et al. 2008).

There is some overlap in the shape features that these six traits individually describes for simple shapes. In other words, some simple shape contours could be described using just one or two of these traits. However, when describing a wide variety of shape contours, the traits describe different properties. In other words, a pair of complicated shapes that have a very similar SA value might have substantially different CL values.

**Historic examples of urban planning paradigms.** We apply the component variables first to a group of historic city maps, selected to qualitatively represent a broad range of urban planning paradigms from various historic periods. The selected cities are Athens, Sabbioneta, Timgad, Milton Keynes, Palmanova, and Heijokyo (see Figure 3). We use historic maps that capture key attributes of the respective paradigm. Unlike the present-day city maps derived from OSM data, the artifact clusters from historic maps are documented manually. We simplify the documented contours using polyline simplification, to remove redundant vertices.

When analysing these historic city maps, we apply the macroscale characterisation to the entire city plan, to capture each planning paradigm. Normalisations are relative to the complete set of components in the city. By contrast, for the present-day cities from crowdsourced OSM data, we apply the characterisation to spatially windowed data, to remove impact of differences in overall city size.

**Morphological homogeneity and heterogeneity.** After quantifying the individual artifact clusters in the historic maps, we consider the aggregate properties of the component variables. We analytically relate the properties to qualitative macroscale information and the planning paradigm of each city. In this context, morphological homogeneity and heterogeneity is an important aggregate property. We charac-
characterise the degree of heterogeneity through the rarity of each artifact cluster’s morphology (frequency of a particular quantitative value). In particular, we test whether this characterisation is able to 1) detect special artifacts within an otherwise regular plan, and 2) distinguish between a city with no central planning and a city designed to look unplanned.

For each of the six microscale component variables, we calculate a rarity indicator as a smoothed distribution of frequencies. For instance, for the rarity $r(x)$ of each component according to $BE$, we sequentially sort all possible $BE$ values $B = (b_1, b_2, \ldots, b_n)$. We calculate the number of occurrences $N = (n(b_1), n(b_2), \ldots, n(b_n))$ of each value present in the components. We smooth the number of occurrences such that $r(b_j)$ is defined as the sum of the values $(n(b_{j-2}), n(b_{j-1}), \ldots, n(b_{j+2}))$, normalised to the number of components present. This gives us the new indicator $rBE$. The concept of heterogeneity established through this rarity indicator is illustrated in Figure 4 for Athens, Greece. In the Ottoman city center of historic Athens, notable for its lack of high-level planning (Kostof 1991), there is an extensive variety of artifact morphology. For the $BE$ value of each component, the spatial mapping and the histogram indicate that the morphology is highly heterogeneous (Figure 4, left). Visual assessment of the city map leads to the same conclusion. However, if we look instead at the rarity of each artifact cluster’s morphology, through its $rBE$ value, the components are highly homogenous (Figure 4, right). In other words, in this example city and according to $BE$, artifact morphology itself is heterogeneous, but the morphological rarity of artifacts is homogeneous – each possible value is almost equally unlikely.

Having calculated the rarity $r(x)$ for all of the component variables, we combine them into a single indicator of an artifact cluster’s overall morphological rarity ($MR$). This overall rarity $M = (m_1, m_2, \ldots, m_n)$ averages $rBE$, $rQP$, $rCL$, $rAR$, $rSA$, and $rPA$, in other words, $m_j = \frac{r(b_j) + r(q_j) + r(c_j) + r(a_j) + r(s_j) + r(p_j)}{6}$. Combining the indicators gives a measure which can be distinct from any one of them. The $rBE$ of Athens is highly homogeneous and has a low mean (see Figure 4), but the $MR$ of Athens is comparatively heterogeneous, with a higher mean (see Figure 5). In this way, $MR$ provides a representation of morphological homogeneity and heterogeneity. We apply $MR$ to analyse both the historic city maps and the present-day cities from crowdsourced OSM data.

**Present-day cities from crowdsourced OSM data.** OSM elements are labelled according to keys developed by the user community (Haklay and Weber 2008), such as amenity, barrier, building, or cycleway [2]. OSM does not include an element type that represents a city block, group of buildings, or similar approximation of an artifact cluster. Obtaining artifact clusters from elements labelled as built structures was found to be susceptible to broad gaps and inconsistencies in this crowdsourced data. We therefore derive contours describing artifact clusters primarily from the elements labelled as roads. We use the following steps:

1. connect coordinates of each element into an open polyline object;
2. perpendicularly offset each polyline segment in 2D by $\theta$ and $-\theta$ (where $\theta = 1$ m);
3. connect the neighboring end points of each
pair of offsets to form a closed polyline outline (i.e., contour);
4. expand each contour by perpendicularly offsetting each segment in 2D by \( \theta \cdot 5 \);
5. remove contours with an area \( \leq \alpha \) (where \( \alpha = 500 \text{ sq m} \));
6. starting with a randomly selected contour, iteratively aggregate (boolean union) with the contour whose vertex (any) is closest to any of the selected contour’s vertices, until all contours are unioned;
7. separate the unioned contour into new individual shape contours, to represent artifact clusters;
8. remove contours with failed boolean unions;
9. remove contours that coincide with OSM elements labelled as parks;
10. add OSM elements labelled as buildings that are outside all contours, to represent a second type of artifact cluster;
11. remove contours with an area \( \leq \alpha \); and
12. simplify the contours using polyline simplification, to remove redundant vertices.

This process results in an approximation of contours for artifact clusters, according to visual assessment (see Figure 6). Though not an exhaustively detailed representation, as one might get by manually documenting or using proprietary map data, it is a useful representation for the current scope of our analysis.

The present-day cities selected for analysis include examples from various continents and cultural influences, as well as planning paradigms. They are Vienna, Austria; Nimes, France; Quezon City, Philippines; Cairo, Egypt; Beijing, China; and Barcelona, Spain. Instead of looking at the full map of these cities (as we do for the historic maps), we select a particular 1.5 sq km area to analyse. When calculating component variables and rarity indicators for each artifact cluster contour, we use a window of 1.5 sq km centered around that contour for normalisations (i.e. including contours outside the analysis window).
Comparison of the full set of OSM elements (left) with the artifact cluster contours derived (right), for Vienna, Austria. As most city blocks in the center of Vienna have a solid perimeter (see Google Earth location [3]), the full set of OSM elements (left) shows the substantial gaps in documentation of individual buildings in this data set.

Results and discussion of analysis

Analysis results of present-day cities and historic maps are summarised in tables 1 and 2, and Figures 5, 7, and 8. We test MR against two performance evaluation criteria, in cities that have interesting relevant attributes. The first test is distinguishing between cities that have no central planning (instead being distributedly organised by inhabitants), and cities that are indeed planned, but are designed with the intention of looking unplanned or “organic” (Kostof 1991). The second test is detecting special artifact clusters within an otherwise morphologically regular city grid. We discuss the analysis results in terms of these criteria.

Distinguishing between planned and unplanned.

From the historic maps, Ottoman Athens is an example of no central planning. The 1960s plan for Milton Keynes is an example of a design meant to look unplanned. Of the present-day cities, examples of little to no central planning in a particular area are Vienna, Austria – old city center; Nimes, France – old city center; Cairo, Egypt – informal settlement neighborhood; and Beijing, China – old residential hutong neighborhood. Multiple present-day examples with low central planning are used, because of the potential variety that may result from distributed organisation. Quezon City, Philippines is a present-day example of a particular area designed to look unplanned, according to the style of the “Garden City” movement (Kostof 1991).

The standard deviation (SD) of MR in Athens is nearly double that of Milton Keynes (see table 1), meaning that Athens is more morphologically heterogeneous. The distribution spreads of MR in the four present-day unplanned urban areas are similar to that of Athens, with three having a larger SD. Nimes has the narrowest distribution spread of the four, next is Vienna, then Beijing, and finally the widest of the four is Cairo. The SD of MR in the planned area of Quezon City is very similar to that of Milton Keynes. Overall, MR characterises the present-day cities in a similar way to the historic maps, according to degree of central planning. This can be visually confirmed in Figure 5. In both the present-day cities and the historic maps, the standard deviations of MR in unplanned urban areas consistently are approximately double that of areas planned to look unplanned (see table 1). Therefore, among the cities analysed, the characterisation MR successfully distinguishes between those that have little central planning and those that are planned in a style emulating distributed organisation. In order to further investigate these findings, a larger set of cities could be analysed.

Distinguishing between planned and unplanned.

From the historic maps, Heijokyo and Timgad are both examples of regularly gridded urban areas with special artifacts periodically distributed. As Timgad is a Roman military town, the special artifacts are civic, while in Heijokyo the special artifacts are imperial (Kostof 1991). Of the present-day cities, a relevant example is the semi-regularly gridded Eixample area of Barcelona, Spain, specifically the area containing the monument Sagrada Familia.
**Method for generating morphology**

We conduct a simple generation of morphology using the characterisation $MR$, in order to suggest directions for future development. First, we generate shapes according to $MR$ and the component variable $QP$. Second, as mesoscale relationships are not currently represented, we distribute the shapes randomly at a sufficient distance that they do not intersect. Third, we spatially condense the shapes through an iterative polygon packing process that preserves their orientations and approximate relative positions (see Figure 9). Finally, we expand the shapes where possible and simplify to remove redundant vertices.

**Results and discussion of generation**

We generate three homogeneous morphology examples and two heterogeneous ones. In each generation, we set $QP$ to no deviation (i.e., all components have $QP$ equal to the mean, before simplification). In the homogenous generations ($MR SD < .03$), we set the $QP$ mean to 4, 5, and 15 (left to right, top of Figure 10). In the more heterogeneous generations ($MR SD > .09$), we set the $QP$ mean to 15 and 4 (left to right, bottom of Figure 10). The results of these simple generations are visually similar to their input degrees of $MR$ heterogeneity. They also give clear evidence for the benefits of extending the characterisation to mesoscale information. Generating morphologies that resemble real-world cities would require input parameters that encompass the organisation and distribution of neighboring components, capturing attributes like density and alignment.

**Future work for a unified multiscale model**

Characterisation of the mesoscale may be incorporated, such that the unified model describes not only individual shapes but the spatial distribution and organisation of those shapes. This would extend the characterisation to better encompass open elements (e.g., plazas), as well as overall structural attributes like density, porosity, and local similarity. Also, generating morphologies according to a full set of variables is an ambitious goal, which could be investi-
gated through shape analysis and machine learning methods.

To support model extensions, contours could be extracted from other data sources. OpenStreetMap data is accessible and sufficient for our current work, but its limits may present obstacles in further developments. OSM’s tagging system [2] does not currently incorporate the designation of open areas as opposed to enclosed areas, making mesoscale information difficult to derive. The accuracy of using thoroughfares as the basis for artifact clusters is also limited. Furthermore, because OSM data is crowdsourced from a member community (Haklay and Weber 2008), small or remote urban areas have limited documentation. For these reasons, it would be useful to extend our method to other sources of city morphology data, such as satellite imagery or light detection and ranging (LiDAR) data (see Jin and Davis 2005; Kabolizade et al. 2010).

The final category of future work is to extend the method to applications by combining our model of morphology with other types of information, such as models of social and economic dynamics. Application to decision-making about real-world systems is a key motivation of the complex systems science approach of extracting important information from large quantities of detailed and unstructured data (Bar-Yam 2016).

**Extending the method to applications**

A possible application of the method would combine it with models of socio-economic city dynamics. This could potentially illuminate phenomena that tie individual buildings to broader occupant behavior (such as the ‘Bilbao effect’ [4]). Additionally, interest has been building in the literature for new methods to analyse the subjective characteristics of built environments and their impact on occupants’ wellbeing (see, for instance, Mouratidis 2017; Sayegh et al. 2016). This interest could be supported by tying morphological characteristics to social media or mobile phone data (e.g., França et al. 2015; De Nadai et al. 2016). Beyond the understanding of city dynamics, the method could be investigated for broader use in generative design, specifically through the representation of high-level design objectives for artifacts that are constructed through self-organisation (see *flora robotica* [5], Hamann et al. 2015; Heinrich and Ayres 2016).

**CONCLUSION**

We presented a characterisation of morphological homogeneity and heterogeneity in urban artifacts, a novel approach to the understanding of multi-scale city morphology as a complex system. Through this, we analysed real-world cities, both from historic maps and present-day crowdsourced data. We used the characterisation to distinguish between emergent urban areas that have no high-level planning and areas that were centrally designed to emulate this effect, as well as to detect special artifacts in an otherwise regular city grid. We also used the characterisation to generate simple morphologies, the results of which support our suggestions for future development.
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Plug-In Design

Reactivating the Cities with responsive Micro-Architectures. The Reciprocal Experience

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Every city has under utilized spaces that create a series of serious negative effects. Waiting for major interventions, those spaces can be reactivated and revitalized with soft temporary projects: micro interventions that light up the attention, give new meaning and add a new reading to abandoned spaces. We can call this kind of operations “plug-in design”, inheriting the term from computer architecture: interventions which aim to involve the citizens and activate the environment, engage multiple catalyst processes and civil actions. Plug-in design interventions are by all meanings experimental, they seek for interaction with the users, locally and globally. Information Technology - with its parametric and site-specific capabilities and interactive features - can be instrumental to create such designs and generate a new consciousness of the existing environment. With this paper we will illustrate how two low-budget interventions have re-activated a forgotten public space. Parametric design with a specific script allowing site-specific design, materials and structure optimization and a series of interactive features, will be presented through Reciprocal 1.0 and Reciprocal 2.0 projects which have been built in 2016 in Italy by the nITro group.

Keywords: reciprocal frame, parametric design, responsive technology, plug-in design, interactivity, re-activate

INTRODUCTION

Plug-in design processes have been first formalized in the context of Sicily Lab in Gioiosa Marea, Italy, to define a bottom-up design process, strongly focused on Information Technology, aimed to the reactivation of public space through interactive participation of the citizenship. Although the very expression “plug-in design” is not common in architecture literature, it is still possible to retrace a class of projects that responds to the definition. Since, as said previously, plug-in design interventions are experimental by their own nature, illustrating specifics design processes is the best way to accomplish knowledge about their purpose, function and result. Therefore,
the paper will go through a definition of the methods and aims of plug-in design, a quick survey of most significant plug-in design interventions and finally an analysis of the design and building processes of two interventions, Reciprocal and Reciprocal 2.0.

**PLUG-IN DESIGN METHODS**
Project’s process is triggered by a crisis, which is seen as an opportunity to develop new and efficient methods to heal under utilized spaces, involving the citizenship and offering a new perspective on the public space, lighting up the qualities that are not perceivable. By their own nature plug-in design interventions seek for interaction, acting as catalysts to generate a new common way of living the city. They suggest a new dimension for urban spaces, in which both the public and private actors will be involved. In the last years many of these interventions have been realized all over the world, generating interest and pointing new paths for architectural research.

**DESIGN PROCESS**
Reciprocal is a plug-in design intervention, a light structure made of PVC bars each supporting the
Figure 2
“Water Playground along the Tiber” is the graduation thesis by Michela Falcone, developed in Rome “Sapienza”, advisor A. Saggio, within the chair project Tevere Cavo. The project, ignited by the crisis of the pollution level of the water, proposes a reappropriation of the river Tiber by its own inhabitants through several multitasking devices which provides, at the same time, leisure areas and decontaminating effects. The design consists in floating mobile structures, labelled as “water tools”, that recall instruments related to the history of the river itself.

other in mutual relations of forces; the structure is temporary, dismountable and reconfigurable, aiming to the minimization of the used resources. From the constructive point of view, the structure has been built using the reciprocal frame model, first conceived by Leonardo da Vinci in the Atlantic Code, in which he details the functioning of the structure and its possible use for temporary shelters and bridges; it's a class of self-supporting structures made of modular, linear elements supporting the weights just by mutual interlacing. Each element works both as a supporting and supportive module, discharging each other's efforts. The minimum module structure consists of three elements, arranged in a triangle in which each element passes over the next and under the previous creating a concatenation of tension and compression stresses. While in Leonardo da Vinci reciprocal structures are following mainly “basket” and concentric geometries, Reciprocal geometry in our case is organic and free form. This is possible by the connection between parametric design and structural, reciprocal, test of the geometry. The Reciprocal 1.0 and 2.0 structures have been realized with a specific parametric software which allows the optimization of the geometry. The optimization process first allows the geometry to have a good structural functioning just by shape, then minimize the number of elements, reducing the quantity of used material. The employment of modular elements allows the structure to be reconfigured in many different shapes, generating a parametric but site-specific piece of design.

Another feature of the structure is related to sound. Reciprocal creates a proper “sonorous environment” thanks to Mogees, a device developed by the Italian entrepreneur Bruno Zamborlin, capable of converting any object into a musical instrument. Mogees is a kind of endoscope that allows to retrace the secret throb of music in common objects or environments, involving the materialization of all those traces that permeate our environment but which go unnoticed. The music produced by the structure is
Albula is an interactive urban device that deals with the pollution crisis of the river Tiber. The installation by Deltastudio (D. Pompei, V. Galeone, S. Massaro), was designed for a young architects competition in Rome and evokes the old roman tradition of watermill along the river. The device generates a reverse ecology taking advantage of water flux, in order to purify the Tiber and giving it back to its citizens. The design proposes a suspended phytoremediation system and generates, at the same time, a new civic space for leisure and play.
Figure 4
TreeIT is an installation designed by nITro in 2013 (Design team: A. Saggio, V. Galeone, D. Pompei, L. Bregni, G. De Francesco, G. D’Emilio, A. De Pasquale, R. Faralli, V. Galeone, D. Motta, D. Pompei) in the historical city of Ronciglione (Vt). This piece of plug-in design consists in a harmonious boardwalk which spreads in several directions, dynamizing the space and outlining its potentialities. Along the boardwalk more than a hundred artificial trees take their place, evoking a natural environment. The trees enlighten through the activation of interactive technologies when people pass nearby: they are mute without the civic action but they light up the environment when the citizens are involved.
Wunderbugs is an interactive installation curated and designed by Francesco Lipari and Vanessa Todaro in Rome. It is a wooden pavilion, realised with simple and repetitive modules, inspired both by the shapes of the Roman Baroque and the geometries insects can generate. Inside the wooden structures six spherical ecosystems host living insects and a number of sensors for motion, humidity and temperature. The data collected by these sensors interact with an audio installation modulating its musical composition.
Figure 6
Reciprocal Algorithm, nITro group

also connected to a light source: the system is regulated by a set of Arduino boards connected to a microphone and a relay system able to discretize the sound wave in acoustic bands of different frequencies. Each acoustic band was matched with a set of LED lights arranged on the top of the bars and spread all over the structure. Aiming to employ the shortest length of cable, a minimal-path algorithm has been developed to identify the optimum path between the light source and the electric board. Therefore, the structure can not only provide shelter for performers, musicians and citizens, but create new “informational” relations between space and sound.

EXPERIMENTAL RESULTS
The paper is not only a description of the software development and the scriptable processes that have created specifically for this projects but also a report of the construction experience, the feedback of the citizens and of the performers. In relation to economical analysis and workflow description, nITro group decided to concentrate on the experience of Reciprocal 1.0, since it represents the beginning of our investigation and the first step of a repeatable methodology. The project has been developed in two main phases: the initial research was conducted inside nITro studio in Rome, the second one in the spaces of Sicily Lab in Gioiosa Marea. During the first phase the team developed the detailed algorithm, realized the models to test the reliability of the structure and of its assembly process using different materials and wrote an assembly manual which allowed to optimize the construction phases, guaranteeing its accuracy. Since the beginning of the software development the estimated time of work has been about a month of a team of 10 people, considering standard work days. It is important to underline that the phase of algorithm design is only needed once, because when the software is completed it can be used on different type of surfaces.

During the second phase the group selected, in accord with local administration of Gioiosa Marea in Sicily, the site of the intervention, which has been measured and digitally reconstructed. The next step regarded the site-specific design, during which we designed the basic surface to be algorithmically processed. This phase took us a about a week. The assembly has been organised in several phases: measuring and cut of the PVC bars in homogenous length (2 work days); assembly of sections of the structure to be joint in-situ (2 work days); in-situ assembly (1 work day). At the end of the exposition the structure
Figure 7
Reciprocal 2.0
digital model and internal view,
Ronciglione (Vt)
2016 by nITro group. Design team: Antonino Saggio, Matteo Baldissara, Valerio Galeone, Davide Motta, Valerio Perna, Gabriele Stancato, Alessandro Perosillo, Silvia Primavera, Manuela Seu, Michele Spano
has been dismounted recovering all the PVC bars in 3 hours. The estimated costs for the material amount to 500 € (200 € for the PVC bars, 90 € for the plastic strips, 125 € for the Mogees). The local administration has also granted a contribution for the amount of the 60% of the total cost.

The feedback from the same administration with the mayor dr. Eduardo Spinella and the Deputy to the Environment ing. Maria Grazia Giardina Papa, has been very positive: in addition to the economical contribution, the local authorities took part in the inauguration of the structure with a public event, showing support and enthusiasm for the initiative. On the other side the citizens interacted with the structure since its assembly phase, exploiting its social potentialities and also showing a certain disappointment knowing that the structure was to be disassembled. The local press and television have reacted very positively to the event, giving room to the initiative and interviewing the design team.

**DISCUSSION**

Despite its character of event-related report, it is still possible to deduce a strategic approach to plug-in design, methods and goals to reactivate the public space with low budget interventions, using the IT as a crisis solver tool. Investigating and promoting new ways to operate in the stratified city using a parametric, interactive design is the main goal of this paper. The authors are also involved in academic work at Sapienza, University of Rome, with the role of PhD candidates, and PhD Program Coordinator. Teaching deals with the impact of Information Technology in architecture. The example of Reciprocal is fit to show not only the theoretical and algorithm aspect of parametric design, but also to involve different layouts and even changings in the algorithm itself due to interaction with students. The project is also scheduled to be built within the MAAM (Museo dell’Altro e dell’Altrove) in Rome, Reciprocal 3.0 will involve the inhabitants that live in this very peculiar environment.
that is at the same time a museum of contemporary art and a community of eleven different nationalities.

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Stratification of Public Spaces based on Qualitative Attribute Measurement

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This paper presents a computational setup for public space quality attribute measurement that leverages GIS technologies, remote access and actual databases. The goal of this research study is to objectify public space qualities established by prior research and verify these in a specific context. In particular, this work uses liveliness as a quality criterion for public space and analyses its interrelationship to space descriptive attributes represented by the objective characteristics of the existing public spaces. The main motivation of this research is to provide for better understanding of public space characteristics that support vibrant social life within contemporary urban settings in Europe.

Keywords: Urban Design, Public Space Quality, Liveliness, Integrative Analysis, Parametric Modelling, GIS

INTRODUCTION

The main goal of this study is to test the interrelation between public space quality regarded through social activity in public space - liveliness - and objective features of existing public spaces - descriptive attributes. Good quality public spaces can impact a wide variety of socio-economic and environmental aspects ranging from increasing the social interconnection and social capital, the promotion of economic exchange and economic effectiveness, influencing of the environment and energy, and issues with liveability and well-being of the residents intended to be served (Madanipour 1999, Carmona 2010, Carmona et al. 2008). However, due to the ambiguity of the concept of public space quality, the choice for its criteria is a difficult task. Public space quality is not a formal problem; thus, there are no specified rules for unambiguous criterion choice (Khan et al. 2014, Beirao et al. 2015). The problem of public space quality is addressed in urban design literature through a variety of descriptive attributes - objective features of space. These are then linked to public space performance attributes that relate to perception and appropriation of spaces by people, mostly through extensive empirical studies.

Since the emergence of the urban design discipline in 1960s, a number of tools for public space quality evaluation and design process support were proposed in the research literature in the field. The tools described use qualitative, as well as quantitative methods. Some are based on the first-hand field observations and are principally theoretical (Canter 1997, Punter 1991, Montgomery 1998, Mehta 2014,
Theoretical frameworks combine findings from preceding research studies that focus on aspects such as social use, space perception, and economic activity (Jacobs, 1962, Lynch, 2012, Whyte, 1980) with studies that concentrate more on the physical form of public space (Cullen, 2007; Krier, 2003). Among the earlier examples of such theoretical frameworks are Punter (1991), Canter (1977), and Montgomery (1998).

With regards to computational tools, Space Syntax employs mathematical methods to study the behavior of urban environments based on topological characteristics of their urban morphologies (Hillier and Hanson, 1993). The determinant factor for movement densities, according to Space Syntax methodology, is the configuration of space (i.e., the structure of urban grid), while economic attractors serve as “multipliers” (Carmona, 2010). There are several measures that can be calculated using Space Syntax, such as integration, connectivity and choice. Urban spaces with higher connectivity and integration values, according to the literature, provide for higher movement densities. Another set of quantitative measures for urban densities is suggested in Berghauser Pont and Haupt (2010). In this study the authors develop a set of indicators that are able to grasp density variations at different urban scales. They underline that varying densities provide for different performances of the built environment, such as degree of urbanity, attractiveness, or privacy and distinguish between “hard” and “soft” performances. The first type can be analyzed quantitatively and is more related to the physical shape of the built environment such as daylight access. The second type, such as place attractiveness, requires more qualitative evaluation and empirical correlation to the “hard” performance indicators.

Beirao et al. (2014) suggest ways for computational representation of urban open spaces in a form of solid voids where a set of morphological attributes of the resulting shapes is measured and interrelated with space qualities, such as enclosure, connectivity, granularity, and others. One aspect that all previously mentioned frameworks and tools share is the use of indicators for urban/public space analysis and quality evaluation. The evaluation process involves the measurement of indicators or attributes for case studies with the goal to obtain certain ratings for individual spaces, as well as to compare and contrast different examples. Measurement outcomes vary depending on the context within which a case study is set; thus, the question that arises is: Do certain indicators’ values mean higher/lower quality of space or not, and what are the criteria against which they should be evaluated? To answer these questions, Berghauser Pont and Haupt (2010) and Beirao et al. (2014) suggest to add a set of performance measures to the descriptive attributes. A similar path is followed within this research work.

Quality and performance of public space is often regarded in urban design literature in connection to vitality, liveability and liveliness. Though, these terms are used interchangeably, essentially, people are at the core of any stipulations regarding vitality or liveability of cities (Jacobs, 1962, Montgomery, 1998, Lynch, 2012, Whyte, 1980, Lennard and Lennard, 1995). The term liveliness can be considered within these two broader concepts. In general, when urban spaces are described in literature as lively, it is most often referred to the level of perceived activity produced by the number of people using space (Montgomery, 1998). However, as precise definitions of the term liveliness vary in research literature (Cilliers et al., 2015), it is defined as a number of people using public space for transit and stationary activities for the purpose of this work.

This research study uses liveliness as a quality criterion (performance attribute) of public space and analyses its interrelationship to space descriptive attributes represented by the objective characteristics of the existing public spaces such as geometry, topology, user profiles, and others, with the main motivation to provide for better understanding of public
space characteristics that support vibrant social life within contemporary urban settings.

The developed method comprises of two main steps: a) identification of “good” public spaces through liveliness measurement, and, b) descriptive attribute measurement of public spaces that were identified as “good” in the first step. This paper describes in detail theoretical and computational setups for attribute measurement in the latter step.

**PROBLEM STATEMENT AND METHODOLOGY**

The main problem identified in most of the writings in the field of urban design is the shortcomings of theoretical frameworks, as well as of computational design and analysis tools, to capture the synergetic relationship between space quality and space descriptive attributes at the necessary level of complexity (Khan et al. 2014). This work suggests a way of constructing an attribute database for integrative public space quality analysis based on the CAD and VPI platforms represented by Rhinoceros [3] and in Grasshopper [6], the algorithmic modelling add-on for Rhinoceros. For data collection and analysis purposes, this study defines an adequate infrastructure that leverages modern GIS-technologies, remote access and actual databases.

In this study, liveliness is measured through the number of stationary and transit activities in space based on methods from the Space Syntax Observation Manual [2] and Zeisel (1986). The measurement results revealed that liveliness is an effective criterion for public space quality evaluation. Using the measure of liveliness, it was possible to determine public spaces that are considered to be successful by the local design experts and lay public. The validity of the developed method may be further supported by the evidence from another research project that uses a different approach to estimate public space quality, as described in Griego et al. (2017). In particular, the study by Griego et al. (2017) is based on the measured emotional response of people to public spaces. The results of this project confirm that people have a high rating of appeal at public spaces with high liveliness measures. Furthermore, the range of received liveliness measures could be clearly associated with particular public space types, such as urban parks and urban squares, as well as with one more context-specific category that was identified in the course of the study - die Wiese. The developed method lays out the basis for the inverse urban design method by starting from captured evidence of ‘good’ public use by means of performance indicator - liveliness, which is then empirically interrelated with descriptive attributes. The set of descriptive attributes that was compiled from the literature review is comprised of 45 attributes in total. It contains descriptive characteristics that a good space should have according to mostly empirical valuations of design researchers and practitioners.

When speaking of descriptive attributes of public space, it is important to recognize that urban space is a scalable category. Jacobs (1962) suggests three scales for exploration of urban spaces, which are: the street scale, the neighbourhood scale and the city scale. She also suggests attributes that are important for each of the scales and that should be mutually supportive to provide for diverse, lively and practical urban environments. The prerequisite for a good urban setting is, according to Jacobs (1962), the diversity of place. Diversity is a complex concept that involves variation of the physical form of place, as well as the social groups of its users, of the activities and uses that place supports. Consequently, scale-based classification of descriptive attributes for this research work was carried out based on Jacobs (1962) with one exception, which concerns the neighbourhood scale. Instead, the present research study considers the catchment area of ten minutes’ walking distance from the analysed public space. Christopher Alexander states that actively used streets must have various uses within ten minutes’ walking distance to provide for the flow of people between destinations as well as for the diversity of activities that they can reach on foot (Alexander et al. 1977). The same logic may be applied to an individual public space. The
more activity in the area around the spot, the more people it may bring into it. Thus, attributes were categorized with respect to the three following scales: city scale, catchment area (ten minutes on foot), and the scale of an individual public space (Figure 1).

Among the city scale attributes are accessibility, connectivity and integration [8]. They characterize how well space is integrated within a city fabric and, consequently, how easily it can be accessed by people. The city scale is defined by the city administrative boundaries.

The liveliness of public space also depends on the activities within the immediate vicinity. It is emphasized in Alexander et al. (1977) that factors such as the number of people living or working, and the diversity of activities or the density of built form within 10 minutes' walking distance from the public space all have direct repercussions on the activity in that particular public space. In the present study, the intermediate urban scale is defined by a polygon that represents the area of ten minutes' walking distance (Figure 2). This polygon is generated by a parametric tool developed in the course of this research study, which uses a graph representation of street network to calculate the distance along the network that a human can walk in 10 minutes. For a detailed description of this tool please refer to Koltsova et al. (2013) and Koltsova et al. (2012).

Finally, the way space is designed and how safe and maintained it is are the attributes of an individual space and should be regarded in relation to the previous two groups. In this research, the boundaries of an individual public space are defined through the cadastral plan or in some cases by the building façade outline surrounding public space (Figure 3).

In practice, the number of attributes of a good public space is large and encompasses about several hundreds of attributes. To reduce the complexity of public space quality evaluation, some studies suggest to sort the numerous attributes into graspable sets (Montgomery 1998, Mehta 2014, Varna 2014). This study begins by combining attributes from the literature into one extensive set. Similarly to the approaches in Varna (2014) and Mehta (2014), and in order to simplify the analysis, the set is then organized into a framework that contains the three following categories: people, interaction and space (Figure 4). The reason for the selection of such categories is the need for a certain homogeneity among the attributes, which is preferable while studying the cumulative effect of a particular category on public space quality. Such homogeneity is a prerequisite in the process of analysing the synergetic effects of multiple, but each of a small influence, range of factors.

The category people include attributes that operate at urban scales above the scale of individual public space (i.e. city and catchment area). They de-

Figure 1
Two attribute sets comprise: a) performance attribute and; b) space descriptive attributes. Attributes are measured at three respective levels of urban scale.

Figure 2
Coloured street network (left) represents the part of the network that a person walks in 10 minutes with the speed of 4.5 km/h; polygon in green (right) represents the area a person can walk within 10 minutes.

Figure 3
Cadastral boundary of Sechseläutenplatz in Zurich is shown as a continuous red line, and the generated boundary as a red dashed line.
fine the potential users of the place, and differentiate between people living/working nearby and the people travelling from other places. For example, in case of spaces of local significance such as local squares, it is important to know the prevailing age groups and their income to understand how well space descriptive attributes fit their needs.

Among the most commonly detected descriptive attributes of public spaces in the reviewed literature are: accessibility, diversity, safety, comfort, connectivity, permeability, transparency, visibility and continuity. Though, many of them are defined as distinct attributes of an urban environment, they have one point in common - they define interaction between people and space. Thus, for the purpose of this study, they are defined as sub components of the interaction category. Also, the interaction between people and space is influenced by how appropriate the scale of the built environment surrounding public space is to human scale (Rapoport 1990). The attributes such as façade transparency, area of “active” façade frontages, building heights or length of building blocks have an impact on the way space is perceived and used by people (Jacobs, 1993, Mehta 2014).

Finally, descriptive attributes in the space category include attributes measured at the scale of an individual public space and cover design elements and their arrangement in space. Table 1 shows the three categories and their corresponding attributes.

**Attribute Data Collection and Preparation**

In the first step of data collection and in the preparation process, space descriptive attributes were organized according to data types. The following groups were identified:

- **Statistical** - the attributes that refer to social aspects, such as people living/working in the area of ten minutes walking distance; N of retail and restaurants; N of activities at/around public space.
- **Geometric** - the attributes that refer to geometry, such as length and width of a public space, height of the adjacent buildings, distance between buildings, and their derived measures such as total area, footprint areas of buildings, space openness and building coverage.
- **Topologic data** - the attributes that refer to topologic street network properties such as integration, choice (Space Syntax measures) measured for city scale, N of transportation hubs and N of embranchment streets measured for an individual space.
- **Design** - the attributes that mostly refer to the design of space and to the properties of elements found within it (ergonomics, interaction etc.)

Next, sources had to be identified to acquire the data. For the statistical data, the two sources used were the statistical data provided by the Statistics Office of Zürich [5], and OpenStreetMap [1]. The office of Geomatik & Vermessung of the City of Zürich [4]
kindly provided the data set containing the information pertaining to the city’s geometric and topologic attributes. For visualization of the statistical data, the acquired GIS data (Shape Files) was converted into geometry within ArcGIS [9] software and exported as .dxf into Rhinoceros. The resultant CAD model required a thorough “cleaning” of geometry, in particular, the remodelling of block instances into Breps (boundary representations), which are the solids constructed from a set of connected surfaces.

The information on the location of the businesses such as shops, restaurants (incl. fast-food and cafés) and attractions such as museums, view points and other public spaces, was exported from OpenStreetMap [1] and imported through the Elk component and through the graphical algorithm editor Grasshopper [6] into Rhinoceros [3]. The process is illustrated on Figure 5. Elk is a collection of tools developed by Timothy Logan for Grasshopper that makes it possible to import maps, as well as topographical information, into Rhinoceros using .osm data from OpenStreetMaps [7].

**Attribute Measurement: Associated Design and Analysis Tools**

The attributes were measured through the means of on site observations, statistical data and urban space digital representations (Figure 6). The latter include plan of Zurich, and the 3D model of Zurich at the level of detail one (LOD1 - extruded building footprints).

To capture some additional features such as the relation between space and elements of building facades, public space photos were employed.

The following analysis methods were used to measure attributes at different levels of urban scale:

- Space syntax analysis methods in DepthmapX [8] (city)
- Data retrieval from GIS through data format conversion (city, catchment area)
- Parametric-algorithmic analysis in Rhinoceros & Grasshopper (catchment area, individual public space)

Grasshopper is a visual programming interface (VPI) that provides additional possibilities for parametric modelling within the CAD platform called Rhinoceros [6]. Such a setup allows for direct and parametric modelling and therefore supports the high flexibility of data integration and manipulation. The attribute data can be combined, measured and stored within a single database in Grasshopper and exported for further multivariate analysis elsewhere.

The data on the number of people working or residing in a walking proximity to a public space has been received from the Statistics Office of Zurich [5]. A polygon representing then ten minute walking distance from the public space was calculated (Figure 7). By using point-in-polygon testing, statistical data for the respective public spaces was extracted from the polygons, resulting in an excel table containing the following data for each space: number of people employed within the polygon area, and the number of residents categorised by age group and income level.
Figure 7
Based on the accessibility analysis along street network (left) the polygon is constructed (middle) and exported as JSON (right).

Analytical Tools for City Scale: Space Syntax Measures
To get an understanding of how well public space is situated within the overall city system, the two attributes measures were analyzed in DepthmapX [8]. The middle lines of the street system were used to run angular segment analysis. The analysis was performed for a 1500-meter radius (which corresponds to the walking distance of 10-15 minutes). The first measure is integration, which indicates how far each segment is from others in a system in terms of topological distance (Klarqvist 1993). The second one is the choice, which indicates network segments with the highest probability of being used, such as a bridge connecting two parts of a city fabric. In this research work, each value (choice and integration) is calculated as an average between the road segments surrounding public space (Figure 8).

Analytical Tools for the Catchment Area Scale
OpenStreetMap served as a data source for transport nodes, retail and other leisure and entertainment facilities within a catchment area. The data was retrieved using Elk component for Grasshopper. The locations of transport nodes, retail and restaurants were represented as points (Figures 9). The analysis of the described locations was used in combination with the accessibility analysis in order to understand the number and kind of functions that can be reached on foot from the analysed public spaces and how those may potentially contribute to the human activity within the spaces. For example, if public space is surrounded by many transport nodes, there is also a better accessibility to it, which makes it attractive for the people who travel to/from their destinations to potentially stop there.

Analytical Tools for Catchment Area and Individual Public Space Scales
Other geometric attributes such as average building heights, average distance between buildings, length of blocks, public space area and building coverage (Berghauser Pont and Haupt 2010) were calculated from the urban model using built in components in Grasshopper at the scale of the catchment area and individual public space. This detailed information regarding the properties of buildings and open space form allows for the understanding of the scale of urban grain and its relation to human scale. According to the reviewed writings, the intricacy of urban form at these two levels of urban scale influences human perception of public spaces and consequently, the use of public spaces (Cullen 2007). More specifically, the interrelation between the area of public

Figure 8
Choice value for one of the segments surrounding public space.

Figure 9
Number of transport nodes from which the space can be accessed within ten minutes’ walk.
space and the height of adjacent buildings influence the level of enclosure. In turn, different degrees of enclosures suggest different viewing and sensory experiences, from a more intimate experience such as having coffee at a small piazza surrounded by historic buildings, to a more exposed one such as doing tricks on a BMX bike in the middle of the square or dancing to Hip-Hop music (Figure 10).

Also, the length of blocks is related to the number of possible routes that bring people to the public space. The more permeable is the area around the public space, the more possibilities for movement there are, and thus, the public space appears lively (Beirao and Koltsova 2015).

RESULTS AND FUTURE WORK
The application of the inverse design support method developed in this thesis for the case studies in Zürich first and foremost allowed to identify the range of liveliness for “squares” as a distinct public space type. Secondly, within this range, the spaces with the highest and the lowest liveliness values were selected and their descriptive attributes were compared in order to test the interrelation between liveliness and space descriptive attributes. The selected case studies are Idaplatz and Brupbacherplatz squares located in the city of Zurich, Switzerland. Both cases are neighbourhood squares mostly used by the local residents and people working close by.

Following the established theoretical framework, the descriptive attributes of both spaces were measured. Measurement results of such attributes as integration, choice, number of retail shops and restaurants, number of transport nodes at the city and catchment area scales did not show a significant difference between the two public spaces. However, at the scale of an individual public space, the attributes that are related to the immediate interaction between people and space scored higher values for the public space with the higher liveliness. Consequently, the conclusion that may be drawn from this result is that for the public spaces of a neighbourhood relevance, descriptive attributes at the scale of an individual public space show a high degree of interrelation to space liveliness. In this particular case, it may be assumed that such spaces are used by people who live or work in the immediate vicinity; therefore, global characteristics such as integration, choice or accessibility measured for the entire urban grid of the city may not play a decisive role in the case of public spaces of a neighbourhood relevance. Table 2 shows a heat map with descriptive attributes values at the scale of an individual public space for both case studies, where Idaplatz received 80% more attributes with higher values than Brupbacherplatz. Consequently, the high liveliness at Idaplatz may be attributed to the diversity of the design elements and their arrangement, as well as to a greater feeling of safety and maintenance, and to the more comfortable microclimate conditions at the scale of an individual public space.

Qualitative information such as the importance of social appropriation of public space should also be added to the above results of attribute measures. Idaplatz has a long history of use by the local residents and it is meaningful to them. It has been continuously used for events such as festivals and open-air cinema. Brupbacherplatz in its current form is relatively new. It has not yet been adopted by the local residents to the same extent as Idaplatz. Possibly, the gradual change of adjacent functions such as retail shops, cafes and restaurants would change the character of the area around Brupbacherplatz and may bring additional vibrancy to the space. In addi-
tion, there is also some restoration work taking place around the square, which should improve the overall appearance of the surroundings.

Table 2
Descriptive attributes measured at the scale of an individual public space

The research results are in line with the current arguments in design and research literature for differentiated public spaces that would fit different processes and activities of varying population groups in the context of changing socio-dynamics in Western European cities. These claims raise further questions about the differentiated qualitative attributes of these spaces which this research work aims at providing the answer to (Carmona 2014, 2015). In particular, it has been observed from the study results that for public spaces of international relevance (e.g. space located in a city centre and tourist destinations) attributes such as accessibility, the number of transportation nodes around, visibility and exposure to the surrounding urban fabric, as well as the choice and integration values measured using DepthmapX (Klarqvist 1993), are important and seem to impact the liveliness in the public space. One exemplary case study is Sechseläutenplatz in Zürich, Switzerland which is located close to the bridge that links the two sides of the city. As an important connection, the bridge receives higher choice values when analysed in DepthmapX. It was observed that the path that goes through this square and connects the end of the bridge to the transport hub is very actively used by pedestrians, which animates the space. On the contrary, such “global” characteristics as choice, integration or accessibility seem to be irrelevant for spaces of local significance such as neighbourhood squares. These spaces are not visited by people from afar and tend to serve the immediate needs of people living and working in their proximity. In this case, the “fit” between the objective characteristics of an individual public space to those needs is important for the degree of liveliness.

To conclude, this work demonstrates the way to combine heterogeneous attribute data as well as various means of attributes measurement within a single setup. Such an integrative approach induces a more systematic view of public space quality and the associated quality attributes. The list of space descriptive attributes derived from literature and used within this work is not all-encompassing. Therefore, the present study suggests technically treating public space as an open-ended model, in which new attributes can be added to the existing database through future research studies. Furthermore, additional data gathered from other case studies and treated statistically to find patterns in the correlations between spatial-morphological attributes and qualitative-behavioural attributes might bring new visions towards the improvement of so called ‘acupuncture’ design strategies, because localized interventions may be applied to produce ‘chirurgical’ transformations in space designed to produce desired effects.

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SPACE PERFORMANCE
Modulated corrugations by differential growth

Integrated FRP tectonics towards a new approach to sustainability, fusing architectural and energy design for a new students’ space

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This Master Thesis research investigates the concept of ‘integrated tectonics’ as a new way of thinking sustainability in architecture, intended as an ecology of different, integrated factors which take part in a seamless design-to-fabrication process. In particular, this new paradigm is applied to the design of a pavilion made of a fiber-reinforced (FRP) sandwich shell integrating multiple systems and performances. A differential growth algorithm mimicking cellular tissue development modulates performance across the surface through ornamental features in the form of corrugated patterns. Iterative feedback simulations allow the exploration of the mutual relations connecting morphogenesis and performance distribution patterns at the architectural scale. Problems connected to simulation inaccuracies and difficult software integration are discussed. A 1:2 scale prototype of a shell portion was fabricated to test material properties and production feasibility.

Keywords: Fiber-reinforced polymers (FRP), integrated tectonics, differential growth, composite materials, ecology, sustainability

INTRODUCTION

This research starts from the intent to design a pavilion hosting spaces for students located on the rooftop of an existing University building in Bologna. The idea of using FRP composite technology comes from its impressive resistance/weight ratio, coupled with a broad morphological freedom, which makes it a prime choice for extreme performance in automotive, aerospace and boat racing. The textile nature of fibers and the production process of composites is strongly surface-oriented, pushing the integration of functions and performances beyond pure structural stiffness as surface features. Therefore, the main potential of this construction system shows up through integrated tectonics approach, one that channels architectural articulation through morphology and organizes tectonic features (massing, structure, ornament) as behaviors deployed across scales throughout the architectural system. Basic principles such as double curvature and thickness variation patterns at the local scale, orientation and layering of the fiber textiles are key factors for structural behavior. That is
why it becomes interesting to develop a system that allows design flexibility and complex control within a continuous surface logic, instead of a stack of discrete, independent systems. Inspiration for the systemic control of corrugation features comes from cellular growth and tissues morphogenesis processes in biology.

BACKGROUND

**FRP integrated tectonics**

The organization of a whole in parts is an essential feature of systems in order to process complexity and growth in the intricate relation between ontogeny and allometry. Architecture makes no exception up until the aftermath of the industrial revolution, in which intensification of labor division and individual parts optimization for the economy of production eventually resulted in the heap of separately designed subsystems that characterize the widespread practice. Even the contemporary architecture characterized by curvilinear forms and fluid aesthetics, still uses framed structures concealed under the surface for load-bearing function and a jungle of different pipes and channels hidden inside unused and resulting spaces for technical systems. Integration is always sought, but never completely reached because functions, physical components and materials are first optimized for a single function and condition and then just put next to each other with little to none interdependency, remaining essentially separated.

Composite materials, instead, allow for a radical shift in the way tectonics can be conceived in architecture. The word ‘composite’ itself means made up of various parts or elements - the analogy with cooking used by Greg Lynn (2011) is particularly explicative here, as it focuses on the transition of the design perspective and scale from a mechanical to a chemical one. Composite thinking is all about layers, fabrics and fibers, glue, additives and resin, all possible materials embedded and consolidated in a unique object. According to Lynn (2011), this new paradigm breaks the traditional juxtaposition of horizontal planes, seen as spaces where organization and motion happens, and vertical elevations, representative of structurally static dimension. Composite shells need double curvature as structural strategy. The same curves and undulations that characterize the shape of boats, aircrafts and cars can be introduced in architectural design, introducing fluid transitions between horizontal and vertical elements, new perceptions and original ways of living the space. This is an unexplored frontier of efficiency and integration, because surface and structure are fused together, so that the envelope can have at the same time load-bearing, insulating and aesthetic properties. Moreover, as explained by Tom Wiscombe (2010), integration can go even one step further and include building systems. In the history following industrial revolution, systems have progressively been considered as a separate and secondary aspect with respect to the supposedly ‘real essence’ of architecture, which was mainly concerned with shapes and structures, objects devoid of processes. They have been either stuffed inside walls and ceilings or exhibited and elevated to an expressive feature, as happened with High Tech. Anyway, in both cases they remained independent and scarcely integrated with architecture. With new composite technologies, instead, true integration of systems in the building envelope discloses new unexplored possibilities. As shown in Wiscombe’s project ‘Batwing’, composite surfaces are highly customizable both in shape and material properties, so that surfaces can fold and wrap creating cavities while resistance to corrosion is no more a problem. Channels can be created inside the composite shell itself and they can conduct fluids and energy systems. Wiscombe (2010) thinks that an extreme interdisciplinary approach and recognition of the relationship between the different parts in terms of ecology are fundamental. Technology can be embedded so deeply inside the architectural surfaces that “high-tech snaps into a higher level of order and begins to appear low-tech again”. This means that biological world is no more so far away. In Wiscombe’s vision, in the future integration between dif-
different features will be so rich that elements will start losing their individuality and functions will blend together. In the end, the goal is interdependency: a single function or task will be performed by a multiplicity of elements, while each element will be able to perform a multiplicity of tasks and functions.

**Morphogenesis and growth**

Cellular morphogenesis is a well-known phenomenon in biology and science-related fields and literature is full of studies about the relationship between growth and form in nature. A particularly interesting reference for this research is the paper ‘Cellular Forms’ by Andy Lomas (2014), in which digital experiments are aimed at creating extremely complex, organic structures emerging from a relatively simple model of cellular growth. Results show an incredible similarity to biological organisms, organs and plants. The model is inspired by cellular division and deliberately conceived as simple as possible, allowing a wider range of possible developments. Each cell is represented by a sphere connected to a certain number of uniformly distributed cells around its surface. Cells can receive nutrients from the environment and they can split in two when these nutrients reach a certain threshold. Cell division causes the creation of new links with neighbor cells, altering the overall network topology. At the same time, internal forces compete to determine cells relative positions until local equilibrium is reached. Links between cells tend to maintain their original length, like a sort of elastic bond, while other forces stimulate cells to assume planar arrangements or, otherwise, boost their tendency to bulk. Depending on various combinations of these forces intensities, different spatial arrangements arise. It is interesting to outline that all the different structures generated by this algorithm arise without cell differentiation; that is, cells are all the same type and behave the same way. In case nutrients are evenly distributed in space, a uniform growth takes place, producing emergent arrangements which mainly look like internal organs. Otherwise, if nutrients production is stimulated by incident sun rays and their diffusion rate among cells is low, plant-like structures tend to arise.

Another interesting reference project related to differential growth is ‘Floraform’ by Nervous System (2014). This work is inspired by growth mechanisms of plants and, in particular, it follows L. Mahadevan’s studies on the shape of rippled leaves and blooming flowers (2010, 2011). Mahadevan suggests that the creased shape of many leaves and flowers can be the result of an increased growth rate at the edges of the developing plant surface. It is all about some parts of the surface that locally grow more than others, generating macro-shape differentiation and specific structures. Another example is tropism: a plant can respond to light directional stimuli growing more on one side of the stem than the other: as a macro scale consequence, it bends towards the sun. Nervous System selects and analyzes a series of organisms and plants that show this kind of ruffled shape and develops an algorithm to simulate differential growth with digital tools. Unlike Andy Lomas’ model, where cells are discrete particles aggregating in space, in Nervous System’s simulation they are represented by vertices of a mesh, so that their arrangement follows a surface logic. Nevertheless, internal physical rules defining elasticity and collision detection among cells are similar in both the studies, showing that, not surprisingly, these principles are the basis of every possible elastic material organization. In Nervous Systems’ algorithm, the mesh longest edges split when they reach the maximum length allowed, consequently creating new edges and changing the mesh topology. Changing the starting conditions of growth leads to different mesh morphologies: in particular, increased subdivision along the mesh perimeter leads to beautiful blossom-looking structures.

**CASE STUDY**

The pavilion is designed to host students’ spaces for the University of Bologna’s School of Engineering and Architecture building in Via Terracini, out of the city center. Despite a planned major University expan-
sion for an adjoining area in the near future, this cur-
rently is an isolated and uninviting place. In partic-
ular, except for a small cafeteria, there is an evident
lack of services and leisure spaces in general. The new
spaces are meant to fill that gap and create socializa-
tion opportunities for the students’ community. The
chosen location is on top of the existing building, giv-
ing function and purpose to an easily accessible yet
unused terrace and avoiding the occupation of new
land. The pavilion is shaped following general design
principles of double curvature use for continuous sur-
faces and the necessary topology to accommodate
flows and functional spaces within said principles. A
differential growth algorithm inspired by cellular tis-
sues in biology is then developed in order to act on
its external surface and create corrugation patterns.

MODULATED CORRUGATIONS
This study is not meant to reproduce or emulate a
specific biological process or morphology in terms of
results. Instead, it aims to explore the relation be-
tween elementary behavioral principles at the ba-
sis of tissues growth and differentiation in general
and the range of achievable ordered complexity in
patterns and shapes. The final goal is to channel
the potential these forms can offer to architectural
applications, and, specifically, to the present case
study. Before undergoing differentiation and ac-
quiring specificity, tissue development always starts
from the same set of simple rules. The environment
plays a leading role in giving direction to the process
through a feedback mechanism. Differential growth,
in particular, is based on the idea that the parts form-
ing a whole grow with heterogeneous patterns and
rates, producing differentiated morphologies and ar-
rangements, without any change occurring at the cell
level. In the present case study, the starting point
for the simulation is the pavilion outer shell surface,
modelled as a triangular mesh. Each mesh vertex rep-
resents a cell in a tissue and, therefore, it can be con-
sidered as a sort of moving particle constrained to
stay on the mesh itself. The growth is implemented
through an iterative process articulated in two nested
loops. The inner loop, called ‘β - Cycle’, allows the
mesh to act as an elastic membrane and represents a
basic relaxation process, driven by elastic and repul-
sive forces. The outer loop, called ‘α - Cycle’, selects
and subdivides the mesh faces, according to a feed-
back mechanism, and feeds them to the ‘β - Cycle’.A variable number of both α and β cycles iterations
leads to completely different growth processes: one
of them is represented in Figure 2 through successive
iterations of the ‘α - Cycle’. A diagram explaining the
overall process is shown in Figure 4.

Figure 1
Overview of
existing building
and the new
pavilion on the
rooftop.
**α - CYCLE**

**Feedback selection**

In this phase, feedback criteria play a fundamental role in driving the selection of mesh faces to be subdivided in the next iteration. This important step qualifies the growth process as ‘differential’, as only the selected and subdivided faces will be able to grow. Selection operates in both bottom-up and top-down approaches, as described below.

**Top-down selection.** Top-down selection takes place at the beginning of each α - Cycle, according to a series of environmental criteria based on performance principles and design decisions. Those external influences are color-mapped on the pavilion outer shell mesh, creating different scalar fields which are used to assign specific values to each mesh face. Performance criteria aim to interpret and address real structural and energy problems previously detected through specific dedicated simulations (Nerla et al. 2017). The growth process makes use of a simplified implementation, avoiding the inclusion of over-complicated simulations with negligible impact on the workflow. From the point of view of energy performance, detailed simulations based on the software EnergyPlus show that the most critical period for the pavilion is the hot season. That is because its lightweight structure has low thermal inertia and is highly exposed to solar radiation. For this reason, the first performance criterion included in the process is a whole year solar radiation analysis: faces with higher values of solar radiation are selected for subdivision. The aim is to induce corrugations in areas where the surface overheating is more likely to occur in order to introduce a distributed self-shading effect. From the structural point of view, preliminary analysis carried out with the Grasshopper plug-in Karamba displays that excessive deformation is likely to occur on the thin composite shell; the second performance criteria introduced depends therefore on the shell deformation data: faces in areas of high deformation are selected for subdivision. Here, the idea is to use the curvature activated by corrugations as local stiffening device.
Moreover, in order to partially address the process with top-down design decisions, the outer surface of the pavilion is mapped with a specific distribution of “nutrients”. It is generated starting from flow lines, representing functional criteria, relationship with the existing building and, again, simulated structural force flow. Zones with higher concentration of nutrients cause the faces next to these areas to be selected before the others. In other words, growth starts where there are more nutrients and then it progressively expands to other areas. This mechanism is further explained in the bottom-up selection section. In conclusion, faces are selected combining data from radiation or deformation analysis and with nutrients concentration, with the resulting set undergoing the consequent bottom-up selection process.

**Bottom-up selection.** Mesh faces from the top-down selection are then checked by bottom-up criteria. The latter are meant to act at the micro-scale of the individual face, regardless of the overall geometry. The first check controls that all the faces have an area which is greater than a certain threshold. In this way, smaller faces are excluded from selection. This is meant to avoid selecting faces that have just been subdivided in the loop before and have not yet had the time to grow enough. This principle explains why the top-down selection based on nutrients is different at each cycle: while areas with higher concentration of nutrients are still growing up, other areas with lower nutrients are progressively selected. After the first subdivision has occurred, a second selection is made to isolate the faces adjacent to the borders of the previously subdivided areas. These border faces are then subdivided a second time.

**Subdivision rule**
A geometric rule governs the subdivision of selected faces. Each triangle is divided into three smaller triangles connecting each vertex to the barycenter (Figure 3). When multiple adjacent faces are divided at the same time, a routine check compares old edges with their flipped equivalent and selects the shorter ones. This ensures a better topology for the mesh. The subdivision stage is repeated twice only on faces along the borders of the selected areas.

**β - CYCLE**

**Internal forces.** Internal forces are introduced to make the mesh behave as an elastic membrane and help keeping it consistent, avoiding self-intersection. This kind of forces govern the relaxation process.

- An elastic force is represented by springs along the mesh edges: they connect the points and tend to keep them at a certain relative distance from each other. Parameters influencing this kind of force are the springs rest lengths and the springs strength.
- A repulsion force prevents the mesh from self-intersecting or overlapping: each point tends to repel a certain number of neighbor points within a fixed distance and with a specific repulsion strength.
- Anchor points maintain a fixed position during the entire relaxation process. In this case, such points belong to the perimeter of the mesh. Their neighbor points have a limited mobility, in order to have a smooth transition between the fixed border and the other central points.

**RESULTS VARIABILITY**
The process outcomes show high variability depending on the chosen combination of values assigned to the different parameters. Figure 5 shows how one of the resulting morphologies, taken as a benchmark with fixed parameters, can differentiate when one or two parameters change their values. Parameters such as ‘Nutrients Gradient’, ‘Min Face Area’ and
Figure 4
Diagram of the process workflow.
Figure 5
Variations of possible results, obtained changing some relevant parameters.
‘Neighbors selection’ belong to the feedback mechanism. The first one is related to the scalar field of nutrients assigned (mapping shown in Figure 4), whose values can change their distribution or can be inverted, as shown in the sample number 1 in Figure 5, so that the highest value becomes the lowest and vice versa. In the benchmark, ‘Min Face area’ is variable between two values because it is different for each mesh face and based on the amount of solar radiation they received. Examples such as samples number 3 and 5 in Figure 5 show what happens when this parameter gets a fixed value, respectively the minimum and the maximum. ‘Neighbors selection’ refers to the number of faces which can be selected around the points with highest concentration of nutrients, at each α - iteration. Parameters such as ‘β - Cycle’ and ‘Repulsion Strength’ belong to the relaxation process and affect, in turn, the number of iterations performed in the β - Cycle and the repulsive force strength.

**PROTOTYPE**

A small part of the pavilion shell is selected and adapted for fabrication. The idea is to test in a smaller scale and with a lower budget approximately the same workflow, techniques and know-how that can be used for the entire pavilion fabrication off-site. A scale of 1:2 is chosen for this prototype, resulting in a 0.6m x 1.2m fabricated panel. The prototype uses the same material system as the pavilion: an FRP sandwich, composed of two thin FRP laminates and a polyurethane (PUR) core of variable thickness in the middle. The laminates are made out of textile fibers and resin: in particular, carbon fiber (CFRP) has been used for the external laminate, while glass fiber (GFRP) is in the inner side of the sandwich. This system is extremely light and resistant, it is load bearing and thermal insulating. Moreover, electrical systems, part of drainage and conditioning pipework is integrated inside the PUR core, as well as a LED lighting system. The latter is placed adjacent to the GFRP laminate, exploiting their typical translucency to create a glare effect in the evening hours.

Figure 6

**Picture of the fabricated prototype and exploded view showing the different layers.** The prototype was fabricated by Stilplast S.r.l. and IDesCo, with the precious consultancy of Mattia Mercatali for mould engineering and composite design.
DISCUSSION AND CONCLUSION

The resulting morphologies show interesting patterns that vaguely remind of biological distribution systems and branching. Different phases of growth are present at the same time on the shell, showing a wide range of possibilities and enabling smooth transition from flat to corrugated surface. Aesthetic criteria, as well as energy and structural performance aspects, influence these patterns in a way that blurs the boundary between performance and ornament. The same occurs in biological organisms: it is impossible to distinguish if a certain task is performed solely by a single part, because it might be carried out by a multitude of different components together, while at the same time it is hard to detect the entire range of functions pertaining to a single part. Considering that this extreme integration of different aspects (interdependency) is one of the defining characteristics of ecosystems, brings up the concept of sustainability in a broader sense. Nowadays, sustainability protocols tend to be holistic, taking into account all different aspects of a project by setting up checklists. There, the sum of all the points assigned to every single aspect gives an evaluation of the project sustainability. This approach encourages designers to optimize each aspect taken separately, regardless of its interaction with others. This scenario reduces complexity of reality, suggesting that the sum of local optimizations gives the best possible solution. On the contrary, we could rather say that the total is more than the sum of the parts, because global coherence and interrelationships between different aspects could matter more than the sum of the single optimizations (Nerla et al. 2017).

Implementing this kind of complexity and integration of different aspects through the use of software is not easy. For this research, the authors used Grasshopper for Rhinoceros 3D and a series of specific plugins for modelling, energy and structural analysis, such as Karamba, Honeybee and Ladybug. Unfortunately, these tools have revealed their weaknesses in trying to handle more complex, unusual and detailed situations and correlations. For example, growth and energy simulations required models with very different resolutions, as the detailed corrugations in the overall model could not be precisely handled by energy simulation software. This leads to errors and imprecisions that make results unreliable. Energy Plus, anyway, is good for overall building simulation. As there is no software available in the market which could be able to support this integrated approach, an ad-hoc software could be useful. Nonetheless, software integration is not the main obstacle towards the direction proposed in this paper. In fact, at the basis of innovation there should be a radical shift in the common mindset, avoiding segregation of different disciplines, industries and professionals during the design process.

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Parametric Room Acoustic workflows

Review and future perspectives

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The paper investigates and assesses different room acoustics software and the opportunities they offer to engage in parametric acoustics workflow and to influence architectural designs. The first step consists in the testing and benchmarking of different tools on the basis of accuracy, speed and interoperability with Grasshopper 3d. The focus will be placed to the benchmarking of three different acoustic analysis tools based on raytracing. To compare the accuracy and speed of the acoustic evaluation across different tools, a homogeneous set of acoustic parameters is chosen. The room acoustics parameters included in the set are reverberation time (EDT, RT30), clarity (C50), loudness (G), and definition (D50). Scenarios are discussed for determining at different design stages the most suitable acoustic tool. Those scenarios are characterized, by the use of less accurate but fast evaluation tools to be used in early design stages, or by more accurate but slower tools for later-stage design stage detailing and delivery phases.

Keywords: Geometrical Acoustics, Parametric design, Real-time acoustic analysis, Virtual reality

INTRODUCTION

Despite the increased recognition of acoustic as a primary and important factor in the well-being and health of people especially in urban environments, issues relating to acoustics are often considered late in the architectural design process. When acoustic specialists are involved in late design stages, the improvement and optimization of ill-conceived designs becomes difficult and costly. The involvement of specialists in early design stages is not encouraged in the current paradigm: consultants typically use independent models for acoustic analysis, separated from the CAD environment, rendering inefficient and time-consuming the processes of generation and evaluation of different design proposals. Each iteration involves operations as simplification of the CAD model, exporting, and application of acoustic attributes to surfaces. Those operations require to spend considerable time in coordination and communication among the parties involved. The exchange of information is not continuous and it makes it difficult to engage in heuristic design process.
On the other hand, recent advances in the architectural design processes have seen the increased popularity of parametric software as Grasshopper3d for McNeel's Rhinoceros. This environment allows to develop only one parametric model where both architectural and acoustic design are updated synchronously. Iterative design processes are enabled, encouraging the investigation of geometry exploration with performance analysis already from the early design stages.

Conventional CAD systems focus design attention on the representation of the artifact being designed. Currently industry attention is on systems in which a designed artifact is represented parametrically, that is, the representation admits rapid change of design dimensions and structure. Parameterization increases complexity of both designer task and interface as designers must model not only the artifact being designed, but a conceptual structure that guides variation [Aish, 2005].

In such environment designs are conceived within a topological space, i.e. a non-metric space built by the relationship among geometric entities subjected to a prescribed set of generative and transformative actions [Aish, 2013]. A topological space allows rapid changes in the design and geometry through a set or parameters, and allows to rapidly explore multitude of geometrical configurations.

While the definition of a parametric model requires more effort while compared to a model which merely represent the artifact being built, parametrization enhance exploratory design phases by facilitating iterative processes between form exploration and performance evaluation. Iterative, and interactive processes, are enabled since early design stages.

The present paper investigates the interoperability of three different acoustics analysis tools with Grasshopper3d, by benchmarking speed of analysis, accuracy, and speed of exchange of data between the geometric and the acoustic model.

**AIM AND METHODOLOGY**

During the last decade parametric design systems has started to emerge as a tool for architectural design. Such an environment allows to add levels of information to the geometrical primitives, assigning attributes which in turn allows to create an uninter-
rupted chain of information from the geometrical model to analysis tools and BIM software through IFC library. This has sparked novel design processes which attempt to bridge the gap between architectural and engineering design by improving the exchange of data between Grasshopper and analysis software. In particular it is possible to witness the diffusion of plugins dedicated to structural analysis and environmental analysis that follow mainly two different paradigms:

1. (i) the use of customized analysis tools developed and integrated within the same environment of the geometric model:
2. (ii) the use of plugins which enable a continuous transfer of information to external applications as commercial software.

Both the alternatives have advantages and disadvantages [Mendez et al 2013]; on the one hand, the use of integrated software allows to maximize the speed in which the output of the analysis is retrieved, making it more useful whenever a fast feedback loop needs to be established, for instance with the use of optimization algorithms [Mirra et al, 2016, Saviola & Svensson 2015]. On the other hand, the use of interlinked external software requires more time for retrieving the output, but it allows typically to access more in-depth tools and purposely developed interfaces for analysis and evaluation.

Three different geometric acoustic analysis tools have been chosen as case study to assess their potential in engaging in parametric design processes: Pachyderm for Rhino and Grasshopper, CATT, and EMRT-system. While each software is based on ray-tracing, they differ substantially in terms of modelling interface, interoperability, target users and speed of analysis.

**Geometrical Acoustics**
The acoustics of a room can be modeled under several different frameworks and for various purposes.

The two main approaches are based either on numerically solving the wave equation or on the assumptions of geometrical acoustics (GA). In principle, wave-based modeling is able to provide the most accurate results. However, these techniques are computationally very expensive; thus, it is often more ap-
appropriate to resort to faster but less accurate techniques such as those based on GA.

In GA, all of the wave properties of sound are neglected, and sound is assumed to propagate as rays. This assumption is valid at high frequencies, where the wavelength of sound is short compared to surface dimensions and the overall dimensions of the space, but at lower frequencies the approximation errors increase as wave phenomena play a larger role [Parker et al., 2010].

In GA each ray carries information on how far it has travelled (l), and how much energy it contains (e). Each surface of the model is prescribed two numerical values in the interval of 0 and 1: absorption and scattering. The absorption coefficient describes how much of the incoming energy that is absorbed. Scattering decides whether a ray is reflected in a specular reflection, as light in a mirror, or scattered, as light on a piece of white paper.

When a ray intersects with a surface, three things happen:

- The distance between the intersection point and the sound source is added to the total distance the ray has travelled. Multiplied by the speed of sound, this gives the delay of the sound impulse from this path.
- The absorption of the surface is multiplied by the energy the ray carries. This gives the amplitude of the sound impulse of this path.
- A new ray direction is calculated, and a new ray is sent out, with added travel distance and lowered energy from the collision.

When a ray has a negligible remaining energy, its propagation is terminated. When all rays are terminated, the impulses from all different paths are gathered to form the impulse response of the room. From this, most common acoustic parameters (Reverberation time, Definition, Clarity, Early decay time etc.) can be calculated.

**Pachyderm**

Pachyderm is a plugin developed by Arthur Van der Harden. It is an open source acoustic engine embedded into the Rhinoceros 3D(TM) modeling environment [1]. Pachyderm has both a Rhinoceros interface and a Grasshopper interface. Pachyderm allows representation of curved surfaces with NURBS, without resorting to discretization into planar elements, typically meshes. By allowing access through scripting
interfaces, it intends to facilitate customization and new possibilities for creative use of simulation technology.

Figure 11
Isometric view

Figure 12
Plan of the classroom

Figure 13
Absorption coefficients

Figure 14
Picture of the classroom

The results of the analysis can be retrieved directly into Grasshopper, enabling a seamless exchange of data between geometric and material variations and their impact on the acoustic performance. This software belongs to the paradigm (i), i.e. it is a tool embedded in the parametric environment that allows a continuous stream of data between the parametric model and the analysis. However, due to the time required for an acoustic analysis, the stream of data is slow and the benefit of the complete integration within Grasshopper cannot be taken full advantage of.

**CATT**

Computer Aided Theatre Technique, CATT is a room acoustic prediction and auralization software. The developer of CATT describe their prime users as room acoustics consultants and universities.

The geometry is handled through input-files are in text-format and the data entry is done using any suitable editor or via an export from AutoCAD and SketchUp. A DXF-conversion via DXF2GEO or via a modeling plugin is provided. The input-file format has been made very forgiving allowing for blank lines and comments and symbolic constants, expressions, calls to math functions, IF-statements, tracing statements, loops, interactive input, and hierarchic files for the geometry are incorporated.

The author D. Parigi has developed a plugin which exports Grasshopper and Rhinoceros geometries to CATT through the generation in real-time of a geometry input file. Parametric variations are immediately reflected in the file that is read from CATT. This process belongs to paradigm (ii), where a plugin allows to enable a continuous transfer of information to external applications as commercial software. The benefit of CATT is the possibility for extremely accurate analysis and auralization through a dedicated interface.

**EMRT-System**

The EMRT-system is a GPU-accelerated geometric acoustic engine, using stochastic ray tracing. This means that sound energy is propagated by rays travelling in straight lines, interacting with room surfaces. The system is implemented by author E Molin using the Nvidia ray tracer OptiX [9]. It is implemented as a library to facilitate integration with CAD software, and the long term design goal is to allow acoustic evaluation early in the design process. The au-
thors E Molin and D Parigi are currently developing a plugin for the full integration of the EMRT-system in Grasshopper. The current benchmark does not yet use the plugin, but a transfer of data between the software through txt files.

At this moment therefore this software belongs to paradigm (ii), while future work is intended to provide a full integration within Grasshopper. The benefit of this software is the speed of calculation thanks to the use of GPU processor. The speed allows to take full advantage of a complete integration within a parametric software.

**BENCHMARK**

The software is benchmarked on two spaces for learning. The first is a classroom in Malmö and it was chosen because the classroom acoustical performance was assessed and documented in the report: “Measurements of room acoustical parameter in classrooms” by Ingemansson Technology AB, Project manager Leif Akerlof, 8/11/2005. The report has been provided by the author D. Bard. The report provided the data necessary to validate the results from the acoustic analysis tools. The second is a classroom in Montecarasso and it was chosen due to the unique spatial and architectural qualities of the room. The double-height and curved ceiling challenge the typical box-shaped rooms for classrooms and together with the asymmetry of the room it was deemed as an ideal room to test the response and consistency of the software in analysis.

**Malmö**

This section presents the results of the analysis on the Malmö classroom. The geometry and the materials of the room are shown in Figure 1,2,3,4. Figures 5 to 9 show the results for each of the acoustical parameter and Figure 10 plots the time required for the analysis for each software.

**Montecarasso**

This section presents the results of the analysis on the Montecarasso classroom. The geometry and the materials of the room are shown in Figure 11,12,13,14. Figures 15 to 19 shows the results for each of the acoustical parameter and Figure 20 plots the time required for the analysis for each software.
DISCUSSION

Each of the analysis has been carried with a number of rays calculated with 50 times the volume of the room in cubic meters. Such number of rays has been chosen as it guaranteed very stable results, while it should be noted that consistent results are obtained already with a number of rays 25 times the volume. Differences among software is relevant but satisfactory. In particular in the Malmo classroom the presence of measurements validates the results of the analysis of the ray tracers, despite differences are found in the order of 10% across the parameters. At the same time it is very important to understand how sensible is the human hearing system to variations in all acoustical parameters, i.e. how big a difference is perceived by the listener. This values are called Just Noticeable Differences (JNDs). The ISO 3382-1 standard reports a JND for EDT of 5%, for C80 of 1 dB, for G as 1 dB (Mendez, 2013). Despite variations in the results may be in some acoustical parameters the order of two times the JNDs, the benchmark shows that such a result can be attributed to the intrinsic limitations of geometrical acoustics rather than to a specific tool. Results differ across software and depending on the acoustical parameter in analysis. Despite CATT offer more possibility to fine-tune the analysis and potentially obtain more accurate results, the present study is aimed at the present stage to early design stages, where a balance between accuracy, speed and interoperability is crucial to facilitate the integration of acoustical considerations. In this respect particular relevance assume the results obtained with the EMRT-system (Figure 21), where a dramatic reduction in the time of analysis is coupled with a good accuracy of results and integration with parametric environment.
FUTURE WORK
The design process is assumed to have an iterative nature as illustrated in Figure 22, where a number of design alternatives can easily be generated and analyzed with regard to a number of performance criteria including acoustics among others. The analysis results from different disciplines form the basis for negotiations and common decisions among the involved parties, leading to suggestions for improvements of the initial design proposals. In this process, there may be a need to present analysis results in different ways depending on the audience. Professionals in engineering and architecture will typically communicate results from analysis and simulations in a technical language, which will not necessarily be understood by non-professional end users of the planned facilities. To facilitate the presentation and discussion of design proposals and the analyzed acoustic performance with end users, it is the intention in the current research project to test a combined virtual reality solution, which includes both visual and acoustic aspects of the design proposal. In this respect the EMRT system shows good potential for integration with virtual reality toolboxes.

CONCLUSIONS
The paper has investigated and assesses different room acoustics software and the opportunities they offer to engage in parametric acoustics workflow and to influence architectural designs. The benchmark of three different acoustic analysis tools based on ray-tracing has showed the suitability of each software to different design stages and to different user type. Moreover, it has showed how the dramatic drop in the analysis speed of the EMRT-system, coupled with a good level of accuracy, enable new design paradigms, by linking real-time acoustic analysis with virtual reality toolboxes.

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Machinic Agency

Implementing aerial robotics and machine learning to map public space

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The research presented in this paper is focused on proposing a new digital workflow, involving unmanned aerial vehicles (UAV) and machine learning systems, in order to detect and map citizen's behaviors in the context of public spaces. Novel machinic abilities can be implemented in the understanding of the human context, decoding, through computer vision and machine learning, complex systems into intelligible outputs (Olson, 2008), mapping the relationships of our reality. In this framework, robotic and computational strategies can be implemented in order to offer a new description of public spaces, bringing to light the hidden forces and multiple layers constituting the urban habitat. The presented study focuses on the development of a methodology turning video frames collected from cameras installed on drones into large datasets used to train convolutional networks and enable machines learning systems to detect and map pedestrians in public spaces.

Keywords: mapping, drones, machine learning, computer vision, city

INTRODUCTION
Nowadays technology can be considered an established force, producing a deep impact on political and economical choices shaping cities and urban habitats. In the case of Responsive Cities, sensors embedded into everyday objects are adopted to gather data and produce information describing multiple urban realities. These networks of sensors are becoming an additional layer over the City’s infrastructure, yet only able to respond in terms of limited outputs to the different inputs gather from the surrounding. This study is a first step towards the implementation of unmanned aerial vehicles (UAV) as data collection agents in the delicate context of the city, turning drones into a new dynamic infrastructure able to potentially adapt to its surrounding, establishing stigmergic relationship among all different factors shaping the urban habitat. Drones can be programmed as agents that can complete their objectives while situated in a dynamic and uncertain environment (Jennings, 2000). In our effort to develop a dynamic robotic system, this research focuses mainly on the ability of drones to detect pedestrians and map citizen’s behaviors thanks to artificial intelligence aided-decisions tools. Many computational models for pedestrian detection are and have been developed based on different methods such as edge-based detection (Geismann et al., 2008), infrared detection (Bertozzi et al., 2006), wi-fi signal trace detection (Danalet et al., 2014). Those methods have
proved a solid reliability, allowing to recognize profiles of pedestrians under different lighting conditions testing multiple camera filters. In this paper we propose to adopt a very diffuse edge-detection algorithm based on the histogram of oriented gradients (HOG) and local binary pattern (LBP), merging computer vision algorithms to detect specific targets and drones ability to provide multiple information from alternative perspectives. Algorithms for pedestrian detection have received also very limited implementation in proper mapping operation, mainly adopted to quantify spaces, but very little to map urban areas and trace behaviors of crowds or individuals within the public space. Thus, we can assume that this study is promoting a new ground in the development of an intertwined robotic and computational infrastructure able to inform advanced mapping operations. (see Figure 1)

As a case study for this research, it has been selected the urban area of Barcelona known as Poblenou. This neighborhood has recently been transformed, thanks to the implementation of a new urban model called Superblock, which the municipality of Barcelona wants to adopt in different areas of the city. Several studies demonstrated that in the Barcelona’s metropolitan area, air pollution is responsible for more than 3500 premature deaths each year, provoking critical effects on local ecosystems and agriculture. According to the World Health Organiza-

METHODS
The research presented in this paper wants to offer a new dynamic methodology to map and understand public spaces, tracking flows of pedestrians using cameras installed on drones, computer vision and machine learning. The overall process brings together technologies from the field of aerial robotics, computer vision and machine learning. The research protocol is structured in three different operations, from the generation of customized drones to the definition of precise data acquisition process and finally a data interpretation methodology implementing computer vision and machine learning. The following description of the study will deepen into the process mentioned above.

Drone Customization
The first part is focused on the construction of a small parametric drone implementing GPS sensor which makes it programmable for autonomous operations and enables to set specific instructions as georeferenced missions. The software used for this stage is McNeel’s Rhinoceros3d and it’s plugin platform Grasshopper3d, a visual scripting platform based on a parametric modeling logic. Grasshopper incorporates many add-ons implementing multiple logics from structural analysis, energy simulations, optimization processes. Those additional plugins empower the main Grasshopper platform, allowing to
introduce in the design phase multiple inputs which inform the entire design strategy. Controlling drone’s dimensions is crucial for flight performance, allowing to find the right equilibrium among all onboard components, maximizing stability, energy consumption and flight time. It is also crucial to limit frame size in order to decrease its perception in the context of public spaces, allowing robots to become silent observers over the activities produces in the surrounding. The mechanical frame of the robot is produced through an algorithm that controls and defines all proportions among the frame. This code allows simulating mechanical behaviors of the drone structure under stress configurations, enabling to integrate into the design process fabrication principles, improving resistance and structural performances. For the topological optimization of the frame structure, it was implemented another Grasshopper add-on called Millipide. Millipide is a library for structural analysis and mesh topology optimization. It allows calculating material layout within a given boundary condition, taking into account specific sets of loads and constraints, with the scope of maximizing the system’s performance. The actual topology optimization over the frame structure was calculated setting as load condition vertical forces over the wings positioned along the axis of the brushless motors and propellers. A central negative load was also applied in the central part of the drone, simulating loads of battery, electronics and cameras. As a final output, the code provides a closed mesh shape ready to be 3d printed, using an iso-surface mesh component integrated into Millipide. In order to decrease 3d printing time and frame load, the frame integrates also 4 carbon fiber rods of 10x10 mm square section, 92 mm length each for overall weight 35 gr. All bars are position along the wing axis, connecting the motors to the central frame. The complete setup of the drone consists in 5 3d printed pieces and 4 carbon fibers bars. In order to host cameras and batteries, the frame is also connecting to a fixed gimbal system also produced through additive manufacturing techniques. (see Figure 2)

The drone is also provided with an external cage designed in order to absorb external impacts and preserve drones stability and integrity. This external shell integrates multiple materials. We adopted laser cut plakene polypropylene sheets and carbon fiber pipes and 3d printed joints. The overall number of pipes are 6 rods of a 733 mm length and 4 rods of 777 mm length, weighting 35 gr. The structure is conceived and optimized in order to be as lightweight as possible, providing an elastic behavior that allows bending the main carbon fiber pipes, avoiding collision with the internal frame and the rotating propellers. The 3d printed joints are fixing all bars in a bent position and hosting the main pipe where the internal frame is installed. The entire design and fabrication process aims at reducing time and costs of production, increasing the possibility to customize and control the mechanical part of the drone according to specific needs or task it might need to cover. (see Figure 3)

The electronic board is also a custom-made board called Sathsakit. Sathsakit is family of microcontroller integrating general-purpose boards, developed by Daniele Ingrassia during a digital fabrication course called Fab Academy. Born from the necessity to have a fully featured and reliable board produced with cheap Fab Lab equipment, Sathsakit is made by CNC milling FR2 copper sheet and common electronics components. The board is based on AVR microcontrollers, mainly the ATMega328p and the ATMega1284p, integrating an MCU atmega328
which makes it programmable as a commercial arduino. The pcb-board is entirely fabricated and assembled in a fablab using precision tools for CNC cutting while all electronic components are fixed using soldering stations, accessible in any fabrication laboratory (fablab) registered to the fablabs.io network. Using the Arduino libraries, Satshakit is able to use all the sensors and shields made for the Arduino platform, giving to the user a wide range of utilization possibilities. Different versions of Satshakit exist, each for a different purpose or scenario. For the purpose of the research presented in this paper, we implemented the Satshakit flight controller: a customized version made with the purpose to control a drone, embedding a power distribution board and supporting up to 8 motors and 6 channel receivers. Implementations of the Satshakit have been made for experimental drone development. As per the customization capabilities, a special Satshakit was designed to implement a low-cost drone automatic control system, which involves a multi-microcontroller system. Having two microcontrollers on a single board enables the satshakit to simultaneously manage two different aspects: one microcontroller is managing the flight mechanics, while the other microcontroller is managing a set of sensors and can take the control of the flight to let the drone fly automatically. As per flight mechanics, one chip is implementing the control of the motors by continuously polling the Inertial Measurement Unit sensors (accelerometer and gyroscope) and the values of the radio channels. The other microcontroller is connected to the microcontroller which manages the flight using serial communication and can use a
software interface to override the radio channel values coming from the manual control. This microcontroller can automatically determine when is needed to take the control, on the basis of perceived sensor data (e.g. a sonar sensors detect the presence of a near object). (see Figure 4)

Data Collection
In order to autonomously fly drones in the public space, we used MissionPlanner a software developed by ArduPilot. This program enables to configure multirotor, setup processes for autopilot mode and set specific flight plans. MissionPlanner planner has a user-friendly interface which allows to program multiple frame types, adjust drone’s onboard sensors such as gyro and barometer and maximize precision level for the GPS signal. This process is crucial to increase accuracy for flight plans and assure risk-free flights. Regarding flight plans, missions were programmed by defining waypoints directly on the same software. As onboard GPS we installed a NEO-6 u-blox 6 GPS NEO-6T which comes with a time pulse output between 0.25 Hz up to 10 MHz. We registered a precision gap between 50 to 85 cm and for this reason we contained paths at least at 2 meters from every possible obstacle. Regarding video collection, images were captured using a Syma X5C camera, with a resolution set to 1280 x 720. This camera enables to record 30 frames per second. This is a very lightweight and compact camera, already integrated into several commercial drones thanks to its qualities.

Data Interpretation
Third and last phase consists in the recognition of pedestrians from video frames collected through our cameras installed on drones. Tools used in this stage are all python based scripts. All codes tested relies very much on OpenCV (Open Source Computer Vision Library), an open source library for computer vision and machine learning. The computational strategy implemented are based on HoG (Histogram of Oriented Gradients), an image descriptor used in computer vision for object detection. Among the different techniques experimented we tried to detect pedestrians using background subtractions which is a technique used to detect moving objects based on camera recordings. A crucial disclaimer in the selection of the best solution was given by camera position. Since all videos were recorded from a drone, camera perspective was constantly changing, preventing the implementation of many techniques. Finally, we used a script relying on Object Detection using HOG as descriptor and Linear SVM (Support Vector Machine) as a classifier. SVM are supervised learning models also known as a non-probabilistic binary linear classifier. (see Figure 5)

Implementing Hog and Linear SVM allowed to automatically detect pedestrians in images. Applying a method described by Adrian Rosebrock in an open-source document, we were able to assign non-maxima suppression to overlap rectangles contained in a set proportion in bigger boxes. This procedure allows refining the calculation of human figure, culling boxes that are recognizing only smaller parts of the
body and not the entire body. As for the last operation, we counted the box and draw center points for each one of them, detecting frame by frame the trajectory of each pedestrian. Detecting pedestrian is the first phase of the action needed in order to achieve a map showcasing the movement of a pedestrian along a path. (see Figure 6)

In order to rebuild GPS coordinates for every single human figure detected, we implemented an operation called triangle similarity, fundamental to calculate target distance from a specific camera position. As described in multiple articles focused on computer vision, calibrating a triangle similarity requires two fundamental steps: knowing the target dimension and the initial distance of the target from the camera. The parameters involved in this operation are the focal length of our camera (F), the width of our target (W), the apparent width in pixels (P) and the distance from the camera. To calibrate our distance detector, the first step is to calculate the perceived focal length F of our camera: 

\[ F = \frac{(P \times D)}{W} \]

Once F is known, it is possible to apply triangle similarity and calculate the target's distance from the camera: 

\[ D' = \frac{(W \times F)}{P} \]

As \( D' \) is calculated, it is possible to obtain the GPS (global positioning system) coordinates of the target in the picture. Since the drone is already implementing an onboard GPS sensor, we were able to easily obtain the target position associated. To convert the GPS drone location to XYZ coordinates and calculate target’s location, we used again Rhino Grasshopper3d, more precisely the gHowl plugin developed by Luis Fraguada. This library allows to convert WSG84 coordinates to XYZ parameters and remap points on a specific domain. Looping this operation over multiple images we achieved to calculate trajectories for pedestrian, which can be adopted to reveal citizen's behavior in the context of public spaces.

**CONCLUSIONS**

In this study we are presenting a methodology implementing autonomous drones, computer vision and machine learning algorithms producing dynamic maps describing pedestrian flows in public areas. The overarching research is aiming to introduce drones and autonomous vehicles in the context of public spaces as a new robotic network of devices able to perceive and describe dynamically urban contexts. This first research has proven that with the combination of a specific technology and computational techniques we can increase the amount and accuracy of data that can be collected to describe how citizens behave in public areas. We consider this first achievement as a solid base for a future development of more advanced mapping models. Significant further modifications need to be implemented: a more compact and better equipped quadcopter; a more robust algorithm for pedestrian detection to georeference into bidimensional maps; photogrammetric models where to parse point clouds according to their topology. Regarding the mechanical components, we are looking forward enforcing frame rigidity by extruding in continuous carbon fibers filament using a Markforged 3d desktop printer. Those printers leverage additive manufacturing capabilities, allowing to extrude even metal materials through a process called Atomic Diffusion Additive Manufacturing, or Adam. This alternative fabrication method can decrease as well frame’s weight, as rigidity and stability. Another process we are investigating is focusing on how to strengthen the 3d printed frame, informing the infill pattern porosity according to compression and traction forces. We are considering recursive subdivisions over a hexagonal grid in order to reinforce internal structures or increase shell section based on stress analysis. Regarding the algorithm implemented for pedestrian detection, we are planning to construct a custom HOG descriptor in order to refine the detection process and implement multiple strategies not accessible through the default method encoded in OpenCv. The steps to introduce in this code implementation regards experiment preparation, feature extraction, detector training, non maxima suppression, hard negative mining and detection retraining. One of the most interesting implementation those changes will represent is to gener-
Figure 6
Image Processing - Pedestrian Detection

ate an experiment and training data where to set a proportional square detection around multiple figures at different scales. In order to address multiple scale detection we will test image pyramid strategies to detect objects that are either larger or smaller in comparison with my window dimensions. We believe the methodology presented in this paper can provide a meaningful impact on mapping strategies for public space, producing qualitative maps over quantitative data. Extracting flow information, in fact, can determine citizens behaviour under multiple circumstances from public events, daily activities, different usage over time and weather conditions. In order to consider all this factory is an appropriate input to add a multiple onboard sensors, collecting environmental data. A possible solution could be integrating a smart-citizen kit, already tested on our drones in previous experiment. The smart-citizen kit is an ambient sensor board carrying sensors measuring air composition, temperature, humidity, light intensity and sound level. This set of data can provide a more robust system to inform the understanding and design process of urban contexts. We consider future development to yield more results which will inform further iterations towards overall research goals.

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CIM-St

A Design Grammar for Street Cross Sections

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The design of streets plays an essential role in shaping the quality of our cities. In particular, the design of a street's cross section determines in many aspects the realm of its use, enhancing or reducing its ability for being walkable streets or traffic oriented streets. This paper shows a street cross section design interface where designs are controlled by an ontology and a parametric design system supported by a shape grammar. The ontology provides a semantically ordered vocabulary of shapes, symbols and descriptions upon which the grammar is defined. This paper focuses on the grammar definitions and its translation into a design oriented interface.

Keywords: Parametric Design, Ontologies, Compound Grammars, Street Cross Section, Urban Design Systems

1 INTRODUCTION

CIM-St is an extension to a City Information Modelling (CIM) tool, dedicated to the (semi-)automatic generation of street cross sections of street types selected by the designer.

The design system combines computational ontologies (Gruber, 1995) with a compound grammar (Knight, 2003), an extension of the shape grammar formalism (Stiny & Gips, 1972). The former describes and structures knowledge about a specific knowledge domain (in this case, the city) and are used to inform and control the design generation process, ensuring the semantic accuracy of the final design. The compound grammar, on the other hand, combines generic shape rules (Beirão et al., 2009) enhanced with description functions (Stiny, 1981) that, informed by the ontologies, select which rule to apply and provide meaning to the designs. The compound grammar follows a procedural structure and is composed of two parallel grammars, one that generates the street section and another that generates the corresponding plan view.

The combination of shape grammars with ontologies results in a generative design system with analytical capabilities, ensuring the production of valid design solutions at the end of the generative process (Grobler et al., 2008). The knowledge base of our system was built from part of the Networks ontology, itself a sub-ontology of the City ontology (Beirão, 2012), and provides a taxonomic structure of the concepts of the street system and transportation networks.

In this paper, we will show that the semantics of the design system is supported essentially by the ontology structure which also controls the sequence of procedures through its hierarchic structure, while
shape rules are very simple ones, essentially additions of parametric quadrilaterals where the parametric variation is provided by the ontology depending on the specifications of the shape class.

2 THE NETWORKS ONTOLOGY

The networks ontology describes networks within the City domain. The most representative one is the streets’ network, not just because it describes one of the strongest morphological factors in urban morphology, but also because it is the physical support of most of other networks - public transportation; bicycle network; infrastructural networks, etc.

The street network is composed of several sub-ontologies (Figure 1), a set of street names (SN - Street Nomenclature), a set of descriptions defined in terms of the role of the street as part of the Transportation Network (TN), a set of street descriptions (SD) describing the partial components of a street section for each basic street type, and a set of street parametric components (SC) that combined according to the provided descriptions will generate a street section in two types of Euclidian representations - plan view and section.

Conceptually, as a design interface, the system was developed considering that a designer soon after laying out the main ideas for a master plan will design the streets considering as input the width of the street section. Therefore, the initial shape in a street section design generation will be an abstract section composed of two opposite facades on opposite sides of the street at a distance corresponding to the street width. Technically, in terms of shape generation the initial shape is the center point of the street section. However, the generation process starts with the generation of a street description by means of a description grammar. The outcome of the description grammar will then inform the compound shape grammar which will, in turn, be responsible for generating the representation of the street profile. A parallel shape grammar generates the plan view of the same street profile.

3 GENERATIVE PROCESS

The street section design starts from a raw profile inherited from a plan design (not addressed in this paper). This raw profile contains the following information: building section on both sides of the street, a center point half distance between them and a hierarchic value which constrains the association possibilities with the street types in the sub-ontology SN (Figure 2). This hierarchic value is obtained from a basic axial representation of streets by means of their centerlines which should have been already generated as a rough urban plan. This axial representation simply classifies four types of street axes (from a1 to a4) each admitting a consequent transformation to a limited subset of the total set of SN and TN street types. The transformation of each raw profile into a coherent and valid street profile is done in four steps: the selection of the type of street to be designed (limited to the previously mentioned subset); the definition of the components present in the final street profile; the specification and generation of each component’s geometrical representation and, finally, the assembly of the final representation of the street profile and its evaluation.
3.1 Street Type Selection
SN provides a vocabulary of street types: Street (st), Avenue (av), Boulevard (bv), Main Street (ms), Promenade (pr), Grove (gr), Lane (la), Alley (al), Cul-de-Sac (cs) and Ring Roads (rr). In a first step, a description rule replaces the hierarchic information given as label associated with the street centre by a street type, for instance, Street, and associates the label “st” with the street center. Technically, it erases the hierarchic label (any between $a_1$ and $a_4$) and adds “st”. The hierarchic label restricts the list of admissible street types for a given raw profile based on its width, setting it as a ceiling for the minimum possible width of the minimum description of each street type. In terms of the design interface, all the user is required to do is select one of the possible street type options from a pull-down menu in the interface.

TN is an additional classification given in terms of the role of the street as part of the transportation network. Adds a second classification given from another semantic viewpoint. This classification allows a user to define the role of the street from a transportation oriented viewpoint. Transportation Network (TN) as is defined in Beirão (2012) is a five-level hierarchic classification of car oriented streets that should be combined with SN street types in order to have a full street classification.

Considering that the classification provided by TN is essentially transit oriented while the classification given by SN is essentially based on a cultural description of a street that expresses its qualities in a name given in a particular language, we can say that TN provides a transit oriented structure while SN provides a human oriented viewpoint. The idea is that by giving different weights to the classifications the system may privilege one or the other approach. However, till now, none of the TN options have been yet implemented, so we will omit more information about this sub-ontology. The reason for omitting this part of the ontology was to skip some computational complexity that would only be focusing on car oriented planning, factor that is nowadays criticized as being responsible for destroying public space quality since the advent of modernist planning. However, this implementation has not been forgotten as we will argue in the discussion section.

3.2 Street Description
At a second step, a description rule establishes the minimum description of street components for each street type. For instance, a Street (st) is composed at least by two sidewalks and a car lane in the middle. Street Components (SC) is a set of street profile components such as the ones defined in Table 2. Note that in Table 2 street components are ordered as follows: 1- street parking; 2 - sidewalks; 3 - bicycle lanes; 4 - bus lanes; 5 - car lanes; 6 - green stripes; 7 - noise protection; 8 - tree alignments; 9 - tram lanes; 10 - canal; 11 - leisure walkway; 12 - protection rails. The integer numbers associated to the street components will be used as indices in the descriptions.

The rule can be written as:

$$D_1 : st \rightarrow <2|5|2>$$

Street descriptions are composed of four main elements: symbols “<” and “>” marking the boundaries (beginning and end, respectively) of the street description; a sequence of integer numbers like “2” and “5” (as in the description rule D1) representing different street components and their order in the street profile; and the symbol “|” working as a splitter of the description, marking a separation between street components. If a street is composed of a single component, as in the case of a narrow pedestrian street, no splitters are required in the description.

The minimum street description can then be extended by adding other street components. For instance, in a Street (st) we may add a bicycle lane (D2) or a parking lane (D3) at the side of each sidewalk.

$$D_2 : 2|5 \rightarrow 2|3|5$$

$$D_3 : 2|5 \rightarrow 2|1|5$$
Rules D2 and D3 can be applied only once on each side of the street while rule D4 can be applied many times until a total street width is “filled up”, adding as many car lanes as required. By applying such rules, we may obtain variations of the street type (st) with formats like $<2|3|5|1|2>$; $<2|3|5|3|2>$ or $<2|3|5|2>$. Other options can be obtained. Note that rules D2 and D3 can be applied symmetrically as follows:

$D2 : 5|2 \rightarrow 5|3|2$

$D3 : 5|2 \rightarrow 5|1|2$

The Street Descriptions (SD) column in Table 1 prescribes which adjacent components are admissible, according to the profile schemas of Table 2, therefore specifying which are the valid adjacencies accepted in a street description. So, the rules shown above produce street descriptions which are always symmetric and define what will be the components of the street cross section to be generated. In order to develop non-symmetrical street layouts we added a rule that allows overriding the predefined street descriptions at any point:

$D5 : |\rightarrow x|$ where x is a variable representing any street component that respects the adjacency constraints mentioned above.

The reader should keep in mind that we do not show the complete set of street description rules and therefore should imagine possible additional rules available for applying other street components not mentioned in the examples above.

<table>
<thead>
<tr>
<th>Street Nomenclature (SN)</th>
<th>Minimum Street Description (SD)</th>
<th>Possible relations to Transportation Network (TN)</th>
<th>Stratification by speed (after Marshall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>st - street</td>
<td>$&lt;2</td>
<td>5</td>
<td>2&gt;$</td>
</tr>
<tr>
<td>av - avenue</td>
<td>$&lt;2_8</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>bv - boulevard</td>
<td>$&lt;2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>ms - main street</td>
<td>$&lt;2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>pr - promenade</td>
<td>$(S^2 + I) + S^2; (S^3 + I) + S^3$</td>
<td>$S^2 + I + S^2; (S^3 + I) + S^3$</td>
<td>$S.2.5 - S.2$ With horizontal stratification</td>
</tr>
<tr>
<td>gr - grove</td>
<td>$(S^2 + I) + S^2; (S^3 + I) + S^3$</td>
<td>$S^2 + I + S^2; (S^3 + I) + S^3$</td>
<td>$S.2.5 - S.2$ With horizontal stratification</td>
</tr>
<tr>
<td>la - lane</td>
<td>$&lt;2</td>
<td>5</td>
<td>2&gt;$</td>
</tr>
<tr>
<td>al - alley</td>
<td>$&lt;2; &lt;2</td>
<td>5</td>
<td>2&gt;$</td>
</tr>
<tr>
<td>cs - cul-de-sac or impasse</td>
<td>$&lt;2; &lt;2</td>
<td>5</td>
<td>2&gt;$</td>
</tr>
<tr>
<td>rr - ring roads</td>
<td>$&lt;7</td>
<td>12</td>
<td>4x5</td>
</tr>
</tbody>
</table>

Table 1
Partial representation of the SN object class
Parallel to the generation of street descriptions, the system generates a detailed description of each component’s parameters. Table 1 shows a column indicating profile parameters which are user input variables constrained within a range of accepted standard values taken from well-established urban design standards (the reader may find additional information on this topic in Beirão (2012); for the purpose of this paper the used values are the same as found this latter reference, mostly taken from Pedro (2002)). For instance, sidewalks are composed by the following set of parameters: \{w, e, d, h\} where the total sidewalk width is equal to \(e + w\), and \(w = s + d\) including a tree alignment at \(d\) distance from the sidewalk border. The parameter \(w\) which may be considered the usable sidewalk width can variate between 1,25 and 5 meters. In the computer implementation, the maximum limit was actually made flexible to accommodate automated adjustments because the sidewalk width is actually liable to be the most flexible parameter. The value \(e\), is particularly important in terms of street performance because it is the value that provides a space for activities developed inside the buildings to ‘drool over’ the sidewalk contaminating the public space with the activities found inside the private spaces; for instance, a fruit stand or a Cafe’s esplanade (Gehl, 2011; Barton, Grant, & Guise, 2010; Higueras, 2006). So, parallel to the street description rules for any situation where, for instance, a sidewalk (“2”) is generated we will have a description rule generating the description of the sidewalk:

\[ C1 : 2 \leftarrow \{w, e, d, h\} \] where the parameters \(w\), \(e\), \(d\) and \(h\) are all user input.

Additional description rules for other street components can easily be defined following Table 2.

Through this example, the reader can understand that the total width of the street can be easily checked automatically while generating the street description providing information whether the street cross section is already fitting the total street width or not. Until this point it is also obvious that the whole procedure is strictly symbolic.

3.3 Component Specification and Representation

At a third step, Street Component labels are replaced by their representations. First, the components are specified as one of their sub-types (when they have one), as in the differentiation between “lateral” and “central” sidewalks. These specifications are the result of the component’s position in the description, options introduced by the designer or restrictions defined in the ontologies, such as admissible adjacent components. Lateral sidewalks, for instance, appear in the street description immediately after or immediately before a description boundary symbol (i.e. “< 2 |” or “| 2 >”, respectively), while central sidewalks always appear between description splitters (“| 2 |”). Some street components (2 - sidewalks; 6 - green stripes; 7 - noise protection) still allow a further level of specification through their combination with other components, as in the case of sidewalks with tree alignments. These levels of specification correspond to user input and may be considered as part of the platform’s design flexibility.

To avoid ambiguity, the “_” symbol was introduced to link associated components’ indices. If we consider the following partial description “| 2_8 | 6 |”, we can undoubtedly state that the tree alignment (“8”) is part of the central sidewalk (“2”), despite being placed next to a green stripe (“6”). Adding tree alignments to sidewalks, therefore, is as simple using the following description rule:

\[ D6 : 2| \rightarrow 2 – 8| \]

, while adding tree alignments to green stripes and noise protections follow similar rules:

\[ D7 : 6| \rightarrow 6 – 8| \]
\[ D8 : 7| \rightarrow 7 – 8| \]

Description rules D6, D7 and D8 could be generalized as a production system (Gips & Stiny, 1980) with variable \(a\) and a single rule, where: \(a \rightarrow a_8 \) and \(a\) is a component that has no restrictions regarding the addition of trees.

After the specification of the street components, the system is ready to generate their representations accordingly, following a tree derivation of the com-
Table 2
Partial representation of the SC object class.
pound grammar using a simple set of parametric shape rules. Street components’ shape stem from the center point of the street which, as we will see in the next step, will be moved to its final position according to the street descriptions generated in the previous steps.

The shape rules applied in this process are of two kinds:

1. An addition rule adds an insertion point and respective label for each description; the placement coordinates of the point correspond to a translation given from the street center point.

2. A rule erases the label and replaces it with the correspondent street component.

3.4 Profile Assembly and Evaluation

The global representation of the street cross section comes with the verification of the total width of the street together with the semantic accuracy of the profile, which is ensured by the ontologies during the generation process.

The last step mentioned in the previous section, distributes the representations of the street components along the profile of the street, according to the final description including already all the options given by the user. In fact, due to the semantic structure given by the ontology the generated cross section contains in addition to all the morphologic description any further qualitative information associated with the options that might be considered useful for analytical purposes. Furthermore, the relationships between the street components and the cross section as a whole define spatial relations within the street space that might be evaluated differently according to the purpose of the street within the plan or simply as a definition of public space quality. Therefore, we added a set of analytical tools that provide additional information about the generated profile that could express some of its qualities.

The analysis implemented until now are simply based on morphologic information and are composed of two simple graphics summarize in two pie charts. The first graphic gives a chart on street component impact. The color code gives an immediate overview of the distribution of component types differentiating those dedicated to people (in greenish tones) from those dedicated to traffic (in reddish tones). This gives some information to the designer about whether the street is essentially a pedestrian or a car oriented street. The second pie chart indicates a rough measure of how much trees cover sidewalks. This value is calculated considering both the tree width inputs in the user interface and the total width of sidewalks. The obtained chart is a very rough representation of a relation of tree coverage and available sidewalk space which might be argued to lack important information such as tree type or distance between trees. Still, the chart provides a first impression to the designer about a possible effect of tree coverage along a street.

4 USER INTERFACE AND OUTPUTS

CIM-St interface for street profile design was meant to be as simple and intuitive as possible, posing simple and direct questions to the users that will generate their designs and providing the necessary parameters in order to edit them. It was also meant to provide enough flexibility for users to compose their own street descriptions at will, in a simple and expedite fashion, through the direct manipulation of the symbols in the street description. (Klerk & Beirão, forthcoming)

Working mostly at the symbolic level, using production rules to define and manipulate descriptions and set components’ parameters, allowed us to sim-
plify not only information processing but also user interaction with the generative system. Simple, objective questions that can be mapped to Boolean or enumeration answers became the primary design mechanisms, allowing users to design at a semantic level using natural language. Answers to these questions target different levels of the ontology maintaining semantic relations and controlling the application of the compound grammar’s rules.

Should the user desire a more direct approach to the generation of the design, or if the street profile required is not standard, the option to override the description enables users to directly specify the type of street components to use and where they will be placed in the profile. This translates into controlling the procedures of the grammar. In the interface, the user simply introduces the street component index where it is considered necessary.

The system was implemented with Grasshopper 3D mainly for educational purposes, so that architecture and urban design students willing to understand the inner workings of the application could easily “take a look under the bonnet” and even modify or extend the application at will. Ontologies were represented using XML format and stored in external files which are fed into the system using a custom XML parser (refer to Klerk & Beirão (forthcoming) for more information). As for the user interface itself, we decided to implement it using Andrew Heumann’s Human UI [1] add-on for Grasshopper 3D, giving it a clean and responsive look with dynamic updates and a dedicated pop-up window with visual analytics (Figure 4, right). The resulting design is displayed in Rhinoceros front viewport (Figure 4, left) and can be “baked” into the CAD application for further editing.

Users control the generation of the design through CIM-St’s main window, starting with the selection of the type of street they desire and its total width. A series of simple, pre-defined questions and parameter sliders will allow them to quickly customize their design. The questions posed to the users are related with the existence of street parking and its type, if there are any bicycle lanes (one or two-way), if there is a canal, if the system should use Green Stripes to adapt any remaining space of the street and if it should automatically add Tree Alignments to Sidewalks larger than 5 meters. A tab with sliders to control specific components’ parameters is also available in the interface. Still in the “Definition” menu, users may override the given street description as mentioned above; on the “Extras” menu, they will find the controls for secondary elements (trees, acoustic panel, buildings) and visualization options. Additionally, CIM-St provides a pop-up window with visual analytics, providing real time information to aid the design decision process, as mentioned above.

A preliminary study with graduate and undergraduate students taking the course of Parametric Urban Design at the Faculty of Architecture, University of Lisbon (2016-2017), showed the interface to be “clear and intuitive”, “user friendly and understandable”, with a “concise” and “visually appealing layout” that “can be used easily” (user feedback).

5 DISCUSSION AND FUTURE WORK

The generative system behind CIM-St allows it to support designers in the rapid creation of large quantities of street profiles, relieving them from repetitive tasks and promoting the test and comparison of many different solutions, leading to more qualified design solutions.

CIM-St was thought to be a design tool containing additional information to support design decision during the ideation phase. During the development of the tool as is presented here and even during the writing of this article, we were able to raise our
awareness on possible improvements or additional features that can be easily introduced while providing additional information to support the users. As such, in this section we provide an extended discussion on these topics.

As mentioned in section 3.1 the implementation of the TN sub-ontology is still missing. The implementation of this sub-ontology will allow introducing better evaluation criteria while distinguishing or balancing information between traffic oriented streets and pedestrian oriented streets. This addition will introduce the interesting topic of deciding how to weigh the two different vocations which cannot be treated linearly because the topic is essentially network oriented. As such, this particular topic, although stressing its underlying interest, should be carefully treated including the development of appropriate methods to approach it which should certainly include topologic analysis as part of the method.

At a representation level, it is evident that the system would profit from having the generation of the street cross section together with a partial plan representation, let’s say, an extension in plan about 10 meters in length, which could provide the user also a plan view of the street produced by that cross section. The use of the plan has not been implemented yet but is foreseen to provide further possibilities in terms of design information.

The design interface already considers relatively abstract information about the buildings containing the street. Such information might be added to the representation model and used for analytical purposes. So, more evident and probably easier to implement than the previously mentioned issues, there are topics of analysis that can be promptly added to the system. Here is a list of already planned work:

- A street parking indicator inspired on the Parking Performance Index (PPI) of Berghauser-Pont and Haupt (2010), using the information gathered from the use of the street parking component (“1” in Table 2). At least, our street profile can set the assumptions regarding the street’s parking capacity need to calculate PPI.
- Evaluating the potential of the sidewalks to support street life based on its width and already mentioned supporting theory. This topic could be evaluated just roughly from the morphological properties of the sidewalk but more accurately by adding information about qualities of the ground floor such as transparency and building porosity. In fact, the tools shown here could be easily crossed with the tools found in Beirão and Koltsova (2015) providing positive inputs in both research approaches.
- Evaluating the canyon effect of the street profile together with the tree coverage. The reader should understand that the system developed until now allows the user to input the measures of trees - trunk and canopy - which although not indicative of a particular tree type, allows the designer to set the ideas about the kind of tree form planned for a space providing evidence that might support such decisions.
- Introducing street components with hybrid functions. Presently, it is not possible to [explicitly] create street profiles with areas sharing different functions, such as a predominantly walkable street that allows a reduced level of traffic to pass through it. This happens because current street components are function-oriented and there is no option available to inform the system that a certain component may share some properties from another.

The system might also be improved by establishing a connection between the generated representations (which are low detail representations of street profiles) and BIM providing constructive detail and hence including the detail design phase in the design flow. As this intention can be easily obtained by simply connecting this representation with already existent IFC objects available in commercial software
we decided that it could be interesting to add a kind of pre-detailing sub-ontology where schematic constructive intentions could be added to the design; for instance, setting permeability characteristics of pavements which may allow the calculation of additional quality indicators like the street’s surface permeability index, information that may contribute towards the design of more sustainable streets.

As a conclusive statement in this section, we would like to stress that many of these features are so easy to implement that we plan to have them ready before the end of the year. After concluding such tasks, the research will focus on the relations between street morpho-types and building morpho-types to try to measure their mutual positive synergies.

6 CONCLUSIONS
The design interface described in this paper was implemented on a parametric visual interface following a compound grammar mostly composed of symbolic rules operating on ontology descriptions. The semantic control over the design generation is obtained through the ontology which controls the relationships between the components of street profiles. The result is an elegant grammar composed of a few description rules and two parallel shape rules replacing a description with an equivalent shape, one generating the cross section representation and the other the respective plan representation. The implementation follows the simplicity of the grammar and puts its efforts on the interactivity of the design interface.

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Exploring the Three Dimensional Spatiality of Polyrhythmic Drum Improvisation

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This paper reports on creative practice design research founded on the translation of complex polyrhythmic digital drumming into the spatial domain. We outline four exercises in the use of drumming improvisation as a methodology for the spatialization of polyrhythmic drum improvisation; as static Spatial Drum Notation and representation as 3D models, artefacts and in Virtual Environments and live drumming performance inside a VR CAVE. These creative exercises bring forward concepts of affordance of musico-spatial representations, a theoretical ‘musico-perspectival hinge’ and the continuum of performance, notation and representation.

**Keywords:** Music and Architecture, Drumming and Polyrhythm, Virtual Reality

**INTRODUCTION**

This paper reports on design research operating at the intersection of music and architecture within the context of a post-Xenakian musico-spatial design creative practice. The great Iannis Xenakis provides the template for a creative practitioner operating within and across the domains of music, architecture and beyond. Through the linkage between scored compositional works such as Metastasis, and architectural works such as the design of the Philips Pavilion (ostensibly under Corbusier’s name) wherein ruled surfaces are derived from glissandi from his composition, Xenakis shows us how the designer can operate within and across domains. His propensity for complexity is manifested through his expertise in mathematics, computational and stochastic music and his unique notation systems and methods as outlined in his manifesto, Formalised Music (Xenakis 1971).

Since Xenakis, there have been many design investigations into what Elizabeth Martin describes as the “Y-Condition”: ‘the middle position of music and architecture when translating one to another (Martin 1994)’. The work of, for example, Ferschin, Lehner et al. (2001), Radiojevic and Turner (2002), Christensen and Schnabel (2008) Krawczyk (2012) and Fowler (2012), utilize computational methods to translate elements of music into the spatial domain. The comparison with the quote attributed to Johann Wolfgang Von Goethe, that ‘music is liquid architecture; architecture is frozen music (von Goethe 1832)’ has been used by many as the basis for comparisons be-
tween the domains. This literal association, however, acts to simplify a complex set of associations wherein the designer has access to multiple means and methods through which to map, translate and parametricise musical elements in the spatial domain.

In relation to the connection between music and spatial design (architecture), three elements differentiate our research from much of the previous works on music and architecture:

- The focus on drumming performance on the digital drum kit as the driver for the creative practice.
- The focus on improvisation on the digital drum kit as a generative modality.
- The focus on the translation of music in the spatial domain as notation and as representation.

The creative practice research is undertaken through the teamwork of a drummer- architect in association with computational architect and Virtual Reality visualisation specialist. The principal proposition is that significant opportunities are available in the use of computation tools, media and methods to form a bridge through which to examine elements of the creative process of music making. We utilise computational tools to provide spatial definition to drum-based improvisation in both an analytical and generative capacity.

Through translation of digital drum music into the spatial domain, we propose that novel insights are afforded into the complexities of polyrhythmic drumming that are not available through translations into traditional musical notation. We speculate on the affordances of operation across representational media in 2D, 3D and Virtual Reality in both static and live playing. The concept of ‘affordance’ was established by Gibson (1979) was furthered by Norman (2002) to relate to design, wherein the attributes of designed objects provides visual cues as to how they are to be used. Thus, our paper provides a snapshot of four scenarios wherein polyrhythmic drumming is translated into the spatial domain and we offer insights into the affordance each medium provides in terms of performance, notation and representation.

**DRUMMING, POLYRHYTHM AND IMPROVISATION**

To begin to understand the higher order complexities of polyrhythmic drumming, we must first outline what it is that drummers do. The art of drumming involves the physical interaction with the drum kit with hands (via sticks) and feet to produce drum beats, fills (short expressions within or alongside beats) and drum solos. For the purposes of this study, we concentrate on drum playing within a solo capacity. Drum beats, fills and solos operate as the placement of overlays of notes (bass drum, snare drum, hi-hats, toms and cymbals) within a meter or tempo (measured in beats per minute) along a time line. Capacity to play in time, with other musicians and creatively is a function of training, practice and individual creativity. Bruford (2015) defines the ‘Functional-Composition Continuum (FCC),’ as the creative spectrum of drummers: from ‘recreative’ drummers who just ‘make it work’ to highly expressive, technical and creative drummers that ‘challenge the limits of the known drumming world (Bruford 2015).’

We argue that live drumming is a highly complex creative activity that occurs in real time, with microsecond response and reaction times that acts as a very intense, quick and responsive design activity. Live drumming requires the instantaneous engagement in ‘tacit-knowing-in-action (Schön 1983)’ using a lexicon of ‘referent (Pressing 1987)’ patterns and phrases built up over the performers career. The speed at which musical decisions are made highlight
the drummer’s capacity to ‘design’ in real time and in response to internal ideation in a solo capacity or interactions with other musicians.

We are interested in the more complex, compositional end of the FCC, and focus on polyrhythmic drum improvisation. Polyrhythmic drumming ‘require(s) the simultaneous production of two (or more) conflicting but isochronous motor sequences (Summers and Kennedy 1992).’ For drummers, this occurs when the drummer overlays several time signature elements within a beat or solo contemporaneously. A basic polyrhythm may consist of the right hand may be laying 5 beats whilst the left hand plays 3 beats during the same time period. Virtuoso drummers such as Bill Bruford and Terry Bozzio perform highly complex, multi-limb polyrhythms in the form of ostinato patterns in solo performance. This highly complex, polyrhythmic drumming is the foundation for the exploration of diversity in musical creativity and is the focus of our exercises outlined below (see Figure 1).

Improvisation is a highly evolved skill that operates at the end of the FCC to enable the instantaneous generation of musical ideas. Whilst much research has been undertaken on the neurophysiology, methods and models of improvisation Pressing (1987), phenomenology Benson (2003), the Field of Musical Improvisation Cobussen, Frisk et al. (2010), improvisation theory and the relationship between jazz musical improvisation and architecture (Brown 2006), we propose improvisation as a methodology. We also propose that improvisation is a design activity. Through modalities of playing and repetition on the digital drum kit, a massive amount of musical data can be generated that provides insights into the form, shape, patterns and phrases of a players’ repertoire. Through improvisation, the id, the personality and the style of the drummer is revealed. The fluidity and flow of the musician’s engagement in the instrument is a phenomenon that provides the basis for entertainment, analysis and, in our case, as a means of exploring connections between the domains of music and architecture. The key to the extemporization of music is the enabling of this flow in ways that may not be fully fluid in parametric tools and processes (Ham, Schnabel et. al. 2016).

The key to polyrhythmic improvised drumming is the purposeful generation of complexity through bodily engagement in the instrument. Through training, practice, repetition and copying and evolving the drumming of others, highly complex combinations of patterns and phrases are enabled wherein polyrhythm occurs at the macro and micro scales. A macro-scale polyrhythm may form the temporal foundation of a musical piece or drum solo. Within this overall time structure, a highly skilled drummer will be able to introduce small-scale repetitions of this structure, or even different polyrhythms founded on different time signatures, tempi or other complex combinations. Like architectural designers, not all drummers purposefully seek complexity. The style of the drummer, as with the architect, is a highly complex combination of factors. Ultimately, the success of a polyrhythmic drumming performance is measured in terms of musical aesthetics—whether through responsive perceptions of order and harmony (e.g. Miles Davis) or disruption (e.g. The Sex Pistols or Slayer).

This aesthetic is manifested also in the notational aesthetic, in the way in which polyrhythmic patterns and phrases are transcribed into traditional notation (See Figure 1). We are interested in the exploration of ways of representing polyrhythmic digital drumming and outline four exercises through which we have explored this translation of music into the spatial domain as a means of enhancing the affordance of the musical notation, providing virtual immersion and as a generative means of creating music and spatial elements in the CAVE.

FOUR EXERCISES IN POLYRHYTHMIC DRUM IMPROVISATION SPATIALIZATION

1. Exercise 1: 3D Spatial Notation and Representation of Polyrhythm

The foundation of the first three exercises was a massive musical data set derived from a hundreds of improvisations on the digital drum kit, as described in
Ham and Prohasky (2016) and Ham et. al. (2016). Improvisations on the digital drum kit are played live in the studio, recorded as sound, captured in MIDI (Musical Instrument Digital Interface) format, exported from the Reaper Digital Audio Workstation in MIDI format then translated into .csv format. From here, a Rhino 3D Grasshopper definition assigns spatial parameters to the MIDI attributes of drum events in time, note velocity and note duration. Drum events from each ‘note’ on the digital drum kit are represented as a timeline along the “Z” axis; with velocity (the intensity of the hit) with note duration manipulated using the full range of tools available in Grasshopper. From this, a 3D spatial drum notation system was developed that represents the spatiality of the drum kit and acts as an alternative to traditional music notation (see Figure 2).

Through playful manipulation of the musical parameters, multiple creative outputs have been explored that enables the spatialization of drum data as architectural elements (tunnel structures, panels, lattices etc.). Through the strategic placement of drum notes as lines along a Y axis, polyrhythmic drum patterns can be represented as clusters along the X axis with note velocities represented along the Z axis. From this, a series of spline curves are sent along each drum note, and then the resulting curves are lofted in Grasshopper. Through this process of lofting, the core drum data is stylized and abstracted, allowing for creative interpretation of the form and flow of a polyrhythmic drum improvisation to occur. This technique has been used to provide a spatial representation a six part improvised drum composition, ‘Layered Relationships’ (see Figure 3). By overlaying the spatialized layers of the composition, the lofting highlights the complexity of drumming patterns and the inter-relationships between constituent elements of a musical composition wherein this highly complex representation becomes an art form in itself. This methodology enables representations provides pathways into digital fabrication and 3D printing, which are outside the scope of this paper.

2. Exercise 2: Static 3D Spatial Notation in Virtual Reality

Working with the University of Stuttgart High Performance Computing Centre Virtual Reality 5-sided CAVE (Cave Automatic Virtual Environment), we have experimented with ways of extending 3D Spatial Drum Notation within Virtual Environments (VE). By importing VRML files of drum improvisations into the CAVE, spatial immersion into the Virtual 3D ‘score’ is enabled (See Figure 4). These scores represent drum notes along different elements of a timeline, defined by bars in a spiral notational schema that represents the spatiality of the digital drum kit (see Ham, 2016). One of the principal attributes of the 3D Spatial Notation is the ability to freeze (bake) polyrhythmic drum improvisations thus locking in the relationships between elements of the polyrhythm. This may include including ghost notes, slurs and low-velocity accents that constitute the elements of individual style. Velocity (how hard a drummer strikes the drum) is an
essential ‘lever of control (Bruford 2015) for the hierarchisation of complex polyrhythmic overlays and patterns, wherein a minor polyrhythmic patterns can operate below, in and around the foundational drum pattern being played. By ‘flying through’, in and around drum improvisation spatializations in Virtual Reality, detailed examination of these musical ‘design decisions’ that constitute a drum improvisation is enabled.

3. Exercise 3: Dynamic 3D Spatial Notation in Virtual Reality
The second method of spatialising drum improvisations in the CAVE involved the development of a plugin to read MIDI files directly into the VR software. This enables the playing of the sound of the drum polyrhythm contemporaneously with the visualisation in Virtual Reality in the CAVE. The 3D Spatial Notation schema was adapted and translated into a VRML spatial container. Drum notes are represented as colour coded spheres emanating from the spiral container, with sphere diameter and the initial velocity with which these spheres are emitted in virtual space dependent on the note velocity. The spheres are integrated along a force field providing a gravity-like effect, thus enabling a second layer of experience in, and around the person in the CAVE.

This real-time dynamic spatial notation, alongside the sonic output provides affordance to understanding drum-based polyrhythm in both the sonic and spatial domains. The temporal relativity between the spatial immersion in the ‘design’ decisions of the drummer making the polyrhythm and the sound output within the CAVE allows for a very quick learning curve on understanding the meaning of the 3D notational schema. The dual modes of visualization of note velocity (sphere diameter and initial velocity vector) provides further affordance to the understanding the dynamics that constitute personal drumming style. The element of time and space is introduced by the velocity-dependent projection of drum events into the CAVE. VR users can move forward in space to experience drum events that have recently occurred contemporaneous to hearing and seeing current musical events (See Figure 5). This spatio-temporal engagement is thus a defining element of dynamic representation and notation in CAVE environments.

4. Exercise 4: Live Drumming in Virtual Reality
The fourth exercise reported here involves the installation of a digital drum kit inside the CAVE, with
the simultaneous output of MIDI data to the visualisation engine and sound to speakers inside the CAVE. This overcomes the time and effort overhead in recording drum improvisations and translating these recordings into MIDI and/or spatial form. The spatial template adopted for this exercise was founded on the drummer as the key actor in the CAVE, and utilised the same notational language of spheres from previous exercises. Spatial forms generated from live drumming emanates radially in and around the drummer, as the central actor in the CAVE. Whereas Exercise 3 projected note velocities “up”, this exercise projected notes “out” and away from the drummer. In order to achieve this, the force field which accelerates the particles was changed to a radial field. Initial velocities not only change their magnitude depending on the velocity of the note but also change their orientation. High velocities are oriented forward and low velocities backwards, towards the drummer.

Through live play directly inside the CAVE environment, with 3D glasses on, the drummer generates the sound and constructs the virtual spatial elements contemporaneously. The act of playing inside the CAVE—generating sonic and spatial outputs whilst responding through improvisation to these visualisations redefines the definition and potential modalities of both drumming and improvisation. The drummer becomes a spatial drummer, improvising variably using a pre-defined (but always evolving) language of ‘referent (Pressing 1987)’ patterns and phrases but completely new spatio-temporal patterns and phrases in the virtual environment. The necessity to wear 3D glasses further acts to disengage the drummer from the drum kit, and improvised response is to spatial emanations appearing before the drummer’s eyes (See Figure 6). A feedback loop of the gravity engine returning previously played note representations to the field of vision furthers improvisational opportunities as the drummer can improvise in response to the dynamic events occurring in and around him or her.

**AFFORDANCES IN EXPLORING THE SPATIALITY OF POLYRHYTHMIC DRUMMING**

Each of the modalities described above has distinct attributes that provide affordance to the understandings of music through notation, representation or immersion and experience, operating within a continuum of live performance to notation to representation. Following Rebelo’s (2010) purposes of musical notation as being to document, to communicate, to reflect and to produce, design representations aim to ‘achieve (a) situational awareness that allows for meaningful criticism of design (Kalisperis and Pehlivanidou-Liakata 1998)’. These notations and representations are either static. A static representation appear to have the advantage of better enabling reflective and analytical modalities, thus providing affordances unavailable in dynamic representations.

Exercises 1, 2 and 3 utilise pre-recorded MIDI files derived from historic drum performances, thus the experience and analysis can occur long after the performance has been completed. We describe in this paper only a small element of a larger creative practice embodied in Exercise 1. The outputs available for the analytical, representational and creative translation of drum polyrhythm are many, however the process of translation (from drum performance, to MIDI to CSV to CAD) is time consuming. This is where the scripting for the CAVE, by virtue of reading directly from the MIDI data, significantly reduces overhead and the errors and glitches that sometimes occur in translation.
The third and fourth exercises introduce the element of dynamism and movement to the spatialization of polyrhythmic drum improvisation. Although static representations appear to be more useful for notational purposes, dynamic CAVE spatialization of drum polyrhythm operate better at the representation and performance ends of the performance - notation-representation continuum. We report on two short workshops held in the CAVE, thus the extent of design creativity into CAVE-based spatialization is limited. However, the principal experiential attribute of working in VR in the CAVE is dynamism and dynamic representations of drum music in the CAVE provide a different affordance to static representations.

The generation of sound contemporaneous to dynamic spatial representations in the CAVE enhances the sensory affordance by enabling the simultaneous engagement in the polyrhythmic drumming with both eye and ear. Static representations may require additional cognition in order to afford understandings because of the intrinsic dissociation between the musical and sonic representation and the spatial representation. Adopting the concept of the ‘perspectival hinge’ (Pérez-Gómez and Pelletier 1997), this ‘Musico-perspectival hinge’ acts to limit understandings of music in ways that are similar to the limitations of 2D drawings to understand design (Ham 2017). We propose that the direct association between dynamic spatial representations in Virtual Reality and musical (sound) output from MIDI files enhances the affordance by further breaking down this musico-perspectival hinge.

Drumming in Virtual Reality brings together the contemporaneous generation of musical output and spatial representations through the act of live performance in the CAVE. Principal to the playful engagement in the spatialization of music is the ability to purposefully play the musical instrument with the intention of generating music, music and spatial output or spatial output alone. Whilst the form of spatial output in these early investigations is very basic, learning the parameters, and playing the parameters is fundamental to successful engagement. Knowing the system, and gaming the system, is key. Drummers, as experts in real time music ‘design’ decision making, with skills, dexterity and experience with the interface of the drum kit, hold an advantage in their ability to generate both musical and spatial output in the CAVE.

Live drumming in the CAVE allows performance to serve as the driver for the creative and dynamic generation of complex polyrhythmic drum music. Significant opportunities in performance art arise from this modality. The experiential opportunities for the drummer in the CAVE purposefully generating virtual spatial forms and music for an audience in the CAVE are considerable. For the drummer, creative opportunities arise from the knowing generation of spatial forms ‘in front of their eyes’ but also the creative musical reactive feedback loop between the dynamic forms previously generated and improvised response. This environment truly redefines the “Y-Condition” - the theoretical middle position between music and spatial design where the architect-drummer acts as spatial designer and musician contemporaneously. This ‘musico-spatial design’ modality offers new opportunities in the domains of both music and spatial design that are currently being explored.

**CONCLUSIONS AND FURTHER RESEARCH**

We have outlined four exercises in the exploration of the “Y-Condition” as the intersection of music and spatial design (architecture) that operate along the continuum of musical performance to the notation and representation of music in the spatial domain. Each of these methods, representational outputs and environments provides different and contrasting affordances to the understanding and experience of the structural and relational elements of complex polyrhythmic drumming. Whereas static representations may provide greater affordance for analytical purposes of 3D Spatial Notation, dynamic representations, when visualized in Virtual Reality, offer greater creative insights into the dynamic aspects of drumming music. Returning to the post-Xenakian concept of an integrated ‘Musico-Spatial Design’ cre-
ative practice, we propose that the exploration of the spatiality of polyrhythmic drum music in the form of live drumming in the CAVE allows the drummer the greatest level of design exploration. This is particularly relevant for persons skilled in both music and spatial design. We are working beyond the basic spatial representations presented in this paper towards ways that fully relate to the complexities of polyrhythmic drumming. We propose that an extension of drum-based performance in Virtual or Augmented Reality into full multi-speaker spatial sound holds great potential for both enhancing the affordance of the connections between music and spatial representation and creative potential of the musico-spatial design creative practitioner.

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Towards defining perceived urban density

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The aim of the paper is to identify parameters that influence perceived urban density. Whilst it is standard for architects and planners to consider urban density, there is often no consideration of how individuals might perceive such density. We report the findings of a study in which participants rate photographs of urban scenes according to perceived urban density. The case study area is central Zurich, Switzerland. The images are analyzed according to six parameters: visibility, amount of buildings, street width, amount of sky, amount of green space, and amount of vehicles. We report the findings of where images were ranked along a scale from lowest to highest perceived urban density. Findings show that visibility alone is not enough to explain the rating of perceived urban density. The study is a first step towards reaching a definition of perceived urban density that can be applied to different urban contexts.

Keywords: urban density, perception, behavioural study, 3D reconstruction

INTRODUCTION
Planning for the densification of growing urban settlements is a challenge that was already highlighted in the field of urban planning in the 1970s (Rapoport, 1975; Borukhov, 1978; Jacobs and Appleyard, 1987). Urban environments that strike a balance between accommodating a large number of people whilst retaining a pleasant atmosphere are those that are most likely to succeed (Jacobs and Appleyard, 1987). Such qualities are reflected in comments on the livability and urbanity of a space (Lampugnani, Keller and Buser, 2007). Measuring such qualities is desirable to gain an understanding of what it is about certain spaces that lead to a positive experience (Eberle, Troeger et al., 2014). For the most part, the response is subjective, that is, it is bound to an individual and to a context in time.

Whilst it is standard for architects and planners to consider urban density, there is often no consideration of how individuals might perceive such density. For example, in the planning disciplines it is standard practice to calculate FAR (floor area ratio). This is often calculated at project or neighbourhood scale. However, the way in which the FAR ratio is perceived will vary from space to space. Whilst the FAR ratio is a useful index for how a project will fit with the surrounding urban density, it does not quantify how people might perceive such density. This is an under-developed aspect of research on urban density. We
aim to investigate this property of urban environments by examining how individuals perceive urban density.

**Previous work**
A few studies have examined the topic of perceived urban density. Whilst early research commented on the need for work on how urban density is perceived (Alexander, 1988), a recent paper that discusses the concept of density dedicates a section to research on perceived density and architectural features (Cheng, 2010). One approach in understanding how individuals perceive urban phenomena comes from the tradition of psychology. A few studies use behavioural experiments to examine how individuals perceive urban density. For example, Zacharias and Stamps conducted two experiments using photomontages to see whether perceived urban density was affected by i) the size and spaces of buildings and ii) by surface details (2004). We follow in the behavioural science approach by conducting a questionnaire study in which participants rate the perceived urban density of photographs. Another set of studies examines to what extent perceived urban density is related to visibility, measured through the spatial openness index (Fisher-Gewirtzman, Burt and Tzamir, 2003; Fisher-Gewirtzman, 2016). Our study continues from this line of research through the formulation of the research hypothesis, which is that perceived urban density is the inverse of visibility.

We report the findings of an initial study aimed at identifying parameters that might be relevant for the perception of urban density. The context of the study is rooted in the perception of western European cities, specifically in the context of Switzerland. We see this study as a first step towards developing a larger research agenda, where i) individual differences and ii) cultural differences in the perception of urban density are taken into account.

**Factors influencing perceived urban density**
Based on the literature, we select a few parameters (1-6 listed below) that we suppose have a bearing on how individuals perceive urban density. Parameters 2-6 are based on the content of the photographs. These parameters cover a minimum number of categories that we believe, based on the literature, are relevant for the perception of urban density. These parameters are computed using an image segmentation algorithm - see below for more details. Figure 1 gives an example of the results of the analyses conducted per image.

1. Visibility. Visibility is a critical factor for the perception of space. It relates to the openness of a space. Research has shown that human behaviour in space is related to a formal analysis of the visibility properties of the space. These findings come both from the fields of architectural analysis (e.g. Turner 2001) and spatial cognition (e.g. Wiener et al. 2007). Studies have also related visibility to
perceived urban density (Fisher-Gewirtzman and Wagner, 2003; Fisher-Gewirtzman, Burt and Tzamir, 2003; Fisher-Gewirtzman, 2016). We calculate the formal visibility properties of each image. Specifically, we calculate the median value of the visibility of each image, as measured off the depth perception map (see Figure 1). Our research hypothesis relates to this factor. It states that perceived urban density is the inverse of visibility i.e. the further one can see, the less dense the space is perceived to be.

2. Amount of buildings. Buildings are a crucial element of urban density. We adopt a measure that relates to the amount of building matter per image, as opposed to the number of buildings, as this is a more reliable measure to calculate using the image segmentation algorithm. Buildings are shown as grey in the analysis (Figure 1)

3. Street width. Street width is one factor that relates to how much space there is between buildings, as therefore has a bearing on both built matter and the openness of the built environment. Streets are shown in purple in Figure 1.

4. Amount of visible sky. Presence of sky is often considered to be an inverse indicator of urban density i.e. spaces that are perceived to be less dense, have higher amounts of visibility sky. Sky is represented as light blue in Figure 1.

5. Amount of visible green space. Green spaces are often considered by urban planners to improve the quality of the urban environment. This parameter is visualised as green in Figure 1.

6. Amount of vehicles. Vehicles are included in this list of parameters as indicators of human activity. Again, we use a measure that conveys the amount of vehicles per image, as opposed to the number of vehicles per image, as this is a more reliable from the image segmentation. Vehicles includes cars, busses, trucks, trams and bicycles, and shown as dark blue in Figure 1.

We design a questionnaire study in which the role of these parameters (1-6 listed above) on perceived urban density is tested. It should be noted that we do not test for the presence of people, which is a parameter that is often cited in the literature. The reason for this is that our image sample set (remarkably) did not contain people (please see more details below). We therefore did not account for this parameter from the study. This is a limitation of the study and should be accounted for in future work.

**METHODS**

**Online questionnaire**

We design a study specifically aimed at identifying parameters that might be relevant for the perception of urban density. The study is an online questionnaire using the Qualtrics online survey platform (www.qualtrics.com). The survey is an optional task at the end of the Massive Open Online Course (MOOC) “Future Cities” course run by the Chair of Information Architecture, ETH Zürich. Respondents of the questionnaire are students of that MOOC.

**Task**

During the questionnaire participants view two photographs of urban locations and choose which one is more dense. The question participants respond to is: “Which location is more dense?” (see screenshot of task in Figure 2). We gather a basic profile of the participants through a number of questions pre- and post-questionnaire. The pre-questionnaire questions are as follows: age; gender; profession/area of study; where they currently lived; how long have they lived there; where they were born; where they grew up; and whether they lived in any other city. The post-questionnaire questions are as follows: which factors were important when making their choice; how they ranked the importance of those factors; and general feedback on questionnaire.
Figure 2
Screenshot of the main part of the online questionnaire in which participants answered the question “which location is more dense?” when shown two images of urban locations.

Case study area
Photographs used in the questionnaire are twelve stills taken from a 360 degree video of central Zurich, Switzerland, that had been created for another project (Hijazi et al., 2016). The video shows the view of a pedestrian on a 1.35km route through a mixed-use neighbourhood with mostly block typology. Figure 3 shows the case study area. By selecting an existing data source as the source for the photographs for our study, we are able to tap into a wealth of existing real-world visibility analyses for the study locations.

Point cloud
In order to create the depth perception map (see below) we create a point cloud model of the route from the 360 degree video. We use a photogrammetry structure-from-motion implementation called Colmap, with help from the Computer Vision and Geometry group at ETH Zurich. The purpose of the point cloud is to calculate a greyscale depth image that a) fits the location and viewing angle of the stills from the 360 degree video and b) includes street furniture such as trees, cars, benches, hedges that are not included in the most detailed 3D model of Zurich available. Also, deriving a 3D model from the footage allows to the best possible match of 3D geometry and imagery.

The stereo-view-camera-rig used for recording the 360 degree video is able to carry fourteen GoPro cameras in seven directions; two per direction. Yet the distance of the two cameras facing in the same direction is too low to compute a 3D reconstruction at building let alone street scale. Therefore we select images from five cameras: front, left forward, left backward, right forward, right backward. We omit down and upwards views. Images from the original movies are selected at an interval of two seconds in order to allow for a two to three meter distance between the location they are taken. Colmap supports a custom image matching mode to compute the 3D point cloud that matches images based on a text file we generated using Python. The Python script matches those images that depict the same ob-
jects. To achieve that we match rear facing images with front facing images from different times. Apart from that many semi-automatic adjustments need to be taken to compute a correct, contiguous point cloud. This was important to avoid errors such as:

- streets connecting at wrong angles
- pleated street canyons because of repetitive façade patterns
- the model being split in many different models because the algorithm didn’t recognize how to connect sub regions of the point cloud

We imported the resulting point cloud to a 3D editor (Blender - www.blender.org) in order to map the cloud with an existing LOD2 3D model of the neighbourhood. Even though the point cloud had no obvious errors, it was necessary to adapt the point cloud manually to the topography: while the point cloud represents the street canyons on a flat surface the LOD2 3D reflects the topographical height difference of c. two meters from over the full extent of the route. Also, due to computational constraints we calculated only a sparse point cloud. In Blender every point is represented as a box with 30cm edge length.

While computing the point cloud from images, a structure-from-motion algorithm also needs to calculate the position of the camera for the individual images. The result of Colmap therefore not only contains points representing the facades but also a category of points representing the camera locations. This allows for the camera positions of the source images to be mapped exactly to the 3D model - tak-

Figure 3
Case study area (left) and representation of the route (route) of the video in Zürich Wiedikon, used in Hijazi et al. (2016), from which the photographs of this study are taken.
ing into account the same topographical distortion as described above. While for the 3D reconstruction process it was necessary to select stills every two seconds, for the survey we select stills every ten seconds. This results in a spatial distance of camera locations of ten to 15 meters which corresponds to the typical width of a building on the route. To allow for further detailing of the image selection process we imported stills from the 360 degree video and mapped them on spheres (see Figure 4). This allows us to move a virtual camera inside such a sphere similarly as e.g. in Google Street View. Furthermore, this allows to implement a rule based rotation of the cameras as described in the following section. We use Kolor’s AutoPano software (www.kolor.com) to merge the individual movies to a 360 degree movie.

**Input Images**
The identified c. 100 locations along the route are set at a ten seconds interval along the route. The process of selecting the final images involved a number of steps:

- select images that have a 40 degree deviation to the road. With a view angle of 90 degrees this results in 170 degree coverage of the street and its context
- If at a location the road turns more than 54 degrees (0.3 x pi) images are selected to match the bisection of the road segments
- remove images that face a wall (i.e. meaningless for the study)
- remove images that are too blurry (the blurri-ness is a result of the video stitching process)
After these steps, there are 86 possible images in the stimulus set. As the experimental design calls for c.10-15 images, we select images that are high (max) or low (min) for each of the six parameters identified above. Thus we have a set of twelve input images (see Figure 5).

**Analysis of images**

The photographs are analysed according to the six parameters (1-6) listed above (see Figure 1).

**Depth perception map.** Parameter 1 (visibility) is computed from a depth perception map created for the study (see Figure 1). We want to calculate visibility measures based on what was actually seen, so we create depth perception images based on the point cloud model (see description above). This depth perception image shows the visibility of each pixel from a range of black (close to the viewer) to white (far away; max depth is set by point cloud model at 200m). We use one value as our visibility value: median grey pixel value. Note that the result would have been different, had we simply used an existing 3D model.

**Image statistics.** Additionally we analyze each image for properties of luminosity, contrast, and r/g/b values.

**Image segmentation.** Parameters 2-6 are computed using an implementation of the Cityscapes image segmentation algorithm (Cordts et al., 2016) tailored for our research question. The Cityscapes image segmentation algorithm allows for the detailed automated classification of items in an urban scene. We use seven classes for our study, corresponding to parameters 2-6 listed above, with the addition of people (red) and traffic lights/sign posts (orange). Figure 1 shows the classes (and corresponding colours) used by our implementation of the image segmentation algorithm. In a subsequent step, we use a pixel counter to calculate the values per image for each of the parameters 2-6 listed above. The final values used in the analysis are normalised from 0 to 1.

**Experimental design**

Each participant views all possible comparisons of every photograph paired against every other photograph (see Figure 2 for screenshot a of the task). This full pairwise comparison experimental design allows for a detailed analysis of the relative importance of each factor on the perception of urban density. The total number of choices each participant makes is based on the following formula: 0.5*n(n-1), where n is the number of stimuli. To enable this experimental design, it is optimal to have a small number of input images (c.10-15 images), so as to keep the questionnaire to a desirable length (ie. to avoid loosing participants who started but did not complete the questionnaire). We opt for twelve input images (see above), so that participants make sixty six choices. The output of the experimental design is to rank the images according to how relevant they are for the perception of urban density. Note that the relatively low number of images used is a limitation of the study.

**Analytic methods**

Analysis of the pairwise comparison method leads to a ranking of preferences for each participant for the stimulus set. This ranking is based on the preference score for each participant for the stimulus set, that is, how often they preferred one image over the other according to the criterion of perceived urban density. The rankings of all participants are aggregated into a rank matrix. The final rank per image cited in the results section is an equal-spaced ranking from most dense to least dense.

**RESULTS**

Results are based on the initial findings from the questionnaire. As the study is on-going, only the initial findings are reported here.

190 participants from 58 different countries took part, of which 123 were male; average age was between 18-30 years old. The pre-questionnaire collected information on the city and country where participants were born, where they grew up, where
they currently live, and whether they lived in any other cities. We are thus able to create a basic profile about the cultural background of our participants. Participants came from a myriad of cities of different sizes. The largest group of participants currently live in India (19 participants); all of them were also born there and grew up in India. We also had a large number of participants (9 or 10 participants from each country) from Brazil, Switzerland, Mexico and Spain. The only country for which there were a considerable number of participants from any one city was for Zurich, Switzerland. A large number of participants (56 participants) reported living in a different country to the one they were born, having changed country only once.

The main finding of the study is the rankings of the images relating to perceived urban density (see Figure 6). The minimum and maximum values of the six parameters (1-6 listed above) is ranked along a scale from lowest to highest perceived urban density. Figure 6 represents the results graphically along a horizontal scale from lowest (left) to highest (right) perceived urban density; the maximum and minimum of each parameter is shown above and below the central line respectively. The rankings show that visibility alone is not enough to explain participants’ judgements of perceived urban density. Our research hypothesis stated that perceived urban density is the inverse of visibility; the findings do not support this hypothesis. Rather a number of factors seem to be at play. The parameter that is considered to lead to lowest perceived urban density is the amount of sky. The parameter that is considered to have the highest perceived urban density is amount
of vehicles. There is no evidence to suggest that the variation of any individual parameter accounts for changes in perceived urban density. That is, the minimum and maximum value of any single parameter do not feature at the extremes of the scale shown in Figure 6. This suggests that perceived urban density is best explained by looking at a combination of factors. More work is needed to be able to shed light on which combination of factors are the most relevant when making judgements on the perceived urban density of locations.

Findings from the post-questionnaire give an insight into factors that participants thought were important when making their judgements. Participants report four factors, almost in equal proportion, to be the most important when making their judgement: number of visible buildings, building height, visibility, presence of green spaces. The number of visible buildings is reported as being the single most important factor when judging the perceived urban density of an image. This corresponds to existing knowledge in the field of urban planning, which emphasises the importance of built matter on urban density.

DISCUSSION

The paper presents a study designed to identify parameters that might be relevant for reaching a definition of perceived urban density. The initial results of an online questionnaire are reported, in which 190 participants made preference judgements according to which location they thought was more dense, when viewing two images. The case study location is Zurich, Switzerland. Thus any findings we report are tied to this content. It is our intention to repeat this study for a greater number of cities, in order to be able to account for cultural norms across the world. The stimulus set is comprised of twelve images from central Zurich. The small sample size facilitated a strong experimental design, and a questionnaire length that was voluntarily completed by a large number of participants; however it is also a limitation. Future work will seek to address this issue. Part of the rationale behind using those specific locations was to be able to combine the preference judgements of perceived urban density with detailed visibility analyses that are being conducted as part of a related project (Hijazi et al., 2016). This analysis will allow us to explore in greater depth to what extent perceived urban density is related to properties of visibility in the environment, and is the subject of ongoing work.

We show that the photographs which rank as having the greatest perceived urban density have high values for vehicles (top rank) and buildings (second top rank). By contrast, the photographs with high values for sky (lowest) and green spaces (second lowest) are ranked as having the lowest perceived urban density of the stimulus set. There is no evidence that low and high values of any single factor determine preference on perceived urban density. The extent to which any combination of factors can explain the preference judgements is part of ongoing work. The findings from the questionnaire are supplemented by participants’ reports of the factors that they considered to be relevant when making their judgements. Four factors are rated as most important in equal measures across all participants: number of buildings, building height, visibility and presence of green spaces. These self-reported comments correspond with participants choices for presence of buildings and green spaces. On the other hand it is noticeable that participants report that visibility is an important factor but this is not reflected in the position of high and low values of visibility along the perceived urban density scale. We hope to examine this phenomenon more in future work. It should be noted that the visibility parameter computed for this study is based on a sparse reconstruction of the point cloud model, thus limiting the precision of the information in the depth perception map. We aim to use a high definition depth perception map, based on the full reconstruction of the 3D model, in future work. More work is also needed on the relationship between the six parameters, and whether there are any effects on the preference related to the image statistics of each image.
Although our results are preliminary, we see merit in the approach and hope that future work will lead us towards a working definition of perceived urban density. We also aspire to be able to account for individuals’ personal preferences also, for example by linking the preferences to the size of the city in which they live.

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SPACE SYNTAX AND ONTOLOGIES
An ontology-based platform for BIM semantic enrichment

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In its application to design phases, BIM has progressively shown limits in terms of semantic representation and efficiency of supporting collaboration. This paper investigates the possibilities related to BIM representation enrichment through semantic web approaches, in order to represent knowledge rather than information and presents a prototypal application oriented to the integration of the informative model of the building with a knowledge base developed by means of ontologies, providing a more structured system of interconnected information.

Keywords: BIM, Semantic enrichment, Knowledge Management, Ontologies

INTRODUCTION

Since its introduction into the AEC field, building information modeling (BIM) has been appointed as a shifting point in the representation, exchange, sharing and management of information during design, construction and maintenance activities. In particular, some of the main causes of BIM spreading in the construction industry can be found in its ability to integrate geometry and semantics in a single modeling environment, providing each object with a set of non-geometrical information able to represent all its determined attributes. Although extremely powerful in theory, this approach is currently suffering from the increasing number of knowledge domains involved in AEC processes, the introduction of new representation dimensions (progressively including variables such as Time, Costs, Lifecycle and, more recently, performances simulation) and, as regards the tools, from the growing amount of proprietary data formats and standards. In this context, the introduction of Industry Foundation Classes has just made things worse. In fact, despite the progressively increasing of dimensions to the BIM paradigm and the improvement in terms of interoperability, the excessive use of IFC standards is resulting in a dangerous “representation bottle-neck”, that cuts off all the knowledge that is not structured or considered in them, while the quality of the information included in the model, its accessibility, its interpretation and finally its use, or rather the theme of the semantic enrichment, is still only partially unexplored (Simeone et al., 2013). While the knowledge about architectural artifacts progressively increases during the complex design process, information models remain poor in terms of semantics, and a large area of knowledge is not integrated into representative reference models. The BIM effect, understood as the widespread diffusion of the BIM paradigm in the construction world, has only highlighted this problem: on the one hand the models are increasingly enriched with information, on the other hand it lacks a conceptual and methodological approach that allows this knowledge to be exchanged efficiently between the various specialists involved in the design process of a building. The efficiency and accuracy of the representation of knowledge are hampered and
therefore designers, customers, users and all the special-
ists involved in the process can access and base
their decisions only on partial knowledge, increas-
ing the risk of incurring in a low-quality design and
therefore generate potential irreparable errors dur-
ing the construction phase. Consequently, current
approaches hinder this integration of information -
provided by different sources of knowledge - which
allows a single figure to gain significant added value.
In the AEC field, the most advanced solution to have
a formal, shared and explicit description of the build-
ing’s information, is related to the use of particular
models called ontologies (Gruber, 1993). These for-
mal representations allow a coherent definition of
objects, not only by describing their characteristics
but also by the relationships that exist between them;
so that we can express and share the meanings, struc-
ture, and nature of the material and immaterial con-
cepts that belong to the various domains of knowl-
edge involved. Concepts are represented by entities
- concrete or abstract objects - grouped into classes
whose identification requires a very careful evalua-
tion of the meaning to be expressed and the seman-
tics and properties that represent all of its aspects.
At present, the formalism of ontologies is the most ap-
propriate approach for the defined theoretical model
and the purposes considered. To this end, the core of
this model is a semantic structure in which all enti-
ties considered during the construction design pro-
cess are represented in terms of characteristics and
interrelated relationships, in accordance with the do-
mains concerned. In this way, it’s possible to provide
a modeling environment where all building-related
knowledge can be homogenously formalized, man-
aged, processed and shared between the various
specialists involved in the process. From an analysis
of applications to AEC design process, the potential
of semantic web technologies is evident and ontolo-
gies, which are progressively introduced in the AEC
sector to support collaboration and sharing of knowl-
edge among the various actors involved in the design
process (Beetz et al., 2005), enable them to represent
entities not only by describing their own characteris-
tics, but also by the relationships between them, pay-
ing attention to the meaning of the concepts and the
structure and nature of the domain of study. On this
basis, this article describes a semantic bridge plat-
form - called S-Enr BIM - which allows the integra-
tion of BIM with a knowledge-based modelling ap-
proach, such as the Building Knowledge Modeling
(BKM) developed by Sapienza research group (Car-
rara et al., 2014) and conceived to provide an effective
representation of all the necessary knowledge, man-
aged and shared during a building design process;
thus obtaining, in a single modeling environment,
three-dimensional informational representation and
all non-geometric knowledge provided and used by
the various actors involved.

STATE OF THE ART
As illustrated, in this context, the information re-
quired for a complete understanding of the prod-
uct is diversified, interconnected and, therefore, ex-
tremely difficult to represent and manage in a sin-
gle information model. In addition, research has
shown that sharing information alone is not enough
for a true understanding and collaboration and that,
in order to achieve this, it is necessary to provide
the information together with their interpretive con-
text. Recently, some research has investigated this
topic - named as BIM semantic enrichment - propos-
ing the integration of BIM representation schema
with approaches and methodologies derived from
the Semantic Web in order to enhance quality and
level of non-geometrical information associated to
tri-dimensional representations. In this field of re-
search, as can be seen from some works by East-
man (2014), considerable efforts have been directed
to improving interoperability through the develop-
ment of new models and representation methodolo-
gies, usually through the implementations and possi-
ble evolutions of the IFC schemes. The development
of an OWL version of the IFC schema, named ifcOWL
(Beetz, op. cit.; Belsky et al., 2016) has partially fos-
tered such approach but the choice of relying on IFC
standards, although if in an ontology-based systems,
still limits flexibility and specificity in AEC knowledge representation and management. In particular, in the last 20 years, the introduction of the Linked Data Approach and Semantic Web technologies has opened up new possibilities for the semantic enrichment of BIM. As described by Pauwels et al. (2013), the analogy between building representation schemes (e.g. IFC) and the descriptive logic of semantic networks (RDF and OWL) favored the creation of information ontologies in the AEC sector, usually in conjunction with IFC schemes and Express rules.

In 2008, Jeong investigated the use of ontologies for semantic sharing in multidisciplinary design. In the same period, Carrara et al. (2009) interprets the ontology as a way to move towards knowledge-based models to improve collaboration in the AEC processes, but to date, the collaboration support is precisely one of the aspects that are not solved in BIM and that, consequently, limit the real use in the field of building design. Similarly to the field of designing new buildings, some research has focused on the integration of semantic web technologies with Building Information Modeling to enrich the representation of historic architectural artifacts. Pauwels and Di Mascio (Di Mascio et al., 2013) rely on integrating the ifcOWL (linked to other heritage-specific ontologies) with game engines to provide a three-dimensional representation of architectural heritage. The mentioned researchers underline the potential offered by the integration of BIM environment with Semantic Web approaches; experiences that are gradually showing all the potential in enhancing the level of semantic representation in the AEC field, providing a bridge to overcome the actual gap and misalignment among the information represented in a BIM environment and those required to perform collaborative design activities.

On this basis, the proposed model is conceived as an integration of the BIM modeling environment with a system of representation and management of the knowledge shared among the actors involved in the building design process.

**METHODOLOGY**

**The conceptual structure of the model**

During a building design process, a large amount of information is produced, used and shared by the
many specialists involved, each using its own methods and timing. Therefore, it is evident the need for a tool able to support information management through a collaborative working environment capable of structuring and formalizing the knowledge acquired by operators. Unlike the existing knowledge management models, the integration of a semantic web-based structure with a BIM environment allows to include in a single model, in addition to the geometric representation of the building and the elements that compose it, also the whole semantics to which they can be traced and which affects the various actors involved in the design process. In the transposition from the semantic web to building information modeling, some of these concepts overlap the elements of families and instances, integrating and enriching the semantic representation of the building.

As mentioned before, the proposed model consists mainly of two elements: 1) a BIM environment where the artefact representation is mainly limited to the geometric characteristics of its components; 2) a knowledge base, developed by means of ontologies, able to formalize and integrate the semantic belonging to different knowledge domains necessary to provide a representation of all the knowledge exchanged during the design process of a building. Although there are differences between ontologies and relational databases (Martinez-Cruz et al., 2012), as in BIM databases, this research exploits the two main analogies of BIM and Semantic Web modeling methodologies: 1) Object-oriented representation - 2) abstract/concrete specification (often known as class/instance relationship). In the BIM environment, buildings are decomposed into an organized set of entities and relationships that correspond to the technological components of the product and their relationships (such as assembling standards or those relating to constructive and behavioral relationships). Likewise, semantic networks are structured as node-oriented nets and strings where nodes are the concepts and strings represent the relationships between two concepts. This correspondence translates the BIM modeling structure into the frame-work of ontologies, integrating entities and relationships into a broader knowledge base that is able to uniformly formalize the representation of different domains of knowledge. The second analogy refers to the abstraction/instantiation process that can be traced both in ontologies and in the BIM environment: Building Information Modeling is based on a family type-instance scheme that can be considered as a simplification of the common class-Subclass-instance, typical of ontology-based systems. These similarities can also be found at the property level, since in both approaches the entities are represented in terms of properties that describe their main features, with associated values to define specific instances. By comparing BIM and semantic web representation structures, we are able to recognize how BIM semantics can be incorporated into a broader homogeneous formal representation where entities, relationships, and rules of the BIM are integrated with other concepts and relationships, extending its domain(s) and increasing the semantic level of representation. In the AEC field, this semantic enrichment process is particularly effective as it provides a homogeneous modeling environment where all knowledge of different domains (with concepts, definitions, patterns and formalization methodologies), necessary for a complete understanding of the design process, can be exhaustively represented and made computable. To validate the proposed research, an ad hoc tool has been developed in order to link the semantic networks formalized in the OWL language with a BIM environment (Figure 1).

**S-Enr BIM: BIM and Ontologies for architectural design processes**

Rather than passing through the IFC schema, the proposed platform directly connect concepts, properties, and relationships represented in the knowledge base with the objects modeled in the BIM environment. This approach results in the following improvements in terms of knowledge management: 1) major flexibility of the knowledge base that can be effectively adapted to the specificities of the AEC pro-
The developed software (S-Enr BIM) allows you to “map” the formalized instances of formal artwork into the ontology editor with their respective objects modeled in a BIM environment. The software imports the DBs of the two tools and allows comparison, verification and overwriting from one environment to the other and vice versa.

The implementation of the connection involves the following steps: 1) exports in Access format, through the plug-in DBLink, of the database containing the objects (and their properties) that make up the historical building modeled in Revit; 2) Conversion into a MySQL open-source database of the ontology formalized in Protégé OWL. This conversion produces an unstructured database but rather made up of strings in single-table format; 3) so is required a reading phase of the ontology database through a tool specifically developed by the research team, able to...
identify the strings regarding the instances related to the components of the building, the properties and the values assigned to them in addition to the Classes they belong to. 4) Manual mapping of the instances - with their properties -, corresponding in the two databases (Protégé-Revit) through the software developed by the research group (Figure 2).

The developed BIM Semantic Bridge operates to remodel the taxonomies of classes, properties, and related instances, of both databases sides, that of BIM and that of ontology, so as to allow the mapping and to perform comparison and data transfer. Currently conceived with a family-instances structure, BIM databases are organized as a set of connected tables, each one representing an element family with instances formalized in rows and properties in columns. Ontologies databases, instead, are usually made of a single table and the differences between classes, properties, relationships and instances are controlled through “type” values and identified with a unique string made of different substrings referring to the “mother class”, the type, etc. By means of this structure, the taxonomy of ontologies results to be extremely flexible and adaptable to the specific knowledge domain to be represented. Classes and properties mapping are stored in a file and can be re-used in similar design processes that involve the same typologies of entities, reducing the time necessary to formalize all the relationships between the BIM representation structure and the ontology taxonomy. The more relevant contribution of the proposed platform is the possibility to customize such mapping organization, in order to integrate the BiModel with project-specific knowledge databases. To date, the instances mapping has to be re-performed for each project as it is still project-dependent. The software interface developed to connect the two databases can override in both directions, from the Database Protégé to the Revit one and vice versa, the values assigned to the properties “mapped” by the user. It is also possible to check for any inconsistencies between the values assigned to the properties of the mapped objects, in addition, to identify which existing information in a database result missing in the other. Through this system, it is possible to fill the knowledge related to the building and formalized in the ontology with the data retrieved from the objects modeled in Revit and vice versa updating the BIM model database with new values and definitions derived through the rules modeled in the SWRL language in the ontology. The prototype has been implemented using the most suitable resources made available by the development of computer technology regardless of the tools currently use in order to connect A BIM database underlying an Autodesk Revit model and formalised through the Autodesk DLink application and an OWL database generated through the ontology editor Protégé 3.5 and an ODBC connection (Figure 3).

CONCLUSIONS
This research proposed a knowledge-based system integrated with parametric object-oriented modeling platforms to improve building process and to enhance collaboration among the involved actors. A model defined in this way can potentially both represent enough knowledge to set up and run a collaborative design process involving a number of specialists from very different specialized fields and represent the knowledge ‘contained’ in the final solution as the result of the design process. This approach has made a new definition of the workflow typical of the design process; the use of the plug-ins and computer programs implemented has shown how this approach can aid the verification of design rules and constraints, demonstrating the system’s overall potential. The system we implemented attests good potential for proposing a new generation of assisted design tools, a field that permits the development of further research and analysis. In terms of the software application, has been presented a custom system that acts as a bridge between a knowledge base developed through the ontology editor Protégé and the BIM environment provided by Autodesk Revit. Our current work is focusing on improving the “semantic
The model consists of an ontological knowledge base and a BIM environment; Ad-hoc software allows integration as well as the ability to perform verification operations between the two databases.

filtering” between knowledge domains for the various disciplines involved in the building design process, and how the knowledge-based approach might be integrated more effectively with that of Building Information Modeling.

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This paper examines the current state of the conventional Design-Bid-Build project, wherein design intentions are manually translated to construction directives by subcontractors based on industry-specific details. This process exacerbates a dilemma in design and construction; that often the designer may be unaware of certain details that are involved in fabricating and assembling building components. Research for Knowledge Base for Architectural Detailing (KBAD) proposes a system that takes advantage of current CAD software and programming language, bringing together the information provided by and important to the design team with the data required by the subcontractor to accurately produce architectural components, during the design phases of a project. The trade of architectural precast concrete is used to demonstrate the potential of such a system. Solid modeling, visual scripting, and programming language techniques working towards KBAD are described. Possible variations of architectural precast concrete panels, detailed with window openings, reveals, and embed plates, are presented.

**Keywords:** BIM, HCI, Collaboration

**INTRODUCTION**

“A great building, in my opinion, must begin with the unmeasurable, must go through measurable means when it is being designed and in the end must be unmeasurable.” (Kahn, 1961)

In the current state of the conventional Design-Bid-Build project, there are two key descriptions of a building proposal from two different stakeholder points-of-view. The first description comes from the designer and the second comes from the subcontractor. The first will be a set of design intentions, while the second is explicit directions for construction. Design intentions may take the form of drawings, models, and specifications or other narratives. In some ways, then, certain design intentions are unmeasurable. Construction directives - highly measurable - can be shop drawings or coordination models. Each subcontractor on a job will regularly develop their own model based on their own industry-specific fabrication and assembly details. This is the standard contractual procedure of the profession; the designer is not required to provide the means and methods of fabrication and assembly, but a general direction for the design intent and, in due time, various subcontractors fill in the gaps. Often the designer may be unaware of certain details that are involved in fabri-
cating and assembling building components; understanding that craftsmen take for granted. Kahn expanded, “the only way you can build, the only way you can get it into being is through the measurable.” (Khan, 1961) These two different viewpoints and descriptions of the design and construction process are depicted in Figures 1 and 2. In the top-down approach (Figure 1), the designer has a concept for a project which is represented in their design intent model. This model actually portrays various smaller components, organized in an overall composition. Upon handing these descriptions off to the construction team, each of the subcontractors add their expert knowledge of the fabrication and assembly details needed to realize the building. This is referred to as the bottom-up rationale (Figure 2), wherein data at the component level is extrapolated from the detail to the overall coordination and for-construction model.

![Top-down approach](image1)

![Bottom-up rationale](image2)

Research for Knowledge Base for Architectural Detailing (KBAD) proposes a system to capture this integration of design intent and construction model, bringing together the information provided by and important to the design team with the data required by the subcontractor to accurately produce architectural components, during the design phases of a project. In other words, going from the unmeasurable to the measurable. This is portrayed in Figure 3. In order to demonstrate the potential of such a system, this research focuses on a specific trade; architectural precast concrete. Architectural precast concrete is distinguished from other forms of precast concrete in that such pieces are critical components of a building skin - they have a high-quality finish and are integral to the overall aesthetic of the building design. Further detail on the precast industry and background of similar digital workflow exploration is presented in Section 2 of this paper. Section 3 documents the methods used to translate simple nominal extrusion into product models detailed based on input from industry experts. The results as well as reflections of this work are described in Section 4. Finally, Section 5 provides a concluding summary, thoughts on future research to continue this work, and the potential of returning to certain unmeasurable qualities.

**BACKGROUND**

As noted, on most projects, each of the subcontractors involved develops their own shop drawing model based on their own industry-specific fabrication and assembly details. Furthermore, even if the designer develops digital models and building components as they envision them being built, this does not guarantee that the physical building parts can be built as modeled. Many other factors - for example, constructability, budget, or scheduling commitments - may force changes to the original design intent, resulting in time-consuming re-modeling or even loss of significant design features due to value engineering. Digital tools permit even novice modelers to readily create parametric objects. Though now ubiquitous in architectural design, parametric design is not new. Gaudi was arguably practicing parametric design through his hanging chain models in the late 19th century. (Burry, 2002) Thinking and developing designs with editable constraints - regardless of technology - allows flexibility and the ability to quickly...
produce design alternatives during the design process. (Sacks et al. 2004)

In order for members of design and construction teams to be able to effectively communicate regarding their design and construction tasks, they need to exchange information regarding the building proposal accurately among various trades. Translation of this information from one trade-specific software to another - from design intent model to for-construction model - has often taken place manually which is tedious and error-prone. Significant research has been devoted to increasing interoperability through product models. The goal is to define the parametric possibilities and constraints fundamental to building information models based on various experts’ knowledge and point-of-view. (Eastman et al. 2011) IFC (Industry Foundation Classes) provide a neutral platform for transferring digital models among parties. A commendable aspect of IFC is that the data is inherently hierarchical and focused on building; all objects belong to a defined owner, project, site, building, and even building story. However, customizing the code is quite cumbersome and not intuitive. To overcome this, several industries have invested in defining the parametric constraints pertinent to their trade. The steel industry, the precast concrete industry, and the masonry industry (Gentry et al. 2016) have all begun to define how the building components that they provide are represented parametrically through digital information models.

The first step of this research was to document the process of an actual precast fabricator during the shop drawing phase of their work, tracking a real project from design intent model through the incorporation of industry-specific fabrication details. (Collins, 2016) Figure 4 shows a comparison of the design intent model to the for-construction model for
the University of Florida Health Shands building designed by Flad Architects. The model from the design team shows that this base wall of the building is modeled as one piece with reveals to represent the potential individual panels. When they received the project, the architectural precast concrete manufacturer, Castone Corporation, modeled each panel as distinct family types and instances using BIM software. SysML (Systems Modeling Language) was used to encode this workflow. Producing such work flows is a method to improve the process itself. Gane and Haymaker have developed design process optimization tools and techniques, suggesting that the act of mapping the process in-and-of itself can help one to identify inefficiencies or other problem areas as well as opportunities for improvement in future work. (Gane and Haymaker, 2012) One particular aspect of a typical architectural precast concrete project that is identified as improvement-opportune is the current need for subcontractors to remodel components; if the fabrication and assembly details could be embedded in the design intent model, such a model could also serve as the for-construction model.

Similar iterative approaches are noted in Artificial Intelligence (AI) research. Using methods borrowed from cognitive science, the contribution of their work is often twofold. First, modeling computational agents in the way that researchers initially believe humans think helps to develop better computational agents. Second, such modeling gives more reliable insight into how human thinking may or may not actually operate. Upon reflection, the steps repeat and both the process and the model are improved iteratively. These methods are not new to computer science. Expert systems have been developed to supply comparable traditionally human-provided expertise, such as medical diagnosis. A stored knowledge base establishes and organizes a repository of data. Even more intelligent systems have been designed to respond to Raven’s Progressive Matrices questions using analogical reasoning. Knowledge-based AI structures such information to empower an agent with the ability to reason and apply knowledge to new scenarios based on familiar, previous encountered ones. (Goel, 2015). Likewise, described by architect and educator Bill Mitchell, “design exploration is rarely indiscriminate trial-and error but is more usually guided by the designer’s knowledge of how to efficiently put various types of compositions together and that such knowledge can often be made explicit, in concise and uniform format, by writing down shape rules.” (Mitchell, 1990) Such rules constitute the designer’s internal tacit knowledge, or knowledge base. The same is true for industry experts. In fact, this quote could be adapted in consideration of our research goals to read:

Construction descriptions are rarely indiscriminate trial-and-error but are more usually guided by the industry expert’s knowledge of how to efficiently
put various types of building components together and that such knowledge can often be made explicit, in concise and uniform format, by programming detailing rules.

**METHODS**

When developing a design intent model that includes architectural precast concrete panels, the designer is mostly concerned with panel composition on the overall façade - joint and reveal layout and relationships with adjacent materials. Panels are placed and dimensioned relative to structural grids and finish floor elevations. Geometry is nominal and made of simple extrusions. Information regarding surfaces finishes may be included, but structural detailing would not. (Afsari and Eastman, 2016) Even within the relatively straightforward transformation depicted in Figure 4, there are many decisions that have been made regarding the architectural precast concrete pieces to be built. These include aesthetic desires, industry knowledge, and material constraints. A visual scripting model is produced to replicate some of these decisions parametrically, translating a base wall into individual editable panel components. The inputs and outputs of this model are diagrammed in Figures 5 and 6.

It is important to note that in Figure 5, the output is one box. A base wall is generated with width, depth, and height input to yield one piece of geometry. This echoes the one piece of geometry that would be provided in a design intent model similar to Figure 4. When this wall is brought into the script in Figure 6, the output is ten closed B-reps (boundary representations). The base wall is broken into individual panels via three more inputs: number of panels vertically, number of panels horizontally, and thickness of joints. The number of panels that this operation yields is dependent on the number of panels desired. The example shown in Figure 6 lists ten panels as there are five vertically multiplied by two horizontally.

Working to advance this current process and as a test for expansion in future studies, programming language is used to link the visual scripting model with solid modeling software. The software queries the user for input which directly effects the base wall panelization. As a demonstration, three questions are posed to the user:

- How many panels should there be vertically?
- How many panels should there be horizontally?
- What is the joint thickness between panels?

The user responds to each of these questions and the base wall model is automatically subdivided. A diagram of the inputs, outputs, and innerworkings of this process is shown in Figure 7. From these individual editable panel components, the models can be extended to include additional parametric features and each panel and be unique. This shadows the logic of the precast fabricator developing a shop drawing model.

Upon receiving the design intent model - typically in the form of printed Contract Documents, but increasingly accompanied with a digital model - the precast fabricator first determines the quantity and variety of architectural precast concrete pieces the building will require and what parameters or alternatives for each piece will need to be obtainable. Pan-
elization is confirmed or suggested adjustments may be made. The precast fabricator begins to consider site logistics, structural loads, connection details, required embeds, reinforcing, and lift hooks. Actual geometry, as opposed to nominal, is taken into account. The shop drawings that are generated serve as the basis for costs estimates and aid in scheduling. The shop drawing model then serves to produce additional documents for fabrication, such as shop tickets.

Additional parametric features are added to the visual scripting model; window openings, reveals, and embed plates. A relational database of these panel features and attributes is shown in Table 1. These variables are translated into the visual scripting input parameters listed in the right columns. The user can flex any and all of the constraints to explore additional precast concrete architectural wall panel designs - at both wall (top-down) and component (bottom-up) levels. Future work will incorporate these and more features into the above described programming language for additional “semi-automated” detailing. Loukissas describes similar practices Co-Designing, where “tools have profound implications for the social distribution of design work... in an evolving search for the roles and relationships that can bring... greater control over design.” (Loukissas, 2012)

Table 1
Relational database
Figure 8
Variations of translating base walls into panelized walls.

Figure 9
Variations of window openings, reveals, and embed plates.
RESULTS AND REFLECTION

Figure 8 shows some possible variations of the above described modeling technique, translating base walls into panelized walls. Each example lists the variables that are used to generate the panel components. These examples clearly are not exhaustive, but demonstrate some panelization variations. Figure 9 shows a sample of individual editable panels with alternatives for window openings, reveals, and embed plates. Variables for each of these features are listed in the right column of Table 1 as previously discussed. While it is not known whether some of these are constructible, one of the goals of this work - aided by the ease with which they can be readily produced - is that proposals such as these stimulate a conversation between designer and industry expert. The flexibility granted through parametric modelling, coupled with embedded fabrication and assembly knowledge, enables further design control. Research for KBAD aims for rigor while facilitating the possibility of play. A variety of options should be possible, limited by realities such as constructability and budget. For instance, the above programming language currently allows the base wall to be divided into any number of panels. The code could be modified to limit the size of the panels - or the number of panels that are allowable given a base wall dimensions - based on the constraint of the size of the precast fabricator’s casting bed. This construction intelligence contributes to a design proposals’ measurability.

Several other assumptions, which have an effect on design possibilities and outcomes, have been made in the process of developing the above described models, including:

- Rectilinear base wall geometry
- Joints in a regular grid
- Vertical and horizontal joints same thickness
- Equal spacing of panels centered on wall
- Panelization based on number of panels rather than dimensions of panels

Future work will aim to overcome and transcend these assumptions and limitations of the current model. Paradoxically, while looking to allow for new design possibilities, research will look to historical precedents. Some examples demonstrating both the flexibility of the architectural precast concrete panels as well as the impact the material has on the overall aesthetic of the building design are shown in Figure 10. Historic preservation architect Jack Pyburn has documented three distinct architectural precast concrete production systems where developed in the mid twentieth century, each supporting “greater control of the casting and curing process and thus better and more consistent quality of concrete, rising labor costs and the potential of precasting to reduce labor requirement in concrete construction,

Figure 10
Architectural precast concrete examples from the 1960s.
shortages of steel after World War II, built up demand for housing and commerce, and the availability of competitively priced raw materials.” One of these systems, the Mo-Sai approach, Pyburn notes faded away over time due to “lack of foresight and motivation to grow technologically.” (Pyburn, 2008) Technological advancements make the time right for such (re)investment. Indeed, Shelden asserts that “new geometries - the non-Euclidian forms that characterize much of contemporary architectural form - set the stage for architecture’s reengagement with the physical world...Families of geometry admit specific surface qualities that can enable or prohibit specific ways of making.” (Shelden, 2014) Research for KBAD aspires to permit designs to be constructed that may otherwise have been value engineered because constructability, budget, or scheduling issues were detected too late in process.

CONCLUSION
This paper has described the potential of a design computation system to bring together design intentions and industry-specific fabrication and assembly details during the design phases of a project. The trade of architectural precast concrete was used to demonstrate the potential of such a system. Solid modeling, visual scripting, and programming language techniques working towards a Knowledge Base for Architectural Detailing were described and possible variations of architectural precast concrete panels generated through the system were presented. In particular, the system “semi-automatically” translated a base wall into a panelized wall of individually editable panels. These panels were then detailed with additional parametric features; window openings, reveals, and embed plates. This work is grounded in the notion that both design intentions and construction directives are (paraphrasing Bill Mitchell) “rarely indiscriminate but more usually guided by knowledge and that such knowledge can be made explicit by rules.” Future work will extend this foundation to overcome present assumptions and limitations, allow additional design possibilities, and incorporate additional knowledge and rules. Particular interest will be paid to the representation of nebulous design intentions, material attitudes and identities, and unconventional approaches which CAD platforms do not currently facilitate; those qualities that take mere building to architecture, to unmeasurable

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SOFTWARE USED
In this paper, generic terms are used in place of software names in order to describe a process that is, ideally, more universal than software-dependent. For reference, the programs used include:

- Solid modeling : Rhinoceros 3D
- Visual scripting : Grasshopper
- Programming language : RhinoScript / Python

PHOTO CREDITS FROM FIGURE 8
a) Embassy of the United States, Dublin, Archiseek.com; b) Philadelphia Police Department Headquarters/Roundhouse, Dominic Mercier; c) Bank Lambert, Thomas Ost

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Ontological Instrumentation in Architecture

A Collection of Prototypes Engaging Bodies and Machines from the Inside Out

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This paper provides a theoretical discourse on ontological instruments in design by exploring the ways in which design and technology might help get us back to an understanding of our own humanity. The intent of this theoretical discourse is to illuminate the possibilities of what can be, by looking at history as a way to see the world with perspective and as a predictor of what may happen. Another objective is to demonstrate the proof of those possibilities through the presentation of two design research projects which actualize those ideas. The first project is a prototype for an interactive chair that explores the calming effects of conscious and synchronized breathing. The second project is a reinterpretation of the veil and explores the relationship between the individual and the public. Both projects are artistic and performative in character and are embedded in a theoretical discourse on ontological instruments and investigate the opportunities of interaction of the human body with the environment moderated by technology.

Keywords: prosthesis, cyborgs, robots, technology, humanity, culture

INTRODUCTION

Architecture has a long history of body-centered designs, evident from antiquity through modernism, with Vitruvius and Le Corbusier using an ideal figure as a scalar reference to proportions. Walter Gropius similarly implores, “The size of our body (of which we are always conscious) serves as a yardstick when we perceive our surroundings. Our body is the scale unit, which enables us to establish a finite framework of relationships within the infinite space” (Gropius 1955). However, today common body related discourses in architecture range from the anthropocentric to the post human. Within this spectrum, we see the work of Karen Franck’s socially engaged practice, which focuses on the prioritization of human needs, on one end, and Antione Picon’s theoretical stance on the cyborg, as an exemplar of digital culture, on the other. The key components drawn from these discourses, for the sake of this paper, are the notion of the body as a guide for prioritizing humanity in architecture and the awareness of technology radically affecting the way we inhabit our environments.

Observing the spectrum, the research outlined here draws on both ends. Important to human centric design is Franck’s understanding of the investigation of bodies as both objects and subjects. She explains to design for the body as an object, is to step outside the body and view it from the outside,
as done with the Vitruvian Man or Mies’s idea of the ideal posture in his design of the Barcelona chair. However, designing with an understanding of the body as a subject, requires one to be within it, feeling, sensing, and engaging its experiences (Franck 2001). Not forgetting this notion of engaging the body as both object and subject, nor blindly moving forward without considering technology, the suggestion within the research is to question how design and technology might help get us back to an understanding of our own humanity by exploring opportunities for ontological instrumentation in architecture.

WHAT IS AN ONTOLOGICAL INSTRUMENT?
Relative to Heideggerian notions of “readiness to hand,” the body can seamlessly expand to engage with tools without noticing, thus creating a condition where tools themselves are amalgamated extensions of the mind and body (Heidegger 1962). The Greeks understood this relationship between tool and body in that they had one word for organ and tool, organon, which literally translates to “that with which one works” (1). Georges Teyssot further explains this relationship of tools, bodies, and environments, when he writes:

“The relation between organ and tool, attested to by etymology, history, and theory defines our action on space, on the environment, on the world we inhabit. Such a relation can ‘unfold in the space created by our technologically supplemented bodies, not merely that of our natural flesh.’ The first task architecture ought to assume, therefore, is that of defining and imagining an environment not just for ‘natural’ bodies but for bodies projected outside themselves, absent and ecstatic, by means of their technologically extended senses. [...] We must conceive tool and instrument ‘like a second sort of body, incorporated into and extending our corporal powers.’ It then becomes possible and even necessary to logically invert the terms of our proposition on the role of architecture. The incorporation of technology is not effected by ‘imagining’ a new environment, but by reconfiguring the body itself, pushing outward to where its artificial extremities encounter ‘the world’” (Teyssot 1994).

Teyssot argues we no longer perceive or engage with our environments directly through our bodies, but instead it is through technology that we experience the world. Therefore, architecture encases bodies “prosthetically expanded and articulated through tools and media technologies,” suggesting there is no ontological separation between our bodies and our instruments (Velikov 2016). Marshall McLuhan in his work, Understanding Media: The Extensions of Man, also reiterates how media acts as technological amplifiers and extensions which alter our perceptions, which often happens without notice or re-
sistance (McLuhan 1994). From these etymological and theoretical observations lies the premise of ontological instrumentation. For clarification, an ontological instrument, for sake of this research, is defined as a device, which mediates between bodies and space, and provides unique ways of engaging the world through technology.

Ontological instrumentation correlates to the context of the cyborg and prosthesis in architecture as seen in the work of Haus Rucker Co’s Environmental Transformer and Yellow Heart, Han Hollein’s Mobile Office, Coop Himmelblau’s Heart Space-Astro Balloon, Walter Pichler’s TV Helmet (portable living room), and Diller Scofidio’s Braincoats (Cummings 2012). Donna Haraway, in her “Cyborg Manifesto,” uses the cyborg as a figure, which blurs the relationship between human and machine and moves beyond traditions related to gender promoting feminism (Haraway 1991). From Haraway to Hollein, these examples challenge the way humans interact with their environments through instrument-enhanced bodies. Madeline Schwartzman’s, Seeing Yourself Sensing, provides a more detailed survey of projects where designers view bodies as “sites for unimaginable interventions many of which blur the boundary between humans and machines” and where “the architecture of the body is not simply something to behold, but rather something to analyze and explore from the inside out” (Schwartzman 2011). Inside out also being two key words in the title of the book, Architecture from the Inside Out, co-written by Franck, which focuses on designing architecture which exists for people with emotional and physical needs and relationships to one another (Franck and Lepori 2007).

While the cyborg has a history of many dystopian fictions associated with it, the collection of projects presented in this paper steer away from such anxieties and embrace technological prosthesis as a design method for appropriating computation and technology to explore “newfound intimacies with our selves, each other and the world around us” (Velikov 2016). The research focuses on a set of questions, which ask, what are the possibilities of using technology to enhance the effective qualities of architectural spaces? How have technologies opened possibilities for how our bodies communicate with our environment? How might technology remind us of aspects of our own humanity? How might we embed environments with technological bias for enhanced life? In response to these questions, this paper outlines two projects, which focus on prototypes to study how ontological instrumentation affects our experiences and interactions. The first project, Synchronous Rhythms, engages the body through an interactive family of chairs, which use conscious breathing techniques to transfer user experiences. The second project, Kinetic Veil, is a transformable structure, which draws on the traditions of a veil, has the capacity to cover and uncover, and can attach or detach from the body.

SYNCHRONOUS RHYTHMS

Synchronous Rhythms is a family of furniture that synchronizes with rhythms of the body, specifically by looking at the positive calming effects of conscious breathing. It includes the development of prototypical responsive pneumatic chairs, which encourage synchronization in breathing patterns. Drawing upon the idea of ontological instrumen-
tation, this project tries to expand the possibilities of using technology to mediate psychological and physiological states in spaces for beneficial ends. It asks, can technological devices re-introduce aspects of our own humanity by providing an opportunity to feel, experience, notice, and then begin to interact with one’s body and physical sensations in an agentic and possibly self-soothing way?

The research method involves the development of a taxonomy pairing kinetic responses to rhythms of the body and later the development of small-scale models and full-scale prototypes (see Figures 1, 2, and 3). The models explore design options, materials, and actuators. These models include ideas for rocking chairs, which rock according to the rhythm of a user’s breath and inflatable chairs, which inflate and deflate relative to patterns of inhaling and exhaling. The prototypes not only test the feasibility of a device, but also provide a means for testing ways to encourage synchronization of breath and provide calming effects.

The full-scale prototypes use fans and air pumps controlled with Arduino. Drawing from epistemic observations in Ant Farm’s *Inflatocook Book*, the inflatable models used polyester fabrics and polyethylene (Lord, et al 1973). Integrating piezo vibration sensors into an interface directly in front of the user’s mouth and nose provide an input to inform the system when the user is inhaling or exhaling. This input activates a relay circuit to turn on or off in order to correspond breathing patterns to the inflating and deflating of the chair. A set of tests informed the rate of inflation or rocking in order to match the rate of breathing measured in breaths per minute. The first full-scale prototype takes in a single user and develops an inflating chair, which synchronizes in real time with the breathing pattern of that one user (see Figure 4). If the sensor was not picking up a normal respiratory rate, which is twelve to eighteen breaths per minute for an adult, the inflation would change in the chair to the ideal rate to encourage normal breathing patterns (2).

The second full-scale prototype draws on the notion of empathy and experience transference; it takes input from two users and attempts to encourage synchronization of breath between both users. In this scenario user one sits in the inflating chair while a sensor takes in the breathing pattern of user two and causes a corresponding inflation. This became a testing ground for understanding how technology might play a role in encouraging empathy and enhance shared relationships between people. In robotics today, Japanese researchers are rapidly developing systems for elderly care giving robots. However, what they are realizing is that while the devices are providing assistance with basic daily care the problems remains that people do not want empathy from machines, but want empathy from other people. Engaging ideas of instruments that are fundamentally related to aspects of our being and life, these prototypes question how design and technology might allow for the further exploration of the human condition and promote mindfulness.

While the synchronous rhythms research draws from psychological studies of the positive effects of conscious breathing and heightened intimacy of synchronized breathing, the intent for the research is to
explore shared languages and encourage new forms of communication through technology by mediating between our bodies and environments. The research acts an evocative model of strategies for embracing the immeasurable and encouraging the integration of qualitative and human-centric attributes in our machines and devices. It specifically does so by reengaging the chair, which Galen Cranz articulates as a crucial part of our culture and environments. She further explains this importance when she writes, “We spend much of our waking lives in a chair [...] We touch chairs not just with our hands but with our whole bodies. Yet despite their intimate place in our lives, we know little about them and their effects on us, physically and mentally. Without a doubt, their efforts are profound. What is true of the chair is true of all the artifacts we create. We design them; but once built, they shape us. As sitting in chairs spread to the common person over the centuries, it left its mark on the human body and human consciousness. The chair offers a glimpse into our collective ideas about status and honor, comfort and order, beauty and efficiency, discipline and relaxation. As our ideas change, so do our chairs.” (Cranz 2013).

KINETIC VEIL

Engaging technology as an extension of the body, the kinetic veil project does not respond by developing an architecture for a man-machine amalgamation, but instead looks at ways to reconfigure the body itself by designing really close to the skin. It draws upon Gottfried Semper’s idea that clothing was the first mediator between bodies and environments by providing an immediate means of protection. The research explores the body as a site for architectural intervention and looks for ways to redesign our technologically enhanced bodies through the development of a second skin (see Figures 5 and 6).

The project creates a reinterpretation of a veil, which is no longer about morning, but operates under a new social manifestation. This reinterpretation deals involves the design of an exoskeleton, which has the capacity for hiding as a way of revealing and tries to be provocative by extending out into and claiming public space. Drawing from tradition of covering and understanding the importance of providing the capacity to cover and uncover, the veil is capable of opening and closing based on the control of the user and allows for the joining and linking together with other kinetic veils. Either as a singular or joined exoskeleton, the veil defines a spatial configuration based on intimacy by creating a private room within a public space.
cating connections made from a delaminated module to appropriate the bending range of the material (see Figure 7). The connection between two single ply ends of the module allows for a flexible connection while the connection between two double ply ends creates a rigid connection. Through this series of details, the transformable geometry is able to open and close while also changing the range of aperture and allowing for visibility through a physical barrier. The configuration of the flexible system results in a dome structure surrounding the upper portion of the body from the waist up altering the scale of the body and creating a unique spatial awareness (see Figure 8 and 9). The lightness of the structure also allows for a flow and rippling across its surface which corresponds to the rhythmic movement of walking. The project intent is to evoke the imagination of new environments based on how architectural prostheses engage, encounter, and affect our experience of the world and it does so by blurring conditions between public and private, intimate and social, and natural and artificial.

CONCLUSION

Marshall McLuhan writes, “During the mechanical ages we extended our bodies in space. Today after more than a century of electric technology, we have extended our central nervous system itself in a global embrace” (McLuhan 1994). Ontological instrumentation in design explores these changes and seeks to investigate “the contours of our extended being in our technologies” and their implications on our experience of the built environment (McLuhan 1994). This small collection of research outlined attempts to find resolutions between man and machine, organic and mechanical, and the computable and incomputable. It ask, as our buildings, cities, and bodies are retrofitted with technology, how might designers respond with visions of new modes of research and practice? If we look back at industrialization in modernism we see a history of the epistemic changes in architecture and redefinition of its effects (Picon 2014). This paper similarly calls for a redefinition of architecture in a digital culture and argues it must go beyond the fixation with data driven design, the metrics of simulation, and the appropriation of industrial robots. It instead calls for the reinstatement of the qualitative, the immeasurable, and the subjective through the appropriation of ontological instrumentation in design, which requires us to imagine human-centric design sensibilities and opportunities for intervening between bodies, technology, and space.

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Sky View Factor Calculation

A computational-geometrical approach

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Sky view factor (SVF) is a well-known parameter in urban-climatic studies, but there is a lack of consensus on its effectiveness, especially with regard to the interpretation of changes in urban air temperatures. This led the authors to develop the new concept of the partial sky view factor (SVFp), which showed promise in a previous study. The objective of this study is to save the time associated with manual methods of calculating SVF and SVFp by developing a Rhino-Grasshopper component to quantify them via the hemispheric projection of a 3D model. In addition, a different approach, in terms of a hemispheric projection to calculate SVF, will be introduced by another component, and the pros and cons of each approach are considered. We will name these methods 'Ray Method' and 'Geometrical Method' respectively. The Ray Method has achieved a good balance between accuracy, processing time and urban scale and complexity compared to the Geometrical Method.

Keywords: Sky view factor, parametric design, Rhino - Grasshopper, urban morphology, partial Sky view factor

INTRODUCTION

Identifying links between urban configuration characteristics and microclimatic factors can contribute to promoting urban forms that create a more comfortable and sustainable experience for city residents. Therefore, it is desirable to investigate these links and quantify the parameters that impact on the conditions within urban areas and the interactions between the urban morphology and urban microclimate - this is especially important in the context of urban heat island effects being exacerbated in the future by global warming.

Sky View Factor (SVF), a definition...

Sky view factor (SVF) is a one of those parameters that supports current understanding and knowledge about urban-climate relationships through intensive and diverse studies that have investigated SVF and its relationship with urban heat island (UHI), thermal comfort, energy budget, air temperature and day-
lighting. SVF refers to the ratio of radiation that is received by a specific point to that which would be received from the whole hemispheric radiant environment around that point (Johnson & Watson 1984). The effect of this ratio on the radiant energy flux density in an urban space may be subject to surfaces properties and their geometrical relationships in terms of distances between the surfaces and their orientations (Steyn 1980). Therefore, SVF can be considered as the ratio of visible sky that can be seen from a location in the urban space to whole sky dome that contains both visible and obstructed sky. The limits of this ratio range between 0, which refers to an entirely obstructed sky, and a value of 1, which represents a totally unobstructed sky (Lin et al. 2012). Many methods to calculate SVF have been developed and this study will consider some of them.

**Calculation Methods of SVF**

**Analytical or Geometrical Methods.** These methods uses the geometrical characteristics of an urban space around a specific point as inputs to equations to estimate SVF, where the energy budget of urban spaces is subject to these characteristics in terms of radiation exchange with the visible sky. SVF for general simple geometries have been calculated by Oke’s formulae (Oke 1988). These formulae were enhanced to be suitable for more realistic scenarios that represented unsymmetrical and finite urban geometries by projecting the surroundings onto a hemisphere; calculations are then performed on the hemisphere to calculate the fractions of wall view factor and then sky view factor with respect to the monitoring point (Johnson & Watson 1984). These models were used to develop algorithms and parametric methods to estimate SVF by some softwares(Chen et al. 2012).

**Photographic Methods.** These methods are used to calculate sky view factor from geometrical characteristics of the radiating environment surfaces by taking in to account their orientations and distances between them. Therefore, these methods are suitable for real cases with complicated or simple configurations and with or without trees. They utilize a fish-eye lens to capture an image that shows the 3D surroundings on a 2D circular plane, using a hemispheric projection as a middle stage between them. There is a similarity with Nusselt’s method or unit sphere method, that is used to calculate view factors in radiative heat transfer in terms of an equiangular hemispheric projection concept, which develops a graphical manual approach with its equations dependent on a plane polar co-ordinate system to calculate SVF (Steyn 1980). Currently, a group of software supported by image processing abilities is used to calculate SVF from fisheye images. However, the sky condition in terms differences of cloud cover and direct sunlight can cause problems for results of these software. In addition, this method may be time and effort consuming and, therefore, it is not suitable for large urban areas (Chen et al. 2012).

**Computational Methods.** Advances in the efficiency of computer performance have contributed to the development of software that can process the complex factors in the built environment and gives outputs that help to analyse it, and SVF is an example of one of these outputs. Two main approaches have been tracked to calculate SVF - vector and raster(Chen et al. 2012). This study will focus on the vector approach, which processes the data of 3D models to define the skyline border on a hemispheric dome dependent on a measurement point location. This dome can be divided in to equal slices and then integral calculus algorithms are applied to calculate the parts under the line, which are summed and then subtracted from 1 to get the SVF value. Software such as GIS-Arc View shows the ability to develop and apply algorithms like this (Gál et al. 2009)(Unger 2009). LSS Chronolux is a SketchUp extension that is limited to the version 2013, and which deals with the hemisphere in a different way; it is divided in to a grid with unequal numbers of vertical segments to horizontal segments. SVF describes the relationship between the area of cells that represent the visible sky and the area of obstructed cells by surroundings from a monitoring point in the urban space[1].
For the software Rhino - Grasshopper a plugin was written in Visual Basic net to calculate the single point SVF from a 3D model based on the analytical method algorithm with a new method to estimate the altitude angles that affect the calculation of obstructed parts from the slices of hemisphere. Also, this plugin has the ability to produce map that show continuous SVF for a determined urban area with high accuracy and a short processing time (Wu et al. 2013).

For Grasshopper-Ladybug, the SVF can be calculated from the view analysis component. However, the results are not aligned with findings from a pioneering study of Oke that defined the connections between SVF and high to width ratio for urban canyons. This mismatch may be due to the calculation of SVF as a geometric ratio of visible sky [2]. Another work supports this opinion where other metrics, that are related to the calculation of seen sky from the urban space, cause confusion in understanding the SVF because of the convergence of its basic ideas. Therefore, Ladybug with Honeybee has been used to develop a component to calculate these metrics in addition to SVF [3]. Ladybug does not have the ability to take a fisheye image as a direct input to calculate SVF; however, that can be done by rendering a fisheye scene from a point by using Honeybee. Then, the number of sky pixels can be accounted by Grasshopper’s image sampler component that processes images and returns the colours for each pixel [5]. Another Grasshopper component has been developed to calculate SVF on surfaces of urban masses as a ratio of the total rays that shoot out from nodes on a half-sphere to the number of the rays that hit the obstacles. The main output is a colour gradient map on the surfaces [4].

Although there is all this attention concentrated on SVF, there are conflicting results about its role, especially with air temperature. While some studies highlighted that SVF has an important impact, other studies indicated its negligible effect (Krüger et al. 2011). Many reasons may account for these different views, with one of them being that a single value of SVF can actually express various configurations for different locations. To overcome this problem, the specificity of the urban configuration of these locations need to be distinguished. Therefore, the first and third authors of this paper have previously suggested dividing the one value of SVF into four values related to the four cardinal directions. Each sector, known as partial sky view factor (SVFp), represents the ratio of the visible sky from this sector to the whole circular projection of the fisheye image used to calculate SVF (Al-Sudani & Sharples 2016). The results showed that SVF did not appear to have a significant relationship with air temperature; conversely, SVFp typically showed a strong correlation (Al-Sudani & Sharples 2016). Therefore, the objective of this study is to develop a Rhino-Grasshopper component to quantify SVF and SVFp depend on hemispheric projection of 3D model. This component will save time compared to long manual processes needed to calculate SVFp, with the ability to determine it in any number of sectors (i.e. not just four). In addition, a different approach, in terms of hemispheric projection to calculate SVF, will be introduced by another component, to reveal the pros and cons of each approach. We will name these methods ‘Rays Method’ and ‘Geometrical Method’ respectively.

**THE PROPOSED SVF CALCULATION METHODS**

To achieve the objective of this study, two components will be developed and validated, according to the pre-defined titles, as follows:

**The Rays method**

This component (Figure1) has six inputs. First, measuring point(s) (Origin). Second, the radius of hemisphere as (Radius). Third, the north direction in degrees. Forth, the number of sky sectors to calculate SVFp as (Divisions). Fifth, the segments of hemisphere is determined for one sector as (segments). The 3D model should be a mesh and not a BREP so that users can use many modelling software (e.g. 3ds MAX) and export it to Rhino as a mesh. The outputs of this component are SVF, SVFp and hemispheric pro-
jection that show the north sign and the diameters that determine the side borders of sectors and extend outside the perimeter of the sphere to define visually the number of sectors and their locations.

The proposed component calculates the SVF by algorithms that generate rays in the form of a hemisphere; each ray starts from the measuring point(s) that represent the centre of the hemisphere and gets its direction from the centre of each sphere segment. Once the ray of each segment hits an object of the 3D model then it will have a (true) value. The sky view factor will be the ratio between the summation of the areas of segments that are open to sky with (false) values and the total surface area of the hemisphere (Figures 2,3).

In addition, this algorithm can calculate SVFp and extract the segments of each sector, where SVFp is the ratio of the total area of the segments that represent the open sky within borders of the determined sector to the area of the whole hemisphere. The accuracy is subject to the number of segments per sector, where the number of horizontal segments equals the number of vertical segments for each sector. The SVFp values list is ordered counter clock wise from the north direction (e.g. for 4 sectors, north, west, south, east is 0,1,2,3 ) (Figure 4).

In detail, the algorithm workflow is in 5 phases as follows (Figure 5):

- **In phase 1**: a sphere is drawn with the measuring point as the centre with the radius size from the input ‘radius’ and rotated by the angle input ‘NorthDir’ to have a rotated sphere as Result A.
- **In phase 2**: the sphere is divided to become a hemisphere and then divided in to sectors according to the ‘divisions’ input, then subdivided into segments according to the ‘segment/division’ input. So, Result B is a rotated subdivided hemisphere.

Figure 1 the proposed grasshopper component

Figure 2 Test model shows the rays generated from the measurement point and the hitting the masses

Figure 3 the ability to test unlimited number of points simultaneously.

Figure 4 hemispheric projection with four sectors
Figure 5

In phase 3: the rays are generated from the measurement point and the segments of the sphere that represents the visible area of the sky is determined, to obtain a list of these segments in the output C.

Phase 4: is the calculation of the SVF and the SVFₚ as a summation of the total area and area per sector, divided by the surface area of the hemisphere.

Phase 5: is to create the graphical representation of the hemisphere with north direction and sectors.

The geometrical method

The following figure (Figure 6), shows the proposed Grasshopper definition to calculate SVF using a geometrical method. The proposed algorithm is a literal application of the geometrical method principles to calculate SVF. Each object visible to a measuring point makes a solid angle that represents its visibility and intersects with the solid hemisphere that represents the point’s field of view. The subtraction between them will define parts that blocked from and open to sky. The inputs of this component are a 3D model that should be in BREPS but mesh can be used and converted to BREPS in phase 1, while the Buffer Zone represents the extent of the urban context around the measuring point and will be included in the calculation. The radius of the hemisphere is the last input and should be smaller than the distance to the nearest object.

The main steps of this algorithm to calculate SVF are visibility detection, SVF extraction and fisheye image extraction.

Visibility detection. The visibility detection is used to optimise the processing time needed to calculate the SVF, by determining the object’s segments that are really facing the measuring point. This is calculated through three phases.

Phase 1: is to detect the objects in the buffer zone, by calculating the distance between objects and the measuring point, and comparing it with the ‘radius’ input. The result (A) is the objects within the buffer zone.

Phase 2: is to detect the objects’ segments facing the point, by evaluating the smallest planar angle between each segment’s normal vector from it centre, and the vector from this centre to the measuring point (figure 7). If this angle is acute (i.e. less than 90°) then it is fac-
the proposed grasshopper definition to calculate SVF using a geometrical method
ing the point; if it is not then it is not facing the point (figure 8). Result (B) is the segments facing the measuring points.

• Phase 3: the previous phase had some defects in detection of the facing faces but it was a suitable way of reduction (more than 50% of the input objects’ segments). One of these errors occurs when an object is behind another. The previous method detects that both objects are facing the point but the one in the back is not actually visible. So, the former ray method is employed to detect the segments that are really visible (figure 8), by subdividing these segments into points, and generate rays from the measuring point to them. The result (C) is the visible segments that firstly hit these rays (figure 9).

**SVF extraction.** After identifying the segments visible to the measurement point, point extrusion is employed to generated viewing angles that look like prisms that have the measurement point at their head and the facing segments at their bases (Figure 10). Afterwards, solid-union is employed to combine these prisms as one object. Then, it is subtracted from the hemisphere generated in (D) (Figure 6). The subtraction will result in the geometry (E), which is the part of the hemisphere that represents the visible area of the sky (Figure 11). The SVF is the surface area of the resultant geometry (E) divided by the surface area of the hemisphere.

**Fisheye image extraction.** Another output that can be generated by this technique is the fisheye image - this is a flat representation of the visible area of the sky (Figure 12). Although this representation is not accurate for calculating the real visible area of the sky, some researchers prefer to use it. This technique offers a vector drawing for these images that can be easily exported to AutoCAD or Illustrator and area calculation will be more accurate compared to other software based on image processing.
The validity of components
The SVF values of the two components have been validated against outputs from LSS Chronolux-SketchUp 2013 for eight points that were distributed in an arbitrary way around the masses of a test model (figure 13), where LSS Chronolux has been utilized previously by other studies (Paramita et al. 2016; Zwolinski & Jarzemski 2015). (Figure 14) shows the scatter plots where the determination coefficients (R-Sq) between LSS Chronolux and both the components were 99.9%.

PROS AND CONS
Processing times for the geometrical method were faster than for the ray method in the simple test model (1 second compared to 30 seconds). However, once the geometrical method was tested in a larger and more complicated scene the process failed. This may because, in the ray method, the processing time depends on the number of rays generated from the measuring point whereas the geometrical method generates rays from the scene. In other words, the details of the scene are controlling the processing time and accuracy of the geometrical method, whereas the number of rays and sphere segments are controlling the processing time in the ray method. Another reason could be the quality of the input model; some faces are doubled, overlapped or unnecessary that make the considered input segments a substantial task to calculate. Finally, the ray method and its proposed modifications are preferred in calculating SVF in large urban environments despite its lower accuracy compared to the geometrical method.
CONCLUSIONS
Grasshopper- Rhinoceros 5 software has been used to develop an algorithm to calculate SVF and SVFp to overcome the manual, time-consuming process that is used to calculate these parameters from fish-eye lens images. A ray tracing method has been utilized and achieves a good balance between accuracy, processing time, details and scale of case study. Another component has been developed to apply literally the geometrical method to calculate SVF. Although the accuracy and processing times were good for simple urban models, this method failed to deal with complicated urban morphologies. The methods developed in this study offer more opportunities to describe and analyse the built environment through supporting the calculation of SVF by using Grasshopper- Rhinoceros software. The work still in progress to develop these components as a part of the PhD research of the first author.

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Morphology & Development

knowledge management in architectural design computation practice

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In this paper we address the problem of knowledge management in architectural design computation practice, reflecting on our practice at Dsearch - a design computation network within White arkitekter. As a means to investigate relevant aspects of visual scripting, we introduce the notions of code, algorithm and note. We also introduce two different modes of operation within architectural practice: morphology and development - which help us distinguish the diverse knowledge types typically occurring in the structure of visual scripts. We describe two sets of tools developed by Dsearch to continuously integrate planning and documentation with design development work. The main conclusion from our practical experience of this approach is that it allows critical reflection into an efficient workflow. This constitutes a new kind of practice based and action oriented knowledge that can be curated in the form of design narratives.

Keywords: design computation, architectural practice, knowledge management, visual scripting, Grasshopper

INTRODUCTION
This paper presents a vocabulary and a set of conventions supporting knowledge management in architectural design computation practice. The conventions comprise a set of tools and routines for Rhinoceros (RH) & Grasshopper (GH), a common 3d-modelling and visual scripting environment. These are developed by Dsearch, a network of architects specialised in design computation within White arkitekter - a large architectural practice. An earlier version of this work, in particular the Dsearch Graphic Standard, have been used external to White during the Textile Hybrids workshop at Hafen City University to facilitate collaborative development between architecture and engineering students (Lienhardt and Runberger 2017).

Grasshopper, affords the designer a high degree of freedom to organise the visual aspects of the script to be more legible, without changing the underlying graph - the specific logic that executes the script. GH also allows the graph to rearrange itself. This can for instance be utilised in a powerful way by using genetic programming (Harding 2016) to evolve new versions of scripts. Dsearch has instead chosen a nim-
ble approach, deploying small, and in some cases disposable, auxiliary objects to rearrange or gather information from the script. This paper states the case for considering the layout of a visual script as a design task in its own right - vital for knowledge management. Examples of how this kind of design thinking relates to learning and communication are drawn from the practice of Dsearch.

Such knowledge often remains the internal concern of an organisation, but the purpose of this dissemination to a wider audience is to continue an established development within the discipline of architecture, relating computation to design thinking and management (Derix 2009; Hudson 2010; J. Runberger 2012; Davis 2013; J. Runberger and Magnusson 2015; Magnusson and Runberger 2017).

METHOD
The research behind this paper has been carried out through design and through practice. The authors are themselves members of Dsearch and active in the development work being described and discussed here. To make the voice of the paper clear, the arguments and experience of the authors as researchers are consistently expressed using the pronoun ‘we’. When discussing work or established conventions at White, we refer to Dsearch and its network.

Dsearch is positioned to address questions and identify potentials in ongoing projects within White, and address them through design of new design workflows or organisational changes. The authors, being part of this network and its larger context, have collected and analysed feedback from these interventions; through direct experience as practitioners complemented by interviews of individual peers and focus groups. Expressions such as “in our experience” or “we find that” are used throughout the text; such statements should be read as originating in several years of prototyping development, facing the full complexity of architectural practice (Schrage 1999; Capjon 2004).

We define this practice based approach to research as a designerly form of insider action research (Magnusson and Runberger 2017; Brannick and Coghlan 2007); seeing practice oriented and academic knowledge as a continuous spectrum - rather than different in kind. That approach aligns with the definition of design research as placing “...specific focus on the creation of new insights and knowledge through the actual design work or professional practice” (Hensel and Nilsson 2016, pXVI) or science of design, in which design strategies from everyday practice are carefully studied and used as valid sources to generate new knowledge and understanding of that practice (Cross 2006). It is also placed within the field of research by design. This field has on the one hand identified digital technology as a common theme in many practises (Hensel and Nilsson 2016), but also pointed to the importance of the projective aspects of research in architectural practice, that go beyond internal instrumentalism, addressing additional questions (Leatherbarrow 2012). This parallels a contemporary ambition to reform architectural practice as a project of knowledge production, separate from or overarching individual building project needs. One example here could be UN Studio where computational techniques are seen as one of several important platforms (Berkel and Bos 2016).

VOCABULARY
Three ubiquitous concepts are appropriated and used with specific definitions within this paper: code is defined as ‘instructional notation, determining computation’; algorithm as ‘descriptive notation, representing code agency’; and note as ‘operative notation, facilitating project development and use’. These concepts are not mutually exclusive properties of an object, but should rather be seen as different aspects of a script. They are introduced here as part of a terminology aiming to establish an integrated understanding of computation within design practice.

The notion that one single object can express itself in several ways can be exemplified in GH by describing a component - one node of the data-flow graph, the code layer underpinning the visual, algorithmic, layer in GH. As code, each component de-
terminates one stage of the data-flow, one node in a graph, turning input data into output. As algorithm, it notates this process with name, icon, and a mouseover text description. There is also more indirect information arising as a result of the process: hints of data types and structures at input and output parameters. Together with the algorithmic aspects, such information allows the designer to construct a mental representation of not only the computation performed at that specific stage, but its significance in relation to the overall design project. Grasshopper also offers components that can display visual or textual information without affecting the data-flow. This is analogous to comments in text-based programming, but the visual aspects allow for a more intricate relationship between code, algorithm and note. In Figure 1 the textual algorithmic information provided by the GH component is for instance complemented by the inclusion into a colour-coded group and the placement next to a text panel with notes relating to project development aspects.

The authors have also found it useful to distinguish between design and development processes on the one hand, and the computational and morphological processes performed by a script on the other. While the former develop sequentially over time, the latter execute momentarily according to a predefined logic. The deterministic morphological process is thus not to be confused with the open ended design process; the morphological process is rather subjected to modification through the iterations of a design process.

Dsearch has developed sets of tools and conventions for both modes of operation, supporting designers with the planning and documentation of script development. The Morphology Set deals with various ways to create and collate algorithmic information, aiming to represent the data-flow processing as a process generating architectural form. The Development Set conversely supports quality assurance in planning and documenting project issues, beyond form generation, as well as the capture of ideas and issues of relevance beyond the specific project. These modes are strongly intertwined with each other and with the underlying code; for instance when morphological aspects are linked to design decisions taken at a project meeting.

**MORPHOLOGY**

In our experience, stringent naming of parameters facilitates mental representation by linking algorithmic description to the code. Following Woodbury’s credo of *clear names* (Woodbury and Gün 2010), Dsearch has put forward the convention of Lineages in order to represent parameters as they are processed throughout the data flow (Figure 2). This is done by relating the name of ‘parent’ parameters to their downstream ‘offspring’. If a module output parameter is considered the downstream offspring of an input, the input name is suffixed, captioning what difference the intermediate process brought to the Lineage.

The Lineage Set object lists all named parameter components and moves the grasshopper window to their most upstream instance (Figure 3). This provides a descriptive overview as well as access for
Deeper investigation or maintenance. The Renamer object facilitates reorganisation of lineages by batch-finding and replacing parameter names. Lineages paint a rich picture of how parameters are processed in the script. Some parameters have been observed to form long lineages, using other lineages for their process without losing identity; a phenomenon correlated with significance within the design process.

Davis, Burry & Burry agree with Woodbury on the importance of clear parameter names and add that also modularisation is critical for “...the legibility of the script, and therefore the ease with which the script can be shared, reused and modified” (2011, p374). If naming conceptualises the relation of parameters to the overall morphological process, it is also helpful to visually and conceptually distinguish parts of the script - establishing sub-processes with explicit input and output parameters. Dsearch proposes to use the GH functionality to group components and then nest these groups within larger groups - in Dsearch terminology: components within Modules within Segments within Blocks (Figure 4).

This enhances legibility and comprehension in that it structures the definition into levels of scale. The visual scale cues should also aid the navigation of an abstraction gradient, ranging from comprehensive understanding of script agency to in-depth technical detail of the code (Zboinska 2015). The script is modularised on the code level by grouping components so as to form a coherent process. By adding specific input and output parameter components the interior of a module can be reprogrammed without losing input and output connections.

Algorithmic aspects include colour coding of the group and annotation that is legible in various scales. A concise heading is written in a big font for large scale overview. Close up, input and output parameters are arranged so that their linages can be browsed in conjunction with a comprehensive textual description of the module, entered into the Morphology Note (Figure 5). This arrangement is complemented with small panels of annotation highlighting vital and/or unintuitive parts of the process.

The Morphicle, a portmanteau of the words morphology and chronicle, automatically creates a textual and visual summary of the script, arranged according to its modularisation (Figure 6). All Morphology Notes and headings are grouped with input and output Lineage names to form a description of each...
Module, and its relation to Segments and Blocks. A visual sequence is created from selected Lineage geometry and data, and displayed via the Human UI interface.

This object is inspired by the *literate programming* approach of Knuth, urging programmers to prioritise the human reader over the computer. Knuth developed a language and a set of programs he called the WEB system where any program serves as a source language for two processes. “One line of processing is called *weaving* the web; it produces a document that describes the program clearly and that facilitates program maintenance. The other line of processing is called *tangling* the web; it produces a machine-executable program” (Knuth 1992, p101). Grasshopper, being a visual data flow based environment, is continuously ‘tangling’ the code while a script is being developed. What the Morphicle object adds is a script that ‘weaves’ various textual descriptions together, mediating a visual layout into a kind of literature.

The Dsearch *Graphic Standard* stipulates a colour for the group, according to functionality (Figure 7). Examples include: referencing and baking Rhino geometry, manual control or input of parameters, executing advanced script modules, etc. One primary use of this colouring is to highlight the *User Interface* part of the script where parameter controls are located for use by non-specialist collaborators. This is then distinguished from the back-end *Development* section where the actual code is found (Figure 8).

**Development**

The note aspect is supported by the *Development Note* - a pre-configured panel component for noting down issues relating to script and project development (Figure 9). The designer enters text in the syntax of “category: heading - note”. Categories include: log, todo, feature, bug, etc. Headings can ei-
ther reference parts of the script such as Lineages or modules, or they can come from the project in the form of design concepts, evaluation criteria or contractual agreements. In this way project discussions can be coupled with specific aspects of the morphology. Conversely, project issues can be raised by the designer with minimal disruption of the programming workflow. Tangentially related ideas and concerns inevitably crop up, triggered by thinking on the problem at hand. While important and in need to be noted down, they threaten to disrupt the designers train of thought. Our experience shows that the possibility to record a thought in its relevant context minimises the time needed to describe relevant background in order to remember, or explain it to a team member - thus minimising the disruption.

The **Development Note Set**, collects all notes from one GH script and sorts them by category and heading. This allows the designer to see for instance a list of all tasks on the todo list, or all notes regarding a specific bug. Project management, such as time planning and task allocation, is also here supported by rich, context-specific information by zooming the GH window to a specific note and review it in the context of the script. One way to tick off an item on the todo list during a review would then be to simply delete the note.

The **Autolog** object continuously records project development events along with a time stamp (Figure 10). This entails changes and additions to the Lineage Set, Morphology and Development Notes as well as quality assurance data, such as filenames and plugin versions. The designer can enter information by using the log category in a Development Note. Events such as key development steps of the definition functionality and the iterative exports of definitions for the use by non-specialists are recorded in this way.

A potential development for the Developer Notes and the Autolog is to integrate them with other project communication planning and documentation tools, such as mail and meeting minutes, or a task management system, such as Trello. The key consideration here is how to establish a filter for curration of this data, so that it forms a relevant description of the project history - beyond log data. Such a **Chronicle** would complement the **Morphicle**. We believe that such cross referencing of continuously collected information, can result in new insights regarding project specific issues, methodological and organisational strategies and wider disciplinary questions. Runberger proposes to format this kind of knowledge as **design narratives**; rich histories of project decision-making, cross referenced with morphological motivations (2012, p82-83).
DISCUSSION
On a general practice level we can state that these conventions facilitate breaking down the dichotomy between management (as in planning, task allocation and documentation) and actual design work in projects. We argue that by integrating management into the development workflow, conditions for designer agency and increased efficiency are established. This ethos is in line with contemporary software development culture, for instance expressed by the agile programming movement: “The best architectures, requirements, and designs emerge from self-organizing teams.” For the presented conventions, Dsearch makes heavy use of developments distributed throughout the Grasshopper community - especially the Metahopper and Human UI plugins developed by Heumann, Syp and Holland. What is offered back to the community is a long experience of applying and contextualising this development in a way that provides quality assurance and knowledge management within design computation practice.

The time pressures of practice risk leading to cultures where reflection is delegated to the lowly prioritised task of documentation - separated from the tasks and deliveries at hand. We would like to stress the importance of integrating this reflection on practice with the daily design work in projects. Only the practising architect that has access to project specific knowledge, can communicate this first-hand knowledge from a critical perspective - to a wider audience. This knowledge brokering is vital for individual organisational learning, as well as the development of the architectural community of practice (Wenger 1999). We recognise the necessity to carry out this kind of knowledge production as intuitively as possible, so as not to disrupt daily practice. The design narratives, sketched out above, can hopefully strike a realistic balance between learning and production - layering quality assurance driven documentation with critical reflection.

For the wider academic audience the relevance of this research lies in the conceptual framing of the content. We see a need for a vocabulary concerning visual scripting in architectural practice, beyond software specific nomenclature. Though computer science can provide technical definitions for a directed acyclic graph based data flow programming language such as Grasshopper, much of that terminology is out of reach for the design disciplines. For architectural practice, terms must be defined that relate visual programming to issues of design development, project management and strategic knowledge management. This paper presents Dsearch terminology that to a varying degree has stood the test of time. More importantly the underlying distinctions and conceptualisations have already proved to be valuable in the internal discourse at White.

CONCLUSION
The graph, defining a computational process, is a genuinely new kind of representation for architecture. Forcing the designer to express design decisions explicitly, the representation of form is no longer constrained by a final static geometric description, or tied to a historical narrative of its design process. This notion of morphological process as distinct from chronological design process, and the corresponding graph based representation, are regarded as novel additions to design methodology with great potential for further theory development.

Zboinska proposes to annotate visual scripts with a supplementary algorithm in order to boost comprehension, knowledge sharing and collaboration (2015). This is done by the use of standard GH components placed in parallel to the script. The main argument of this paper is that it is possible to expand on this idea, by relying even further on the visual aspects of Grasshopper. Dsearch allows the algorithm to be scattered and partial during development, with its constituents carefully placed in the context of the script. Only post factum is it then curated into a coherent form.

The use of notes to relate issues regarding programming, design, project management and strategic development to the script context, is a minor feature with major implications. This cross referencing
between morphology and development concerns, creates opportunities for new insights. Continuously collected along with the algorithm, this information can be synthesised as a design narrative - a new kind of practice based and action oriented architectural knowledge.

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VIRTUAL AND AUGMENTED REALITY
3D Spatial Analysis Method with First-Person Viewpoint by Deep Convolutional Neural Network with Omnidirectional RGB and Depth Images

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The fields of architecture and urban planning widely apply spatial analysis based on images. However, many features can influence the spatial conditions, not all of which can be explicitly defined. In this research, we propose a new deep learning framework for extracting spatial features without explicitly specifying them and use these features for spatial analysis and prediction. As a first step, we establish a deep convolution neural network (DCNN) learning problem with omnidirectional images that include depth images as well as ordinary RGB images. We then use these images as explanatory variables in a game engine to predict a subjects' preference regarding a virtual urban space. DCNNs learn the relationship between the evaluation result and the omnidirectional camera images and we confirm the prediction accuracy of the verification data.

Keywords: Space evaluation, deep convolutional neural network, omnidirectional image, depth image, Unity, virtual reality

INTRODUCTION

The fields of architecture and urban planning widely apply spatial analysis based on images. Examples include the use of the sky-view factor [1] to indicate the amount of sky visible and the green view rate (Takeshi et al. 2013, Yakui et al. 2016) to indicate the amount of green space visible to observers. Generally, when using images to analyze and evaluate spaces, we tend to think that it is necessary to extract meaningful calculable indices from the images. However, many features might influence the spatial conditions, not all of which can be explicitly defined. Even if some can be defined, extracting those features from images is a laborious task. To date, there is no analysis method with which we can quickly evaluate spatial designs and efficiently analyze large image databases, such as Google Street View, 3D interior images by Matterport [2], or the MIT Places Database [3].

Currently, deep learning techniques are attracting much attention for their ability to automatically extract features from raw data. Of these techniques, the deep convolution neural network (DCNN) has expanded the application of deep learning by significantly improving the accuracy of image classification, as compared with conventional methods that use explicit features. In this research, we use DCNNs in a spatial preference evaluation based on images.
General spatial images are considered to be insufficient as spatial analysis data. This is because the spaces themselves are three-dimensional, whereas images are two-dimensional. A photographed scene will change depending on the direction of the camera, and not all areas in the scene can be captured by the camera in one image. However, omnidirectional cameras have become available that can record all the information surrounding the shooting point (so-called first-person viewpoint) and, in this research, we utilize omnidirectional images for image analysis and learning.

Our next consideration is that the features acquired from images tend to be mainly related to color and texture. However, in the world of spatial analysis, methods for analyzing geometric features, such as spatial spread, as typified by the isovist concept (Benedict 1979), have long been used. Understandably, the computer graphics modeling procedure considers spatial characteristics to be influenced by both the geometric features of objects within that space as well as the color and texture features. Therefore, although these features should be handled in a unified manner, they are handled separately due to their different analysis methods. Also, it is difficult to acquire geometric spatial information and then match it with color and image information. Today, laser scanner and infrared sensor technologies are being developed for acquiring spatial depth information. Furthermore, the development of structure-from-motion techniques (Westoby et al. 2012) is advancing, in which 3D surfaces are reconstructed from plural views, so the above difficulty is being addressed. Although these techniques are still in development, the creation of three-dimensional data that once required intensive labor and advanced expertise will become easier as these technologies mature.

In this research, we propose a new framework that uses deep learning to extract spatial features without explicitly specifying them and then uses these features for spatial analysis and prediction. First, we defined a DCNN learning problem with omnidirectional images that include depth images as well as ordinary RGB images. We used these images as explanatory variables in a game engine to predict subjects’ preferences regarding a virtual urban space. To do so, we conducted preference evaluation experiments using virtual reality (VR) with multiple subjects, used DCNNs to learn the relation between the evaluation result and the omnidirectional camera images, and confirmed the prediction accuracy of the verification data. If we can successfully solve this problem, we believe that our proposed framework will also be effective in the analysis of more complicated and realistic spaces.

Past studies that have applied deep learning to landscape evaluation include those by Yabuki et al. (2015) and Abe et al. (2016). In contrast to our work here, these studies used pre-trained models with generic images stored in the MIT Place Database rather than omnidirectional images and depth information. Returning to the isovist concept, a 3D isovist was developed in recent years (Derix et al. 2008, Morello and Ratti 2009, Varoudis and Psarra 2014). However, complicated geometric calculations are required to obtain this 3D isovist, so there are associated difficulties with its implementation and slow calculation speed. In this research, we are able to directly acquire depth information images with high speed and accuracy that correspond to a 3D isovist from the z-buffer of a GPU. Furthermore, although Batty (2001) proposed indices for 2D isovists, the shape of a 3D isovist can become complicated, so those features alone may not be sufficient to describe the characteristics and it is difficult to explicitly define other features. In this research, we use a novel approach in which we apply a deep learning automatic extraction method of feature quantities.

The remainder of this paper is organized as follows. In the next section, we propose our evaluation system. Next, we describe our preference evaluation experiments and the DCNNs we use for learning. Finally, we present our results and conclusions.
SPATIAL EVALUATION SYSTEM BASED ON A GAME ENGINE

In this research, we use the popular Unity [4] game engine as the foundation of our 3D space evaluation system. In addition to its good operability in 3D space, this game engine can efficiently measure various kinds of spatial information through its application programming interface (API) and has improved real time rendering. Therefore, it is reasonable to use this game engine as the basis for our spatial evaluation system, the details of which we describe below.

Spatial data

Zenrin Co. Ltd., a Japanese map production company, released the ZENRIN City Asset Series [5], which contains the assets of Unity’s 3D spatial data. Based on actual measurement data of urban spaces in Japan, this asset comprises lightly arranged textures for games, and can be used as a real spatial model. We used the Namba area of Osaka City (Japanese Naniwa City) as the study space to be evaluated. The area centered in Namba spans a range of about 700 m east-west and about 600 m north-south, as shown in the model in Figure 1.

In the preference evaluation experiment, since we asked subjects for their spatial preferences when looking at the city from pedestrian walking areas, we needed to measure the spatial characteristics of each place.

For pedestrian pathways on roadways, we considered the center of the sidewalk (if a sidewalk was present), both sides of the road if there was no sidewalk and the road was wide, and the center of the road if there is no sidewalk and the road was narrow. Then, we set observation points along those pathways at 5-m intervals, for a total of 2,029 observation points (black dots in Figure 2). Since it would be too laborious to conduct a preference evaluation experiment using all these points, we randomly selected 50 points, as illustrated by the green points in Figure 2, and used them as observation points in our preference evaluation experiment.

Extraction of spatial features

When extracting the features of each observation point, we considered both the textural and geometric features of the space around each observation point. Using Unity’s omnidirectional camera asset, Spherical Image Cam [6], we created a script to capture and store omnidirectional images at each observation point in real time. In addition, we asked the author of this asset to modify it so that we could also take omnidirectional images of depth information from the camera in real time from the z-buffer of a GPU.

Normally, omnidirectional images are outputted as an equirectangular projection map with a height/width aspect ratio of 1:2. Due to the data input limitations in a CNN, when using images for learning and validation, we outputted them as reduced images in a square of 256 × 256 pixels.
We output the depth information as a one-channel grayscale image. When creating a depth image, the original depth information in a z-buffer must be cut by a certain distance value to fit it within the range of the pixel values. In this paper, we omit depth images and call them D images. Then, we created an RGBD image from a pair of omnidirectional RGB and D images taken at the same observation point and angle. Figure 3 shows examples of RGB and D images before being reduced in size to a square.

In the D images, pixels whose distances are closer to the viewpoint are whiter and those farther away are blacker. As we can see from the figure, in an equirectangular projection map, the lateral width of an object is enlarged and distorted from the top or bottom of the image.

**Construction of the preference evaluation experiment system**

Since we used omnidirectional images as learning data, it was necessary to evaluate subject preferences regarding the whole space visible from each observation point. For this purpose, we used a head-mounted display (HMD) of the Oculus Rift as an interface for conducting our preference evaluation experiment (see Figure 4). If we run a Unity application with an HMD and an ordinary camera instead of an omnidirectional camera, users can experience the immersive feeling of 3D space without any complicated setting. We customized Unity so we could move interactively between the 50 observation points of our preference evaluation experiment and input the evaluation value of each point. Figure 5 shows an example of a screen shot at a certain evaluation time, in which we overlaid the number of the observation point and the evaluation value in virtual space to facilitate our evaluation.

**DCNNs**

Of the several implementation techniques in the deep learning library, we used Chainer [7], which is popular in Japan. In the sample files of Chainer, a Python script trainImagenet.py is available for learning with DCNNs. This is an image classification script for the main 1000 kinds of objects included in the large image database ImageNet. We customized this script to suit our purpose. For our DCNNs, we used AlexNet (Krizhevsky et al. 2012) and GoogLeNet with batch normalization (Szegedy et al. 2015). AlexNet consists of five convolution layers and three layers that are all connected. GoogLeNet comprises much deeper layers. The classification error for the 1000
classes in Imagenet with GoogLeNet is less than that with AlexNet. Since we used depth images from one-channel and RGBD images from four channels as our training data, in addition to the normal 3-channel RGB images, we corrected the input part of the script image data from the original three channels. In addition, as we see later, since we solved the problem of the two-class classification, we reduced the number of output nodes of the final layer from the original one thousand to just two. The padding and stride parameters of the DCNNs are the same as those of the original.

**PREFERENCE EVALUATION EXPERIMENT**

In our preference evaluation experiments, our subjects included eight college and graduate students majoring in constructions engineering. The subjects were instructed to make intuitive judgments with respect to four levels: 1 (poor), 2 (slightly poor), 3 (slightly good), and 4 (good). Table 1 shows the evaluation value distribution for each subject in the preference evaluation experiment. Two of the subjects had evaluation values of roughly 2. We averaged all the evaluation values at each point and obtained a maximum average of 3.9 and a minimum of 1.4. Figures 6 and 7 show images of the points with the highest and lowest evaluation values, respectively. Three places received the lowest evaluation values, and we show one of them. When comparing these places, we found them to differ with respect to their geometric features, such as the degree of spatial visibility, and their textural features, such as landscape planting and stone sidewalks. Therefore, as explained in the introduction, we consider the geometric and textural features to be related to spatial evaluation results.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Evaluation value</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>27</td>
<td>15</td>
<td>8</td>
<td>0</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>17</td>
<td>17</td>
<td>8</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>22</td>
<td>24</td>
<td>3</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>6</td>
<td>23</td>
<td>13</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>7</td>
<td>23</td>
<td>16</td>
<td>4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>20</td>
<td>20</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>15</td>
<td>17</td>
<td>10</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td>10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Ave.</td>
<td>13.3</td>
<td>18.8</td>
<td>12.5</td>
<td>5.5</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
LEARNING DCNNs
In this section, we described the DCNN learning process with images and evaluation data.

**Preparation of data**
First, using Unity, we took images to be used for learning from each observation point. When dealing with images in deep learning, data is artificially increased by enlarging and rotating a part of an image, which adds noise. In this study, for each observation point, as shown in Figure 8, we rotated the camera from 0-340 degrees in 20-degree increments with respect to the vertical axis, and generated 18 images for each of the RGB and depth images. As such, for the 50 points, we prepared 900 images for each type of image.

Next, these images are divided for learning and verification data. Since it seems to be difficult to classify to 4 classes because the number of images with an evaluation value of 4 is a little as listed in Table 1, we simplified it to the classification problem with two classes where the evaluation values 1 and 2 belong to Class 0 and the evaluation values 3 and 4 are belong to Class 1. Table 2 lists the number of observation points in the case of two class classification. In consideration of the ratio of each class, the points were randomly divided for each subject so that the data for learning and verification are approximately 3:1 (Table 3). Therefore, the image data set of an observation point appears only in the data set for learning or verification. Through the above procedure, a total of 900 image data were divided into 666 images for learning and 234 images for verification.

Learning was performed for three types of image data: RGB, depth, and RGBD images. We set the mini-batch size for learning to 32. We conducted preliminary learning, and set the number of learning times (number of epochs) to 40 epochs for AlexNet and 20 epochs for GoogLeNet. The learning error of the learning data converged almost to 0 in both cases.

<table>
<thead>
<tr>
<th>Subject</th>
<th>1 or 2: Class 0</th>
<th>3 or 4: Class 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>34</td>
<td>16</td>
</tr>
<tr>
<td>C</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>D</td>
<td>29</td>
<td>21</td>
</tr>
<tr>
<td>E</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>F</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>G</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td>H</td>
<td>26</td>
<td>24</td>
</tr>
</tbody>
</table>
Results
Based on the above setting, the DCNN learned using three kinds of image data sets for each subject, and for verification, we applied the data sets to the obtained model to examine their error rates. Tables 4 and 5 list the error rate for each DCNN. Overall, GoogLeNet tended to have a lower error rate than AlexNet. GoogLeNet is a more recent DCNN than AlexNet and is known to have better classification performance for general images, and our results are consistent with this. Next, we found that the error rate differs greatly depending on the subjects. Comparing the evaluation values listed in Table 1 for subjects F and G, who
had a particularly low error rate, with subjects C and E, who had a large error rate, the subjects with small error rates have low average evaluation values of between 2 and 3.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Learning data</th>
<th>Validation data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class 0</td>
<td>Class 1</td>
</tr>
<tr>
<td>A</td>
<td>31</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>C</td>
<td>17</td>
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<tr>
<td>D</td>
<td>22</td>
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<tr>
<td>E</td>
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<tr>
<td>F</td>
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<tr>
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<td>13</td>
</tr>
<tr>
<td>H</td>
<td>19</td>
<td>18</td>
</tr>
</tbody>
</table>

As such, when the evaluation value near the preference boundary is large, the error rate is considered to be large. In addition, the error rate of the model for depth images with only one-channel information is the smallest in AlexNet, and even in the case of GoogLeNet, there is not much difference compared with the models of other data sets. This is a significant point—a depth image has less information than an RGB image, but the DCNN has constructed a model with depth images comparable with or superior to the model learned with RGB images. However, the error rate tends to differ for each person. The depth image models of subjects A, D, and G have lower error rates than the RGB-image models. On the other hand, the model learned with RGB images of subject B has a lower error rate than the depth image model. Thus, a DCNN seems too simple to precisely model human spatial cognition, but it is sufficient for considering the different weights of geometric and textural features for the spatial evaluation of each person.

Overall, we found the error rate of the GoogLeNet model using RGBD images to be the lowest. There is a possibility for constructing a spatial evaluation model with higher precision by a DCNN by integrating color and textural information with geometric information.

**DISCUSSION**

In this research, we addressed the problem of predicting spatial preference and confirmed that a DCNN can learn from omnidirectional images with some degree of accuracy. Since this method automatically extracts features from complex spaces, we believe that the framework of this research can be widely applied to fields dealing with spatial features. For example, this framework might be used to predict how often actions and events are likely to be triggered by certain spatial features. In the past, we built a model to estimate the location at which urban street crimes are likely to occur (Takizawa 2013). During this research, it took a long time to create detailed street space data, such as the areas of each building’s wall openings as viewed from each observation point on the street. The framework used in this research can be expected to efficiently and highly accurately analyze a large amount of 3D spatial information from the first-person viewpoint.
However, further basic research is necessary prior to any full-scale applications. To clarify what kinds of spatial features DCNNs can extract from omnidirectional images, we can use visualization methods such as Grad-CAM [8]. We must also improve model accuracy. In this study, we performed learning and verification using data from only 50 observation points. However, since the sampling data of the study space was more than 2000 points, in principle, more data can be used for learning. However, it is not easy to increase the number of points for preference evaluations due to evaluator fatigue. Therefore, to compress high-dimensional spatial information to a low dimension, we could use an auto encoder, which can perform learning without objective variables, and then use that information as an explanatory variable. Furthermore, since the lateral distortion of shapes in an omnidirectional image increases with greater widths, there is a possibility that the convolution of the square area of DCNNs is not appropriate. Therefore, we plan to develop a new method that can directly convolve a spherical surface, rather than projecting a spherical image onto a plane.

CONCLUSIONS

In this study, we used a CG model of a street in Osaka to capture omnidirectional images of observation points, including depth images, conducted a VR preference evaluation experiment using 50 street observation points, and learned the data using two types of DCNNs. Our results show that the model error rate was lowest for RGBD images, which suggests the necessity of a new spatial evaluation method that integrates color/texture and geometric features. Since this method automatically extracts features from complex spaces, we believe the framework used in this research can be widely applied to fields dealing with spatial features, although further basic research is necessary prior to full-scale applications.

ACKNOWLEDGEMENT

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Studying Architectural Massing Strategies in Co-design

Mobile Augmented Reality Tool versus 3D Virtual World

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Researchers attempt to offer new design tools and technologies to support design process facilitating alternative visualization and representation techniques. This paper describes a comparison study that took place in the Department of Architecture, at the Istanbul Technical University between 2016-2017. We compare when architects designed mass volumes of buildings in an marker-based mobile Augmented Reality (AR) application with that of when they used a collaborative 3D Virtual World. The massing strategy in the AR environment was an additive approach that is to collaboratively design the small parts to make the whole. Alignment and arrangement of the parts were not the main concerns of the designers in AR, instead the functional development of the design proposal, bodily engagements with the design representation, framing and re-framing of the given context and parameters become the discussion topics.

Keywords: Augmented reality, virtual world, massing strategies, protocol analysis

INTRODUCTION

The practice of architectural design is changing rapidly with the prevalent use of technology. Through the advancements on virtual worlds, parametric tools, computer aided design tools, interactive three dimensional (3D) simulations for spatial design development, architectural ‘massing’ study become possible in digital environment. The advanced digital tools that would support architectural massing study is a growing research area (Sun et al. 2013; Donath and Lobos 2008, see also, Khan and Loke, 2017 for a review). In architecture, massing refers to the consideration of building volume and/or breaking up enormous volumes. In a massing study, different principles for generating architectonic shapes and spaces would be demonstrated such as additive or subtractive form generation principles (Krupinska 2014). The external architectural form is decided through the massing studies, in particular, visual area, partitioning, fenestration, faced articulation and the overall topology of the design proposal are extensively articulated.

The employment of 3D modelling tools in design process would provide designers opportunities of exploring new types of architectonics that may not require continues reconstruction, in contrast to analogue tools such as sketches and physical models, which ‘involve considerable redrawing, tracing and scale model making’ (Achten and Joosen 2003). Although the employment of the physical model mak-
ing and sketching in the design process have been extensively studied in the individual cases (Janke 1978; Goldschmidt 1988), and also in the group processes (Schön 1985; Ward 1987), there is a lack of study that compares designers’ massing strategies in Augmented Reality (AR) and Virtual Reality (VR) in a collaborative design context.

The recent mobile Augmented Reality (AR) technology has the potential to offer new opportunities for co-designers as a new design platform where the physical and visual models are superimposed during the architectural massing study. In this paper, we present a comparison study that is conducted in the Department of Architecture, at the Istanbul Technical University between 2016-2017. We investigate when architects designed mass volumes of buildings in an marker-based mobile Augmented Reality (MAR) application with that of when they used a collaborative 3D Virtual World, Second Life.

ARCHITECTURAL MASSING AND MODEL MAKING

Architectural massing refers to the considerations of three dimensions (3D) of a building envelope that would define an interior space or the exterior space (Jacoby 2016; Thompson 1999). The consensus on the definition of ‘massing’ appears to the centre on the idea of “the physical volume or bulk of a solid body, or a grouping of individual parts or elements that compose a unified body of unspecified size” (Burden, 1995, p. 48). Massing study is also known as “mass reduction, additive or subtractive spaces, or facade articulation” (Stamps, 1998, p.825).

Architectural design is widely accepted as a dynamic and complex process that starts with massing study (Akin and Moustapha 2003; Leyton 2001). During architectural massing study, spatial arrangements of shapes and forms and the relationships of the design proposal with the surrounding context are studied. During design process, architects make models as a “means of exploring and presenting the conception and development of ideas in 3D” (Nick, 2014). Massing study through model making has the potential to facilitate the presentation of the materialisations of design ideas, by getting as close as possible to the actual appearance of the design proposal. Model making in particular, can help with the creative process of visualizing 3D space directly by helping the inspection of the complex visual relationships (Porter and Neale 2000).

The research shows that massing process improves the management of the overall design process through strategies that rely on the use of regulating elements in the analogue and standard CAD situations (Akin and Moustapha 2003). Architects do not have to rely on only the standard CAD situations, as researchers attempt to offer new design tools and technologies to overcome the complexities by alternative visualization and representation techniques. With the recent developments on digital design tools, model making takes place on the computer screen during the early phase of architectural design process, such as using Building Information Modelling tools, parametric tools and recently VR and AR applications.

Researchers developed a hybrid virtual environment system and direct visual editing techniques for architectural massing study, investigating quick modelling and the implementation of physics for an effective design experience (Chen, 2011). Donath and Lobos (2008) discussed the phenomenon of the envelope design for high-rise buildings, proposing digital tools in the early stages of a massing study that “helps to reduce the working time, increases the confidence on the generated solution and it also contributes to the exploration of several alternatives in a short time” (p.108). Woodbury and Chang (1995) developed building technologies for massing studies that facilitate the exploration of the many possible approaches to massing. In their massing technologies, there were two types of massing objects: those that enclose functional spaces and those that stand for compositional concepts. In contrast to those studies, we focused on the design strategies of architects during massing study in the early phase of design process when they employ two different digital environments.
METHODOLOGY

In this paper, we compare architectural massing strategies of six designers when they are using two different emerging digital design technologies using protocol analysis: (1) co-design with a marker-based mobile Augmented Reality tool (MAR session) and (2) co-design in a Virtual World - Second Life (VW session). Protocol Analysis has been widely used in design studies (Gero and Neill 1998; Suwa and Tversky 1997) and in collaborative design studies (Gabriel and Maher 2000, Gül and Maher 2009).

The participants of the study were the final year architecture students in Istanbul Technical University. During the sessions, they were given two different design briefs with similar complexity including similar construction area requirements and mix-use programs (office - residential and commercial). Each session that was recorded on videotape lasted 30 minutes. During the experiments, the designers’ actions and speech were video-taped and protocols were produced. Then these protocols were studied and encoded by using a specific coding scheme that has been developed for this research.

Segmentation: The data of the research consists of continues stream of video and audio. Since the aim of the research is to understand the massing strategies of designers, there is a need for a thorough investigation of designer’s physical activity and externalizations. The hybrid segmentation strategy that is based on ‘who’ is doing ‘what’ action during the sessions was applied in order to understand the behaviour of co-designers (as explained in Akin and Moustapha 2003; Gül, 2007). The hybrid method was based on two research: (1) Gero and McNeill (1998)’s definition: ‘flag the changes in actions and intentions,’ (2) Maher et al. (2005)’s definition: ‘flag when there is a change in the ‘who’ and ‘what’ items.

Coding Scheme: Finally, the segmented protocols were examined by using the coding scheme, as shown Table 1. We focus on the utilized massing strategies to model the design representation that was captured from the design dialogues and video recordings of the designers. Thus a ‘massing’ class that includes discussions on regulating elements, spatial relationship (spatial adjacency, arrangement, alignment, gesturing), referencing (ego-
centric, allo-centric), design approach (part-whole), architectural tectonics (program-form-materialization), framing and reframing given problem parameters and context, and visual inspection is developed as the coding scheme, as shown in Table 1.

**Experiment Apparatus**

First, a marker-based mobile AR application was developed using Unity3D game engine with Vuforia AR plug-in. Vuforia AR plug-in offers a set of target objects' library, object recognition and extended tracking, as shown in Figure 1. First, a set of marker images are defined in the Vuforia AR library, and then the data set of the image targets was uploaded in the Unity 3D platform. The AR environment was enhanced for the collaboration with a physical model and a wide-shared visual display for supporting the design activity (for more details of the AR system, please see Gül et al., 2016).

In the marker-based mobile AR design session (MAR), participants were given the basic primitives for the massing study; cube, sphere and cylinder objects that are associated with markers on the physical model. The designers were able to operate dragging, rotating, scaling and changing the colour of the basic 3D geometries on x, y, and z axes. One of the tablets’ view was shared and projected on the glass-table, and both designers were able to control the commands for creating and editing the geometries using the AR interface on their tablets. Figure 2 shows an instance from the MAR experiments where two designers were working together.

In the second phase, designers collaborated in a multiuser collaborative 3D virtual world, Second Life (SL). A virtual island, VirtualITU, in Second Life was given to designers to build an office tower, as shown in Figure 3. SL is an object-based design environment, which provides designers with the basic 3D geometries such as, cube, sphere and cylinder etc. with wide-range of editing capabilities. Figure 3 shows study participants working remotely, sharing the SL design platform.

**RESULTS AND DISCUSSIONS**

The results of the analysis show that utilized mechanisms of collaborative massing activity have some differences in each design environments. Table 2 shows the duration percentages of the massing activities that are measured based on the coding scheme. The particular differences are observed as follows: the duration percentages of regulating elements (alignment (37,6%) and adjacency (22,4%)), form and materialisation of the architectural tectonics (26,97% and 10,81%) are higher in the VW session. The duration percentages of the framing (7,22%), reframing (11,56%) and referencing of the global relations based on environmental features (allocentric 26,44%) and referencing of local relations based on one’s current location (egocentric 16,19%) and program (21,39%) related articulations and gesturing (12,57%) are higher in the MAR session. The time spent on the visual inspection of the design proposal (67,73% in MAR and 85,71% in VW) is the highest in both design sessions. The results and findings are reported as follows:

In the MAR session, during the experiments, designers started with introducing new objects onto the scene, (modelling activity starts with registering the markers) and then, they assigned an architectural function to each object on the screen referring num-
Figure 1
The development of the Marker-based Mobile Augmented Reality Application in Vuforia Developer Portal

...I load the first marker, OK. Save it... Our first cube, number 1, that would be the podium level of the shopping mall.

Participants of the study did not articulate the overall building mass at once. The affordability of designing in the MAR environment might have an impact on this strategy. Since the MAR tool affords the manipulation of one basic geometry at a time, thus the massing strategies was to manage the small parts to make a whole building. In short, an addictive massing approach was observed.

In the MAR session, the main regulating element was the boundary lines that was the periphery of the neighbour buildings, park and road boundaries. The designers indicated those boundaries as the extension lines of the alignment by pointing gestures while they were adjusting the size of the proposed building blocks by altering the X and Y coordinates for the desired alignment (visually inspecting the design proposal at the same time) in the MAR session.

The significant difference is observed in the ‘gesture’ code, as shown in Table 2 (12.57% in MAR and 0.35% in VR). Here, gestures are the hand movements of the participants that are employed to explain the spatial relationships of design ideas playing the role of extension lines in a sketching activity. For example, the designers gestured by pointing on the model when they indicated a street direction or a park area as the alignment axis for the building mass. In addition, another type of gesturing that is bodily movement and touch screen gestures occurred when a designer wants to reflect and elaborate an idea, particularly the visual inspection of the design proposal through bodily movements (bending, leaning etc.) was observed. Co-located working and the presence of the physical model might also have an impact on this finding that requires further investigation.
In the VW session, during the experiments designers discussed about the design ideas and proposed architectural tectonics as a whole building mass, rather than articulating ideas on collection of small parts. For example, D2 said:

[. . . let’s have a building, like a box... that would be large on ground and with some cantilever parts on the upper floors facing to the sea].

Once they decided on the design proposal by verbally articulating what the finish building would look alike, then they spent the rest of the given time for constructing the model in 3D world. Thus, we observe making of the model in VW started with the consideration of the whole building mass. They decided the overall building tectonics in their imagery in consensus, then, they did some task allocations on making the mass one by one: One designer would be looking at the top view monitoring what the other designer is doing by examining spatial relationships and the visual appearance, such as size, form, texture and colour.

VW of the study, Second Life (SL), is an object based multiuser virtual world with some build and edit tools. As mentioned earlier, the inbuilt making of model features of SL consists of primitives of the basic geometry such as cube, sphere, cylinder and prisms as well as some complex forms such as torus, tree object etc. An object building starts with dragging a basic cube onto the scene, then designer needs to scale, rotate, move and change its size, shape, colour, materials as s/he wishes. In SL, the VirtualITU island consists of some landscape features such as a lake in the middle with several hills around and flat areas as well as some buildings to be the context for design activity. The existing buildings in SL played an important role that was to provide a sense of scale as well as being the precedent, the designers altered the size of their proposed design entities by taking into account of the size and the style of the existing buildings in the island. The main regulatory element is the existing context, in particular the volume and height of the existing building and vista points in

### Table 2 Durations

<table>
<thead>
<tr>
<th>DURATION</th>
<th>MAR %</th>
<th>VW %</th>
<th>MAR Mean D.</th>
<th>VW- Mean D.</th>
<th>MAR- SD</th>
<th>VW -SD</th>
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<tbody>
<tr>
<td>WHOLE</td>
<td>17,16</td>
<td>19,22</td>
<td>12,145</td>
<td>10,47</td>
<td>11,11</td>
<td>10,565</td>
</tr>
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<td>PART</td>
<td>17,895</td>
<td>13,445</td>
<td>9,275</td>
<td>10,76</td>
<td>6,77</td>
<td>8,96</td>
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<tr>
<td>GESTURING</td>
<td>12,575</td>
<td>0,355</td>
<td>10,265</td>
<td>6,45</td>
<td>7,11</td>
<td>0</td>
</tr>
<tr>
<td>ALIGNMENT</td>
<td>11,38</td>
<td>22,42</td>
<td>10,005</td>
<td>14,285</td>
<td>11,075</td>
<td>11,495</td>
</tr>
<tr>
<td>ARRANGEMENT</td>
<td>15,61</td>
<td>37,615</td>
<td>13,615</td>
<td>18,81</td>
<td>9,82</td>
<td>19,78</td>
</tr>
<tr>
<td>REF-ALLOCENTRIC</td>
<td>26,44</td>
<td>18,865</td>
<td>11,895</td>
<td>12,39</td>
<td>10,425</td>
<td>9,505</td>
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<tr>
<td>REF-EGOCENTRIC</td>
<td>16,19</td>
<td>11,825</td>
<td>13,205</td>
<td>10,56</td>
<td>10,72</td>
<td>8,765</td>
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<td>PROGRAM</td>
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<td>9,855</td>
<td>7,57</td>
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<td>FORM</td>
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<td>11,895</td>
<td>10,76</td>
<td>11,63</td>
<td>8,325</td>
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<tr>
<td>MATERIALISATION</td>
<td>4,885</td>
<td>10,81</td>
<td>10,06</td>
<td>12,97</td>
<td>8,72</td>
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<td>FRAMING</td>
<td>7,225</td>
<td>4,83</td>
<td>12,365</td>
<td>10,3</td>
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<td>RE-FRAMING</td>
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<td>6,5</td>
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<tr>
<td>VIS-INSPECTION</td>
<td>67,73</td>
<td>85,71</td>
<td>11,31</td>
<td>13,58</td>
<td>10,24</td>
<td>14,8</td>
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</table>

MAR: Design in Marker-based mobile augmented reality session, VW: Design in Virtual World (Second Life) session, Mean D.: Mean duration in seconds, SD: Standard deviation of duration
the landscape become consideration points for the design proposal in SL. The alignment of the parts and the spatial adjacency of the design proposal in the context become an important topic of discussion and activity during the VW session. The alignment and arrangement activities become important as internal regulatory features. That means when they model the 3D design proposal, designers engaged with the individual parts of the mass in relation to a prior building part. Higher duration percentages of alignment and arrangement also indicate this finding. In addition, designers spent considerable time for the visual inspection by flying over the design proposal in SL.

**FUTURE REMARKS**

Although the initial results of a study presented here focuses on the massing strategies of architects, it is a part of a larger research effort dealing with the impact of place and representation types on designers’ activities and sense of presence. The results of the comparison study indicated that the affordances of the design features of the studied environments have an impact on the designers’ massing strategies. A further study will be conducted to design and evaluate more on the use of AR based collaborative design environments providing varied 2D and 3D design objects (ability to draw and make notes on the representation and providing more geometric primitives and library of customized building elements) to understand the effects of the affordances of the interfaces on design behavior. Additionally, there are a lot more characteristics of a user not explicitly focused in this study that could be of importance, e.g. novice vs expert in design with AR, level of familiarity of the tools, learning effect and so on. The long-term goal of this study is to empirically measure the essential influencing factors on interaction during basic design tasks, to establish the foundations for typical user behavior in more complex design scenarios.

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Lines from the Past

Non-photorealistic immersive virtual environments for the historical interpretation of unbuilt architectural drawings

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The trajectory of virtual reality for architecture is towards photo-realism. While this may be effective for some contexts, we propose that abstraction is more appropriate for the purposes of a historian interpreting drawings of unbuilt works of architecture. The case study we are using to explore this proposition is the Palazzo Littorio competition set in 1934 Rome. We present two prototype immersive virtual reality (iVR) applications developed in Unity for Oculus Rift: the first uses an etching aesthetic to produce a quasi-realistic site context and an interface that enables the comparative evaluation of competition entries from key viewing positions; the second application takes an even more abstract approach, where the aim is to immerse the historian within a 3D drawing, along with other historical material (drawings, photos, paintings, narrations of texts) and uses spatialized sound to evoke the ambience of the period.

Keywords: Virtual Reality, Non-Photorealism, Architectural History

INTRODUCTION
The development of low cost, high performing head mounted displays (HMD) coupled with widely available authoring software such as Unity, has led to a renewal of interest in immersive virtual reality (iVR) within the CAAD community. These include a re-evaluation of workflows in the design studio (Dokonal et al, 2016) and for architectural exhibitions (Kreutzberg 2016). Our interest in iVR is in relation to architectural history, in particular the translation of architectural drawings of unbuilt architecture. Unlike historic reconstruction where there is an emphasis on faithful representation based on photographs or 3D scans of the building, historic drawings are projections (both literally and figuratively) of the imagination of the designer. As Robin Evans explored in depth, the age of projective drawing by hand required translations from orthographic and perspective projection to a mental image of what it would be like to occupy and move through the project (Evans 1995).

The advent of 3D modelling has enabled the virtual construction of unbuilt architecture for some time. The focus of our research is on non-
photorealistic approaches that aim to extend understanding through abstract, generally multi-sensory approaches. For example, Virtual Terragni used virtual re-construction for analysis, rather than visualization. Eschewing any attempt at photo-realism, the translation from historical drawings to three dimensions explores what Saggio refers to as the hierarchical structures that emerge from an “operation of analytical disassembly and reassembly” (Saggio, 2000). Such a ‘digital forensics’ methodology is also to the fore in research that reveals the constructional logic embedded within an unbuilt work of Auguste Perret (Webb and Brown 2011). The research of Sirbu is based on an alternate approach with the idea that remediating a drawing to digital form, provides the possibility for translation “into a navigable virtual space that is close as possible to the original artefact (the drawing)” (Sirbu 2003). Through a case study of a project by Henri Labrouste, Sirbu documents a process where the lines’ colour, texture and lighting of the historic drawings are used as the basis for the digital modelling and animation. In a similar vein, the research into ‘digital etching’ by Voordouw adapts 17th century techniques to develop a novel approach to 3D modelling, based on the idea that “historic modes of representation can engage a deeper cultural context” (Voordouw 2014).

The above precedent forms the background to our research into the potential of iVR to extend historical methodology for the interpretation of unbuilt works of architecture. Our research with iVR is informed by the theory of affordance. Initially developed in psychology by James J. Gibson (1986), the concept of affordance has been re-defined and used in a range of domains. From a literature review, the simple definition by Stuckey in relation to the design of virtual environments is the most appropriate for our research - “...we use the concept of affordance to refer to the latent possibilities for action presented by an artefact, tool or environment.” (Stuckey 2009).

For the architectural historian, what does immersion in a virtual environment afford, that is not readily available via non-immersive technology? One obvious starting point is in terms of engagement: rather than manipulating a model on screen with a clear distinction between the observer and 3D model; there is potential to explore from a position of visual and aural immersion; and the capacity to experience volumes, spatial sequences and relationships between architecture and external context. As one set of considerations, we can posit the affordance of iVR enables alternate visual, aural and kinaesthetic experiences of the drawing. Leading on from the implications of immersion is a second set of affordances related to embodied interaction. Authoring content for iVR enables a range of interactions that include: head tracking; haptic interfaces; temporal shifts; teleporting; and not least the interactive augmentation of the 3D model with analytical volumes, images, and narratives from key texts. Our research explores these two sets of affordances based on the technical capacity of Oculus Rift HMD and Unity VR content authoring software.

**Scope**

As the means to explore the above agenda for translating drawings to immersive experiences, we are undertaking a case study using the 1934 Rome Palazzo Littorio competition. The competition attracted leading Italian architects from an important period in architectural history, when Italian rationalism was developing alongside the legacy of 19th century historicism. The best known project from the competition is that of the team led by Giuseppe Terragni, whose ‘Scheme A’ presented a curvilinear façade suspended from a truss structure to give the appearance of a 80 metre surface appearing to float in space. Receiving comparatively minimal attention, Terragni’s ‘Scheme B’ shifted the theme of suspension to the cantilever, proposing a monumental block projecting along a similar distance. These two projects have recently been exhibited as photorealistic renders of 3D models based on the drawings (Casa Dell’Architettura 2015). While we appreciate the accuracy of these models, once drawings are actualized and superimposed within contemporary site photographs, para-
doxically they become more resistant to critical interpretation. Our position is that unrealized projects have and will continue to provide a pivotal role for architectural theory and history. But the power of the unbuilt to extend architectural thinking and provide historical insight, resides in the capacity for the drawings to be interpreted. Our aim is to avoid verisimilitude, to explore a mode where productive suspension of the virtuality of the drawing within iVR may enable the historian to accrue new insight.

This article is a collaboration between a design researcher who uses drawing as an openended process of feedback and negotiation, an architectural historian who engages with drawings of the unbuilt in a mode of critical interpretation, and a technical team who are exploring the affordance of VR technology to extend research methodology. In the following sections we articulate the role of drawing for critical design practice, and how drawings in combination with other historical sources enable critical interpretation by the historian. From this we project how the multi modal affordance of the technology can augment ‘desktop’ methods of historical research. We then document two approaches to an IVE application. The first has a focus on the external context to enable a comparative evaluation of Terragn’s two schemes plus competition entries by Liberia, Moretti and Palantini. The graphic approach involved modelling the immediate context, adding textures using an etching filter, in combination with a skybox that provides a background panorama. The second approach is more abstract, enabling the occupation of the Terragni drawings, overlaid with volumetric analysis of the geometry, supplemented by atmospheric sound and artworks that evoke the period in which the projects were conceived. Through discussion of trials with our with an expert in Italian history from the period, we reflect on the iVE interface design and the efficacy of the two non-photorealistic approaches. In conclusion we outline the next stage of the research, which will involve developing and evaluating the interface in response to the specific requirements of a range of unbuilt works.

**DRAWING AND HISTORICAL INTERPRETATION OF THE UNBUILT**

*The role of drawing for critical practice*

Before embarking on the design of the prototype, discussion on the role of drawing for critical practice is required. Drawing has traditionally played a key role in the practice of design; it has been, and still is, the primary way in which built space, that is yet to come into existence, can be immersively explored. In analogue drawing this has come with the advantage that the immersion is incomplete. Through vagaries of pencil and paper, the built space predicted in the drawings can’t be fully described, it remains incomplete, sketchy and reliant on the mind of the drawer - the drawer is prompted to imagine space within or between the lines. Another factor is the spatiality of drawing. Analogue drawing is its own spatial world, one where the materiality of marks in the drawing, their qualities of weight, delicacy or even the speed in which they were made, is evocative of atmospheric conditions, hovering between the drawing world and the world of the yet to be built. This makes drawing an immersive world with a complex spatiality. In drawing, this tends to operate in two ways concurrently: drawing is descriptive, of built space, and evocative of things beyond easy description.

The twin conditions of drawing are vital to its role as a tool for thinking and immersion in the world of the yet to be built. Representations of three dimensional space, in ways which can be read by a cultivated viewer as projected built space, are augmented by drawing’s inherent capacity to prompt imagined occupation, in a sensory, emotional, or even affective way. This is carried through drawing’s qualities as an inherently open medium, through its gestures, marks and materiality. The marks in a pencil drawing hover between delineating the composition of a plan, or a pictorial scene, and alluding to atmospheric conditions: mass might be evoked through heavy shading or dense enclosure implied through erasures of a darkly drawn mass of graphite; lightness might be conveyed through a febrile, delicate line, or move-
ment in space implied by arcing diagrammatic tracings. Qualities of light, time, and density of occupation can also be evoked. The shifting qualities of light can be implied through careful shading, a sense of occupation through subtle outlines of people, trees - or temporality through the inclusion of ephemera, such as cars, aeroplanes, or even clouds and weather.

This drawing world is built up through its descriptive and evocative marks, marks that are known, but also marks that are less known. Much of the sensory, temporal and emotional information is subtly conveyed through marks in the drawing that have this dual role, marks that are partly semiotic and partly non-semiotic - the ‘brushstroke, pencil line, smudge, and erasure’ and the ‘recalcitrant, “meaningless” smears and blotches’ (Elkins 1995). These qualities allow for sensory and emotional projection into a representational system that can be read, by a cultivated viewer, as built space, and at the same time imaginatively occupied. This paired capacity hinges on drawing’s qualities of open-ness, the ability to evoke, imply and invite a multi-sensorial occupation. Through this, an analogue drawing provides much more than a digitally created, rendered and supposedly complete scene.

Drawing is more than an instrumental way of predicting space it is a way to capture intangible qualities of that space and engage with a cultivated viewer, such as an historian. It is from the critical practice of drawing, that we draw inspiration for conceiving approaches to VR for the interpretation of unbuilt works of architecture. The aim being to imaginatively occupy the drawings and other historic artefacts, using the affordance of the technology to explore alternate modes of historic inquiry.

**Augmenting historical inquiry**

Our objective is to develop prototype applications that explores the potential of augmenting historical inquiry through the adoption of iVR. The ‘desktop’ historian typically works with historic drawings (printed or onscreen) and other reference material relevant to critical interpretation of the project. These include historic photographs, other works that provide insight such as paintings associated with period, text documents and in some cases sound recording. In a sense the desktop historian makes virtual connections between these disparate sources by studying the visual material, reading historical accounts and listening to soundtracks. The office of a typical researcher is packed with reference material, multiple books open and with various images in peripheral view, as they critically interpret the theoretical and historical significance of the drawings in question. As indicated in Figure 3, our proposal for augmenting this methodology is through the affordance of the technology. In particular the capacity to engage the kinaesthetic and aural senses alongside the visual. Stuckey at al (2009) have used the concept of affordance in their research on virtual environments. Their reference is to Gibson’s original concept of affordance as the latency presented by an artefact, tool or environment for action. Using this broad definition, they present a distinction between what they term constructed and native affordances. Their approach looks at the latent possibility of a mimetic world in terms of the ‘native’ affordance of environment, the multitude of mimetic objects and experiences provided. ‘Constructed’ or non-mimetic affordances systematically violate the constraints of the natural affordances, to introduce such interface elements such as the overlaying of information and images. For our purposes, native affordances involve the inhabitation of an abstract mimetic world of the 3D drawing placed in a quasi-real physical context. Complimenting the abstract experience of the ‘built’ form would be set of constructed affordances such as the superimposition of volumetric analysis or the capacity to teleport to key viewing positions.

Figure 1
Simon Twose: Plan drawing for ‘White House’, Wellington 2005
Our concept of the ‘iVR historian’ is that of immersion in an abstract world, where he/she can navigate through drawings transformed into 3D experiences, exploring spatial relationships and sequences. Potentially, immersion and the engagement of kinaesthetic senses can trigger new insight on the significance of the work and the intent of the designer. An underutilized affordance of virtual reality for historical research is spatialized sound. As has been well established in videogame design, interactive soundscapes based on spatialized sound samples is central to evoking atmosphere. For the purposes of historical interpretation this could include ambient sound from the period in relation to streetscapes, supplemented by sounds within volumes that suggest activities, and footstep sounds can be associated with different room volumes to reinforce spatial interpretation. Such affordances are in effect ‘native’, in terms of a mimetic occupation of the drawings and the evocation of the historical period.

A second set of constructed affordances can augment this quasi ‘natural’ occupation of the 3D drawing. The work of Galli and Mühlhoff (2000) provides precedent for supplementing the drawing with exploded isometric drawings that identify geometric relationships. The capacity to switch from a perspectival ‘experience’ of the drawings to more analytical ‘birds eye’ views of the underlying geometry and spatial relationships, facilitates mixed modes of engagement with the drawings. Other constructed affordances involves the superimposition of historical material through an image library that would contain
the original drawings, photographs from the period and other works associated with the unbuilt work. Reading a large amount of text within a virtual environment is physically fatiguing. We could however provide access to narrations of texts such as the architect’s description of the project or key critiques by theorists and historians. In the next section we describe two iVR prototype applications we have developed structured around the distinction between natural and constructed affordance.

**TWO iVR APPLICATIONS**

*iVR App 01: Designs in context.*

The purpose of this first application was to evaluate the competition entries in context, with the emphasis on providing multiple ways to navigate and compare different designs. The site encompasses key monumental building including the Coliseum, Basilica of Maxentius and numerous excavations of Roman ruins. Our approach involved the accurate volumetric modelling of the immediate context with images parsed through an etching shader to provide an abstraction of the building detail. The background was provided via a ‘sky-box’ where a panorama image taken on site provided a sense of the overall context. Six of the competition entries were selected (chosen by our historian collaborator) and these were modelled with a level of detail approximating the original competition drawings. Twelve key viewing angles were selected around the competition site and a simple interface enabled teleporting within the VR scene to these positions. The six competition models can be swapped in and out through the Xbox controller, enabling comparison of the designs from key viewing positions as illustrated in Figure 3. As well as using the 12 viewing positions to quickly navigate around the scene, the user can also navigate freely and record screen grabs of points of interest. These screen grabs and camera positions are added to a linked database and can be accessed through a ‘saved views’ menu. Selecting an image within the panel teleports the user to the viewing position from which the image was taken. The image browser enables another form of navigation and a way of identifying points of interest that can be shared with another researchers. They also provide a set of reference images to be used outside of the iVR environment.

*iVR App 02: Atmospheric occupation*

The purpose of the second prototype application is to provide an interface that enables the historian to examine the unbuilt project in multiple modes: firstly a non-photorealistic 3D model that is accurate in scale but is graphically realized to align with the original drawings; to provide a second mode of analytical graphics that reveals the underlying geometric relationships; and a third mode where historical materials (photographs, associated drawings and painting, and narrated transcripts of key writing) can be browsed and overlaid within the VR scene. Given these multiple modes, we have chosen to implement the prototype using an Xbox controller as at present this interface allows the widest range of controls. Figure 4 shows the mapping of functionality to Xbox controls and illustrates some of the features. The application can be run in desktop mode to enable the scene to be set up and to familiarize the user with the Xbox controls. Once in VR mode the user can move freely on the XY plane, adjusting the speed as suits the task. The textures for the 3D drawings can be adjusted by using alpha channel and noise parameters and a number of layers that be overlaid. Inspired by the Terragni drawings we have developed a crowd simulation that uses the Unity terrain engine, substituting the ‘grass’ sprites with individual figures that randomly populate the scene. We have also implemented a ‘map view’, that reveals pre-set animation paths that allows the user to be taken through a spatial sequence of the projects. There is also a volumetric mode that shifts the camera to orthographic projection and superimposes analytical drawings of the geometry. The image viewer panel opens up a browser that enables access to a database of images relevant to the historical context that can be selected and placed within the scene.
IVR Historian Application 1: Enables comparative analysis of unbuilt proposals in a quasi-real context.
DISCUSSION

The two prototypes have been developed by the technical team in a three way conversation between the historian and design researcher, who are located in different institutions. Prior to their full implementation much of the discussion was based on exchanging screen grabs and videos of the early mockups. Through these exchanges, while more clarity was established in terms of the potential, generally the response to the images and videos was less enthusiastic. The transformation in reception to the prototypes dramatically improved when the team assembled in the lab and the non-technical collaborators could experience the prototype through the oculus rift. Particularly for the historian, who had minimal experience of iVR, the immersion in both prototypes received much more positive feedback. The following are initial reflections on what insight was gained in relation to the two Terragni schemes.

For Terragni’s Littorio projects A and B an immersive environment afforded re-examination of previous interpretations. Here we might point to three main issues. First, site: on the newly created Via dei Fori Imperiali, with its light carpet of tarmac newly laid across the ruins of imperial Rome to link Colosseum and Piazza Venezia, immersion afforded free movement along it and around the building such that the interaction of the building with views to and from the Colosseum could be tested, along with the apse of the Basilica of Maxentius across the road. This was the primary objective of iVR historian prototype 1, where the use of the etching approach to the site...
modelling worked well in terms of enabling dimensionally accurate comparison, but without the jarring impact of photo-realism. Immersion enabled the testing of the proposition that both of the Terragni projects are crucially animated by the curved masses of the Basilica ruin: project A, with its great curved façade, by assimilation and project B, with its rigid masses, by contrast. The ancient predominantly arced structures nearby are met sympathetically by the inverted arches in the façade of project A. Second, gravity: immersion afforded the ability to sense the immense weight of the great porphyry screen 80 metres long suspended above the street and the enormous hovering mass of project B, which is one of the largest cantilevers of its day. The capacity to teleport between key viewing points to enable quick and accurate comparison between schemes was very effective, particularly for a comparative novice at engaging with VR interfaces. Then the ability to roam the Piranesi like streets to find alternate viewing angles and to record these positions for later reference was a useful addition, enabling transfer to ‘desktop’ mode for reflection and interpretation on the image captures after the VR session.

By contrast, iVR historian prototype 2 enabled an open ended and metaphoric engagement with the competition drawings. Occupying this abstract space of drawings afforded the possibility of prioritising certain aspects of the imagery presented, especially in project A, whose façade has variously been described as a dam, curtain, face and stage set. Not fully realising the rendering means allowing these readings to be highlighted in turn, along with volumetric analyses of the compositions. The immersion grants the occupation of a drawing, affording not only close examination of spatial sequences, key routes and paths, but also the evocation of atmosphere, which with the envelopment of sound from the period was particularly poignant. Accompanying these evocative soundscapes were narrations of the projects from their extant reports by the design team, as well as key interpretations by scholars such as
Manfredo Tafuri, Alberto Cuomo and Thomas Schumacher. Moreover, aspects of contemporary drawing and painting styles, those of Terragni and his collaborator, the painter Sironi, can be embedded in the rendering of line, shade and colour without the finality of verisimilitude. The capacity to browse other reference images from within the VR scene and superimpose these while exploring the reconstituted drawings was a useful part of the interface, but further work is needed to enable easier placement and resizing of the images.

CONCLUSION
We have articulated a position for a non-photorealist approach to the use of virtual reality for the interpretation of unbuilt architecture based on the affordance of the technology. This position is based on a collaboration between a design researcher and an architectural historian who describe the importance of not rushing towards photorealism but, rather, a deferral, a ‘room for play’ (Spielraum) which involves a ‘realm of thinking’ (Denkraum), in art historian Aby Warburg’s terms. Only by opening up such a realm can interpretive insight be granted. Two VR prototype applications have been developed to explore this position, with the Palazzo Littoria competition providing the context for evaluation. As discussed above we have received an initial positive response to these prototypes from our collaborating design researcher and historian. We will refine the prototype and undertake fuller evaluation with a number of historians and design researchers using survey techniques. The survey responses will be triangulated with tracking data that captures the user’s movement, and identifies what interface elements are most frequently used. From there the intent is to undertake a series of case studies of unbuilt works, refining and developing other interface elements in response to different case study contexts and user feedback. The Unity authoring software has proved a robust platform, which has the additional advantage of being able to produce tablet, screen and AR output from the same code, albeit extra work is required on the specifics of the interface. We are open to collaboration with other researchers interested in developing and using this approach to VR for history or other application contexts.

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Designing Colour in Virtual Reality

Comparing a Virtual Reality based and a Screen based Colour Design Method

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Designing colours for architecture with digital tools is still a challenging topic. Especially for customers and students the perception of a full-scale coloured interior room is hard to imagine. This paper presents a software prototype and a small user study, which addresses the colour design process with professional digital tools and a virtual reality head mounted device (Oculus Rift DK2). The user can navigate within an imported three-dimensional model freely and change colour, texture and light properties with a real-time updated radiosity visualization. The presented user study compares a screen based working method with the developed virtual reality based design support and interaction method.

Keywords: Virtual Reality, Colour, Design Support, Real-time, VR-glasses

INTRODUCTION
With the advent of virtual reality (VR) hardware at consumer price level, it will not be long before the architect’s everyday practice uses this media. Professional applications are already available. The continuing pressure from the computer games and hardware industry will improve the VR devices further and make them even more affordable. Thus, usual presentations and design processes of architecture will soon take place with the help of VR environments, too.

Even wearing VR glasses could complement the everyday office work utilizing screens. Currently, computer games dominate the VR software development, but also big CAD software companies start offering VR solutions in their portfolio (see e.g. Autodesk [1], Unity 3D [2]).

CONTEXT AND SETUP
This research uses a digital design support software for colour designing to compare a VR-glasses-based process and a screen-based process. Both design modes utilize the software prototype “Colored Architecture” (see Colored Architecture [3]). A single pre-calculation in this software enables the free variation of material textures and colour attributes of all architectural faces as well as the daylighting. This achieves an interactive, high-quality visualisation with radiosity light simulation. To connect the prototype with the VR glasses Oculus Rift DK2, a new network client extends the underlying FREAK software framework (König et al., 2010). This “Oculus Rift Viewer” client displays the central “Server Five” data model with the textured and shaded geometry model in VR and captures user interactions. The graphical user interface (GUI) elements in the VR environment are pie
menus (see fig. 1) and reduced windows with slider scales placed on the faces of the virtual model. An earlier projector-based augmented reality solution (Tonn et al., 2008) introduced these GUI concepts already. Users can move freely in the VR model. The view direction replaces the “mouse pointer” of a traditional screen GUI and the attached X-box-controller substitutes the “mouse button functionality”.

RELATED WORK
This work is part of a broader research topic, which might be entitled “Digital Colour Design Support for Architecture”. Within this context the application in a VR environment is just one aspect. Another aspect was the colour design support in a projector-based augmented reality (AR) setting (Tonn et al., 2008 and Tonn et al., 2009). Since then it seemed obvious to move on from desktop screen VR over projector-based AR to a head mounted VR device for colour designing. In contrast to Stahre (Stahre et al., 2004) the presented work does not target the precise reproduction of perceptual colour for virtual environments, but is rather focused on the fast real-time update of the radiosity colour visualization for the early design stages. This is achieved without off the shelf software, but is coded from scratch using C++ and OpenGL. To get an overview of state of the art VR-applications in the built environment please see Kim (Kim et al., 2013). One further application of VR together with colour design, which comes closest to the presented work, is from the studio Arrowstreet and was presented at Spar3D 2017 with a HTC Vive VR device [4]. In this application one could throw coloured balls at a predefined room’s surfaces, which in turn changed their complete appearance. In contrast, the used engine in “Colored Architecture” also supports radiosity colour interreflections and lighting changes in real-time.

INTERACTION
One objective of the interaction concept was to minimize overlaying the 3D perspective with any permanent menus or widgets. While working in VR only one single user-selected tool is active. To select a tool the users has to press a certain “start-menu” button (e.g. the “Y”-button on the X-Box controller) and a pie-
menu appears centred around the view-direction-cursor on top of the focused 3D-modell surface. The pie-menu-direction-parts depict the underlying tool function with an icon and after waiting for 3 seconds, an additional tooltip with a description text shows up (see fig. 1). Moving the cursor in the direction of the required function and releasing the button selects the tool. The interaction with the now active tool consists of the view-direction-cursor and the primary button (e.g. the “A”-button on the X-Box controller). This way, only one tool can be active and the user can choose functionality from a cascade of pie-menus with maybe even more sub-pie-menus.

**TOOLSET**

What tools were available to the test persons during the survey? The following tools were used in the VR as well as the desktop working method:

- The most used functionality was the “Colour Drag and Drop” tool. The users selected the colour of a surface under the cursor and then dragged it with the view-direction-cursor to another surface. After this, the other surface got the selected new colour and the radiosity visualization along with its colour reflections updated.

- With the “Change Colour” tool, it was possible to change the hue, saturation or brightness of a surfaces colour. Utilizing sliders in a small window on top of the selected surface, the user changed the colour object and got immediate feedback from the updated radiosity visualization.

- The “Change Sunlight” tool allowed altering the daytime with a slider from morning to evening, which in turn adjusted the position of the sun. In addition, the clear visibility of the sun from brightly visible to obscured and the overall brightness-adaption of the eye could be set.

- There were tools to create new colour variants and switch between them with an updated visualization. With this, one could easily compare different colour alternatives of the design.

- There were also tools to sketch with a pen onto the 3D model, but this had no impact on the radiosity colour reflections. The main purpose of the sketch functionality was to mark and discuss parts of the design during presentation.

**EXPERIMENT**

The experiment consists of a fictive scenario that handled well with both interaction modes. The used 3D model was a virtual living room, which is based on a real construction project of a terraced house. The abstract 3D model was additionally equipped with a fictive colour study which fulfilled two functions. On the one hand it served as a design element in this setup and on the other hand it delivered a predefined colour palette (see fig. 2).

The test persons were colleagues of the FARO 3D Software GmbH. The experiment took place on two different computers (see fig. 3). Thus, the test persons could work in parallel on one operation mode and switch to the other afterwards. The first desktop computer (CPU: Intel of Core i7-2600K) was equipped with a competitive graphics hardware (GPU: NVidia GeForce GTX 1080) to enable a good frame rate display on the VR-glasses. The second computer, a laptop (CPU: Intel of Core i7-3610QM, GPU: NVidia GeForce GTX 675M), was used for the screen-based working.

Fourteen people took part in the study. Seventy one percent of the test persons had already carried out a colour design. Judging from their job profile, all test persons are rather computer affine. The average age was 40 years.

The task for the test persons was: 

*Please design colours for the living room of your new built house. A wide picture has already found its place over the future couch corner. Maybe all surfaces around the picture shall be coloured, too. Please, create a comfortable, warm colour design, which suits your taste.*
Figure 2
The virtual living room for the colour design experiment.

Figure 3
Setup - on the left: VR-based mode, on the right: screen-based mode of colour designing.
RESULTS
After the test, the test persons had to complete a questionnaire. Similar to the augmented reality experiment (Tonn et al., 2009), for both methods ten statements had to be answered on a scale from is not right (-2), rather not (-1), do not know (0), is right rather (1) to is right (2). Table 1 gives the asked statements for each working method together with the answered average result. The lower with plus and minus marked values represent the standard deviation of the upper average value in the table cell. In addition the significance level alpha from a two-sample Student’s t-test and a column to indicate an advantage for the screen-based compared to the VR-glasses-based method is given.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Screen-based Method</th>
<th>VR-Glasses-based Method</th>
<th>Significance Level Alpha</th>
<th>Advantage for</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. You have applied this working method often already.</td>
<td>-0.714 +/- 1.204</td>
<td>-1.929 +/- 0.267</td>
<td>0.00138</td>
<td>Screen</td>
</tr>
<tr>
<td>2. You can imagine the whole room and the colour design.</td>
<td>0.5 +/- 0.855</td>
<td>1.357 +/- 0.745</td>
<td>0.00111</td>
<td>VR-Glasses</td>
</tr>
<tr>
<td>3. You felt sick/uncomfortable (VR-simulator-effect) during your design experience.</td>
<td>-1.538 +/- 0.877</td>
<td>0.571 +/- 1.453</td>
<td>0.00131</td>
<td>Screen</td>
</tr>
<tr>
<td>4. This working method is practical for the architectural design process.</td>
<td>0.857 +/- 0.864</td>
<td>0.643 +/- 0.929</td>
<td>0.53283</td>
<td>Screen</td>
</tr>
<tr>
<td>5. This tool/interaction concept is easy to use.</td>
<td>0.429 +/- 0.938</td>
<td>1.071 +/- 0.997</td>
<td>0.15627</td>
<td>VR-Glasses</td>
</tr>
<tr>
<td>6. You trust the colour visualisation and quality of this tool.</td>
<td>-0.071 +/- 1.141</td>
<td>0.143 +/- 1.231</td>
<td>0.55148</td>
<td>VR-Glasses</td>
</tr>
<tr>
<td>7. You feel limited through the means of the tool.</td>
<td>0 +/- 1.301</td>
<td>-0.857 +/- 0.663</td>
<td>0.06073</td>
<td>VR-Glasses</td>
</tr>
<tr>
<td>8. You could compare different alternatives.</td>
<td>1.571 +/- 0.852</td>
<td>1.5 +/- 0.65</td>
<td>0.77527</td>
<td>Screen</td>
</tr>
<tr>
<td>9. The working method is efficient.</td>
<td>0.857 +/- 0.949</td>
<td>0.786 +/- 1.122</td>
<td>0.85555</td>
<td>Screen</td>
</tr>
<tr>
<td>10. You trust the tool and this working method.</td>
<td>0.714 +/- 0.469</td>
<td>0.643 +/- 1.008</td>
<td>0.77527</td>
<td>Screen</td>
</tr>
</tbody>
</table>

The following screenshots from the software prototype “Colored Architecture” give an impression what the colour designs from the test persons looked like (see fig. 4).

EVALUATION
The direct evaluation produced the following tendential statements. The list enumerates only the significant statements, which reached a significance level alpha smaller than 0.05 computed in a two-sample Student’s t-test:

1. The participants had not applied the VR glasses method yet.
2. The test persons could imagine the room and
the colour design significantly better with the VR glasses.
3. The VR simulator effect (indisposition or feeling of sickness) clearly appeared with the VR glasses.

The following list sums the comments to the questionnaires ordered according to their occurrence. The threshold was that at least two test persons wrote the statements analogously.

1. A more familiar mouse interaction would be good for the screen-based method. (6 test persons)
2. The low resolution of the VR glasses irritates. (5 test persons)
3. The orientation is easier with the VR glasses. The VR glasses are very intuitively in terms of navigation. (4 test persons)
4. The X-box controller interaction in VR is not stomach-careful; on the other hand the head moving is good. (4 test persons)
5. Very good space perception with VR better than the screen. (3 test persons)
6. It is fun. (3 test persons)
7. Currently no device can reproduce colour, contrast and brightness realistically. (3 test persons)
8. There are too many different menus and switches in the screen-based method. (2 test persons)
9. The speed shall be limited with the VR based interaction method to prevent sickness. (2 test persons)
10. There were too few colours to choose from in the model. (2 test persons)
11. A functionality to lighten or darken the VR colours would be nice. (2 test persons)
12. The screen-based method is familiar. (2 test persons)

Figure 4
Examples of colour designs from the test persons.
DISCUSSION

Most people experienced the so-called ‘VR-simulator-effect’ (see result-item 3, above). It manifests itself in indisposition and a feeling of sickness. The effect is known and appears when the optically perceived movements do not match the physical signals of the human senses. Among others, the reason may be:

- A too low frame rate of the VR glasses,
- A too high latency or time delay between head movement and visual image update or
- An artificial optically perceived movement without the matching physical senses.

The used X-box controller interaction method for changing position corresponds to such an artificial movement e.g. by free virtual movements and smooth rotations. It is possible to reduce the effect by moving the virtual person slowly. If the user would change position close along a surface, maybe by “sneaking on the floor” or “moving close along walls” or even by “running through virtual walls” the perceived movement appears to be fast again and the VR simulator effect is back.

In recent VR computer games, the player teleports in the virtual world from location to location in order to neutralise the effect. At the fixed locations, the user has all degrees of freedoms for the head movement (e.g. Doom, 2016). Another option for a VR control is to make the artificial movements like virtual rotations or jumping to appear extra artificial (e.g. Minecraft VR Edition, 2016). This happens through sudden hard cuts of the actually smooth movements. Thus, the user can distinguish these transaction types easily from real head movements. Instead, the tested prototype used smooth movements, sidelong movements, height movements and rotations. With reference to the applied VR control, the critic is that sometimes, less is even more.

Furthermore, the participants found the VR interaction method easier than the screen-based one. In the VR environment the test persons used only the pre-set colour drag-and-drop tool together with the movement control. Besides there were also several pie menus as well as colour scales, brightness scales, saturation scales and daytime scales available. However, the test persons could not use these, because of a lack of training. Hence this reduced method seemed more suitable. In contrast all functionality of the menu, icons, control groups and colour widgets were visible in the screen mode. Probably because of that, the screen-based method seemed more complicated.

Promising results are that the VR glasses communicated the virtual space and the colour design better than the screen (result-item 2) and an improved orientation in the virtual reality with glasses (comment result-item 3).

CONCLUSION

The proposed digital colour design support in VR seems promising after this small user study. Especially for smaller projects like colour renovations and maintenance or also larger VR presentations, the software can be a tool to improve the confidence and the trust to an architectural colour design. However the major part of the required work deals with the creation of the abstract 3D-model. Still with an integrated BIM design practise or with capturing technologies like laser scanning together with appropriate as-built evaluation methods the necessary 3D-models can be efficiently used for VR applications like colour designing.

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gies/using-vr-ar-blur-lines-e-c-o/
Immersive retrospection by video-photogrammetry

UX assessment tool of interactions in museums, a case study

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Studying interactions in museums often omits to consider the complexity of the space and the visitors’ behaviors. Visitors’ walking paths do not provide enough insight of their user experience (UX) since they are distant from the experiential realities. Videogrammetry can convey such dimensions of an environmental experience. Because of limitations of real-time playback, a twofold approach is suggested: “immersive videos” combined with “photogrammetric models”. A granular optimal experience assessment method using retrospection interviews is also applied providing a finer evaluation of the perceived experience through time. This method permits to characterize museum interactive installations, according to the perceived challenges and skills of the interaction’s task, based this time on immersive retrospection. This paper proposes the “Immersive retrospection” by “Immersive video-photogrammetry” as a UX assessment tool of interactions in museums. A hybrid virtual environment was used in this study, allowing social VR without the use of headsets, through a life-sized projection of interactive 3D content. The study showed that Immersive video-photogrammetry facilitates the recall of memories and allows a deepened self-observation analysis.

Keywords: immersive retrospection, photogrammetry, videogrammetry, UX assessment, museum environments

INTRODUCTION
Traditionally, museum visitors are engaging with various forms of content communication throughout exhibitions. Textual displays and audio-guides are some examples of what is used to situate the visitors in the exhibit and complement the displayed content. However, some studies (Samis, 2008) highlight that few people engage actively when experiencing those approaches. Part of the reason is the fact that the information disseminated this way focuses excessively on collection-centered rather than user-centered installations, leading to few carefully thought through interaction designs.

Tools commonly used to study visitors’ interactions in museums often omit to consider the complexity of the environment thus designed for inter-
active purposes and visitors’ behaviors. For example, only a top view map of the visitors’ positions and their walking paths (Nasir, Nahavandi & Creighton, 2012) does not provide any insight into their actual gaze or general awareness which could be affected differently through time and the tridimensional space, depending on multiple factors: other visitors’ changing positions, height of the exhibits, different heights of participants, etc.

Such aspects are hard to depict analysing two-dimensional images. These images do not account for subtler physical clues regarding a visitor’s focus of attention or apprehension of a situation in a specific moment: head orientation in contrast to the body’s general position and orientation, or simple gestures such as pointing a certain part of the exhibition’s content or talking to another visitor. Moreover, traditional tools like path analysis constitute a risk of perceptual representations being distant from certain experiential realities of the studied situations, such as the atmosphere (Van de Vreken & Safin, 2010).

In this study, we focus our attention on the interactions as lived by visitors rather than the aspects concerning the exhibit content transfer. We postulate that overcoming undesirable situation implies opting for an alternative approach to exhibition design and evaluation, in this case concerned more with the visitor’s actual experience of the perceived content. In this paper, we propose a new framework by working to relocate, in an immersive way, the participants in key parts of a previous museum visit to assess their experience.

From the original granular methodology of user experience based on retrospective interview (Safin et al. 2016), this study goes a step further by proposing immersive retrospection using immersive videophotogrammetry as strategy to better recall past visits and interactions of a given exhibit. This paper presents for the first time the use of this framework in the case of a given museum space. The preliminary results from only 3 visitors seem to point towards a better evaluation of the user experiences in museums’ interactions.

INTERACTIONS IN MUSEUMS AND UX
Nowadays museums have moved from basic maintenance of collections to public services communicating ideas and providing exchange between them and their visitors. It is obvious that the aim of museums has become to emphasize on human-centered design and holistic experience making. The current approach shifted to focus on visitor’s attention via interactive exhibitions in museums. Interactive exhibitions would encourage visitors to explore them more directly. However, exhibitions that simply include pressing buttons, using mobile guides, etc. are not truly interactive, but rather reactive (Mortensen, 2010). The user experience (UX) for interactive museums is strongly configured by users’ demands of identity-related visit motivations which create a primary direction for visit (Falk & Dierking, 2016). The explicit information of what users see and perceive is covered by the following factors (Falk & Dierking, 2016): User: (prior knowledge, experience, and interest); Physical museum: (exhibitions, programs, goals, interior design and signage); Information: (interactions between users, users and exhibitions, users and physical museum).

ASSESSING USER-EXPERIENCE IN MUSEUMS
There are several methods in UX research that have been used. Observations and interviews are the most suitable to gather UX from non-verbal behaviors. Users may be unaware of their experiences or unable to express them verbally (Hsi, 2003). Moreover, other methods are proposed (Hartson & Pyla, 2012) but require the visitors to hold digital devices or wear sensors to assess their UX while visiting the museum. This can hinder the UX itself. Besides that, surveys, diaries and storytelling have been regarded as an effective way to get information about UX (Arhippainen & Tähti, 2003). This way users can express some of their experiences in a written form, including their background (age, education), prior experiences, expectations and motivations. Another method is to interview users facing a video recording of themselves.
(Hsi, 2003), but eventually because of ethical reasons, videos of the kind are recorded from different perspectives that cannot capture all facial expressions. The last common method is the use of a storyline and prototyping. Storyline (Pujol et al. 2012) is the way to organize and remember experiences enabling users to communicate them. Prototyping experiences of different situations allows designers, clients or users to “experience it themselves” rather than just witness a demonstration of someone else’s experience (Hartson & Pyla, 2012).

**PERCEPTUAL EXPERIENCE OF ENVIRONMENTS ANDVIDEOGRAMMETRIC REPRESENTATIONS**

Ecological perception appears as a fruitful frame for setting a canvas of the implications of our endeavor for a new approach to UX assessment, regarding the human-environment perspective, the experience of space and its interactions as formatted by museum exhibitions. Ecological perception informs us that, from a perceptual standpoint, a visitor’s exploration and apprehension of a museum exhibit (be it direct or mediated) will be directly supported by the perception of its affordances (Gibson, 1979). Perceiving events as changes in the organization of these affordances may provide visitors with additional indications on how to intervene on their direct environment (Chemero, Klein & Cordeiro, 2003), hence interact with the exhibition. Events are temporal by definition, resulting from a change in the state of a situation, demanding some form of dynamism to be observed. Immersive videogrammetry is a media in development with the potential of conveying efficiently such dimensions of an environmental experience, allowing visitors to better remember their perception of a previously recorded situation than when using traditional images and videos for UX analysis. This would bring more depth to the analysis of lived situations during “self-observation interviews” conducted accordingly to Boubée (2011). Videogrammetry encompasses the process in which multiple synchronized video streams of a scene are used to reconstruct its spatial-visual properties as a sequence of 3D models (4D, including time), draped with photographic textures, through image processing. Whereas the process is analogous to photogrammetry, it differs in the way the images are captured: photogrammetry uses successive pictures from different angles with a single camera, while videogrammetry employs instead multiple devices to record videos simultaneously from different positions. While many aspects of this digital technology have been approached throughout literature in computer sciences (Kanade, Rander & Narayanan, 1997), cases of its practical use remain for now widely unexplored and under-documented, limiting our comprehension and acknowledgement of its contribution in practice.

**Immersive videogrammetry**

In light of the informational capacities of videogrammetry, we suggest that displaying the videogrammetric model at life-size in an immersive environment could contribute to a stronger sense of presence for the participant and support a deepened recall of events. A stronger state of presence, in its turn, would reinforce a greater perception of affordances, also aided by the recognition of other individuals that were acting in the space (Stoffregen et al., 1999). This would mean making intuitive the perceived possibilities of action within the perceptual and hybrid immersive representation (Riva et al., 2011) by altering how the users relate their actual bodies to the immersive space (Schubert, Friedmann & Regenbrecht, 2001). A visualization of the kind would allow us to assess visitors regarding their past experiences of an interactive installation without the need to interrupt their actions as they unfold.

**OPTIMAL USER EXPERIENCE AND GRANULAR ASSESSMENT**

To assess UX of museums’ interactions we selected the model of the optimal experience of Csikszentmihalyi (1997). The optimal experience or state of Flow, is characterized by high “challenge” of the task to be
performed and high “skills” of the users. The Flow is an autotelic experience, considered as a memorable, gratifying experience where users lose the notion of time (Csikszentmihalyi, 1997). Other psychological states can be experienced according to the changes between the challenges and skills regarding the task: Stress (high challenge and low skills), Control (low challenges and high skills) and Boredom (low challenges and low skills) (Massimini & Carli, 1988); (Safin et al. 2016). In the case of visitors’ museum, it would be possible to measure the perceived challenges and skills when they must engage with a given interactive installation. Visitors expectations and involvement with the interaction can be unfolded this way, but the remaining issue would be to observe it during time to better understand the reasons of the UX changes. In the context of evaluating designers’ experiences, Safin et al. (2016) developed a methodology of assessing UX in a granular way by using retrospection of self-observation interviews and two sliders (one measuring the challenges and other the skills) in a specific device (Korg NanoKONTROL2(TM)) and software (Max Run Time). This way the whole UX, including its different states (Stress, Flow, Control and Boredom) can be assessed for each second, allowing to combine this data with other kinds of information, like in this study, analysing different kinds of interactive installations. Moreover, the limits of recalling a past activity (or museum visit) using traditional footage during the retrospective interviews could be improved using immersive videos and photogrammetry.

TOWARDS VIDEOGRAMMETRY: VIDEO-PHOTOGRAMMETRY

Considering the current technological limitations associated to videogrammetry - namely its real-time interactive playback and the uncertainty regarding the quality of the models it offers - we propose a more reliable twofold alternative approach to relocate users in parts of their previous museum visit (Fig. 1). To proceed, the events are first recorded as they unfold in the chosen exhibition room using both the videogrammetric setup and a 360° camera (Nikon KeyMission 360(TM)) positioned at the center of the space. Afterwards, immersive videos are presented to the participants allowing them to observe their own behaviours. This immersive spherical video was edited from the 360° footage (Fig. 2)
and adapted to be used in Hyve-3D(TM) (Hybrid Virtual Environment 3D) (Dorta, Kinayoglu & Hoffmann, 2016). Hyve-3D offers a Social virtual reality (VR) experience, without the use of headsets, through an anamorphic life-sized projection of interactive 3D content. The Social VR experience allowed the recognition of other visitors’ behaviours that were participating, asynchronously in the immersive video and synchronously via collective interviews. Through this first re-visit and after the analysis of the UX states, moments of interest are identified to indicate which frames to extract from the videogrammetric data for the production of 3D models.

**Figure 2**
Participant evaluating the challenges and skills while watching the immersive video.

**Figure 3**
Immersive and collective interviews inside Hyve-3D, interacting with the photogrammetric model.

**METHODOLOGY**
Using the granular experience assessment method developed by Safin et al. (2016) as described above, key moments of the subjective experience were identified through the visitors’ evaluations as they were spectating their recorded visit in the immersive video (life-sized scale) from a nodal perspective (from 360° camera point of view). This method calls for participants to indicate how they perceived the “challenges” of the previously lived interactions and their felt “skills” level, all through an interface with corresponding sliders (Fig. 2). This way, we aimed to obtain a finer evaluation and evolution of the lived experience through time, allowing us to pinpoint specific interactive settings based on the UX state they induced. The information thus collected was used as markers indicating which frames to extract from the videogrammetric data to present as immersive 3D models (photogrammetric). A further spatial exploration and evaluation then took place inside the social VR environment of Hyve-3D (Fig. 3) through collective interviews where participants explained together their UX for each interactive setting selected. This case study, presented here as a proof of concept of the proposed framework, develops an assessment of three users (3 researchers from the lab) engaging for the first time different interactions within a recently renewed museum dealing with different engineering and design aspects from the development of a company's flagship vehicles (the name of the company is withheld). In the context of this pilot project and considering its limited sample size, our contribution relates itself mainly to a new framework that can be used for guiding the design and evaluation of interactive installations in museums.

**RESULTS AND ANALYSIS**
The granular UX assessment data was visualized as graphs to facilitate the identification of key moments of UX that should be explored in depth. The graphs (Fig. 4) were composed of opposing curves corresponding to the perceived challenge and skill levels, to which was overlaid a four levels line graph illustrating the evolution of the person's UX, the bottom indicating boredom. A brief review of the original video footage was conducted in parallel with an exhaustive numbering of the exhibition room's installations. This made possible to annotate each participant's graph with the installation concerned at every moment of the visit. A revision lead us to isolate what the data showed to be the most engaging in-
interaction moments (flow state) as well as controversial installations rendered by contrasted experiences oscillating mainly between stress and flow. To lighten the 3D photogrammetric model building workflow, a further refinement of the selection was based on the plurality of experiences - i.e. the number of affected visitors - encompassed by the precise key frame and its neighboring moments. Scenes extracted accordingly are presented in Table 1.

The hypothesis behind the selection criteria is that memories from the key moments of these UX state changes should give us an insight not only into the environmental variables supporting the optimal experience, but also on the reasons leading to their interruption, shedding light on eventual recommendations. The scene occurring at $t = 270$ sec. (see Fig. 4) was discarded due to the camera angles and the participants' positions, making it impossible to obtain

Table 1
Selected installations showing the UX for the key moments.
Table 2
Brief descriptions of the selected installations.

<table>
<thead>
<tr>
<th>Installation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>A fully functional vehicle engine (modified to be powered by electricity) displayed in a transparent acrylic casing. It is equipped with a fixed replica of the vehicle’s handlebars, at the counter’s height, as an interface to run the engine using a single push-button. The handlebar has multiple fictitious buttons for decoration.</td>
</tr>
<tr>
<td>9</td>
<td>Complete suspension mechanism used for the traction unit, encased in a similar transparent cabinet as installation 6. The components are connected into a single longitudinal piece that is secured on two articulated pistons situated at both ends. Two vertical handles are installed side-by-side on the counter, in front of the casing, allowing visitors to observe the component’s various behaviours by pushing and pulling horizontally each handle independently.</td>
</tr>
<tr>
<td>11</td>
<td>Three different versions, from different years, of a part of the vehicle used that attaches itself to its bottom for ground support and vehicle motion. Parts differ greatly in terms of proportions and materials while having a similar shaping and recurrent details.</td>
</tr>
<tr>
<td>14</td>
<td>A complete and real vehicle mounted above head height and further back on an angled surface that extends across the periphery of the exhibit room.</td>
</tr>
<tr>
<td>15</td>
<td>A coarsely textured traction unit fixed (no moving parts) independently on the counter.</td>
</tr>
</tbody>
</table>

a properly reconstructed 3D model, even if it corresponded to the criteria (as illustrated in the graphs in striped lines). Although, few spatial properties were differentiating it from the selected instant occurring a few seconds later at t = 275. As participants were confronted with an extended temporal span of their behaviors while watching the video, they had a chance to reflect openly on the omitted moment. After reviewing the recordings of the interviews, we extracted the main ideas underlying the accounts from each participant.

Installation 6
Of the selected scenes, installation 6 came out as the only one eliciting the flow state for all three visitors: The most important reason is the multisensory aspect of the setup (distinguished sound when interacting with). This factor was remembered as soliciting a heightened engagement: “When others use this interaction, the sound of it creates interest for me” (Visitor 3); “What attracted me to that interface was the sound [Visitor 2] was doing, [...] I was looking and I wanted to do it myself to feel it” (Visitor 1). For another participant, it was the possibility of visually exploring the moving parts from different angles and discovering “complexities inside the moving engine” (Visitor 2) that was felt as an engaging feature, thanks to the object being three-dimensional, close and fully visible through a transparent casing. Yet, a stress state was induced due to shaking upon use, interrupting the flow state. Perceiving this instability, a participant claimed to feel a certain risk that lead him to self-constrain his interactions: “I got scared at some point when it started spinning fast, and I didn’t want- the box didn’t look that solid” (Visitor 2). The same visitor noted the sound he perceived as inauthentic created a disinterest tipping him further out of his engagement. For Visitor 1, inauthenticity was also brought up as a trait hindering the interactive experience. The participant expressed, why it didn’t replicate the handlebars he remembered from using an actual vehicle. For visitor 3, an initial stress state was linked to a poor contextualization of the isolated mechanical component. According to her, the disposition of this installation made it difficult to understand how the engine should integrate itself into an actual vehicle (Visitor 3).

Installation 9
For all three participants, the initial apprehension of this installation correlated with a stress state. The main reason was a lack of information discernable at first glance and clarifying the relation of the component and its operation with the broader context of the exhibition. For one visitor, this notable deficiency extended itself beyond the counter-level installation,
to the signage design of the room. He reported that after discovering specific marks spread across the room's floor, the fact they had an obviously intentional placement and yet seemed irrelevant could have contributed to create confusion: “Only now I realize why this is there. [...] You don't know when you are there.” (Visitor 1). The perceived affordances were a mitigated component of the installation. One participant detailed how the interaction wasn’t self-explanatory for her to figure out how to use it: “I was stressed because only after I see others using it I can know how to use it. [...] I don’t know what’s the function of this device- it’s for what” (Visitor 3). However, for another the design of the installation including two large upright handles “really sticking out” (Visitor 2) turned out highly inviting.

**Installation 11**

Here again, all three participants experienced a stress state during a part of their interaction. For Visitor 2, a lack of information properly designed within the actual installation lead to an interruption of his flow state. Indeed, because the elements were simply laid out, some more specialized mechanical details were less prone to being interpreted with certainty: “They show the [specific parts] but they don’t detail on what I suppose to understand. I see a [specific parts], okay, but now tell me what is behind the it, what it’s actually made of...” (Visitor 2). For another participant, the stress state was induced by a poor contextualisation of the displayed element. Although, by taking the time to turn around and browse the rest of the exhibition, she better understood how the component integrated itself to the vehicles, briefly prompting a state of flow.

**Installation 15**

Installation 15 was marking the endpoint of the room’s visit, participants appeared to be mainly concerned with the more global experience they had when taking a step back. The space’s circular configuration was described as allowing different readings of the exhibition, all the while being structured adequately to make one “see the timeline, feel it” (Visitor 2), which for Visitor 2 prompted a flow state. Although, for at least one visitor who experienced a stress state, this was perceived more as a visual cluttering factor making it harder for her to “classify” (Visitor 3) the artifacts. The specific part displayed, by its shape and texture, turned out quite inviting to touch for at least one interviewee, but its positioning far back on the counter made it difficult to reach and suspended his optimal experience of the initially perceived affordances.

**RECOMMENDATIONS**

Our findings are in line with the idea that authentic stimuli are perceived as a desirable factor from the visitors’ viewpoint (Levent & Pascual-Leone, 2014) and highlight the strength of a multisensorial UX design of these stimuli. On different occasions, participants recalled how parts of their visit evoked memories compared to which the installations’ per-
ceived authenticity played a definite role in the states reached. At one stage when talking about poor contextualization, a participant pointed out that, “after all, to [him], the [vehicle] is a tool, something humans use, so [the museum] should try to figure out a way to show that to people” (Visitor 2). By taking this into consideration, exhibition designers could help future visitors understand more directly the actual uses of different components, and in some cases, strengthen the link between displayed content and everyday life. In Table 3 we synthesized the analysis as punctual design recommendations for the installations to give a brief example of how the framework put forth could percolate in practice.

DISCUSSION
The pilot study hints at the fact that, even with a methodology using 3D models as freezeframes for exploration instead of live videogrammetry, participants’ grasp of memories appeared to overflow the represented moment. Collective interviews inside the social VR system show that participants gained the ability to reflect on what was experienced in the moments both preceding and following the reconstructed instant. We suggest that, by combining the spatial immersive exploration of static settings while switching back and forth with the immersive video including the recorded sound of the surrounding moments, retrospections reached a greater level of detail than they could have prior to this stage. In fact, self-observation interviews showed that participants’ memories of their visit cleared up even though almost three months had passed since it was conducted. Some even openly expressed being surprised at how much they could remember about otherwise forgotten facets of their visit. According to the aspects that were referred to during the interviews, a clearer link traces itself between the reflections shared and the mediatic characteristics of both the immersive spherical video and photogrammetric models. While the sound of various elements was brought up as a constituent part of the exhibition visit, the positions and gestures of other visitors in the recorded images also appeared to have triggered deepened retrospection. This observation points toward the particular potential of social VR environments and fully tridimensional event depiction as a productive interview context. The anchoring of the collective interviews on specific instants, as they were identified by the UX granular assessment, also helped to structure the workflow. Not only did they give participants a starting point to help them verbally express their experiences, they also offered researchers a tool to organize the interviews and analysis.

CONCLUSION
The primary aim of the study was to experiment a new framework for assessing UX in interactive spaces. By conducting a case study in a museum context, we managed to provide a more rigorous picture detailing the impact of using a methodology based on video-photogrammetry and immersive interviews. The study showed that immersing interviewees in interactive 3D photogrammetric models depicting frozen moments of lived events facilitates the recall of memories and allows a deepened self-observation analysis. Future work should try to clarify the link between the quality of the spatial and embodied experience provided by the immersive environment and the details and aspects brought up by participants. More tests could also be conducted to include 3D sound ambiances during the stage when participants navigate through the 3D models. This work also served as an actual eval-

Table 3
Design recommendations.
uation of a designed exhibition, an empirical terrain through which some of the findings corroborate certain propositions from museum design literature. Although the design recommendations here were brief and haven't been thoroughly delved into by an actual group of designers in a professional context, future explorations could attempt to focus on the use of 3D sketches also provided by Hyve-3D as a communication and ideation tool in steps following a similarly structured UX assessment protocol.

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Soft Human Computer Interfaces

Towards Soft Robotics in Architecture

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The emergence of media infused facades and new human computer interfaces have been of great interest in architecture in the recent decades. Most of the emerging examples are geared towards a multi-dimensional graphical output and most commonly stimulate our sense of sight. This paper explores recent developments in soft robotics and material sciences, developed at the Material Dynamics Lab at NJIT, that will allow the human computer interfaces to engage its users by captivating a multitude of senses simultaneously. Furthermore, this paper will contemplate future trajectories for the novel material strategies to improve human-computer or human-robot interaction, that one day may lead to truly robotic architectures.

Keywords: Soft Robotics, Nanotechnology, Smart Materials, Robotic Architecture, Human Computer Interfaces (HCI), Graphical User Interfaces (GUI) to Tangible User Interfaces (TUI)

INTRODUCTION

In recent years, we have been able to witness an increased automation of our homes and a move towards smart buildings and cities (Shaikh et al. 2014; Zarzycki 2016). These trends promise not only improvements of energy efficiency in an increasingly competitive landscape, they are also being studied to address global challenges such as a rapidly growing world population or our significant energy consumption and its associated greenhouse gas emissions. The development of smart building components and systems has been accelerated by advances in network connectivity and big data analytics, but also the availability of more cost-efficient sensor and actuator technologies.

An example for such a smart building element can be found in the Programmable Nest Learning Thermostat [1]. This self-learning and Wi-Fi enabled thermostat can operate our HVAC systems, and optimize them based on user preference, occupancy and location dependent weather data.

With a growing smart building systems market [2], an increase in the number of devices and machines that can control our environment can be expected. The human-computer or human-device interface design will have to be reconsidered.

Nest for example, can be operated through a circular display mounted to a wall in your home that is roughly three inches in diameter. Alternatively, it can be controlled through an app on a smartphone, tablet or computer. Even though the connection to a smartphone can give the Nest system additional in-
formation on the occupant’s location, both types of input devices are experienced as Graphical User Interfaces (GUIs). GUIs display information with a pixel-based system that can be influenced through peripheral hardware such as mice, touchscreens or keyboards (see Figure 1).

Since digital thermostats started replacing their analog predecessors in the early nineties (Peffer et al. 2011), the ubiquitous conventional programmable thermostats in American homes have become increasingly complex to operate. As the physical interface evolved to incorporate displays and buttons, to accommodate the programming capabilities, the information that had to be submitted got increasingly complex. The early interface designs often relied on the willingness of the user to learn how to operate the thermostat. The Nest Interface is representative of an improvement over prior art in particular due to its capability to outsource the programming functions to the internet. (see Figure 2)

Through the integration of computational abilities into our buildings our perception is starting to shift from “computers in architecture, or computers affecting architectural design, to the notion of architecture as the computer” (Senegala 2005). With this emerging paradigm shift, architectural surfaces such as walls, floors, ceilings, windows and doors offer new opportunities for multidimensional output and novel
interfaces for the constructed environment. Opportunities arise for human computer interfaces that can mirror the physical nature of our architectures and even our own bodies, granting our physical experiences a central role in human computer interaction design.

FROM GRAPHICAL USER INTERFACES (GUI) TO TANGIBLE USER INTERFACES (TUI)

GUIs have become the standard mode of interaction with the digital world for us today, but novel ways of engaging the digital realm have been contemplated for the last couple of decades. In 1997 for example, Ishii and Ullmer coined the term “Tangible User Interfaces”. In TUIs, real world physical “objects and architectural surfaces” (Ishii et al. 1997) are coupled with digital information and enable a new Human Computer Interaction (HCI). The new trajectories in HCI acknowledge the importance of embodied cognition (Wilson 2002) and that thought and action, and mind and body, are deeply intertwined. Taking advantage of the richness of human senses, TUIs can increase the user’s willingness to learn and to engage.

At the Tangible Media Group at MIT [3], projects such as SoundFORMS (Colter et al. 2016) or TRANSFORM (Vink et al. 2015) demonstrate the potential of this novel interaction through the creation of active and reactive shape changing interfaces or polymorphic furniture.

EMERGENT AND SOFT MATERIALS

An important key driver in the development of interactive interfaces can be found through emergent materials (Ishii et al. 2012). The intelligent or smart materials (see Figure 3) that are born out of nanotechnology can now be engineered to react to very specific external stimuli with carefully designed material responses. They can respond to inputs such as electric currents, photons of light, temperature differentials or chemicals. The material responses can range from changes in shape and color, the emittance of light or the production of an electric current. Researchers are striving to create truly robotic materials that can take on a number of tasks at the same time (McEvoy et al. 2015). These multifunctional materials and composites can integrate sensing and actuation, and may one day even integrate elements of computation, communication and a power infrastructure.

Another line of investigation strives to create novel materials that mimic the nature of our own human bodies. Materials that are soft and malleable are being researched to improve human-robot-interactions by matching up materials that share a similar rigidity or hardness. By coordinating these particular material properties, the distribution of loads across the surfaces that come into contact with each other can be orchestrated. Through this compliance matching the interfacial stress concentrations can be minimized and hence protect humans from injuries when interacting with robots (Majidi 2014). The nascent field of soft robotics that is emerging at the fascinating intersection of robotics and material science holds the potential to revolutionize the design of TCIs with this material strategy.

CASE STUDY

A research study conducted at the Material Dynamics Lab [5] at the New Jersey Institute of Technology leverages this material strategy to create connections between the physical and the digital worlds.
The interactive Haptic, Audio, and Visual Interface for multi-sensorial experiences (see Figure 4) (Decker et al. 2016) utilizes a dielectric electroactive polymer (DEAP) that can change shape in response to an electric current.

DEAPs consist of a polymeric core that is sandwiched between two compliant electrodes. When an electric current is applied to the material composite, the electrodes become attracted to each other and deform the core in turn. (see Figure 5) In the design for the Haptic, Audio, and Visual Interface the DEAP actuators are stretched over a frame structure that prevents the soft membrane from collapse, and allows for the precise control of the material composite's thickness.

A multitude of actuators can act as an audio visual and haptic interface, by changing the shape and appearance of the electrodes. By expanding and contracting, they can act much like pixels in a screen or the chromatophores of squids (see Figure 6) that allow the ocean dwellers to change colors and patterns on their skin rapidly. Beyond the visual input that is achieved by the polymorphic transformation, the shape change can also be felt, equivalent to refreshable braille interfaces that utilize a similar materials strategy. Acoustic signals can be emitted by the interface through a rapid expansion and contraction of the electroactive membranes. The actuators can also be used as a touch sensor by measuring the capacitance during mechanical deformation. Finally, these fascinating materials have been studied as a power source that can turn the mechanical energy into an electrical output even though this was not in the scope of the above described research project.

DISCUSSION
The Haptic, Audio, and Visual Interface for multi-sensorial experiences has the potential to take on the functions of peripheral hardware including mice, computer monitors, touchscreens, loudspeakers, headphones, keyboards, as well as force feedback devices such as joysticks and gamepads. Instead of using a multitude of auxiliary devices, this interface can fulfill all these different tasks with a membrane that is less than one mm in thickness.

The series of prototypes (see Figures 4 and 7) that were fabricated at NJIT were successful in demonstrating that all the different functions can be achieved with a single membrane design, but the study also revealed that more research needs to oc-
Figure 7
Actuator Design for Interactive, Haptic, Audio, and Visual Interface. by Bartel, Decker, Merz and Zarzycki | Material Dynamics Lab

Figure 8
A constrained soft dielectric material subject to a voltage across the thickness will deform out of plane, producing the buckled shapes as shown. (Wang et al. 2016)

Figure 9
Mockup of Interactive, Haptic, Audio, and Visual Interface for Multi Sensorial Experiences. by Bartel, Decker, Merz and Zarzycki | Material Dynamics Lab
cur before the design with soft materials such as DEAPs can become suitable for larger architectural applications.

In a collaborative undertaking between NJIT and Brown University, researchers endeavor to contribute to a modeling platform that could advance the study of the electromechanical instabilities of soft dielectrics (see Figure 8) (Wang et al. 2016). The unpredictable nature of soft materials does not allow for an intuitive design process and the continued improvement of the modeling platforms are going to be essential to drive the development of soft actuators and robotics.

CONCLUSION
The emergent soft human computer interfaces that were introduced in this paper (see Figure 9), benefit from our dexterity and promote a direct engagement with the physical world. Beyond a physical tool for interacting with digital information, the TUIs might also allow us to create truly interactive and reactive environments. Leveraging the user’s lifelong experience with the physical world, these systems might be an integral step towards the vision of radical atoms (Ishii 2012) and truly robotic environments that are intuitive and easy to operate, turning our architectures into robots for living in (Mitchell 2008).

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Participatory Design Supported with Design System and Augmented Reality

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In this paper we present our research which is focused on developing and testing a method supporting participatory design process with a use of a design system and Augmented Reality interactive interface. We propose a concept of participatory design where participants can directly interact with architectural knowledge encapsulated in the design system. The proposed concept of participatory design supported with a design system was tested during a workshop conducted in Kaunas, Lithuania. The dedicated design system was created in order to minimize physical interaction between the architect and the users while allowing for customization of design solutions by participants. The design system and the participatory design process were linked with the use of a digital communication interface. The paper is concluded with a critical view on the process. The conclusions are based substantially on the results of a survey prepared by the authors and conducted among workshop's participant.

Keywords: Augmented Reality, participatory design, design interface, parametric design

INTRODUCTION
Active involvement of future users in design processes is increasingly being introduced by architects to ensure that the design outcomes meet the users’ needs. Participatory design has been studied for decades, what results in the development of many collaborative design methods (Batchelor and Lewis 1985, Wates and Knevitt 1987, Zadow 1997, Kelbaugh 1997). The potential of augmenting these processes with the use of computer technologies was already foreseen over four decades ago (Cross and Maver 1973, Wrona 1981). The popularity of computer technologies allows architects to create their own design tools. Designers are now well equipped with tools to analyse the physical context of the project, but the ability to gather information about the social context is limited due to the lack of effective communication channels with future project users. The users can improve the final design by sharing their knowledge of the site along with their own needs and expectations for the project. On the other hand, the designer can support users by sharing his professional knowledge, experience in designing and proper execution of the final solution. Participatory design is a process where the user’s ex-
experience and the architect’s knowledge can be confronted and merged in order to improve the design outcome.

A participatory design process requires efficient channels of communication between the architect, future project users and other stakeholders. The traditional process of direct discussion is limited by the number of its possible participants. Therefore, in order to implement participation with a wide public, alternative communication channels have to be explored. Information technology offers new potentials for citizen participation in urban planning such as Augmented Reality (AR) (Hanzl 2007).

The use of AR in supporting public participation has been attracting researchers’ attention for several years. AR has been used in order to support participation by visualizing the design proposals (Allen et al. 2011, Olsson et al. 2012). While most of the research is mainly focused on using AR to support professional users in the design process (Fatah gen Schieck et al. 2004, Belcher and Johnson 2008) there is also interest in the research focused on supporting non-expert users in design participation (Cuperschmid et al. 2015).

In this paper, we present our research which is focused on developing and testing a method supporting participatory design process with a use of a design system and Augmented Reality interactive interface. We propose a concept of participatory design where participants can directly interact with architectural knowledge encapsulated in the design system. The dedicated design system is created in order to respond to the identified design constraints, minimize physical interaction between the architect and the users while allowing for interaction with the products of formalized design rules and customization of design solutions by participants. The design system and the participatory design process are linked with the use of a digital communication interface. In the course of our research, we have developed a tangible tool a tangible augmented reality tool to support multi-user participatory process.

PARTICIPATORY DESIGN SUPPORTED WITH DESIGN SYSTEM
Algorithmic design methods allow formalization of design principles used by the designer in a form of an algorithm. A parametric description of the project gives the designer a number of benefits, which include the possibility of exploring various design options, dynamic management of various design solutions and automatization of the search for optimal solutions. But algorithmic methods allow also to postpone the selection of final design solution, allowing others to co-design in respect with formalized design rules.

The ability to explore multiple design solutions gives the opportunity to review them, verify and evaluate according to their individual properties. Therefore, users interacting with a design system can learn, in a practical way both the exposed architectural design knowledge and the limitations and possibilities of an individual design solution. In this way, the users are equipped with the knowledge to make an informed decision based on the analysis of the advantages and disadvantages of each solution.

The concept of participatory design supported with design systems assumes that communication between the designer and the potential user can take place without direct dialogue between them. This concept supports user’s own interaction with the design system as well as the interaction of multiple users. In order to enable such interaction additionally a digital communication medium is required.

Therefore the proposed concept consists of three components (fig. 1) necessary for its proper application. The design system and the participatory design process are connected with a use of the digital communication medium which allows the exchange of information between them. All these elements are interrelated and their proper interconnection is essential for the effective application of the proposed method.
THE EXPERIMENT

The proposed concept of participatory design supported with a design system was tested during a workshop conducted in Kaunas, Lithuania. Our ASK research team was commissioned to conduct a 5-day design workshop, which aim was to redesign Romuva Square by complementing it with a multifunctional urban bench. During the span of the workshop, organizers expected not only to create a design proposal but also to fabricate and assemble the designed object. The workshop participants were supposed to be, most of the city residents, who know the location of the project. Such conditions were a good opportunity to verify our concept of participatory design. The decision about the final shape of the design had to be postponed until the workshop was held in order to support it with a knowledge of potential users of Romuva Square. Additionally, the design system had to be developed beforehand in order to allow for fabrication of final object during a scheduled time of the workshop, while maintaining a high degree of possible modifications by workshop participants.

The aim of the experiment was to verify proposed concept of participatory design process supported with the developed design system and an interactive interface. Developed tool had to allow modifications of the design by the users and simultaneously visualize possible design solutions in real time. The visualization had to inform the discussion and choice of final designs in a multi-user environment. The digital medium of communication was intended to enable intuitive interaction with the developed design system and facilitate the search of the solution satisfying all workshop participants. The workshop’s participants were supposed to jointly decide on the form, function and precise location of the proposed objects. Moreover, due to the tight schedule of the workshop, the participatory design experiment had to be conducted during only one day. Additionally, the developed tool was supposed not only to support the design process but also to guarantee the realization of the design in a scheduled time. The main aim of the planned experiment was to validate usability of the developed tools in a participatory design process and to test it in the real case scenario.
PARAMETRIC DESIGN SYSTEM

The form of the bench was designed in a parametric environment, Grasshopper, that allows controlling the object's parameters at any stage of the design process. The intention of the design was to allow the participants to modify the layout of the bench and to control the detailed parameters of its transverse shape (fig. 2). The bench layout has been determined based on the location of physical objects, placed on a printed map of the location. The objects corresponded to control points that, when meeting some distance criteria, connected in order to form a bench segment.

Manipulated control points were divided into three types, which determined the shape of the cross section of the bench and thus its function. Each of the cross-section types was assigned a range of influence that controlled at what distance the points formed a connection between them (fig. 3).

If the distance between the two control points was less than the sum of their range values, the connection between the points was generated. Changing the ranges of the influence of each control point in relation to each other or all simultaneously influenced the scale and proportions of the generated object.

The developed design system assumed the possibility of selecting and changing the profile type, on the individual segments of the bench, by the participants in the design process. For this purpose, we have developed 3 different seating profiles whose design principles have been formalized using parametric design tools. In this way, different sections of the bench can be assigned a different function, such as the seat with the backrest, deck chair as well as support for the standing person. In addition, the parametric design rules of each of the transverse sections allowed for the detailed modification of its form by the participants of the experiment. In this way, we not only allowed the ability of users to select the function of the selected section of the bench but also to modify the detailed parameters of the sections to suit their individual design expectations (fig. 4).
DIGITAL COMMUNICATION INTERFACE

In order to enable testing of different spatial layouts of possible design solutions in relation to their direct surrounding and to enable rapid information exchange between the participants of the design process, we created a dedicated, Augmented Reality-based, interface.

The decision to implement Augmented Reality comes from research conducted by Markusiewicz (2016). The technology seems to be at least partially solving issues with ‘traditional’ human-computer communication based on a mouse, a keyboard and a screen. Viewing digital objects in three dimensions using a mobile device work through direct manipulation of the virtual camera through device movements - as if one had a video camera in their hands. Implementing AR also allows for targeting multiple senses when communicating information and thus increasing the effectiveness of a message. The use of AR-based tools in architectural participatory design does not require users to have a high level of technological familiarity to understand its purpose and utility (Cuperschmid et al. 2015).

Another sense that provides immersive interaction with a computer is touch. Research conducted by Kim and Maher reveals that tangible user interfaces positively change designers’ spatial cognition, and then these affect the design processes by increasing designers’ problem-finding behaviors (Maher and Kim 2006).

Following Billinghurst’s classification of augmented realities, we decided to combine AR-based visualisation with tangible interaction in order to provide an immersive experience: by extending physical models and combining access to digital information with intuitive physical-model interaction.

The hardware setup (fig. 5) of the interface consists of:

- Augmented Reality tracker: a printed panel being a graphical representation of the site plan that at the same time determines the workspace.
- Control blocks: nine digitally augmented physical elements of three different types. They represent control points that the participants distribute on the workspace. Different types stand for different sections of the bench: a bench without backrest, a section with backrest, a barrier - a vertical element without a place to seat.
- A video camera placed above the workspace responsible for transmitting the image of the distribution of the control points to a dedicated software.
- Mobile devices equipped with a custom application for visualizing the generated form in real time using Augmented Reality.

Three main software solutions are used to synchronize users’ actions and interface elements:

1. reacTIVision - an open-source framework developed by Martin Kaltenbrunner and Ross Bencina for image recognition in the project ‘Reactable’ (Jordá et al. 2005) - is responsible for interpreting the image from the camera and mapping the position and rotation of each of control blocks. It passes the information about their coordinates to a Grasshopper definition using UDP protocol.
2. Grasshopper definition - developed by the authors. The position and orientation of control blocks serve as input for the algorithm generating the geometry of the bench. Each pair of control points placed close to each other is converted into a bench segment through lofting the section curves assigned to each type of control blocks. The resulting geometry is represented by a polygonal mesh. The information about the mesh is converted into a text message consisting of a list of vertex coordinates and sequences of vertex indices that form its faces. The message is passed to the next software using UDP protocol.
3. AR-based application - developed by the authors in Unity using Vuforia plugin to implement Augmented Reality. The application
runs on mobile devices. It constantly receives information about the geometry of the bench in form of a text message generated by the GH definition. It decodes the message to generate a mesh representation of the bench that can be rendered in real-time using Unity’s rendering engine. By recognizing the AR tracker, it virtually places the geometry on the site as viewed by the user of the mobile device.

The way users work with the dedicated interface is a recursive process. It starts with distributing control blocks on the AR tracker. The information is captured by the camera, decoded by reacTIVision and passed the Grasshopper definition that generates the geometry and sends all the necessary information to mobile devices that the users constantly hold during the procedure. The application on the devices renders the mesh superpositioned on the tracker so that any user is able to verify their actions and introduce changes by altering positions of the control blocks (fig. 6). The whole process is relatively fast (10 - 500 ms depending on the complexity of the geometry and the number of mobile devices used simultaneously) and allows for real-time verification of actions. Multiple users may interact with the interface to create one digital model that is rendered on all the mobile devices.
Figure 6
Augmented reality visualization of design solutions modified by physical control blocks.

Figure 7
Multi-user participatory design process supported by design system and augmented reality communication tool.

PARTICIPATORY DESIGN PROCESS
The workshop participants mostly were architects or students of architecture. Therefore, in order to mimic participatory design process participants were divided into groups. Every group was assigned a task to represent one or two of the identified social groups of potential users of the square. We planned the participatory design process to be conducted in three stages: analysis, designing with a use of developed interactive interface and choice of the final project. The first two stages were conducted by every group individually while during the last stage all the groups were confronted.

During the analytical stage, every group was supposed to carry out their own study of the project site context in order to define the main design assumptions. They conducted their own functional-spatial analysis, including analysis of the form and scale of the architectural elements of the square, analysis of terrain, human movement and visibility. Additionally, in order to set their design goals, we asked every group to define the needs of the social groups they were representing. This knowledge allowed them to prepare conceptual drafts of the square improvements while still not being aware of the possibilities and limitations of the interactive design interface they were going to use in the next stage.

Upon completion of the analytical stage, every group had an opportunity to use the dedicated interface to visualize their design. During 60-minute design sessions, members of each group tried to either recreate their own design concepts or create new designs based on the developed ideas (fig. 7). In both strategies, initial design ideas had to be confronted with the capabilities and limitations of our tools. At the time of this design phase, every group was able to create several design solutions and compare them. At the end of this stage, each group had to choose the best, in their opinion, solution that meets the needs of the user group they represent.

In the last stage, all workshop participants had to decide on the final design to be fabricated. During this stage, every group had to present their final concept explaining main design ideas. These presentations were supplemented with AR visualization of the design using the same interactive tool that was used for designing. After the presentation of each of the groups, the other participants were given the opportunity to ask questions and discuss together the proposed solution.

After listening to five presentations and analyzing design proposals in augmented reality, all workshop participants selected two design solutions through voting. The final design solution was chosen after a discussion where the disadvantages and advantages of both solutions were pointed out. These
arguments convinced the authors of the chosen solution to make further improvements. Among others, at the request of the workshop organizer, the selected project was reduced in size to allow its fabrication within the time constraints. All changes were made only by the authors, and the effect of the changes was visualized in real time to all participants. As a result of the planned process, a compromise solution was developed which was accepted by all participants and fabricated during the rest time of the workshop (fig. 8).

EVALUATION OF THE EXPERIMENT
In order to evaluate the experiment, participants were asked to complete the evaluation questionnaires at the end of the workshop. The questionnaire consisted of 34 questions and 13 out of 17 experiment participants filled out the survey. Among the people who completed the questionnaire were representatives of all focus groups. Most of the workshop participants (92.3%) were practicing architects, but more than half of the respondents declared that it was difficult for them to take on the role of future users. At the same time, most people felt engaged in group work and indicated that they had an impact on group design proposal.

The survey showed that not all participants in the experiment managed to obtain a design solution that they sketched. Almost 54% of the participants failed to obtain their preliminary design solution using the dedicated interface. At the same time, 11 out of 13 participants (84.6%) were satisfied with the final solution achieved by their group. All the respondents indicated that the proposed tool helped their group in choosing a design solution.

The responses in the survey confirmed the observations made during the experiment that the choice of the final design solution was difficult for the majority of the participants and that the chosen solution was a compromise. Only one person indicated that he/she was very satisfied with the chosen solution while 7 people were rather satisfied.

The questionnaire also included open questions. The workshop participants were asked to indicate what was lacking in the participatory process. Among the given answers, two dominant groups of comments can be distinguished. Firstly, the participants thought there were too many design constraints. Secondly, there was a general opinion that the time dedicated to the design and selection process was too short.

The survey also included questions about the intuitiveness of the developed tool. For most workshop participants, a printout of the map representing the site was intuitive. For the majority of users, physical interaction with markers that modify the shape of the bench was rather intuitive and changing the shape of the bench by changing the location of the markers was intuitive. But 4 people indicated that modifying the bench section by rotating the physical marker was counterintuitive. Nevertheless, the majority of respondents stated that making changes using physical elements while observing the effects of these changes on mobile devices was easy.

CONCLUSIONS
The conducted experiment fulfilled its objectives and assumptions. All the scheduled research tasks were successfully completed within the set timeframe. Computer-aided design participation was also successfully conducted. During one day the participants were able to find a shared design solution that was
a compromise between different expectations of five groups representing distinct social groups. The workshop allowed to simulate the conditions of a real project in which a computer-aided participatory design process could be used.

In our opinion, the effectiveness of computer-aided participatory design process was partly due to the initial limitation of possible design solutions. The limitations were introduced in the proposed design system by its designers. The authors of the design system consciously - based on their own analyses and imposed time-technological constraints - decided to limit possible design solutions to the various forms of space arrangement using the object of the bench. Such decision allowed to reduce the discussion on alternative and detailed solutions while giving the opportunity to focus on selected topics. The discussion about the final design was limited to problems issued for modification by the workshop participants.

As the surveys showed, the participants noticed many design constraints that limited the ability to obtain their pre-developed design concepts. It should be noted that all the participants in the experiment were professionally trained architects or architectural students. Most likely, on a daily basis, they are designing while being exposed to a variety of digital and non-digital design tools expanding design capabilities. The analytical phase, which concluded with design sketches, has awakened the design expectations of the workshop participants. However, in the stage, they were confronted with the possibilities offered by the tool. Additionally, the requirement of voting for only one final solution was limiting the expectations.

However, dynamic discussion accompanying the choice of the final solution was effectively supported by the developed tool. The possibility of modifying the designs in real time, verifying the obtained solutions with personal design assumptions and verifying the results in relation to the environment allowed the participants to carry out a substantial design discussion supported by visualized solutions. In addition, the proposed tool allowed to multiply the number of project iterations and accelerate the design process by avoiding manual modeling and visualizations. The proposed design and visualization method was so convincing that the participants at final stages of design process modified designs without looking at the visualization by simply moving the physical markers on the map (fig. 9).

For most participants, the process of choosing the final solution was a difficult task, which ended in the choice of a compromise solution. The process ended with a very different degree of satisfaction for each participant. This may indicate that the participants were very much attached to their individual design ideas, which they found hard to abandon in favor of a solution proposed by another group. Therefore, it seems necessary to continue the experimental research, with a focus on conducting it with non-designers, representatives of the various social groups using selected space.
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