FUTURE TRAJECTORIES OF COMPUTATION IN DESIGN

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Edited by

Gülen Çağdaş
Mine Özkar
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Gülen Çağdaş, Mine Özkar, Leman F. Gül and Ethem Gürer (Eds.)

Future Trajectories of Computation in Design

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Preface

The Computer-Aided Architectural Design Foundation was established in 1985, and ever since, has encouraged state-of-the-art research and practice of computing in architectural design through conferences and publications. Istanbul, the vibrant metropolis that lies between Asia and Europe, is the host for the 17th CAADFutures Conference.

For the designer in the multidisciplinary world of the 21st century, computation provides a powerful medium for the extension of understanding other disciplines. In accordance with this global change in the field of design, CAADFutures 2017 called for papers around the theme of "future trajectories of computation in design." In fostering a multidisciplinary discourse for the future of computation in design, the conference aimed at not only gathering the latest research, design practice and pedagogies but also revealing the possible phenomena, factors and forces that will influence these trajectories in design with an exploratory perspective.

In the first stage of paper evaluations, 184 abstracts were received from 27 different countries. In a two-tier double-blind review process, 66 papers were selected for the conference. This volume includes full texts of 44 of these papers and the abstracts of 22 that were selected for an edited book published by Springer. The content of this proceedings volume can be accessed in Cumincad (cumincad.scix.net). Each paper was reviewed by at least three experts from an international committee of 80 experienced researchers.

The papers in this volume have been organized under twelve headings: (1) Shape Studies, (2) Urban Studies, (3) Building Performance Studies, (4) Design Geometry and Form Studies, (5) Building Information Modelling, (6) Decision Support Systems and Human Computer Interactions, (7) Fabrication and Materiality, (8) Parametric Tools and Models for Design, (9) Pedagogical Approaches to CAAD, (10) Augmented and Virtual Reality Environment Studies, (11) Generative Design Systems, and (12) Rethinking Design in Digital Context. The first group provides research on mathematics of shapes in design. The second offers examples of various applications of computation in studying the urban environment. Whereas the third showcases research on building performance, the fourth comprises of papers that offer in-depth understanding of form. The fifth group displays various approaches to BIM, and the sixth group includes a broad range of studies in optimizing the creation and sustainment of the built environment. The seventh group reports on new ways of making that incorporate materials and computational thinking. The eighth group opens new horizons for parametric design studies. The ninth group of papers offers discussions on the recent roles of computational approaches in design curriculum, and the tenth group provides explorative insights for virtual experience in design. Finally, while the eleventh group of papers reveals the qualities of generative design systems within different scenarios, the twelfth group provokes new discussions on the character of design in digital contexts. Contributors of this volume are researchers from the fields of architecture, design, urban design, computer science, engineering, and other disciplines that address issues of computational design.

As editors of this volume, and organizers of the conference, we thank Professors Bauke de Vries and Tom Kvan of the CAADFutures Foundation for their continuing support in the process of organizing the conference and the preparation of this book. Gabriela Celani, the chair of the 2015 conference, has been extremely resourceful and helpful to us from the very beginning. We also thank all members of the scientific committee for their diligent reviews that paved the way to match the high academic standards CAADFuture conferences are known for. We are also grateful to each member of the conference organizing committee. Finally, the conference would not have been possible without the support of Istanbul Technical University Rectorate, the Faculty of Architecture, and our generous sponsors.

It has been a great honor and pleasure to organize and host the CAAD Futures Conference in Istanbul. We hope that this great selection of papers is an indication of the contribution of the conference to the field and that you enjoy the book.

Gülen Çağdaş
Mine Özkar
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July 2017, Istanbul

Keynote Speakers

 

Anna Dyson teaches design, technology, and theory at the School of Architecture at Rensselaer. She is the founding Director of CASE (2007-present) which hosts the Graduate Program in Architectural Sciences / Built Ecologies. CASE is committed to bridging diverse worlds by proposing a new collaborative model for building research that unites interdisciplinary academic research with building and development practices. The consortium attempts to achieve this collaborative model without the schism that has typically divorced building science pursuits from the aesthetic, social and conceptual aspirations of architectural design inquiry. Anna has been recognized with multiple awards for her designs and innovations, and her work has been exhibited internationally at venues including the Museum of Modern Art (MoMA), The World Future Energy Summit (WFES), The Center for Architecture and the Postmasters Gallery. Dyson holds multiple international patents for building systems inventions and is currently directing interdisciplinary research funded by the National Science Foundation (NSF), the U.S. Department of Energy (DOE), the New York State Energy Research and Development Authority (NYSERDA), and the New York State Foundation for Science, Technology and Innovation (NYSTAR) to develop new building systems that integrate advances in science and technology from diverse research fields.
Director, Center for Architecture Science and Ecology, Rensselaer Polytechnic Institute & Skidmore, Owings & Merrill, LLP. Professor, School of Architecture, Rensselaer Polytechnic Institute.

Ahu Aydogan Akseli is an architectural designer and researcher focused on the development of a plant-based dynamic filtration system to clean indoor air and reduce energy consumption profile of buildings. As Assistant Professor at the Spitzer School of Architecture, CCNY she teaches construction technology courses with an emphasis on the integration of environmental feedback loops into design processes. Aydogan Akseli conducted design research as a HASS Fellow at Rensselaer Polytechnic Institute Center for Architecture Science and Ecology (CASE), where she received her Ph.D. in Architectural Sciences in 2012. She has practiced with CASE and Skidmore, Owings, & Merrill on the design of international projects that integrate next-generation building technologies. Her current research facilitates the interdisciplinary design of sustainable systems and technologies for integration within the built environment. Akseli earned her master's degrees both in engineering management and architecture from Izmir Institute of Technology in 2005. Her background addressed the complexity involved in the management of design problems.

Built Ecologies

Christoph Hölscher is Full Professor of Cognitive Science in the D-GESS at ETH Zürich since 2013, with an emphasis on Applied Cognitive Science. Since 2016 Christoph is a Principal Investigator at the Singapore ETH Center (SEC) Future Cities Laboratory, heading a research group on 'Cognition, Perception and Behaviour in Urban Environments'. He holds a PhD in Psychology from University of Freiburg, served as honorary senior research fellow at UCL, Bartlett School of Architecture, and is a visiting Professor at Northumbria University Newcastle. Christoph has several years of industry experience in Human-Computer Interaction and usability consulting. The core mission of his research groups in Zurich and Singapore is to unravel the complex interaction of humans and their physical, technical and social environment with an emphasis on cognitive processes and task-oriented behavior.

Human behavior and cognition of architectural space – assessing psychological building performance

Advances in digital media and computation have spurred renewed interest in modeling, anticipating and predicting the human experience of architectural spaces. Physical modeling of building parameters such as carbon footprint, thermal comfort, shadow-casting or green features has been clearly established in tools for performance prediction and generative algorithms of form-finding and design optimization. But how does one capture the 'soft' factors of human behavior and human appreciation of a building design? How can psychological parameters be included as part of evidence-based design? This talk will provide on overview of how our spatial cognition research group tackles this with an emphasis on human movement pattern in complex, publically accessible environments. We combine real world behavior observation with Virtual Reality simulation of building design options. This goes beyond traditional post-occupancy evaluation by providing pre-occupancy assessments opportunities. To capture the richness of human perception and environmental appreciation we engage volunteer participants in a series of interaction tasks in a real or virtual, measuring their reactions with behavior and path tracing, eye-tracking and physiological measures of stress and arousal. This helps us identify points of misfit between the architects intentions and the present – or future – patrons reaction to the building design. CAAD tools provide the basis for immersive Virtual Reality experiments to compare design alternatives, as well as for Agent-based simulations of patron behavior, both for individual wayfinding analysis and development of cognitively enriched crowd movement simulations.

Martin Tamke is Associate Professor at the Centre for Information Technology and Architecture (CITA) in Copenhagen. He is pursuing a design led research in the interface and implications of computational design and its materialization. He joined the newly founded research centre CITA in 2006 and shaped its design based research practice. Projects on new design and fabrication tools for wood and composite production led to a series of digitally fabricated demonstrators that explore an architectural practice engaged with bespoke materials and behaviour. The latest research focuses on design modelling strategies, which are enabled through feedback from environment and process. His current work is characterised by strong links to computer science, with a focus on Machine Learning and Point Clouds, engineering, with a focus on simulation and ultralight hybrid structures, and material science, with a focus on bespoke cnc knit. The research connects academic and industrial partners from architecture and engineering, computer and material science and the crafts. Currently he is involved in the Danish funded 4 year Complex Modelling research project and the adapt-r and InnoChain PhD research networks.

Complex modelling

The building profession is in a radical shift of paradigm from architectural representations of unconnected data to practices with an overwhelming amount of information rich data. These emerge as professionals are increasingly engaging in their models with data from external sources and collaborators, such as urban, climate or 3D scanning data, as they create data internally within the practice or project by means of scripting, simulation or sensing. At the same time methods and tools are missing to implement this data in a productive way into design processes. Introducing the term Complex Modelling the lecture will present computational design approaches and projects, which support feedback between different scales of design engagement moving from material design, across design, simulation and analysis to specification and fabrication.

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Weaving, Folding and the Tension Between Them

A Discourse on a Structural Ideation Method

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Abstract. This paper presents a computational ideation method, aiming to generate different structural configurations using mechanical embedding and visual calculation. A set of schema to register mechanical description and the shape-relationship is provided. Our results point to a promising avenue in terms of how visual calculation and mechanical embedding work in tandem to extend the language of structural design and advance the future of interdisciplinary craft.

Keywords: Structure, Ideation, Craft, Shape grammar, Tensegrity

1 Introduction

Despite advances in the generative approach and optimization methods in structural design, there is only a few studies on the way in which the designer/engineer ideation process is translated into a structural design method. With limited references to such ideation processes, one might need to depend on the finalized ideation product, i.e., structural design method that has been explicitly defined either physically or digitally, such as those by Frei Otto, Antonio Gaudi, or Heinz Isler (e.g., mesh-relaxation). The consequences of doing so in the field of design are significant.

On the one hand, there is a mechanical fixation problem. Physical structure synthesis, a process of physically modifying a scaled structure to simulate its full-scale structure (e.g., soap-film model by Frei Otto) can yield various physical design solutions immediately. At the same time, however, physical variables can also fixate such solutions under certain topologies (e.g., tensile-membrane relaxation style). On the other hand, there is the issue of excessive freedom in digital design synthesis. Operating under symbolic point-based representation, metaheuristic algorithms can rapidly generate emergent and unprecedented design solutions. However, without a controlling mechanism, a solution may not be part of the designer's intention.

In responding to the latter, methods for incorporating the designer's intention into an algorithm have been proposed in several studies on structural design synthesis. By computing shapes based on certain design rules (e.g., fractal-based geometry), metaheuristic algorithms can generate optimized solutions that can be found within certain design languages [1-3]. Over time, however, this solution can be saturated into yet another fixation issue. In the case where a specific generative design style is no longer satisfactory, how does one generate alternative structural configurations? Or better yet, how does one escape from one idealization style?

2 Method

The method discussed in this paper focuses on the ideation process before a structure is simulated and optimized, digitally or physically. In particular, we interpret the ideation moment where the association between shape as a visual element and shape as a mechanical element occurs. We maintain that, in order to liberate the structural ideation process, our visual engagement with a shape needs to be able to work independently, yet in close proximity to mechanical registration for such a shape. To explain this process, our paper is structured into two sections. First, we briefly introduce visual embedding to explain how to 'see' a shape as it is, and 'do' something with it using a shape grammar schema (e.g., boundary schema, part schema, transformation schema and identity schema) [4, 5]. Following visual embedding, we introduce mechanical embedding to register the shape's mechanical description using shape grammar's weight and descriptive functions [6]. Visual-mechanical embedding can be performed on paper using either a physical or digital model. However, to lessen mechanical fixation, we suggest running the embedding process on paper or screen before building a physical model or running the structural simulation. Second, we demonstrate how visual and mechanical embedding function together in several crafting techniques, i.e., weaving, folding and tensegrity. Three cases represent different strategies regarding the way in which design precedents, structural configuration and the designer's ideation process are articulated into the ideation process.

The first case considers Kenneth Snelson's tensegrity, in which design precedents, structural explanation, and a series of design exercises are well-documented [7, 8]. However, while the comparison between the precedent (weaving) and the design (tensegrity) is generously discussed, the inventor did not explicitly show the transformation process from weaving into tensegrity. For this case, our focus is to interpret the ideation process of how weaving is transformed into tensegrity. In addition, we also show some derivative designs by continuing this interpretative ideation process.

The second case examines Koryo Miura's fold, where the folding design is digitally generated using a computer. Miura's fold is a result of simulating a thin-plate deformation process using Von Karman's equation, in which one of the results (the wrinkled patterns) yield a herringbone shape [9, 10]. Despite these computer generated designs, we argue that there is a non-computerized ideation moment when Miura *sees* the herringbone shape from a series of computer outputs. To investigate this 'seeing the fold' process, for this case, we use Miura fold creases as a precedent for generating new derivative designs.

The third case investigates Ronald Resch's folding tessellation, where the ideation process and the mechanism are available through video recording and literature [11, 12]. There is a comparable wrinkling process to Miura's simulation; however, in Resch's case, the form-finding process was performed both digitally and physically, using hands. For this case, we use a visual-mechanical synthesis to rewrite Resch's ideation process in order to interpret his modes of design inquiry, and to investigate possible derivative designs from such an interpretation.

By tying-in various types of crafts by different designers, we seek to outline the way in which an explicit ideation process can serve as a platform for extending the language of structural design.

3 Visual and Mechanical Embedding

To ensure that both visual and physical engagements in the ideation process are clearly represented, we distinguish the schema for capturing the visual and mechanical embedding processes. Listed below are visual embedding schemas to represent the shape that is being visually perceived and calculated [4, 5].

- **Recognition schema:** $x \rightarrow x_{ij}$. Subscript ij is added to the identity schema $x \rightarrow x$ [4], where i and j, respectively, represent the shape and space dimensions in the algebra of shape U_{ij}. This schema declares what type of shape is currently being focused on, and in what dimension it can be transformed. The subscript addition reduces the level of ambiguity from seeing shape x using any possible algebra to a specific algebra ij.
- **Transformation schema:** $x \rightarrow t(x)$, transforms a shape with linear or affine transformation, or with certain operators with $x \rightarrow x + t(x)$ (adding, subdividing, subtracting, etc.).
- **Boundary schema**: $x \rightarrow b(x)$, returns a boundary of a shape in a lower dimension (e.g., a boundary of a 3D solid comprising 2D faces; a face's boundaries are lines, and lines' boundaries are points).
- **Part schema**: $x \rightarrow prt(x)$, returns part of a shape within the same dimension; for instance, shorter line segments within a continuous line, or a subset of planes within a surface.

Boundary and part schema have their inversed forms: $x \rightarrow b^{-1}(x)$, which will return the content shape in a higher dimension, as well as $x \rightarrow prt^{-1}(x)$, which will return the original shape in the same dimension. Note that as the boundary and the shape are independent of one another in shape grammar, they are not tightly bound as in the digital computation (e.g., deleting an end-point of a line will not necessarily delete the line) [13].

The significance of these visual embedding schemas and how they work together are demonstrated in Fig. 1. The subscript in the figure is simplified to $x \rightarrow x_i$ with i representing the shape's dimension, and all j values are assumed to be 3 (i.e., all shapes exists in a three-dimensional space). A list of the shape's labels (e.g., L0, L1) assists in providing more precise recognition. Fig. 1a. and Fig. 1b shows an iteration of seeing the shape within the same algebra using recognition schema, and the calculation of new shapes using boundary and part schemas. The schemas maintain a level of ambiguity within specific algebra, as the results from the boundary schema did not affect the algebra for the recognition schema. It always sees the shape either as points or lines (notice the double-arrow ⇒). In Fig. 1c, on the other hand, the computation shows shape derivation across different algebras. The result from one step constrains how a shape is recognized in the next step iteration. If the results yield another type of algebra, the level of ambiguity increases accordingly to recognize other shapes in the new set of algebra.

As shown by the various new shapes in Fig. 1, visual embedding schemas can help to sustain our awareness regarding can be produced from the same shape in the same algebra ij by see it in a different way.

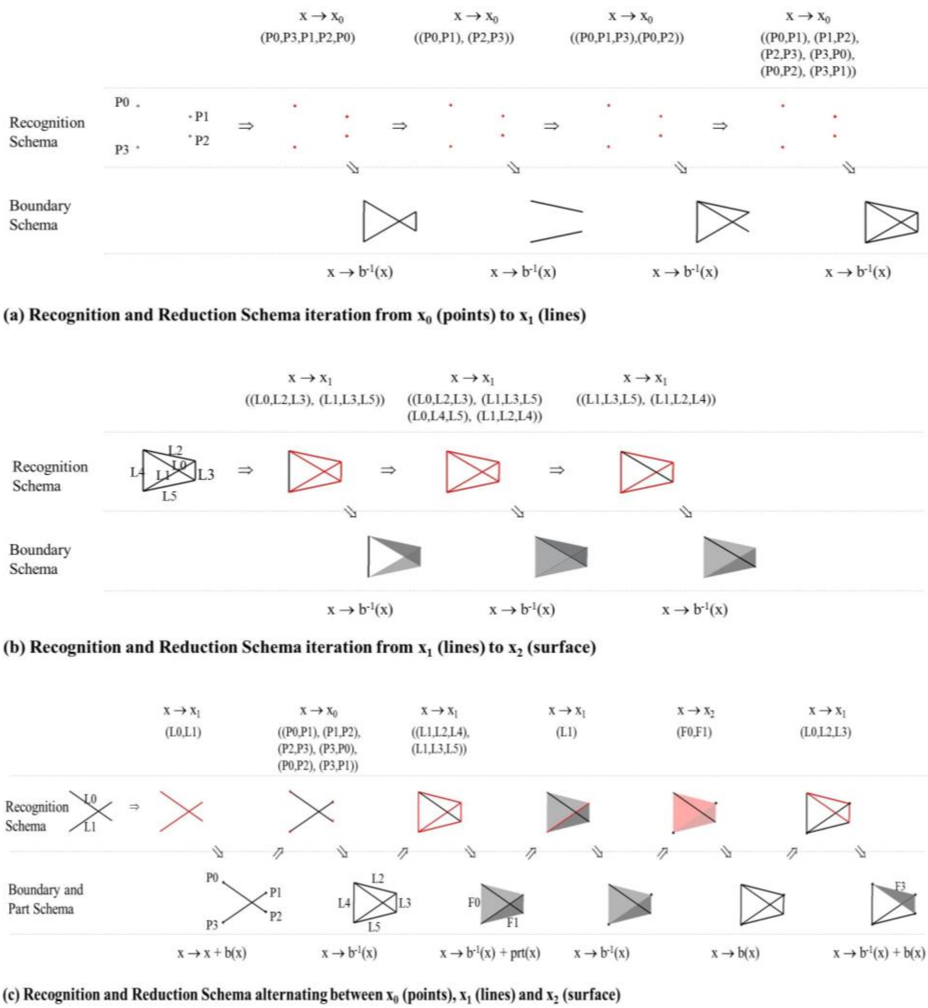

Fig. 1. Visual embedding. The red color signifies shape that is being visually attended; (a) iteration from points to line; (b) iteration from lines to faces; (c) iteration between point, lines and faces.

Mechanical embedding schemas register the shape's physical attributes. In particular, we borrow the way in which the finite element method (FEM) idealizes an object into a discrete model (i.e., an assemblage of vertices, lines, and faces) with mechanical attributes: the line's length between two nodes (L), the line's profile area (A), material stiffness (E), external load (R), and supporting condition (S) [14]. To register orientation attributes such as force's direction and support's degree of freedom, we use a labeling schema: $x \rightarrow x + v$, where v is a label that defines the orientation. Note that since FEM uses a vector to define orientation, our label corresponds only to the oriented points v_{0j} in the algebra of the label v_{ij}.[15]

To register magnitude attributes, such as material stiffness and line thickness, we use weight schema $x \rightarrow x + w$, where w represents the type of magnitude [15]. The notation for v and w is adopted from Stiny's descriptive list (a_1, a_2, a_3, a_4, a_5), where a_n is a set denoting shape description [6]. In this case, the descriptive list is (L, A, E, R, S). Therefore, having shape (x) visually attended in the recognition schema, the schemas for describing shape x's physical property attributes are defined as follow:

- **Dimensional schema** $x \rightarrow x + (L, A)$ describes the shape's length (L) and its cross-sectional profile area (A).
- **Material schema**: $x \rightarrow x + E_m$ assigns the degree of material elasticity, such as Young's modulus or flexural modulus values (to simplify our explanation, the value is reduced to m = 0 for flexible material and m = 1 for rigid material).
- **Loading schema**: $x \rightarrow x + R_n$ defines the force orientation and magnitude applied to shape x with a vector.
- **Supporting schema**: $x \rightarrow x + S_d$ constrains the support's degree of freedom (d) on the shape's boundary (e.g., d = 0 denotes fixed support).

The way mechanical embedding works with a recognition schema is exemplified in Fig. 2 where different focuses on seeing the shape yield different structural configurations when the material schema is applied. Note that when the recognition schema is applied, the mechanical attributes from the previous step are ignored, as the shape is being perceived without any physical meaning attached. The shape-attributes detachment aims to loosen the mechanical fixation, which may occur in a typical physical ideation process. The shape's mechanical attributes remain in the description list (e.g., [1,1,1(L0,L1,L2,L3),,] based on [L,A,E,R,S]), which will then be updated when a new attribute is attached to a shape. Once all mechanical attributes are properly stored in a list, the shape's physical behavior can later be simulated by satisfying the principle of the virtual equilibrium equation, in order to solve the unknown point of displacement [14].

At its core, the visual-mechanical embedding method demands extra care for each creative decision as the ideation progresses, in order to lessen the mechanical fixation traps, as discussed in the introduction. As shown in Fig. 1 and Fig. 2, the recognition schema constantly asks the user to explicitly declare his/her attention to the shape, inquiring whether the user wishes to continue, reconsider or forget the declared shape and its attached physical attributes. In other words, it raises the designer/engineer's awareness in terms of whether to be fixated or freed from the previous state of perceiving a shape visually and consideration of its physical condition. Particularly in cases where structural ideation involves extensive hand and eye coordination, constant design re-examination is critical. In the following three cases, we investigate the ways in which the declared attentions and decisions aid the ideation process.

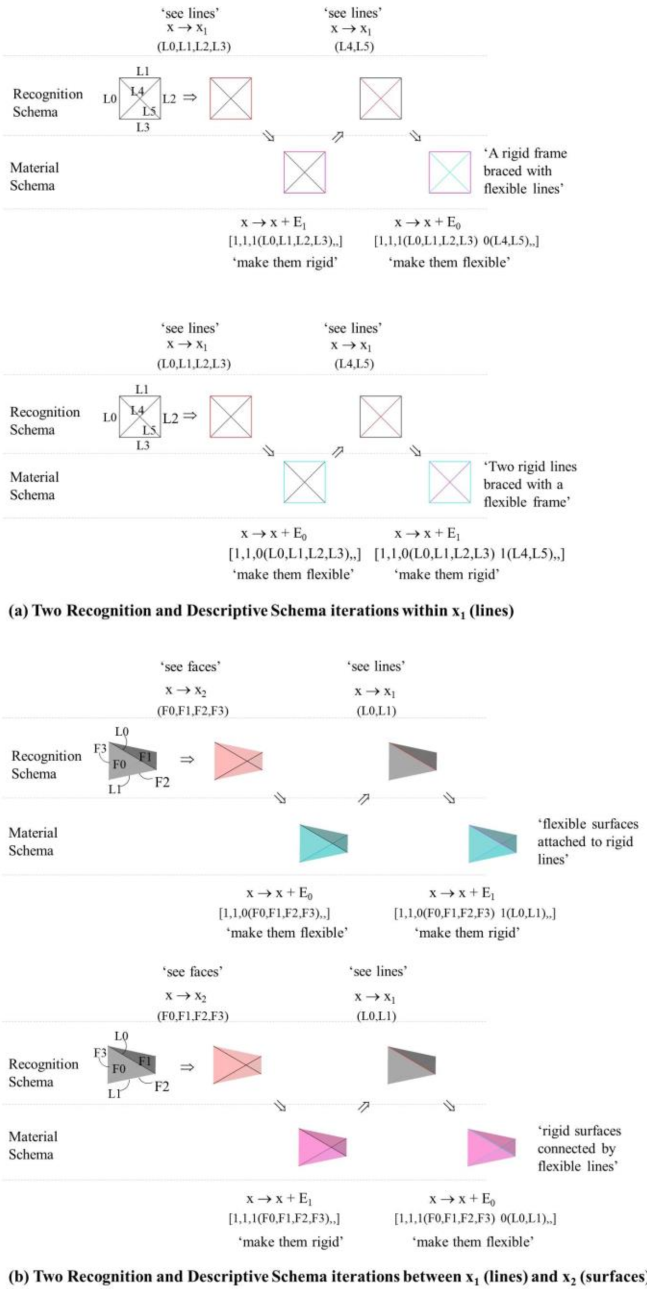

Fig. 2. Mechanical Embedding. Red color signify the visually attended shape, cyan indicate flexible material and magenta indicates rigid material.

4 Case 1: Snelson - Weaving to Tensegrity

Kenneth Snelson’s tensegrity structure is a fine example of structural idealization, through visual and physical means. In *Tensegrity, Weaving and the Binary World*, Snelson addresses the precedents—the weaving principle as the ‘mother’ of tensegrity—through a series type of weaving in different forms, both in a polygonal and a polyhedral weave [7, 8].

From visual to physical, vertices to volume, and compression to tension, Snelson’s description suggests a close relationship between the design’s precursor (weaving) and its successors (tensegrity). His visual comparison shows a close resemblance between the polyhedral woven sticks sculpture, with the suspended strut and cable in the tensegrity structure. The reference to the platonic shapes provides a straightforward reading as to how the two are geometrically parallel to one another. For example, the polyhedral vertices expand into faces, caused by the extended sticks’ length in weave-tetradron, which is inherited in tensegrity, as the faces’ vertices link the tension element (cable) (Fig. 3).

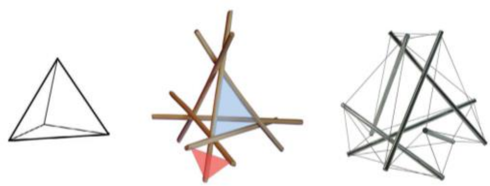

Fig. 3 Polyhedron, Polyhedral Weave-Sticks and Polyhedral Tensegrity [7]

While the weaving-tensegrity relationship is evident, the diagram shows more about how the two mechanisms work independently, but less about how Snelson’s ideation progresses from the moment he began to perceive the weaving as a precursor to tensegrity. While explicit representation helps others in applying the tensegrity mechanism to different contexts [17-20], concurrently, another mechanical fixation can also be developed when a particular tensegrity style is repeatedly replicated. In shape grammar terms, we view this fixation as operating on the same parametric schema (e.g., Snelson’s schema) through a transformation, $x \rightarrow t(x)$, modularization, $x \rightarrow x + t(x)$, and/or their combinatorial iteration. Along this fixation, creativity is sometimes viewed as a problem-finding process that seeks to find good embodiment/application of a system across scales and disciplines [19, 21].

Here, our study focuses not on applying a system across scales, but rather on highlighting the way one system turn into another one. We seek to question how weaving is seen as a precursor to tensegrity; and furthermore, how tensegrity could be seen as a precursor for other types of structure. Could tensegrity be born from another ‘mother’ than weaving? To pursue the answers to these questions, we apply visual-mechanical synthesis rules to interpret the weaving-to-tensegrity transformation, in the following section. The example in Fig. 4 begins with an isometric view of two overlapping rigid lines, from a weaving structure as an initial condition, to the derivation of different structural configurations.

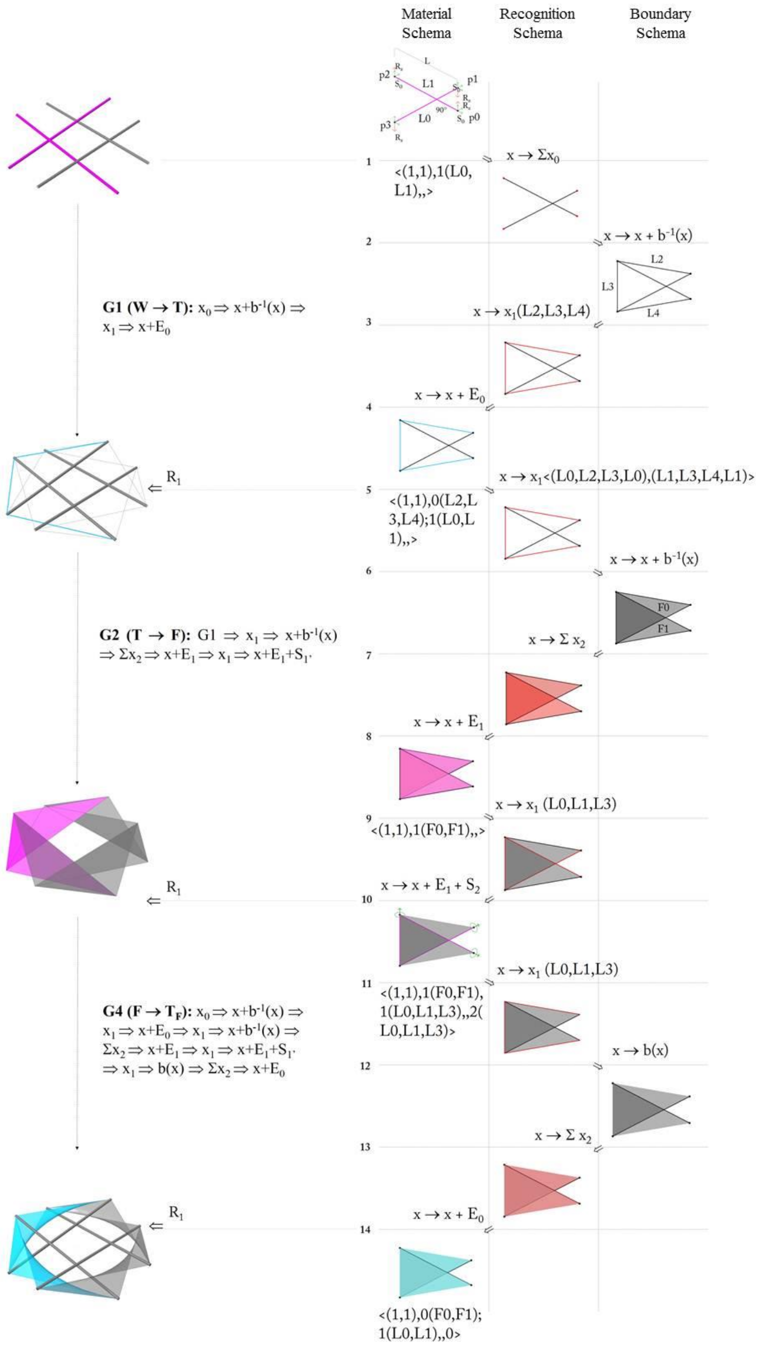

Fig. 4. Weaving-to-tensegrity transformation. The middle column identifies the visually focused shape; the right column shows (inverse) boundary operation; the left column shows mechanical registration. Design, at the far left of the page, shows the outcomes of additive transformation.

As can be seen, the consequence of iteration from step 1 to 4 profoundly changes the original weaving mechanical behavior. The initial lines in the woven-knot, which were overlapped with one another in a compressive mode, are now in tension by new flexible lines, hence, leading to a tensegrity system. From steps 5 to 10, the tensegrity module, composed of line compositions, becomes an assemblage of faces embedded with rigid material, connected with a hinge, i.e., a fold structure (see more details computation in [22]. This explicit interpretation reveals the critical ideation moment, where particular shapes are being focused and transformed, and therefore the ideation process becomes traceable and modifiable.

4.1 Compiler and Inversion

The examples included in Fig. 4 show the ways in which mechanical and visual embedding interpret the ideation process and generate different structural configurations in tandem. The explicit representation provides new ways of understanding and venturing the craft in three ways: First, it establishes alternative steps for transforming weaving to tensegrity (although this may not work for all types of weaving). Second, the exposed translation process can now be hacked (e.g. modifying the rules), in order to synthesize different outcomes. Third, the process, either representing one's design awareness or fixation, can further be formalized into a function as outlined from **Fig. 4** below:

- G1 ($W \rightarrow T$): $x_0 \Rightarrow x+b^{-1}(x) \Rightarrow x_1 \Rightarrow x+E_0$
- G2 ($T \rightarrow F$): $G1 \Rightarrow x_1 \Rightarrow x+b^{-1}(x) \Rightarrow \Sigma x_2 \Rightarrow x+E_1 \Rightarrow x_1 \Rightarrow x+E_1+S_1$
- G3 ($W \rightarrow F$): $x_0 \Rightarrow x+b^{-1}(x) \Rightarrow x_1 \Rightarrow E_0 \Rightarrow x_1 \Rightarrow x+b^{-1}(x) \Rightarrow \Sigma x_2 \Rightarrow x+E_1 \Rightarrow x_1 \Rightarrow x+E_1+ S_2$
- G4 ($F \rightarrow T_F$): $x_0 \Rightarrow x+b^{-1}(x) \Rightarrow x_1 \Rightarrow x+E_0 \Rightarrow x_1 \Rightarrow x+b^{-1}(x) \Rightarrow \Sigma x_2 \Rightarrow x+E_1 \Rightarrow x_1 \Rightarrow x+E_1+S_2 \Rightarrow x_1 \Rightarrow b(x) \Rightarrow \Sigma x_2 \Rightarrow x+E_0$

G1 is a function that transforms weaving-to-tensegrity, and the G2 function turns tensegrity-to-folding. Notes that G1 is nested in G2, in case one would like to start from weaving as the initial shape. G3 is similar to G2, where the only difference is that the nested G1 is now deployed. With access to the deployed steps, one can change the inside parameters. G4, for instance, is a modification of the G3 function. It applies a boundary rule to omit the line ($x_1 \Rightarrow b(x)$) and turns an elastic material in G3 into a rigid one (E_0 into E_1) in the last part. With this new function, G4 will turn a struts-cable tensegrity system into a struts-fabrics tensegrity from steps 11 to 15 in Fig. 4 (see comparable examples in [23]).

In a similar manner, we can inverse parts of function G2: $T \rightarrow F$, $x_1 \Rightarrow x+b^{-1}(x) \Rightarrow \Sigma x_2$ into $\Sigma x_2 \Rightarrow x+b(x) \Rightarrow x_1$ (note how the boundary rule is inversed). Therefore, we have G5: $F \rightarrow T'$: $x \Rightarrow \Sigma x_2 \Rightarrow x+b(x) \Rightarrow x_1 \Rightarrow E_1 \vee E_0$, which will turn folding into a tensegrity structure (the operator 'or' indicates whether a line should be embedded with rigid or flexible material). This inverse function reveals a path to generate tensegrity from another precedent: i.e. folding creases, which will be discussed in the following section.

5 Case 2: Miura - Folding to Tensegrity 1

As mentioned in the method section, the Miura-Ori fold was digitally generated using von–Karman and Fourier's series for simulating the post-buckling results of a compressed circular cylinder [9,10]). From this computer simulation, Koryo Miura's critical ideation moment seems to have occurred, in recognizing the herringbone shape from the virtually deformed plate (Fig. 5). It is the basic of a developable folding module that he formalized into a two-dimensional folding crease.

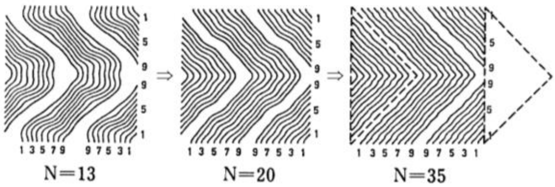

Fig. 5. Miura's embedded Herringbone's shape (right). The numbers along the edges indicate the countour-level, while N is the degree of Fourier-series optimization [9]

As Miura's ideation process has been digitally automated, hence explicit, this left us to turn our focus to the ideation product: the herringbone shape. Here, the visual-mechanical embedding process started by speculating the next possible reinvention process for the Miura pattern. Having a folding pattern as an initial shape, we use this opportunity to exercise the G5 function (F $\rightarrow$ T') to transform Miura Folding to Tensegrity, as can be seen in Fig. 6.

Our exercise is divided into two phases. First, we begin by applying the G5 function in order to turn Miura folding creases into an assemblage of a rigid-tension module. The left iteration in Fig. 6 shows the identity and part schema applied to folding creases to investigate various ways of seeing the creases [4], while the right iteration shows a detailed G5 iteration to one of the outputs. Secondly, the result of G5 iteration is further derived into two- and three-dimensional modules (Fig. 7). In particular, we compute two visual-embedding iterations from the same module. The first iteration uses mostly inverse-boundary and material schema to derive new modules in a higher dimension (Fig. 7a). The second iteration uses boundary, inverse-boundary and material schema to explore other possible configurations in the same dimension. As can be seen in Fig. 7c, not only has the initial geometry changed, the structural configuration is also altered. The physical validation of these modules can be seen in Fig. 12. We then compose these models into a three- dimensional space to further explore how they may serve as a shelter or structural component (Fig. 7b and Fig. 7d).

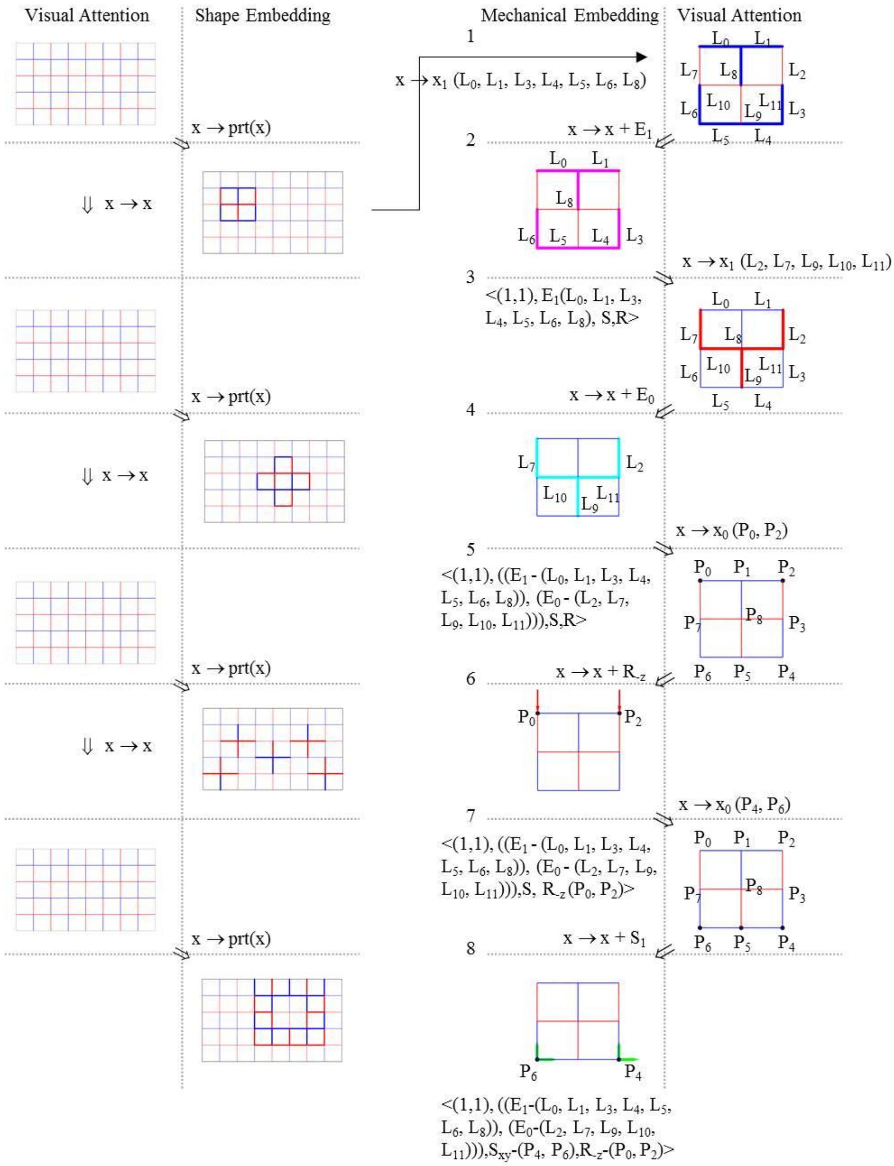

Fig. 6. Conversion from Folding-Creases (left) to Miura Tensegrity modules (bottom-right)

The Miura fold-to-tensegrity exercises above demonstrate the way an ideation product, in this case, Miura's herringbone, serves as an initial shape for another ideation process. Note that the converter function (G5) underlying this process is adopted from yet another product involving an interpretative ideation process. Thus, we begin to see how the visual-embedding mechanism could serve as a platform for cross-disciplinary craft conversion.

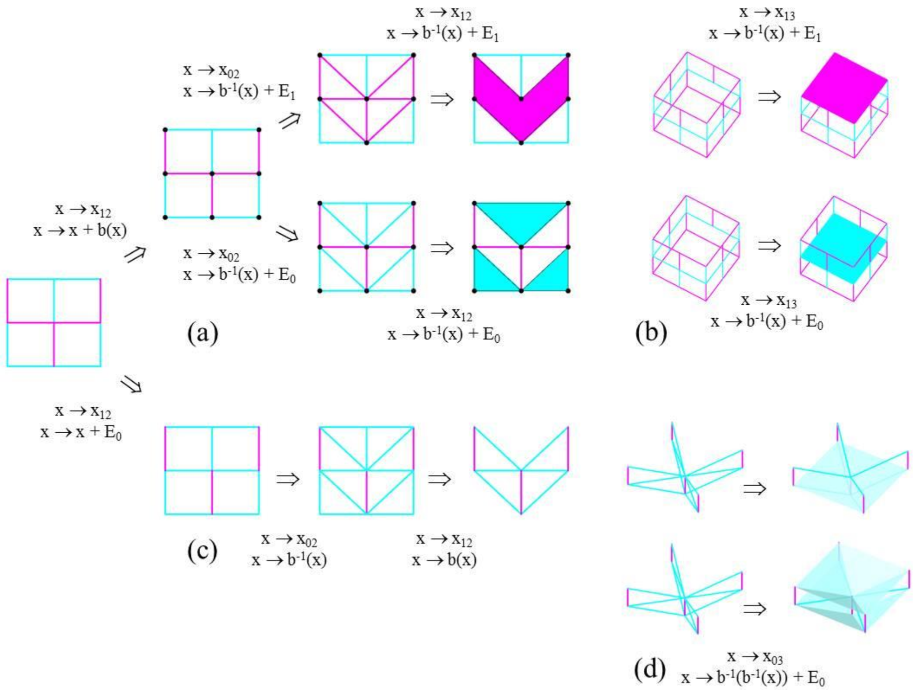

Fig. 7. Recursive visual-mechanical embedding on Miura tensegrity modules; (a) inverse-boundary schema to return higher-dimensional shapes; (c) boundary and inverse boundary schemas to alter original configuration; (b) and (d) transformation and inverse boundary schemas to transform the modules in three-dimensional space.

5.1 Various Access to the Author's Ideas and the Ideation

Snelson and Miura propose their invention in a different articulation. As an artist, Snelson speaks more through his series of sculpture, which allow others to project a good embodiment for tensegrity application. Whereas for Miura, an astrophysicist, disseminating the outputs via a discrete mathematic and concrete application (e.g. a deployable system) is more effective for further development by fellow engineers. Both mechanisms were articulated in different ways and responded with different strategies. Miura's ideation process is already explicitized into codes; therefore, we began our interpretative process from his end product. Snelson's ideation process, on the other hand, is under-articulated, and therefore provides gaps to reinterpret his process, that is the translation between the precedent and the design.

This raises a question of how explicit articulation may contribute to advancing the creative design process. Would a well-documented process leave enough space for a new interpretation? In the following, we extend our investigation to observe craft ideation that is well-documented. In this case, we use Ronald Resch's folding tessellation. Resch's background in computer science and folding craft intersects with Snelson's and Miura's, where his works encapsulate both making and coding.

6 Case 3: Resch - Folding to Tensegrity 2

Resch's folding patterns have been marked as being some of the most famous folding tessellations, allowing deformation in both convex and concave directions. The tessellation discussed here consisted of periodical triangular creases (also known as the *iowa glass mount* [24] (Fig. 8). Each individual triangle is connected to another, so that their edges become either valley or mountain creases and maintain the triangle's surface, as a rigid body motion under a folding mechanism [11].

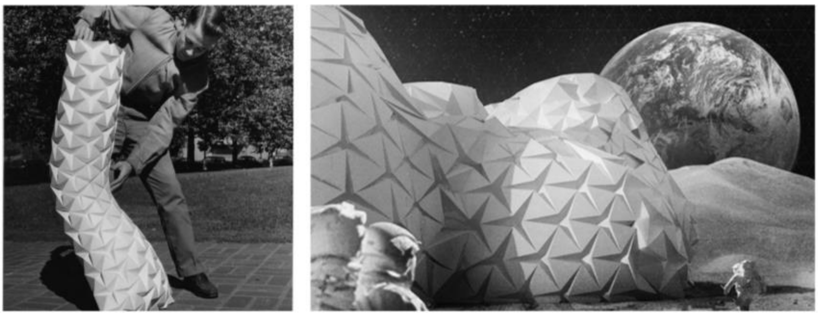

Fig. 8. Left: the Iowa pattern (ca. 1959-1961) and recent reapperance in 2016 lunar architecture competition (Right) [24, 25]

This pattern is chosen for two reasons: firstly, Resch presented it as the initial form that leads to many others of his creative works. Secondly, the pattern was originated by a physical exploration with paper, rather than a digital experiment, and without formal or platonic shapes to begin with. To benefit from Resch's documentation, his ideation process needs to be clearly represented before continuing on a further design alteration process. For this case, this section begins by discussing the role of visual-mechanical embedding for rewriting the ideation process, and then followed by reinventing section.

6.1 Rewriting Resch's Ideation

To represent Resch's visual-physical ideation process, we use the schemas to articulate Resch's physical-visual engagement with shapes (Fig. 9) (see comparable study in [26]).

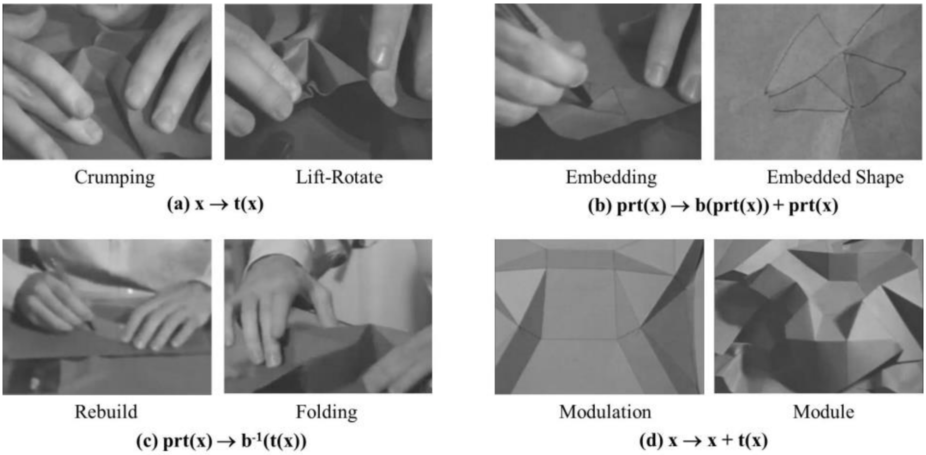

Fig. 9. Snapshots from Resch's ideation process [12].

In investigating the crease's pattern, Resch began by analyzing the paper's mechanical behavior as he deformed it using his hands $x \rightarrow t(x)$ (Fig. 9a). When he discovered a peculiar movement on the paper (i.e., raising and rotating movement), he visually embedded an emergent shape from the wrinkled paper, a triangle [prt(x)], and outlined the triangle with a pen on the paper [b(x)]. This shape-finding process can be rewritten as: $prt(x) \rightarrow b(prt(x)) + prt(x)$ [4] (Fig. 9b). Resch then simplified the folding creases [prt(x)] with straight lines on a new paper [t(x)] to define the triangle face [$b^{-1}(x)$] in order to replicate the movement. Such replication can be written as $prt(x) \rightarrow prt(x) + b^{-1}(t(x))$ (Fig. 9c). The simplified crease is considered as a module with which Resch developed a periodical tessellation, by mirroring and duplicating the module six times with reflective transformation, $x \rightarrow x + t(x)$ (Fig. 9d). The result is a tessellation with rectangular gaps, dividing the initial triangles and a hexagon at the center.

With a parametric transformation $x \rightarrow t(x)$, Resch then modifies this gap, by shrinking its width to zero, turning some polygons into a point in Fig. 10. The new parametric tessellation affords multiple ways of perceiving the emergent shapes. In particular, Resch focused on creases that control the initial triangle, as the new module maintain the rigid body movement of the triangles and the derivative polygon. Resch then modified the new module parametrically, in order to develop different patterns, by expanding the vertices of the triangle (note the similar strategy by Snelson in Fig. 3). The schema is applied repeteadly to the other vertices, creating more surfaces, as it seems in Resch's view some vertices were never a point [x_0], but rather were shrunk faces [x_2] (Fig. 10).

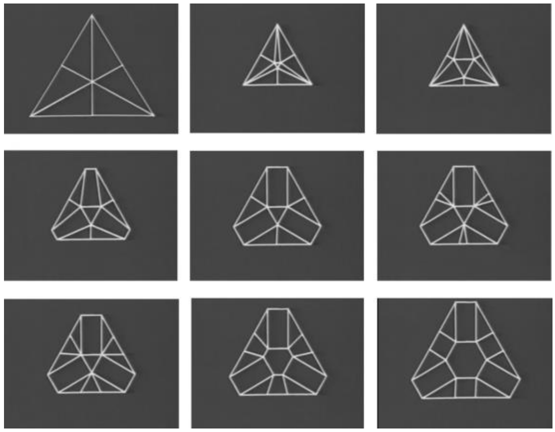

Fig. 10. Parametric transformation of Resch tessellated module [12]

6.2 Reinventing Resch's Creases

We have noted, based on these representations, that throughout Resch's experiment in different works, the material stiffness applied in his sculpture is mostly rigid (E1), despite his initial experiment with malleable paper. The flexible material (paper-film) on his other works is attached to the sticks and therefore, its treated as a rigid body. This left an opportunity for us to speculate on whether different levels of stiffness may lead to different outcomes. In applying Visual-Mechanical Embedding for Resch's tessellation, we use the triangular pattern that governs the Iowa pattern as the precedent. In a similar manner, we convert the Resch fold to tensegrity in Miura fold, using function G5 (Fig 10). We begin by applying visual embedding to the module, and notifying the folding creases, following the separation between the long and short legs within the triangle, as Resch indicated.

1. $x \rightarrow x_1$ (L_0, L_1, L_2)
2. $x \rightarrow x + E_1$ applies rigid material to the lines (magenta). The mechanical registration is as follows: <(1,1), $E_1(L_0, L_1, L_2)$, S,R>; where length and profile-area are normalized into one, and support (S) and external forces (R) are constant.
3. $x \rightarrow x_1$ ($L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11}$)
4. $x \rightarrow x + E_0$ applies flexible material to the lines (cyan). We then have updated mechanical properties: <(1,1), $E_1(L_0, L_1, L_2) - E_0(L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11})$, S,R>.
5. $x \rightarrow x_1$ ($L_3, L_4, L_5, L_6, L_7, L_8$)
6. $x \rightarrow b^{-1}(x)$ returns a face as bounded by the lines (F_0). Note that the lines now disappear.
7. $x \rightarrow x_2$ (F_0)
8. $x \rightarrow x + E_0$ applies flexible material to the new face (cyan). We then have a reconfigured mechanical properties, <(1,1), $E_1(L_0, L_1, L_2) - E_0(F_0)$, S,R>

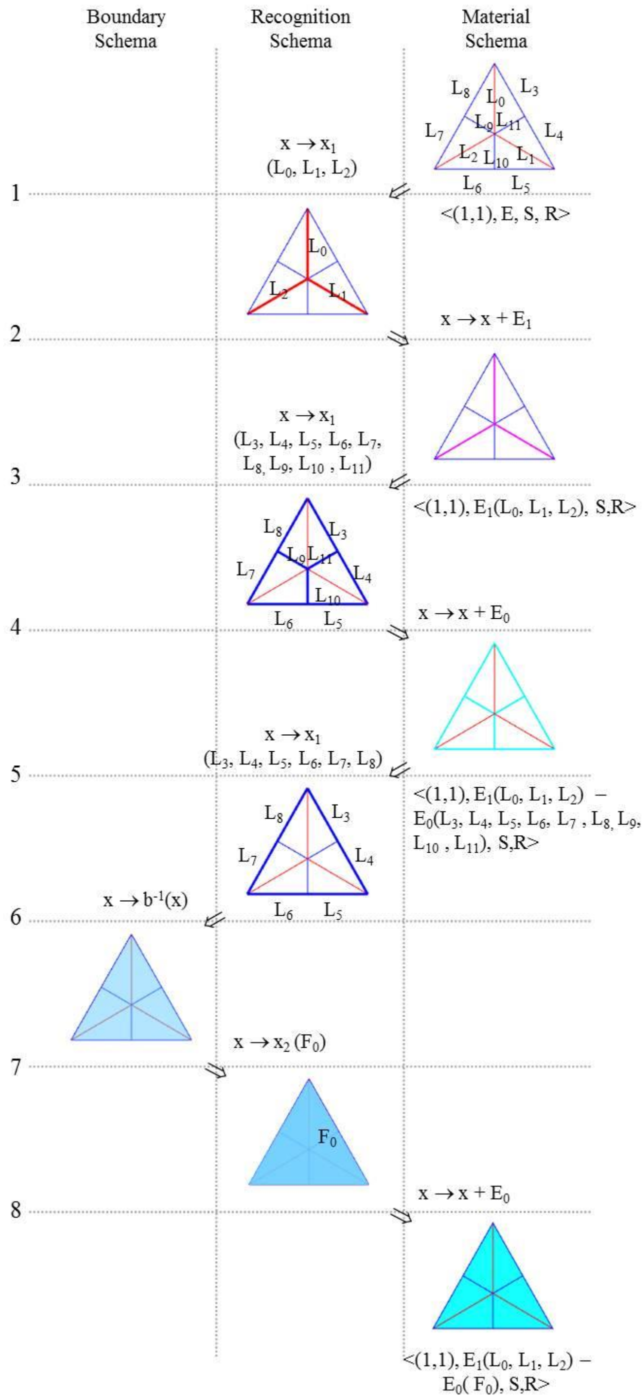

Fig. 11. Visual-mechanical embedding on Resch's fold to tensegrity

This iteration synthesized two new reconfigured modules as seen in step 4: a configuration of rigid and flexible lines; and in step 8: a configuration of rigid lines and a flexible faces (Fig 11). The former resembles a light-weight suspension structure, held by three-pointed star struts and cables. The latter resembles tensegrity with textile structure. The compressed triangle's legs apply tension to the membrane that holds them together. Figure 12 shows the physical validation of this structure. The new structures essentially make Resch's fold creases more rigid, with a compressive-tension mechanism. A mechanism that uses cables is lighter, and therefore might be suitable for supporting exterior or non-covered structures, such as bridges. The textile is heavier, yet provides enclosure, such as for a portable tent (see Fig 12).

The reinventing exercise has demonstrated how shapes are transformed only by modifying their mechanical properties, without a substantial geometrical alteration. This suggests other patterns by Resch, which he transformed parametrically, can also be parametrically translated into tensegrity, using the same function. Modes of design inquiry between Resch and Snelson are now linked explicitly.

In rewriting Resch's ideation process, we noticed the alternating path between visual and mechanical embedding on his physical experiment. The paper-crumping exercise allows Resch to play around with a certain degree of uncertainty, from which emergent shapes appear. However, these shapes only turn into a meaningful design, the moment the author 'sees an opportunity' and embeds a shape on it. Below are several instances captured from Resch's creative moments:

Physical ideation moment (crumping): Resch's ideation moment from crumping the paper can be rewritten as $t(x) = x^f$: $t(x) \rightarrow b(t(x)) + t(x)$. This reads as 'if transformation $t(x)$ yields an interesting shape (x^f) then defines shape x^f boundary on the transformed shape'. The schema prior to the colon (:) represents the condition when a desired shape is found, and the schema following the colon represents the action for such a condition. Notation (^{f}) signifies a desired shape found in the iteration. Yet the found shape is not necessarily a final shape, as computation $t(x)$ can continue to run to reveal other possible x^f in the subsequent iterations, as shown in the previous iteration. Resch's exploration was initiated when he took a class on 'fundamental basic design', where the instructor asked Resch:

"Why don't you just do something with a paper?" from which he later followed up,
"So, I was limiting myself to see what happens to a paper if I crumple it" [12].

As such, there was no initial goal as to what shape x^f was supposed to achieve, which implies that there were also no mechanical attributes or predefined shape that constrained Resch's experiment, other than the paper's physical behavior. The loose attachment to a certain mechanical or visual goals appears to play a significant role in Resch's inventive process. Nevertheless, the schema $t(x) \rightarrow b(t(x)) + t(x)$ serves to record Resch's strategy for capturing potential ideas. This schema shows a promising avenue for analyzing/synthesizing other comparable crafts; examples include the textile tie-dye technique, where the crumpling technique is applied repeatedly to create sunburst patterns, and in architectural paper-based modeling techniques, as practiced in Frank Gehry's studio. However, in order to achieve the desired result, the crumpling function requires careful execution and special care for determining the rules' conditions and parameters, in order to prevent useless results.

Digital ideation moment (scaling): The digital transformation, i.e. the linear transformation to shrink the gap, seems to lead Resch to synthesize his famous Iowa glass mount creases. Subsequently, the two parametric schemas $x \rightarrow x + t(x)$ and $x \rightarrow t(x)$ become very versatile, and are repeatedly used to develop various other periodic paper folding patterns, e.g. a hexagon, a square, etc.

Mechanical moment (pivoting): the mechanism embedded in the creases uses a pivoting motion, originating from the paper's physical behavior. The embedding function, $x \rightarrow x_2 + E_1 + S_1$, seems to continue perpetually in Resch's subsequent works, across different dimensionalities, such as linear hinge and point-hinge, as seen in his series of three dimensional deployable structures $x \rightarrow x_3 + E_1 + S_0$ [11].

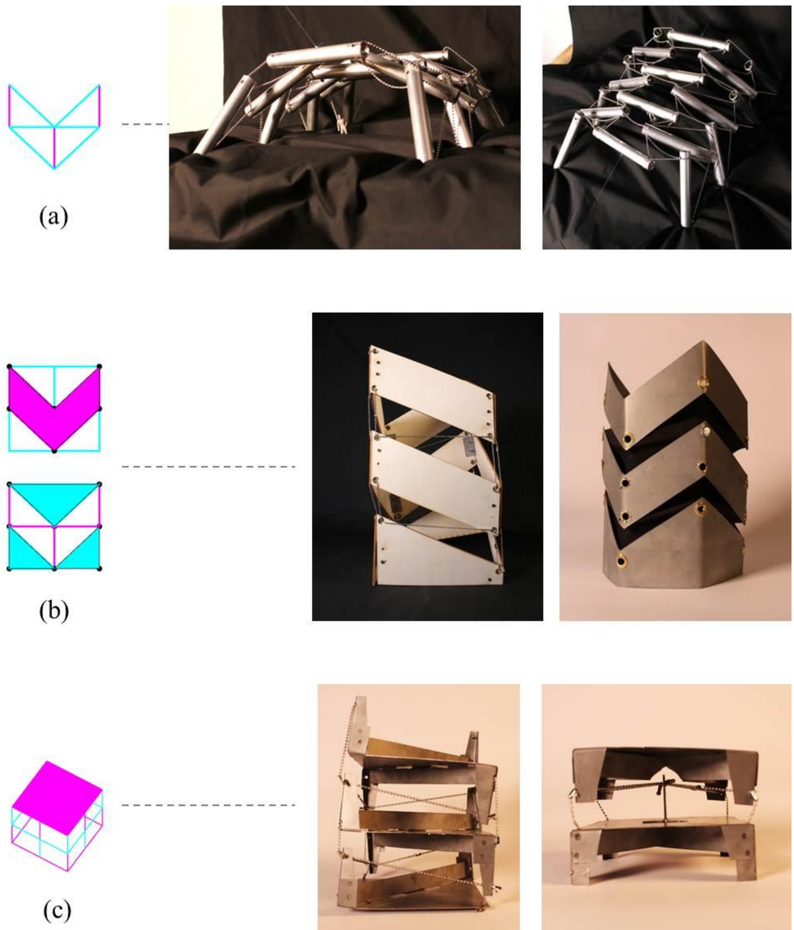

Fig. 12. Physical validation from Miura's tensegrity iteration (note the black fabrics that hold the rigid component in the middle row, far right).

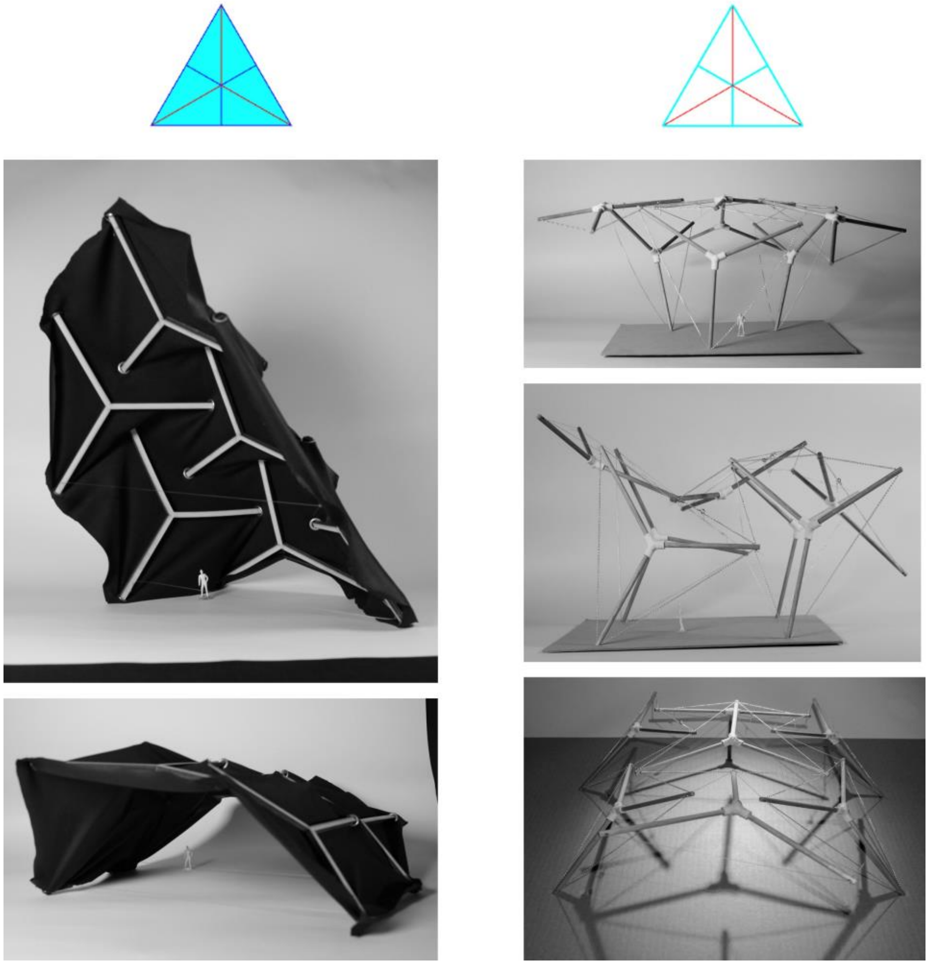

Fig. 13. Physical validation as per Resch's tensegrity iteration.

7 Conclusion

The paper has shown some prospective paths for the incorporation of visual perception and ambiguity in structural design. The iteration in our experiment not only indicates a generative way to develop different types of structural configurations, but also explicitly represents the alteration process. The former contributes to a new kind of structural design synthesis, while the latter could offer benefits to a study investigating the origins of the current type of structural configuration.

Further study is necessary to improve and simplify this method. In this preliminary stage, visual-mechanical embedding relies heavily on the observer's intuition and effort, in terms of deciding which shapes to focus on and what types of embedding should be involved. Therefore, some exhaustive recording steps in the rewriting and reinventing procedures could be automated, letting the user to focus more on the substantial ideation process and rule selection process [27]. Additionally, in order to assess the method's versatility in handling further multi-criteria data samples, more efficient data-processing routines will be needed. For instance, an integration of structural analysis and classifier algorithms could eliminate outcomes that are not physically and functionally feasible.

Lastly, the case studies presented in this article are object-specific (e.g. the crafting principles). Further study on a user-centered experiment could help advancing this technique, so that visual-mechanical embedding would be able to incorporate inter-disciplinary knowledge represented by users from different backgrounds. For instance, various problem findings in applied design research, and to some extent, in scientific research, have advanced a broader application of folding and tensegrity, where some have inspired a new look on the existing system. In the past, Buckminster Fuller advanced Snelson's tensegrity model, through a structural lens, which led him to improve his lightweight geodesic dome system. Donald Ingber, Professor of Vascular Biology, viewed the tensegrity model through a pathological lens, which inspired him to propose novel views on the mechanical property of cells' flexible membrane [28–30]. User-centered studies for such applications could help to associate structural-design principles to wider areas across disciplines.

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From Costuming and Dancing Sculptures to Architecture
The Corporeal and Computational in Design and Fabrication of Lightweight Mobile Structures

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Abstract. This paper describes a new approach to designing and fabricating costuming and dancing sculptures and the potential application of this system at the architectural scale. I present a novel design system based on the movement, form, and spatial relation of characters and dancing sculptures in the Trinidad Carnival. I also present a system that produces lightweight mobile structures from 3D printed connections, lightweight rods, and textile. Through a detailed case study, a new dancing sculpture is designed, and a full-scale lightweight mobile structure at the architectural scale is fabricated. Fabrication of the lightweight structure is achieved using Digital Crafting and Crafting Fabrication approaches to wire-bending, which includes the early development of a digital fabrication program for rod elements. This work has potential implications for costuming and dancing sculptures; architecture; computational design; and craft practices.

Keywords: Lightweight Architectural Structures, Trinidad Carnival, Corporeal, Dancing Sculptures, Fabrication

1 Introduction

This paper describes a design and production system informed by characters and *dancing sculptures* from the Trinidad Carnival (carnival). Dancing sculptures are large three-dimensional structures that are supported and danced by the body, and that communicate human energy. This project's design system uses parameters developed from analyzing existing costumes in the carnival, and their relation to the body, in the design and generation of three-dimensional form. The production system manufactures a lightweight mobile structure from techniques coming out of a traditional craft and computational processes. Specifically, this research demonstrates how a computational approach to design might (1) use the body and its movement to generate form and space; and (2) reframe the design of dancing sculptures for potential applications in architecture. This research builds on other approaches to exploring relationships between the body in motion and space, as design parameters are developed from analyzing the body and its movements in relation to costuming and dancing sculptures. These parameters are used to generate a new design for a dancing sculpture, and possibly architectural form. When it comes to computational approaches to digitally fabricating architectural structures, this work uses a production system based on wire-bending, a traditional craft practice for making costumes and dancing sculptures in the Trinidad Carnival. To illustrate these computational approaches, the reader is taken through the design of a dancing sculpture, and the construction of a lightweight architectural structure.

This paper begins with a brief introduction to costuming and characters in the Trinidad Carnival, and the craft of wire-bending. It continues with a review of previous works on the body in three-dimensional space and form. Then, it discusses how computational approaches are being employed to reframe traditional craft practices in design. After the introduction and background, we describe the design process for a dancing sculpture we name, "The Sail", then present the production system that takes this structure to the architectural scale. Finally, we present and discuss the work's contributions to design.

2 Background

2.1 Costuming in the Trinidad Carnival

French planters introduced Carnival to Trinidad in the 1780's, but it was reinvented by slaves in the 1830s (for a detailed discussion on the Trinidad Carnival see (Hill, 1972; H. U. Liverpool, 1998; H. Liverpool, 2001; Noel, 2015; Brown, 1990; Lee, 1991; Riggio, 2004; Tull, 2005; Ryan and Institute of Social and Economic Research, 1991). Costuming in the carnival portrays its origin, historical events, its people's creativity, struggles, and victories as they perform, gesture, and move in various ways (Fig. 1). The Negre Jardin, which first showed up in the carnival in 1834 (Hill, 1985), was originally performed by freed slaves and planters "*in satiric mockery of their former enslavement and by plantation owners as derisive imitation of the enslaved* (Martin 1998)." The Moko Jumbie or stilt-dancer, like those formerly enslaved, has its roots in West Africa. It first appeared in the carnival in 1895, and dances a jig on stilts as high as 10-15 feet (Crowley, 1956b; Nicholls, 1999). It is "*the spirit of Moko, the Orisha (god) of fate and retribution* (Martin 1998)." Performers of The Bat, which appeared in the carnival in 1899, wear a black or brown skintight suit with wings attached to the feet and shoulders (Crowley, 1956b; Hill, 1985).

Fig. 1. M. Prior engraving, carnival parade, Port of Spain, 1888. From Illustrated London News, photograph by Gordon Means.

Large dancing sculptures in the carnival are called Kings and Queens (Fig. 2). They may depict history, current events, fantasy, or traditional characters, to name a new. Performers are "*an integral part of the costume and must wear and/ or carry the costume*," unlike floats that are "*pushed, pulled or driven*" independent of the performer (National Carnival Bands Association of Trinidad and Tobago 2017). These sculptures sometimes measure 20 feet in width and/ or height. One of the main carnival crafts employed in constructing these sculptures is wire-bending. Wire-bending is a "specialized art, combining elements of structural engineering, architecture, and sculpture" to create two-dimensional (2D) and three dimensional forms" ("Lewicito 'Cito' Velasquez", 2015). In this craft, wire and other thin, flexible strands of material are bent with hand tools to create 2D and 3D structures (for a detailed discussion on wire-bending in the Trinidad Carnival, see Noel 2015). The next section presents background on movement of the body and its relation to 3D space.

Fig. 2. Dancing Sculpture in the Trinidad Carnival (2010). Photo by author.

2.2 The Body and Space

Movement of the body, its relation to 3D space and form, and its documentation has occurred primarily in the field of dance. Oskar Schlemmer, painter and sculptor at the Bauhaus, developed a complex notation system to plan and record the movements of performances. This notation described linear paths of motion and forward movements of dancers. Schlemmer's paintings delineated the two-dimensional elements of space (Fig. 3), while the 3D nature of the theatre provided a place to experience space (Goldberg, 1979). He designed costumes that materialized transformations of the human figure through abstraction via: the form of the body surrounded by cubic space; the body in relation to space; the law of motion of the body in space; and the metaphysical forms of expression of the body (Lahusen, 1986).

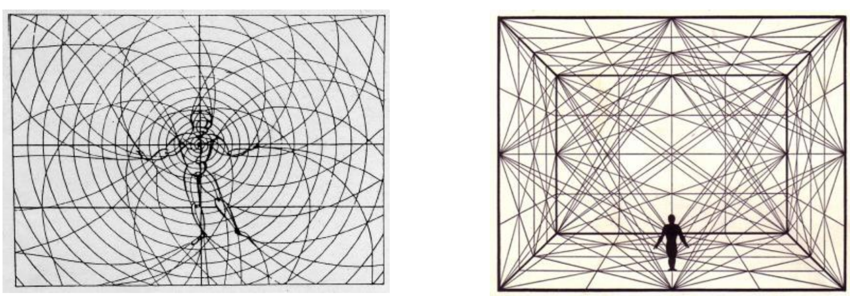


Fig. 3. Oskar Schlemmer's drawing from Mensch und Kunstfigur, 1925 (left), and drawing for "Figure in Space with Plane Geometry and Spatial Delineations", 1927 (right).

Choreographer Rudolf Laban also developed a notation system for documenting and describing human movement. One of his theories, choreutics[1], had an architectural element to it as it dealt with the sculptural quality of movement emerging from the moving body (Fig. 4) (Davies, 2006; Sutil, 2013; Maletic, 1987). Laban used three-dimensional form to better understand and visualize human movement in space.

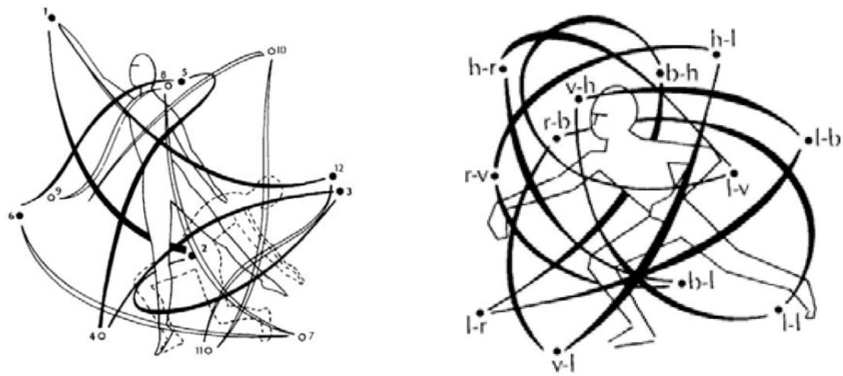


Fig. 4. Harmonies of movement of 12 basic directions of swings in ballet by Laban according to right-left (left), and forward-back (right) symmetry of the body.

Interaction designer and trained classical dancer, Ashwini Asokan, and mechanical engineer Jonathan Cagan (2005) developed a movement grammar using a shape vocabulary created from studying the movement of people involved in coffee drinking and making. They then used this grammar to design coffee tumblers and cups. Architects, Ferreira et al. (2011), used shape grammars to describe the body in motion and space; codified dynamics of the body with these shape rules; then developed a simulation tool based on those rules to generate a choreography. They hoped to use this program to generate architectural space enriched by corporeal experience. Mas[2] man and carnival designer, Peter Minshall, began his study of “kinetic and expressive” costuming in carnival in the 1970s (Gulick, 2000). One costume, The Bat, was the foundation on which he developed a variety of new structural forms he calls dancing mobiles (Fig. 5). These dancing mobiles all start from the form and energy of the performer, achieving new ways of communicating energy up and out into the mas structure (Gulick, 2000; Minshall, 1990; Minshall, 2000).

[1] Choreutics is “the study of harmonious movement sequences and their spatial and expressive relationships” (Maletic 1987).

[2] Mas is the Trinidadian word for masquerade. Some people prefer to use the word "mas" instead of Carnival. Mas is part of the triumvirate of calypso, pan, and mas (Martin 1998).

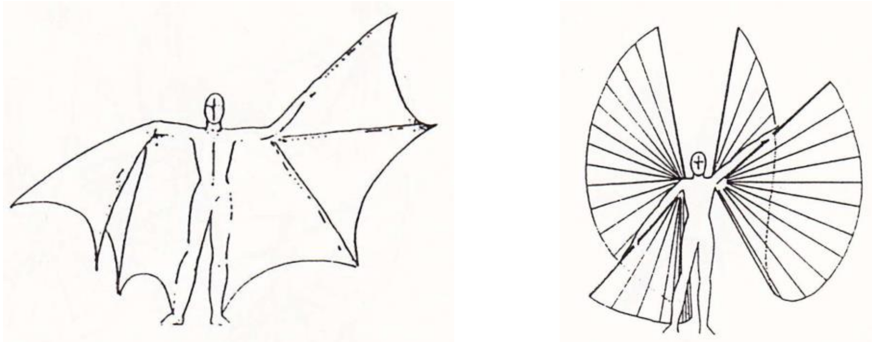


Fig. 5. Drawing of traditional costume, The Bat (left) and dancing mobile (right) by Peter Minshall in "From the Bat to the Dancing Mobile: Technology in Mas'"

This project situates itself amidst these works on the body, space, and form, by using the body and costuming to generate computational rules to design dancing sculptures. For Schlemmer, the 3D nature of the theatre provided a place to experience space. In this work, we envision the 3D nature of these dancing sculptures and their relation to the body as a place for one to experience space, and become aware of their own movements and actions since "we remain unaware of most of our actions, unless an […] event [such as moving in relation with a dancing sculpture] brings them into consciousness" (Jeannerod, 2006; Sheets-Johnstone 2011, 2015, 2009). Building on the work of Asokan and Cagan, and Ferriera et. al., we analyze the dancing action, geometry, and spatial relations of carnival characters to design a new dancing sculpture, and explore its potential in generating architectural form. Like Minshall studied The Bat to develop his dancing mobiles, this work too develops a new dancing sculpture by analyzing and synthesizing traditional and contemporary characters and dancing sculptures from the carnival. To do this we use the body and costuming to generate computational rules to create 3D form for dancing sculptures and architecture. The following section discusses how computational approaches are being employed to reframe traditional craft practices.

2.3 Craft and Computation

Research in computation and technology in traditional craft cultures include merging digital tools with jewelry craft (Jacobs and Zoran, 2015), digital ceramic mold-making (Muslimin, 2013), hybrid basketry (Zoran, 2013), the development of a digital milling carving device (Zoran and Paradiso 2012, 2013), digital steam bending (Schulte et al., 2014), using craft as a site for technical appropriation (Rosner and Ryokai, 2009), critical making (Ratto, 2011), reconceptualizing craft to create architectural components (Muslimin, 2014), and a computational approach to the traditional craft of wire-bending (Noel, 2015, 2016a; TEDx Talks, 2016). Muslimin tested the use of digital modelling and CNC routers in the fabrication of negative molds for ceramics, reconfiguring fabrication devices based on digital methods of transformation. In his work on hybrid basketry, Zoran merged the digital and the traditional by using hand weaving techniques to lace reeds through 3D printed structures he digitally designed and fabricated. In another work, he develops a handheld digital milling device, that carves digital 3D objects out of physical material. Schulte et. al. reclaimed the traditional, historical craft of steam bending through digital design, form generation, and bending. Muslimin (2014) reconceptualized elements of traditional weaving to create architectural components. Through the creation of "woven bricks" and a woven timber installation he proposed architectural applications for expansion of the weaving language. Noel (2016a, 2016b) developed the Bailey-Derek Grammar to describe wire-bending from Trinidad and Tobago. She also developed three novel approaches – Digital Crafting, Computational Crafting, and Crafting Fabrication – to integrating computation and digital technology in wire-bending for the design, fabrication, and assembly of lightweight wireframed artifacts. Like Schulte et. al. and Muslimin, this work reclaims a traditional craft, but also reframes it in a new way using digital approaches to designing and connecting rod elements. The next section describes the steps involved in designing and constructing a lightweight mobile structure called, *The Sail*.

3 Case Study: The Sail

This section describes and illustrates the steps involved in taking a computational approach to designing a dancing sculpture. The six steps shown in Fig. 6 include a design stage which describes the steps in the computational design system, and the production system employed to construct a form at the architectural scale. The processes involve:

Design:

1. Analyzing a corpus of existing costumes/ dancing sculptures;
2. Developing design parameters from that analysis;
3. Parametric modelling of existing dancing sculptures;
4. Computational design of new forms based on parameters;
    a) For application in dancing sculptures,
    b) For form at the architectural scale, and

Production:

5. Fabrication; and
6. Assembly.

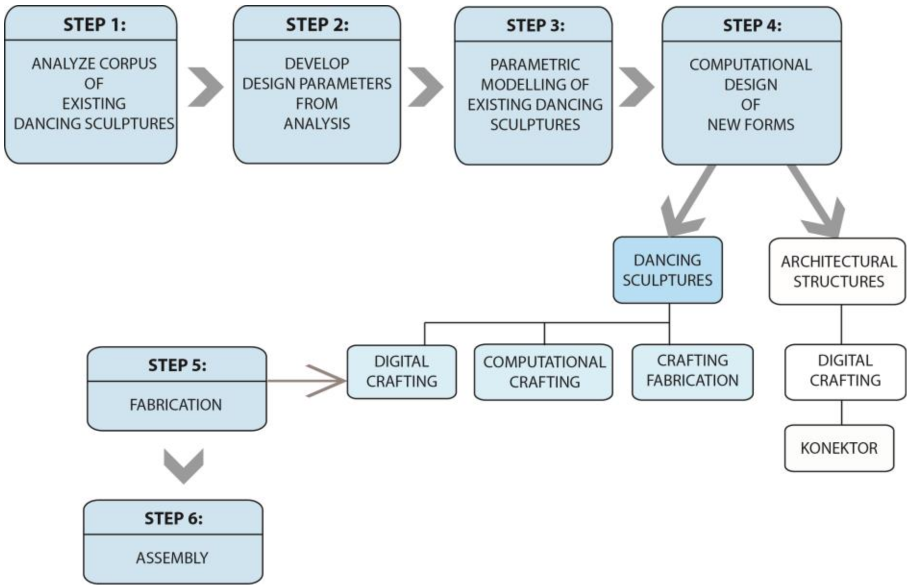


Fig. 6. Steps in computational design and fabrication of dancing sculptures and lightweight architecture.

3.1 Computational Design System

3.1.1 Step 1: Analysis of existing costumes/ dancing sculptures

Characters selected for analysis were chosen based on their dynamic movements, and positions as traditional characters in carnival (Crowley, 1956b; Minshall, 1990). Some of these characters have existed since the 1890s, while others appeared in the 1980s. Nine of them were traditional carnival characters, while five of them were dancing sculptures designed by Minshall. I analyzed literature, video, and images describing the design and movement of the characters, some of which are shown in Fig. 7 - the Bat, the Imp, Midnight Robber, Moko Jumbie, Moon of Kaiso, Fancy Indian Chief, and Tic Tac Toe Down de River (Crowley, 1956b, 1956a; Procope, 1956; Hill, 1985; Minshall, 1990; Noel, 2016c). The wingspread of the Bat (Fig. 7A) is about 12-15 feet, and its movement is such that the dancing actions of the performer's arms, body, and feet are transmitted throughout the structure (Gulick, 2000; Minshall, 1990). The Imp's (Fig. 7B) movements spring from the shoulders with short, sharp, continuous darts of the upper body (Procope, 1956; Minshall, 1990). The Moko Jumbie's (Fig. 7E) movements originates in the legs and feet, dancing a jig (Crowley, 1956b, 1956a; Noel, 2016c).

By wearing the costumes, and moving as these characters shown in Fig. 7, the body discovers not only aspects of the surrounding world such as ground, gravity, and resistance, but also aspects of themselves. This includes the positions, movements, and work of undergone by body parts, limbs, bones, and muscles to place and move the dancing sculptures, discovering the possibilities of their bodies along the way (Sheets-Johnstone 2009).

A. The Bat (1899) (Stegassy 1998) Photo by Jeffrey Chock.

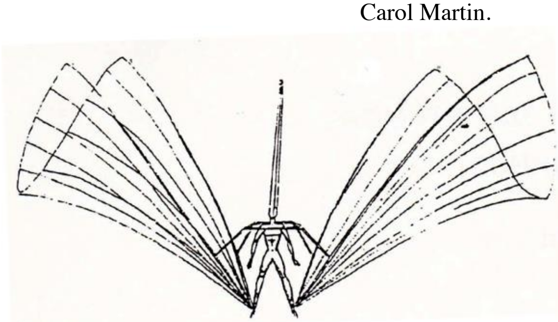
B. The Imp (1912) (Procope 1956) Drawing by Carlisle Chang.

C. Midnight Robber (1919) (Crowley 1956b) Drawing by Carlisle Chang.

D. Moon of the Kaiso (1984) (Minshall 1987)

E. Moko Jumbie (1895) (Martin 1998) Photo by Carol Martin.

F. Fancy Indian Chief (Crowley 1956b) Drawing by Carlisle Chang.



G. Tic Tac Toe Down De River (1984) (Minshall 1990)

Fig. 7. Seven (7) of 14 existing dancing sculptures analyzed

3.1.2 Step 2: Develop design parameters from analysis

Parameters were developed by analyzing movements, geometry, and spatial relations of costuming and the body in space, to generate new designs. Parameters include:

1. Means of support by the body/ structure ($B_{SUPPORT}$);
2. Means of extending space around the body ($B_{SPACE\ EXTENSION}$);
3. The movement of dancing sculpture ($B_{MOVEMENT}$);
4. Location(s) of attachments to the body ($B_{ATTACHMENT\ LOCATION}$);
5. Spatial relation of dancing sculpture to the body ($B_{SPATIAL\ RELATION}$); and
6. Geometry in design of dancing sculptures ($B_{GEOMETRY}$).

3.1.3 Step 3: Parametric modelling of existing dancing sculptures

The third step involved using the body as the "site" for parametrically modelling existing designs (Noel 2016c). Parametric designs of eight existing dancing sculptures were digitally described and modelled on an abstracted human figure. Fig. 8 shows digital parametric models of four existing dancing sculptures: The Bat, the Imp, the Moko Jumbie, and Moon of the Kaiso.

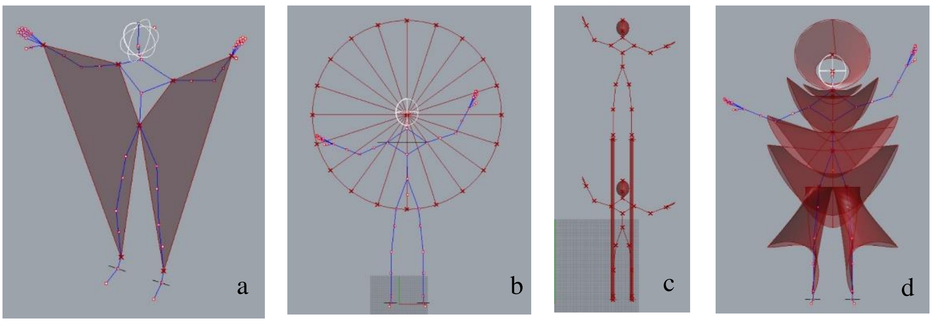


Fig. 8. Parametric models of existing costumes and dancing sculptures (a) the Bat; (b) the Imp; (c) Moko Jumbie, and (d) Moon of the Kaiso.

3.1.4 Step 4: Computational Design of new dancing sculpture

After describing and modelling existing dancing sculptures, parameters used to create a new design included movement, geometry, support, extension, and spatial relation. The main support of the dancing sculpture would be the performer's back, and it would be animated by moving the shoulders, and feet, like the Imp, Moko Jumbie, and Tic Tac Toe (Figs. 7B, E, G). It employs design elements reminiscent of the cape of the Midnight Robber (Fig. 7C), and Tic Tac Toe to enclose 3D space around the body, and have a vertical spatial extension like the Moko Jumbie. The parameters used to design *The Sail* in Fig. 9 are:

1. Support by the body/ structure ($B_{SUPPORT}$) = The back

2. Extension of space around the body ($B_{\text{SPACE EXTENSION}}$) = Lines and planes (e.g Moko Jumbie and Midnight Robber)
3. Movement (B_{MOVEMENT}) = Feet and shoulders (e.g. Moko Jumbie, Tic Tac Toe, Imp)
4. Location(s) of attachments to the body ($B_{\text{ATTACHMENT LOCATION}}$) = Shoulders, feet, and back
5. Spatial relation to body ($B_{\text{SPATIAL RELATION}}$) = Above, sides, left, right, symmetrical
6. Geometry (B_{GEOMETRY}) = Arcs, lines, curves, triangles

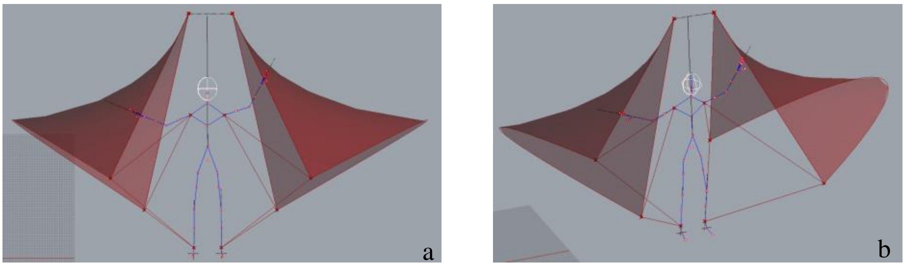


Fig. 9. Form generated using parameters in step 4. Front elevation (left), perspective view (right)

Additional parameters used to develop the form of "The Sail" in Fig. 10 are:

1. The location of control points in relation to the body ($F_{\text{CONTROL POINTS}}$);
2. Height of the form (F_{HEIGHT});
3. Height of the form in relation to the body ($F_{\text{HEIGHT IN REL TO BODY}}$);
    a. Height of form in front the body (H_A);
    b. Height behind the body (H_B);
4. Depth of form (F_{DEPTH});
5. Width of form (F_{WIDTH}), and
6. Surface/ Structural expression of form ($F_{\text{EXPRESSION}}$):
    a. U-divisions for structure (E_U);
    b. V-divisions (E_V).

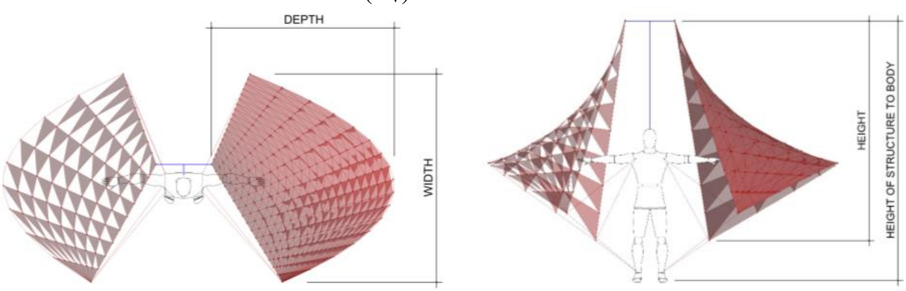


Fig. 10. Plan of The Sail with parameters width (F_{WIDTH}), and depth (F_{DEPTH}) of the structure.). Front view with height (F_{HEIGHT}) of the structure, and its height above the human body ($F_{\text{HEIGHT IN REL TO BODY}}$) (right). Explorations of the density and expression of structure and skin shown on forms on the left.

The design system described above generated a new design for a dancing sculpture, i.e. a large 3D sculpture that is supported by the body, communicates human energy, and makes us aware of our bodies, their actions, and the surrounding world. The next step was fabricating “The Sail.” Due to limited resources, we decided to build one side of “The Sail,” and explore its architectural possibilities by increasing its scale, and using a lightweight construction system built on traditional wire-bending principles. The next section presents our approach to constructing a lightweight architectural structure.

3.2 Lightweight Architectural Structure

Like dancing sculptures in carnival, this structure is made from lightweight rods and materials, and the construction technique used is based on a craft at the foundation of the carnival, wire-bending. Like Schulte et. al., and Muslimin, we are reframing this traditional craft by using digital approaches to designing and connecting rod elements. Like Muslimin, we are proposing architectural applications and expanding the language of wire-bending by creating components that can be employed in the production of architectural structures. We acknowledge that this is a first step and the beginning of future research and development.

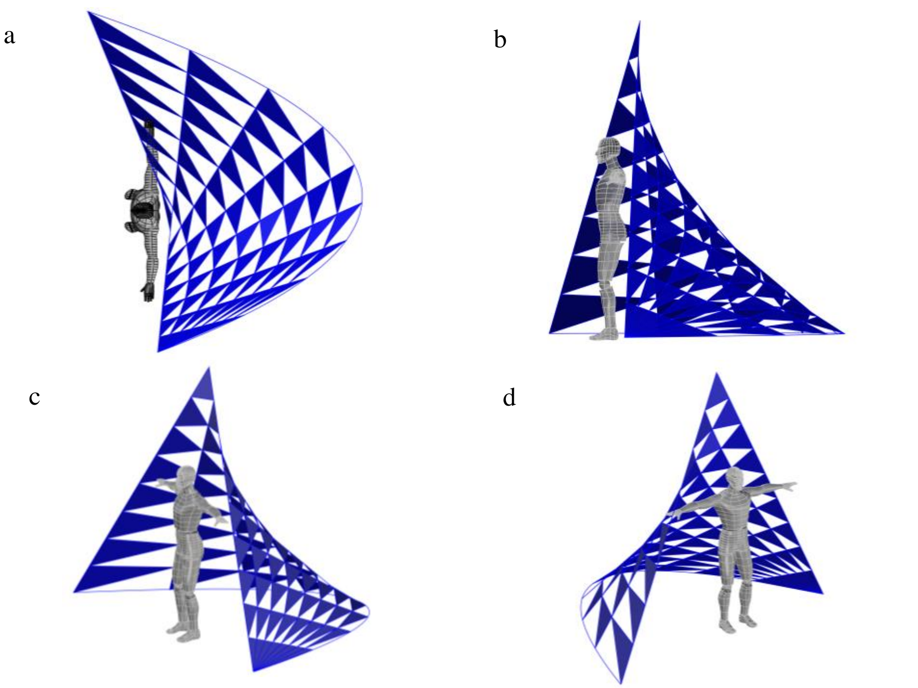


Fig. 11. Plan view (a), and side elevation (b), and perspective views (c, d) of potential architectural form.

The architectural structure shown in Fig. 11 measures 6'-2" in height, 7'-6" in width, and 5'-0" in depth (for a video orbiting the structure see Noel 2017b). The materials and components for construction would be lightweight and modular: fiberglass rods, plastic 3D printed connections, masking tape, and double-sided neoprene fabric for the skin. After designing the structure according to the desired parameters, size, and geometry of the structure and skin, Digital Crafting and Crafting Fabrication approaches were taken to construct the form (for a more detailed description of these approaches to crafting see Noel 2016a).

3.2.1 Steps 5: Fabrication

Digital Crafting of the Structure

Digital Crafting is the "*reinterpretation of a traditional craft using digital processes and technologies [...]. This includes employing digital programs for design, optimization, and automation, [including] CNC machines such as 3D printers or CNC routers for digital fabrication* (Noel 2016a)." We developed a computer program called, "Konektor", which automates the generation of 3D printed connections for lightweight structures (Noel 2016b, 2016a, 2017a, 2015).[3] The program takes a surface as input, and generates 3D objects in the computer at the intersections of linear elements based on desired resolution of the structure, location points, length, diameter, and wall thickness of the connection. We used Konektor to increase the scale and complexity of the connections for constructing the architectural form. Fig. 12 shows the labelled 3D printed connections resulting from a Digital Crafting approach to wire-bending using the Konektor software.

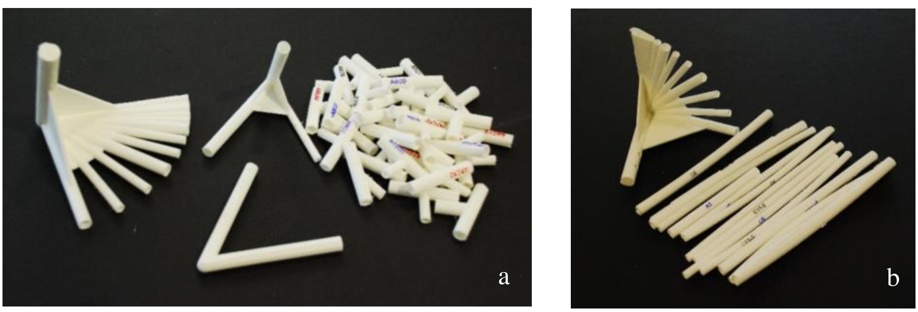


Fig. 12. Labelled 3D printed connections produced from Konektor program and used in the assembly of the lightweight mobile structure.

[3] The Konektor software will be reviewed and presented in detail in a later publication by the author.

Crafting Fabrication of the Skin

The structure's neoprene skin would comprise triangular fabric components, each shape unique to its specific location on the structure. For the full-scale design, however, a Crafting Fabrication approach was taken – "*the use of digital and non-digital tools, processes, and technologies […] in the […] fabrication of artifacts*" (Noel 2016a). Since the behavior of the fiberglass rods and 3D printed connections would not become apparent until their assembly, the textile skin was cut to match the real physical dimensions instead of the digital dimensions. Due to size limitations of the laser-cutter bed, each component was drawn, labelled, and nested onto the 5'-0" wide roll of fabric by hand, then cut with a pair of scissors (Fig. 13).

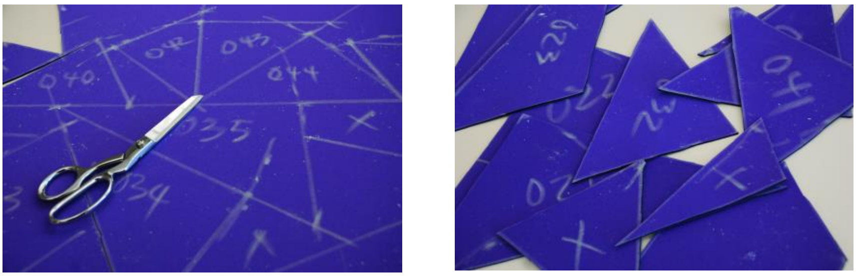


Fig. 13. Crafting Fabrication approach to nesting shapes and cutting fabric components for the skin of the lightweight form. Components were drawn onto the fabric and cut with a scissor.

3.2.2 Steps 6: Assembly of the Structure and Skin

Fiber-glass rods were used to construct the form, with rods labelled and cut according to their required length. Since rods were a maximum 6'-0" long, customized 3D printed connections were designed and labelled to join rods together (Fig. 12b). The main rods for the structure were pushed through their specified labelled connector, with connectors placed at their designed locations along the curves. Masking tape secured the rods in the 3D printed connectors, similar to its application in the Bailey-Derek Grammar (Noel 2015). The assembled fiber-glass structure is shown in Fig. 14. Hot glue adhered the double-sided neoprene skin to the fiber-glass structure.

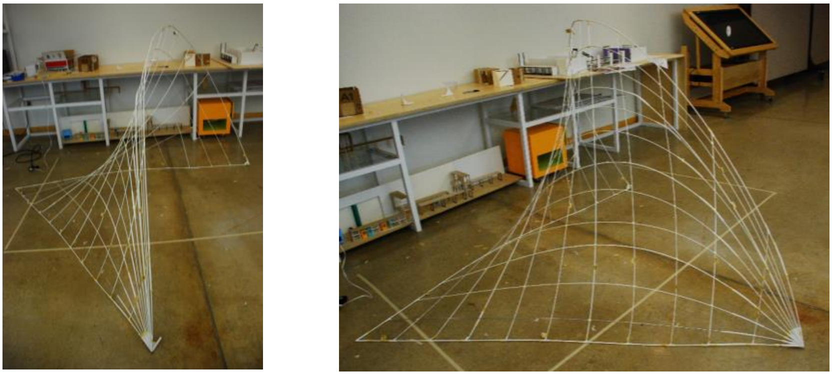


Fig. 14. The assembled lightweight mobile structure constructed from fiber-glass rods, and 3D printed connections.

Figure 15 shows the lightweight mobile structure designed using parameters developed from costuming and dancing sculptures; and fabricated from a novel approach to wire-bending with fiber-glass rods, 3D printed connections, and a textile skin.

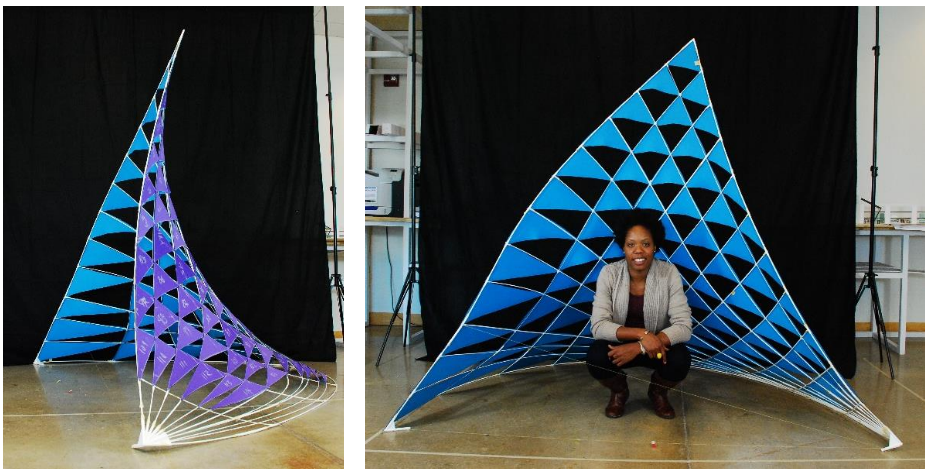


Fig. 15. Photograph of final structure with a person for scale

4 Contributions

This work has promising contributions for costuming and dancing sculptures; architecture; computational design; and traditional craft practices. First, for dancing sculptures in the Trinidad Carnival, we offer a new approach to design that builds on the language and movement of existing traditional sculptures such that designs in the cultural practice continue to evolve. We also offer a novel production system for constructing these artifacts, by building on wire-bending. For architecture, we propose a possible approach to generating architectural form using movement, and spatial elements of the body and dancing sculptures as points of departure. We also suggest the prospect of constructing lightweight architectural form from materials and techniques built on a traditional craft. Like Asokan and Cagan's embedding of culture in artifacts through their movement grammar, we also embed culture in architecture by creating a shelter derived from the form, movement, and craft in a cultural practice. Third, we offer the beginnings of parametric descriptions of dancing sculptures and their relation to the body. These parameters can be used for analysis and synthesis of dancing sculptures and applied in costuming or architecture. Finally, for traditional craft we offer an example of how a practice might be reconceptualized through computation and digital technology for architectural application. We introduce briefly the development of a novel digital fabrication computer program for rod structures. In addition to the aforementioned, we also redefine what a dancing sculpture is: a large 3D sculpture supported by the body, that communicates human energy, makes us aware of our bodies, its actions, and the surrounding world.

5 Discussion

This project demonstrates a system for designing and fabricating a dancing sculpture, and lightweight architectural structure based on dancing sculptures in the Trinidad Carnival. Design rules developed from analyzing the movement, form, and spatial relations of 14 carnival characters and dancing sculptures were used to design a new dancing sculpture and architectural form. A new digital approach to wire-bending created 3D printed components to construct the architectural structure. Building on the work of Sass and Botha (2006) who developed a production system for small wood framed buildings using a CNC router for wood-framed structures, this work suggests an alternative approach to using digital fabrication in the construction of shelters on-site with a high-precision machine, a 3D printer. Our small shelters could be transported and erected from fiber-glass rods, 3D printed connections, textile, and masking tape, all light and easily transported by an individual. Application of this work allows for the erection of temporary shelters for pavilions and camps. These lightweight architectural structures can be aggregated to create shelters for larger objects and numbers of people. By properly planning its disassembly - removing and stacking the textile skin in order, removing fiber-glass rods from their connections, and safely storing the 3D printed connections - one can easily disassemble the structure, and store its components for repeated use. The Konektor program made construction easier since each component was specific to that location, guiding assembly and error correction in erecting the design. Using the Crafting Fabrication approach to install the skin, resulted in less material waste, and fabrication based on the real dimensions of the erected physical structure rather than the planned dimensions from the digital model.

One limitation of this study was the size of the structure. Although the lightweight mobile structure can currently only fit 1-2 people in a sitting position, it still provides us with the foundation to begin designing and constructing larger shelters and pavilions for greater numbers of people. Since hot glue and masking tape was used to secure the textile skin and the tensile rods respectively, the durability and integrity of the structure is not the best. Future studies will explore ways to better secure textile surfaces and connections. Due to the increased complexity of some 3D connections and the tension in the rods, additional structural elements had to be modelled into the connections to prevent failure and breakage. Future studies will look into addressing this issue. Some future questions to be addressed include: How might we use a modular approach to design to create larger networks of lightweight structures? How might we embed material and structural behavior in design to aid in construction? How might designing for kinetic feedback from dancing sculptures to the body further inform our corporeal experience, and design?

Acknowledgements. This work is dedicated to wire-benders Stephen Derek and Narcenio “Senor” Gomez, and mas’ designer, Peter Minshall. This work was funded in great part by The Government of the Republic of Trinidad and Tobago, and in part by The Stuckeman Center for Design Computing. Grateful acknowledgement is given to Xiao Han, Danielle Oprean, Felecia Davis, Daniel Cardoso Llach, and Benay Gursoy Toykoc for their support. Special thanks to my friends at the Stuckeman Family Building.

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Discrete Heuristics

Digital design and fabrication through shapes and material computation

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Abstract. In the case of designers, architects and arts, tools are part of a repertoire of cognitive, symbolic, and semiotic artifacts with which each explores and learn about design problems. Nonetheless, when using digital fabrication tools, a dichotomy between what is ideated and what is made appears as an evident problem since many of the perceptual aspects of sensing and thinking about new things in the making are neglected. It is argued that this establishes a dichotomy between what is ideated and what is executed as an outcome from that idea. How designers can think, learn and augment their creativity by using digital tools in a more relational, exploratory, interactive and creative way? Furthermore, how can we teach design using contemporary fabrication tools beyond its representational capabilities? This paper explores the richness of using digital fabrication tools through the lens of shapes grammars as a design paradigm in order to extend computational making including digital fabrication tools, gestures and material behavior as crucial actors of the design process. Through the use of discrete heuristics - that is, the elaboration of deictic rules for computation with physical objects, materials and fabrication tools in a precise yet perceptual way- this paper shows experiments inside a third year design studio to overcome the hylomorphism present in the digital design and make dichotomy.

Keywords: Digital fabrication · Computational making · Human computer interaction · Shape grammars

Shape Computations without Compositions

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Abstract. Parametric CAD supports design explorations through generative methods which compose and transform geometric elements. This paper argues that elementary shape computations do not always correspond to valid compositional shape structures. In many design cases generative rules correspond to compositional structures, but for relatively simple shapes and rules it is not always possible to assign a corresponding compositional structure of parts which account for all operations of the computation. This problem is brought into strong relief when design processes generate multiple compositions according to purpose, such as product structure, assembly, manufacture, etc. Is it possible to specify shape computations which generate just these compositions of parts or are there additional emergent shapes and features? In parallel, combining two compositions would require the associated combined computations to yield a valid composition. Simple examples are presented which throw light on the issues in integrating different product descriptions (i.e. compositions) within parametric CAD.

Keywords: Shape Computation · Composition · Embedding · Parametric CAD

Rectilinear Floor Plans

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Abstract. This work aims at providing a mathematical approach to the problem of allocating given rooms within a given predefined contour shape, while satisfying given adjacency and size constraints. This work is significant with respect to complex building structures, such as hospitals, schools, offices, etc., where we may require floor plans other than rectangular ones and adjacency constraints are defined by the frequency of journeys expected to be made by occupants of the building along different routes. In this paper, we present an algorithmic approach using graph theoretical tools for generating rectilinear floor plan layouts, while satisfying adjacency and size constraints.

Keywords: Adjacency graph · Algorithm · Architectural design · Dual graph · Orthogonal floor plan

Computing with Watercolor Shapes

Developing and Analyzing Visual Styles

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Abstract. Computers help run visually creative processes, yet they remain visually, sensually and tactually distant [1]. This research introduces a drawing and painting process that infuses digital and analog ways of *visual-making* [2]. It implements a computationally broadened workflow for hand-drawing and painting, and develops a custom drawing apparatus. Primary goal is to develop a computationally generative painting system while retaining embodied actions and tactile material interactions that are intrinsic to the processes of hand-drawing and watercolor painting. A non-symbolic, open-ended and trace-based shape calculation system emerges.

Keywords: Shape · Computing · Painting · Embodied · Watercolor

The Marching Shape:

Extensions to the Ice-Ray Shape Grammar

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Abstract. Contemporary voxel based CAD software uses a predetermined voxel space as a property placeholder for establishing relationships between boundaries and properties (weights). The Marching Shape algorithm, developed as an extension of the Ice Ray Shape Grammar, demonstrate how similar relationships between weights and boundaries can be developed without the fixed structure of Voxels. An extended Ice-Ray is presented that includes rules and schemas for polygons of more than 5 vertices, rules for the manipulation of weights as well as rules that establish relationships between them.

Keywords: Marching · Shape · Ice-Ray · Voxels · Weights

EthnoComputation: An Inductive Shape Grammar on Toraja Glyph

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Abstract. This paper aims to highlight the ways in which Shape Grammar inductive reasoning can analyze and represent design knowledge in a tacit environment. Deductive Shape Grammar has effectively examined designs from the past, where access to the artifacts' authors is not possible. However, in a condition where access to the craftsperson and the making process is possible, there is an opportunity to induce design grammar from the evidence on-site. Nevertheless, in such contexts, direct access to the craftsperson does not necessarily mean that access to their design knowledge is straightforward, as reflected in our case study, *Passura*: a Traditional Glyph in Toraja, Indonesia. In this article, the formulation of inductive Shape Grammar is provided, and applications on the tacit environment are discussed.

Keywords: Passura · Inductive reasoning · Shape Grammar · Toraja · Ornament · Ethnocomputation

Urban Studies

Automatic Parameterisation of Semantic 3D City Models for Urban Design Optimisation

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Abstract. We present an auto-parameterisation tool, implemented in Python, that takes in a semantic model, in CityGML format, and outputs a parametric model. The parametric model is then used for design optimisation of solar availability and urban ventilation potential. We demonstrate the tool by parameterising a CityGML model regarding building height, orientation and position and then integrate the parametric model into an optimisation process. For example, the tool parameterises the orientation of a design by assigning each building an orientation parameter. The parameter takes in a normalised value from an optimisation algorithm, maps the normalised value to a rotation value and rotates the buildings. The solar and ventilation performances of the rotated design is then evaluated. Based on the evaluation results, the optimisation algorithm then searches through the parameter values to achieve the optimal performances. The demonstrations show that the tool eliminates the need to set up a parametric model manually, thus making optimisation more accessible to designers.

Keywords: City Information Modelling, Conceptual Urban Design, Parametric Modelling, Performance-Based Urban Design

1 Introduction

In the early stages of urban design, designers will explore the impact that building layouts and building forms have on various urban performances. For example, building layouts and forms strongly influence solar availability [1] and urban ventilation [2, 3]. One powerful way of facilitating this exploration is using optimisation algorithms. In the optimisation process, designers create parametric models that allow design variants to be easily generated and evaluated according to performance objectives. An optimisation algorithm is used to search for a series of optimal design instances automatically. The advantage is that huge numbers of design variants can be explored and the design can be optimised.

At the building scale, Attia et al. have highlighted how parametric modelling is one of the main technical hurdles for applying such optimisation algorithms [4]. The authors foresee the same technical difficulty for urban design. Currently, designers who do urban design optimisation use parametric modelling applications with a Visual Programming Language (VPL) interface to encode their design as a parametric model [5, 6]. Although it has been shown that design students are able to learn parametric modelling faster through VPL as compared to textual programming, VPL quickly becomes inadequate when applied to complex design task such as generative designs and large scale designs [7, 8]. In addition, VPL network easily becomes unmanageable with too many links, nodes and confusing iteration [9]. Thus, VPL is less than ideal for parameterising an urban scale design. Instead of using VPL, we propose an automated method to facilitate the parameterising of urban models from 3D semantic models.

In this paper, we considered a scenario where the designer is planning a cluster of buildings on a large urban plot. The shape of each building plan is assumed to be fixed, but the position, orientation, and height of the buildings may be varied subject to constraints. One key constraint is the Floor Area Ratio (FAR) of the plot, which results in a maximum total Gross Floor Area (GFA) for all the buildings on the plot. The heights of the building need to be constrained to ensure that this GFA is not exceeded. Other constraints are that the buildings must stay within the plot boundary and must not intersect one another.

To demonstrate this method, we implemented a prototype auto-parameterisation tool. The tool imports a semantic urban model in the CityGML format [10] and automatically generates a parametric model by parameterising the position, orientation, and height of building objects. These parametric models can then be used to optimise the urban layout and forms of these building objects. The usefulness of the tool is that it allows designers to bypass the complex and time-consuming step of constructing parametric models, thereby removing a key hurdle in the application of optimisation algorithms within the urban design process.

2 Method

The proposed method consists of four steps as shown in **Fig. 1**: 1) inputting the semantic model, 2) creating the parametric model, 3) mapping parameter values and generating designs 4) retrieve design variant models.

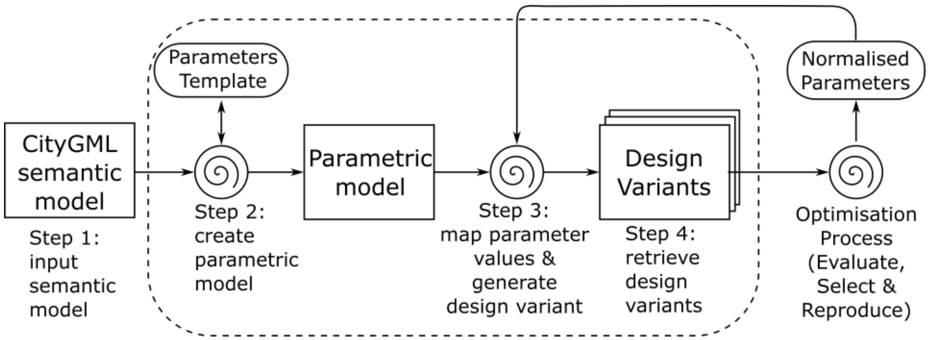

Fig. 1. Proposed method for urban optimisation. The dotted box indicates the steps performed by the auto-parameterisation tool.

In step 1, the method requires a CityGML model as input. In step 2, the tool first analyses the semantic CityGML model and identifies all the building objects that are on the plot. It then creates a parametric model by applying a parameter template to each of these objects. The prototype parameter template defines three parameters: building position, building orientation, and building height. Additional templates can be created and customised by designers for different urban and building typologies. For example, for a carpark, a simpler parameter template may be created that does not have a height parameter, while for a podium block with a tower above, a more complex parameter template may be created that has separate height parameters for the podium and the tower.

The mapping and generate design variants process in step 3 and optimisation process are linked in a cyclical loop. In each iteration, the mapping process generates a population of design variants and the optimisation process evaluates them, and then perform reproduction and selection. The reproduction and selection will generate normalised parameter values for a new and fitter population. The mapping process takes in the normalised values and maps them to model specific values for generation of design variants. For the three parameters; building position, height and orientation, the procedure for mapping the normalised values to the model-specific values are as follows:

1. For the building position parameter, a grid is overlaid on the plot, and each position in the grid is assigned a numeric index. The normalised position value is then mapped to an index value in the range {0, N-1}, where N is the number of grid points. The default number of grid points is 100, but the designer can specify the grid density.
2. For the building orientation parameter, *O,* the normalised orientation value is mapped to a rotation angle in the range {0.0, 360.0}.
3. For the building height parameter, the calculation of the actual height values needs to take into account the FAR constraint. First, the plot area and base floor area for each building are calculated. The number of floors for each building is then calculated as follows:

$$F = (h \cdot a_p \cdot r_p)/(a_b \cdot \sum_{i=0}^{n-1}(h_i))$$

where F is the number of floors, h is the normalised height, a_p is the area of the plot, r_p is the FAR for the plot, and a_b is the area of the building base. The height of the building is then F multiplied by the floor to floor height for the building, for which either a default value of 3m can be used, or a value can be specified by the designers.

The parameters for position and orientation may result in design variants where buildings either intersect one another or intersect the plot boundary. The buildings are placed in sequence to make sure these intersections do not happen, and when constraints are broken, the parameter values are iteratively adjusted until a valid model is generated.

3 Implementation

The proposed method is implemented in a Python library called Pyliburo [11] (*https://github.com/chenkianwee/pyliburo*) as two Python classes, `Parameterise` and `BaseParm`. The two classes use the modelling kernel and the CityGML reader/writer from Pyliburo for their geometrical operations and for reading and writing CityGML files. The `Parameterise` class represents a parametric model. To parameterise a CityGML model, one needs first to configure a series of `BaseParm` classes and append them to the `Parameterise` class. Each `BaseParm` class specifies the parameterisation procedure for a parameter. We implemented the `BaseParm` class as a Python abstract class to facilitate reuse and extensibility. The `Parameterise` class then reads and parameterises the CityGML model according to the appended `BaseParm` classes. A combination of multiple `BaseParm` classes forms the parameter template as mentioned in section 2. Thus, the `Parametrise` class has a one-to-many (1-N) relationship with the `BaseParm` classes as shown in **Fig. 2**, a Unified Modelling Language (UML) class diagram. **Fig. 2** also illustrates an implementation of the `BaseParm` class, `BldgOrientationParm`, which will be discussed in detail below.

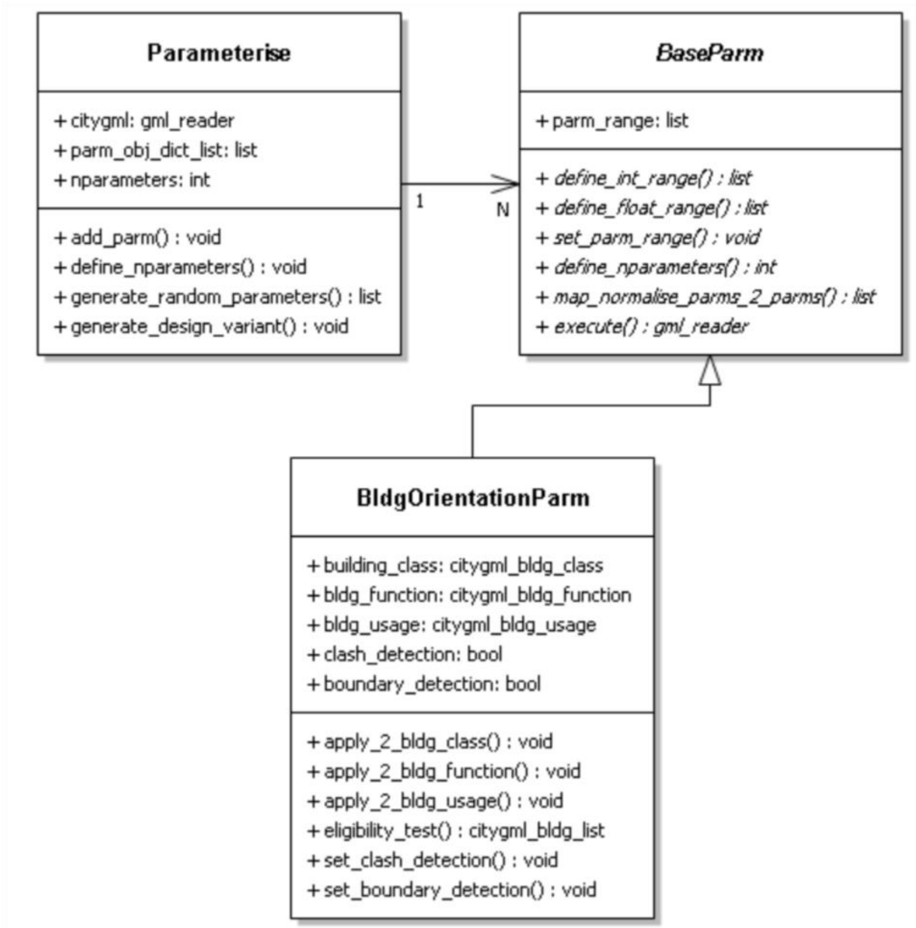

Fig. 2. UML class diagram of the two classes for the auto-parameterisation tool

3.1 Parameterise Class

The `Parameterise` class parameterises a CityGML model according to the added `BaseParm` classes. The `Parameterise` class stores the CityGML data as a pycitygml `Reader` class from Pyliburo. It has two other attributes. First, `parm_obj_dict_list` is a list of dictionaries documenting the appended `BaseParm` classes and the corresponding number of parameters for this parameter. `BaseParm` classes are added to the `parm_obj_dict_list` using the `add_parm` method. Second, the `nparameters` attribute is an integer indicating the number of parameters of the parametric model calculated by the `define_nparameters` method. The `Parameterise` class generates a design variant using the `generate_design_variant` method; a random design variant can be generated by using the random parameters generated by the generate_random_parameters method as inputs.

3.2 BaseParm Class

The BaseParm abstract class defines the parameterisation procedure for any parameter. Any implementation of the BaseParm abstract class has the attribute parm_range, which is a list of all the possible parameter values. The parm_range attribute can be defined by any of three methods: the define_int_range method, by specifying the starting integer, the last integer and the step between each integer; the define_float_range method, by specifying the starting float, the last float and the step between each float; and the set_parm_range method, by specifying all the possible parameter values. With the parm_range set, the map_normalise_parms_2_parms method maps the normalised parameter values received to the defined parameter range. The define_nparameters method calculates and returns the number of parameters generated by this BaseParm. Eventually, with everything configured, the execute method executes the parameterisation procedure for this parameter.

We have implemented three BaseParm classes: BldgFlrAreaHeightParm, BldgOrientationParm and BldgPositionParm. We will describe the BldgOrientationParm implementation to illustrate the abstract class. The BldgOrientationParm class has all the methods specified by the BaseParm abstract class. In addition, we have implemented five additional attributes and six additional methods as shown in **Fig. 2**.

By configuring the attributes and methods, users of the library are defining the constraints of the BldgOrientationParm class. The execute method requires two inputs, the CityGML Reader object from Pyliburo that carries all the information from the CityGML model and the list of normalised parameters. First, the normalised parameters are mapped to the model-specific parameters using the map_normalise_parms_2_parms method. The eligibility_test method then filters the buildings as specified by the bldg_class, bldg_function and bldg_usage attributes to find the eligible buildings. Last, the execute method loops through all the eligible buildings and rotates them counter-clockwise from their original orientation. If clash detection or boundary detection is set to True, and the rotated building clashes with other buildings or is outside the land-use boundary, the building will not be rotated. The method then documents and returns the rotated design in the CityGML Reader object. The CityGML Reader object is then passed on to the next BaseParm classes. After being parameterised by all the BaseParm classes in the Parameterise class, a design variant is successfully generated.

4 Examples

We demonstrate the proposed method and tool on two examples. One simple example shows the operation of the auto-parameterisation tool and the second example shows the integration of the tool into an optimisation design process. For the demonstrations, we develop the tool by writing two Python scripts with the auto-parameterisation Python classes. Both scripts require only one main input: the CityGML file to be parameterised and optimised. The source code is available on GitHub (*https://github.com/chenkianwee/pyliburo_example_files*).

4.1 Example 1

The first example is a simple case of a land-use with 13 residential buildings and two multi-storey carpark buildings (**Fig. 3**a). The example was modelled in the CityGML format and imported into the auto-parameterisation tool.

The automatic parameterisation process is illustrated as follows:

1. Each residential building is assigned the parameters building position, orientation and height, while carparks are only assigned position and orientation.
2. A parametric model with 43 parameters is automatically created.
3. The three parameters are as described in section 2. The ranges of their parameters are as follows:
   a. The density of the grid for the position parameter is 10m by 10m.
   b. The rotation angle for the orientation parameter is $0 <= O <= 350$, $10 \mid O$.
   c. The normalised height for the height parameter is $3 <= h <= 10$, $1 \mid h$
4. **Fig. 3**b shows four design variants generated from the automatic parameterisation process.

Fig. 4 shows a snippet of the script. The script requires one input; the CityGML file path to be parameterised. The `BldgFlrAreaHeightParm` class is first initialised. The `define_int_range` method then defines lower bound, upper bound and the step between each value of the normalised height. As specified by `apply_2_bldg_function("1000")`, only residential buildings have the height parameter. The parameter "1000" is the residential building function code in the CityGML schema. The `BldgFlrAreaHeightParm` is then added to the `Parameterise` class. Random normalised parameters are generated by the class accordingly and used to generate a design variant.

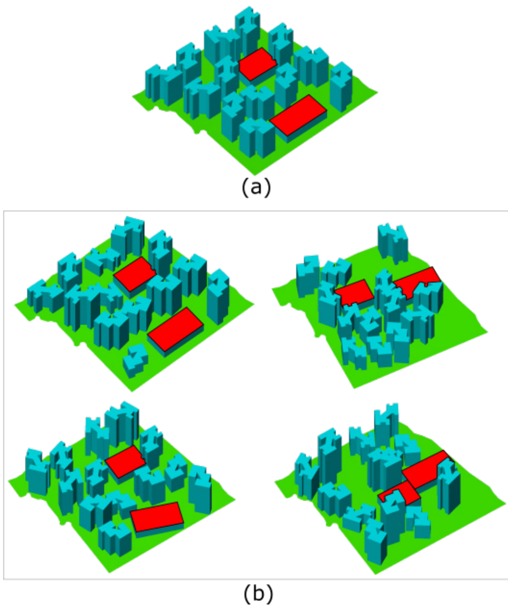

Fig. 3. (a) Example 1 has a land-use with 13 residential buildings (blue) and two multi-storey carpark buildings (red) (b) four design variants randomly generated by the auto-parameterisation tool.

```
input = CityGML_filepath
height_parm = BldgFlrAreaHeightParm ()
height_parm.define_int_range(3,10,1)
height_parm.apply_2_bldg_function("1000")
parameterise = Parameterise(input)
parameterise.add_parm(height_parm)
parameters = parameterise.generate_random_parameters()
parameterise.generate_design_variant(parameters)
```

Fig. 4. Snippet of the auto-parameterisation script with the input CityGML file highlighted in bold

4.2 Example 2

The second example is a land-use with 25 residential buildings in the tropical climate arranged in a five-by-five grid as shown in **Fig. 5**a. The example is parameterised in height, orientation and position as described in section 2; the same parameter ranges are used as in example 1 for the auto-parameterisation process. Through the parametric model, we want to explore the impact of different configurations of height, orientation and position on the solar irradiation and urban ventilation performances. **Fig. 5**b shows two randomly generated design variants.

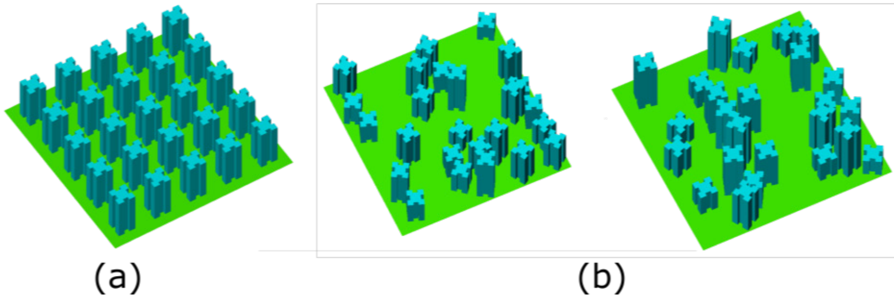

Fig. 5 (a) Example 2 with 25 residential buildings arranged in five by five grid (b) two design variants randomly generated by the auto-parameterisation tool.

We measure the solar irradiation performance using the Non-Solar Heated Façade Area Index (NSHFAI), which is the fraction of the façade area receiving annual solar irradiation equal to or below a threshold value. The threshold value is 227.45 kWh/m^2 and is based on the Singapore Green Mark's maximal permissible Envelope Thermal Transfer Value (ETTV) of 50W/m^2 [12], multiplied by the 4549 annual daylight hours in Singapore [13]. NSHFAI is to be maximised in the optimisation process. We measured the urban ventilation performance using the Frontal Area Index (FAI) [14, 15], which is the ratio of the total façade area projected to a vertical plane facing the user-defined wind direction to the horizontal plane area. The FAI is calculated using the northeast prevailing wind direction of Singapore, and the site is gridded 100mx100m. The average FAI is calculated and used as a performance objective. The average FAI is to be minimised in the optimisation process. Py2radiance [16] is used to execute Radiance [17] for simulating the annual solar irradiation, and Pyliburo is used to calculate the FAI.

The parametric model is used for running an optimisation process with NSHFAI and FAI as the performance objectives. We used The Non-dominated Sorting Genetic Algorithm II (NSGAII) [18] as implemented in the Pyliburo library for the optimisation process. The default values of 0.8 and 0.01 are used for the crossover rate and mutation rate. **Fig. 6** shows a snippet of the script illustrating the integration of the auto-parameterisation library with the optimisation process.

The script initialises the NSGAII optimisation class by defining genes (parameters), and scores (performance objectives) as a list of Python dictionaries. Then for each individual in each generation, a design variant is generated using the genotype (parameters) of an individual through the `Parameterise` class, `generate_design_variant` method. The generated design variant is evaluated in terms of NSHFAI and FAI. The two performances are then used for the feedback procedure, crossover and mutation, in NSGAII. The feedback procedure generates a new generation of individuals, and the cycle repeats until as specified by the user. The main input for the script is the CityGML model of the design, while default values are used for the other inputs for the optimisation algorithm and solar simulations.

```
#define the genes
gene_dict_list = []
for _ in range(number_of_genes):
    gene_dict={"type": "float_range", "range":(0.0,1.0)}
    gene_dict_list.append(gene_dict)
#define the scores
shgfai_dict = {"name": "nshfai", "minmax": "min"}
dfai_dict = {"name": "fai", "minmax": "max"}
score_dict_list = [nshfai_dict, fai_dict]

population=initialise_nsga2(gene_dict_list, score_dict_list)

for generation in range(ngeneration):
    individuals = population.individuals
    for individual in individuals:
          parameters = individual.genotype.values
          design_variant = parameterise.generate_design_variant
          (parameters)
          nshfai = eval_solar(design_variant)
          fai = eval_fai(design_variant)
          individual.set_score(0, nshfai)
          individual.set_score(1, fai)
    feedback_nsga2(population)
```

Fig. 6. A snippet of the optimisation python script

Results.

We ran the optimisation for 40 generations with an initial population of 25 design variants. There are seven design variants on the Pareto-front (red dots) in reference to the base case performance (blue dot) as shown in **Fig. 7**. All the design variants' performances improve significantly in comparison with the base case. Three design variants are visualised in 3D (**Fig. 7**). Two design variants are on the two ends of the Pareto front: one with the lowest NSHFAI and FAI (design variant 853), the other with the highest NSHFAI and FAI (design variant 993). The third design variant is a negative example with low NSHFAI and high FAI (design variant 153).

Design variant 853 has similar NSHFAI performance as design variant 153 with only a 0.06 difference in NSHFAI. In comparison, design variant 993 performs significantly better in terms of NSHFAI by a 0.15-1.21 difference. This is due to the inter-shading between buildings in design variant 993 as shown in **Fig. 8**. However, the close-packing of the buildings increases its average FAI as compared to design variant 853 by 0.04 as shown in **Fig. 9**. The congregation of buildings in the centre of the plot contributes to the increase in FAI. The buildings in design variant 853 are better spaced apart and as a result has lesser inter-shading but better FAI. Although design variant 153 is also well-spaced like design variant 853, its bad building positions and orientations, with their vertical facade facing the wind direction, are blocking the wind flow.

By visualising both the Pareto front design variants and bad performing design variants performances in 3D, designers are able to quickly assess how the building arrangement are affecting the NSHFAI and FAI.

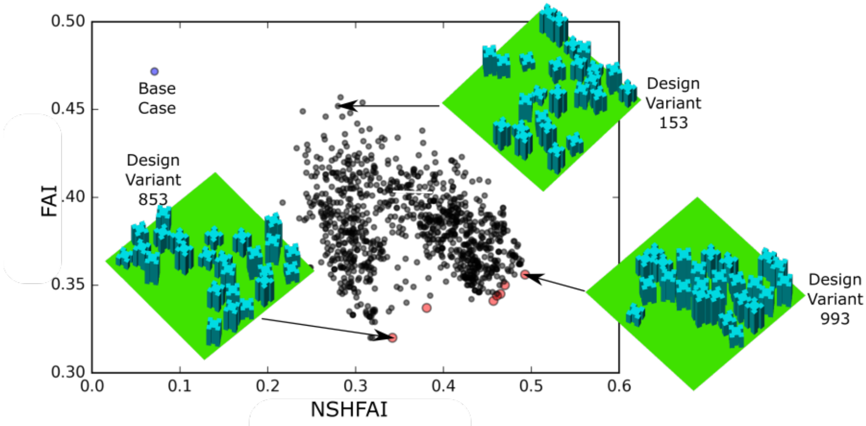

Fig. 7. The optimisation generated 1000 design variants with seven on the Pareto front (red dots) and the base case (blue dot)

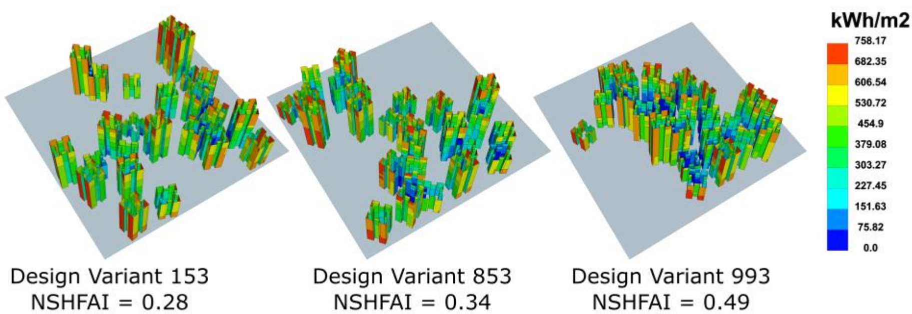

Fig. 8. The NSHFAI result of the three design variants. The blue surfaces are surfaces receiving irradiation less than the threshold value.

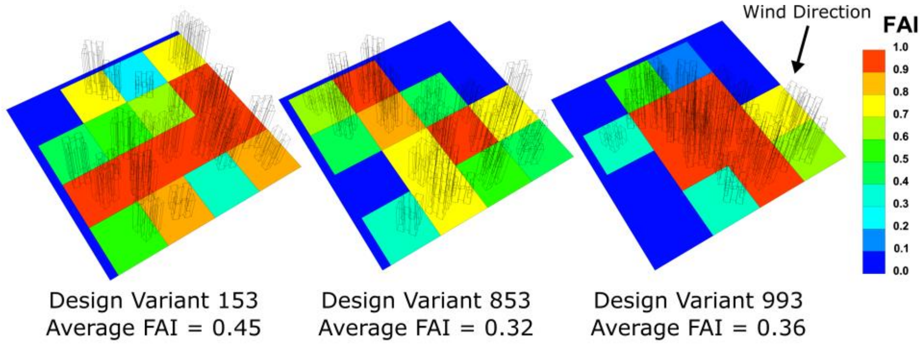

Fig. 9. The FAI false colour diagram of the three design variants.

4.3 Discussion

The two example scripts are able to auto-parameterise a CityGML model in terms of height, orientation and position without additional inputs from the designers. Example 2 demonstrates the capability of the auto-parameterisation tool to engage optimisation in the design process without the need to parameterise the design manually.

The Python library that is used to develop the auto-parameterisation tool offers flexibility for designers with a programming background. This is very useful for customising the parameterisation process for their own project. As shown in example 1, it is straightforward to customise the auto-parameterisation by appending different `BaseParm` classes to the `Parameterisation` class. For example, to parameterise the orientation and height of the buildings, one simply appends the `BldgFlrAreaHeightParm` and `BldgOrientationParm` to the `Parameterise` class and leaves out the `BldgPositionParm`.

While customising the parameter template, designers need to pay attention to the sequence of the appended `BaseParm` classes, as the sequence affects the parameterisation. If the clash detection is active for either `BldgOrientationParm` or `BldgPositionParm`, the same set of parameters will result in a different result depending on the sequence. For the sequence rotate-relocate, a building that is not allowed to rotate because it clashes with a neighbouring building will be relocated to a new position without being rotated. However, for the sequence relocate-rotate, the building will be relocated first and allow to be rotated at the new position as it will not clash with any neighbouring buildings.

We have only demonstrated a very narrow set of parameterisation classes. The auto-parameterisation tool is highly extensible; one can extend the `BaseParm` class to include an implementation to parameterise the building forms of a design. In contrast to the current classes where parameters are assigned to each building, we will parameterise the building forms of a design by assigning a parameter to each land-use. We will define the `execute` method depending on the form that we will explore. In the method, the parameter would influence the building forms on the land-use. While defining the `execute` method, it is important to note whether the implementation is compatible with the other `BaseParm` classes. For example, if the urban form parameter value changes the number of buildings on the land-use, the urban form `BaseParm` implementation must be appended after the `BldgFlrAreaHeightParm`, `BldgOrientationParm` and `BldgPositionParm`. This is because the three classes assign parameters according to the original number of buildings in the CityGML model; if the number of buildings is changed, there will be a mismatch of parameters to the buildings to be either rotated, relocated, shorten or heighten.

Eventually, it is up to the designers to customise their script. The Python library is open and available for any interested designer to develop, extend, explore and experiment.

5 Conclusion

The research demonstrates the feasibility of auto-parameterising semantic 3D city models. The proposed method is a viable solution in helping urban designers computationally encode their designs as a parametric model for optimisation. The auto-parameterisation tool has been integrated into an optimisation process by connecting it with an optimisation algorithm NSGA2. The integration simplifies the encoding process of the urban optimisation process and makes the process more accessible to designers.

Ongoing research to improve the auto-parameterisation tool includes developing a Graphical User Interface (GUI) for designers with no programming background to customise the parameterisation process and integrating the Python library with a parallel computing framework to speed up the optimisation process. Firstly, a parameter tree GUI like a feature-based modelling application such as CATIA will be useful for designers to append and arrange the sequence of the `BaseParm` classes in the `Parameterise` class. Secondly, the optimisation process currently takes up to 155 hours to generate 1000 design variants. The process can be significantly sped up by integrating the optimisation process into a parallel computing framework. We envision an accessible and fast optimisation process will encourage adoption of optimisation algorithm in the urban design process.

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Question of Perspective

Information Visualisation in Games and its Possible Application in Planning Communication

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Abstract. The densification of urban spaces is a major challenge for future cities. With new forms of online consultation, we observe a movement towards open government in urban planning. A stronger participation between a more diverse body of players in a networked environment, is unveiling various discrepancies in the understanding of projects by the different actors in planning, due to access to and the comprehension of planning information. To recognise and utilise the associated capabilities of current transformations, communication between the actors in planning and their sharing of knowledge is vitally important. Information visualisation is an essential form of communication, prompting this explorative paper in considering elements specific to games visualisation and their implications for urban planning. Based on a framework for information visualisation in games it was found that the specifications for actor groups in planning processes mirror the specifications specific to target audience groups in games.

Keywords: Gamification, Urban Design, Information Visualisation, Collaborative Design, Public Participation

1 Introduction

Major cities and metropolitan regions are recording ever increasing populations due to being able to supply an attractive job market; good public transport and education infrastructures; and ample recreational structures and facilities [1]. The resulting and on-going densification and over-population of these areas has a considerable impact on existing urban structures and future planning decisions. Recognising the effects and identifying the arising potentials and challenges is therefore becoming an important factor in urban planning. Current planning communication practices are proving inefficient to analyse and communicate this information. The results are most obvious in public objections to big projects such as the new Berlin International Airport (problems with internal communication) or Stuttgard21 (problems with public communication). Providing appropriate planning solutions, fulfilling sustainability targets and gaining large social acceptance of building proposals, requires a sharing of

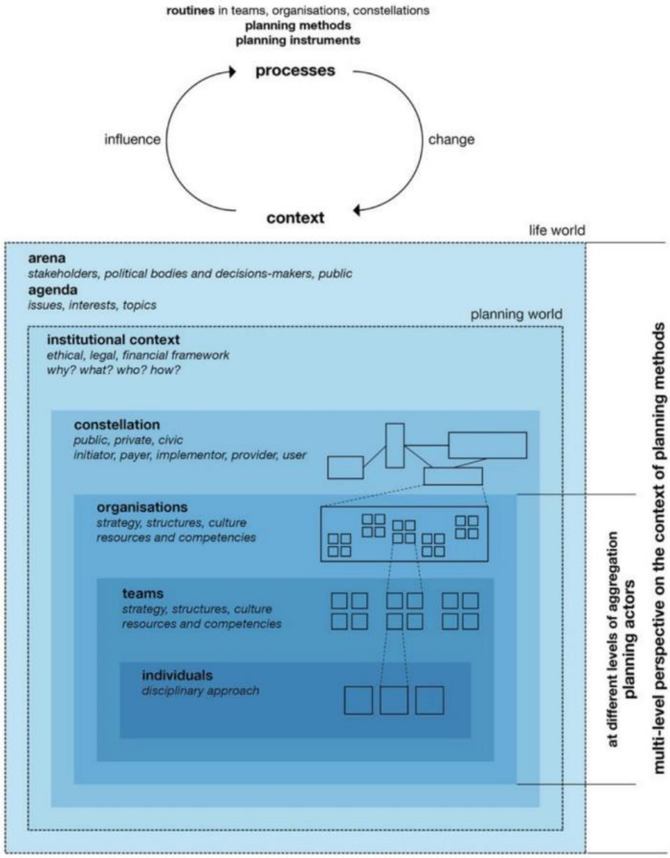

Fig. 1. A multi-layer perspective on the driving bodies involved in planning [2]

knowledge between the driving forces in planning. Globalisation and its accompanying migration mean that the diversity of cities is also on the rise as people from different cultural backgrounds move around. In terms of communication, this can pose problems as signs, symbols and cultural codes differ in use and meaning and are no longer fixed to physical locations. Therefor we can say that communication in planning is affected by the number of people involved and their culture and codes.

When regarding planning processes in terms of communication we find there are two important facets, the driving bodies and planning cycles. Both Förster and Schönwandt see a distinction between what they term the planning world and the life world [2], [3]. According to Förster (Figure 1), the life world includes stakeholders; political bodies, decision-makers; and the public. The planning world includes public, private, communal or civic bodies; initiators, payers, implementers, providers and users. They can take the forms of organisations, teams or individuals. In the life world preservation or modification outcomes are implemented in spatial, social, economic,

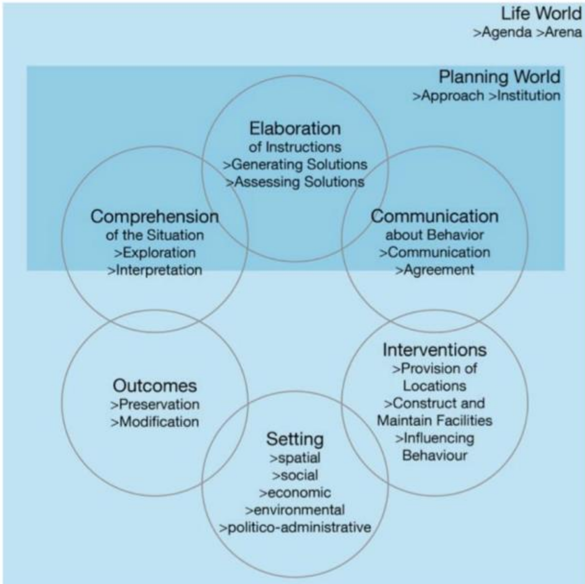

Fig. 2. Planning cycle according to Schönwandt (2002) as presented in Förster (2014) [3], [2]

environmental and politico-administrative settings, causing planning interventions to be constructed in a precise location, influencing their surroundings and needing maintenance, based on Schönwandts planning cycle as seen in Figure 2 [3]. In the planning world, a situation is comprehended through exploration and interpretation; instructions are elaborated to form general solutions which can be assessed; and communication occurs.

Förster states that planning is human interaction, therefore the way in which urban development and interventions are communicated, how local people are involved in the decision-making processes and the transparency of these procedures determine the effectiveness of planning communication [2].

The practice of using games design elements in non-gaming contexts is known as gamification [4]. It has become an interesting field of study within business management, media, sport and education. A successful example within the world of science is *'FoldIt'*, developed by the University of Washington, to utilise crowd-sourcing for research purposes [5]. *'FoldIt'* is a game where the aim is to solve a puzzle by folding proteins. Researchers then analyse the highest scoring variants, to determine if they are usable for real world purposes. Another example is the fitness app *'Zombies, Run!'* by Six to Start, where players follow a story where they are chased by virtual zombies to motivate them to be more active.

Within a larger research project the author is considering the benefits of implementing gamification methods and technologies within urban planning to improve planning communication. Information visualisation is one of the most important forms of architectural communication, which is why this paper takes an explorative approach and considers how using elements specific to games could impact architectural visualisations and how information visualisation relates to gamification. Questions posed include, whether there are any information visualisation elements specific to games and how architectural information visualisation compares to them.

2 Background

Parlett distinguishes between informal and formal games [6]. The first being described as *'undirected play, or "playing around?"'* [6], the second as being defined by having both a means and an end. What he means by this is that a game must have a predefined end, for example a game might end after a specific score is reached, and it has a set of rules which has been agreed upon by the participants. It can be added that these rules are known by all participants making a game something which is transparent with clearly structured objectives. Deterding et al. agree that games are different to play because games adhere to a set of rules, but they take the idea further, dividing games into being inside the game world or outside of it. A game which uses augmented reality would be an example of a game outside the game world [4]. Salen and Zimmerman on the other hand describe games as *'a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome'* [7]. Here again we see that rules are a defining part of games, but also that the outcome is quantifiable. If there is a lack of quantifiable data within urban planning, this last aspect is interesting in regards to possible uses of game elements within a planning context.

Gamers tend to be more spatially aware and have a higher visual literacy than non-gamers [8]. One form of presenting data is by using visualisations. It is important to note, that information visualisations are not the same as the graphics of gameplay. They provide the player with extra information, which the character in the game might not have.

For this paper, a literature review was conducted examining information visualisation, information visualisation within planning communication processes and information visualisation within games. The gathered information was evaluated, relationships between the fields considered and implications of using information visualisation elements specific to games in planning identified. Finally, the process and findings were reviewed and possible future questions and investigations proposed.

2.1 Information Visualisation

To visualise means *'to form a mental image of'* or to *'make visible to the eye'* [9]. These definitions express the nature of why we visualise: to show what we know and to explore what we don't [10]. Card et al. conducted an experiment in the late nineties to examine how using external tools such as a pencil and paper effects our mental performance [11]. They discovered that when asked to perform a complicated multiplication, people would be five times as quick if they used external aids. What they had shown is that humans can increase their mental processing power by using *'tools of thought'* [12] as this frees up working memory, which enables extended and more complex processing. Norman wrote *'the power of the unaided mind is highly overrated. Without external aids, memory, thought, and reasoning are all constrained. [...] The real powers come from devising external aids that enhance cognitive abilities'* [12] and indeed correlations between the development of cognitive tools over time, such as the written word, mathematics, maps, etc., and the development of human civilisation have been drawn [13].

Visualisation allows large amounts of data to be comprehended, and enables the perception of patterns and properties within large complex information which might otherwise be hidden within the data structure [8], [14]. It facilitates the understanding of information beyond a person's expertise [8] and aids the process of forming hypotheses [14]. Mazza describes visualisation as *'a discipline concerned with the creation of visual artefacts aimed at amplifying cognition'* [15]. Ware too picks up on the relationship between the *'internal construct of the mind'* [14] and a visualisation being *'an external artefact supporting decision making'* [14]. To make and communicate decisions we need information. Information visualisations differ from other types of visualisation, such as scientific visualisation where physical properties are made visible even if we can't physically see them, by its ability to be abstract in nature and its degree of disconnection to the physical world. With the introduction of computers, visualisation capabilities have increased and real-time interaction with data facilitated. It allows for a layering of information, temporal integration, simulation possibilities and gives the user control over what content they wish to view [14], enabling an active examination of data.

In his eloquent description of the strong link between visualisation and human perception, Tufte stated that *'when principles of design replicate principles of thought, the act of arranging information becomes an act of insight'* [16]. Ware identifies three levels that govern how we perceive the world around us [14]. The first level of Wares framework comprises of details within our field of view which we perceive in quick succession. They are directed by certain factors and include direction, length, thickness, colour, brightness, number, form, size, movement and most importantly spatial positioning [10], [17]. On a second level, we detect and recognise patterns through the proximity of elements, their similarities and relative connection [10], [17]. Lawson wrote *'we are not very good at any form of perception, but we are much better when relying on relative comparisons'* [17]. The visual-semantic language of the brain governs these aspects [17]. Important examples include the laws of proximity, similarity, continuation, figure-ground, symmetry.

Goal-orientated and sequential processing make up the final level of perception, where a verbalisation of the perceived occurs [10].

Whilst there is evidence that visualisations are universal by nature, it can be argued that only certain aspects are indeed, universal. Tufte argues that *'the principles of analytical design are universal – like mathematics, the laws of Nature, the deep structure of language – and are not tied to any particular language, culture, style, century, gender, or technology of information display'* [18]. In contrast Ware clearly differs between arbitrary and sensory principles and aspects. Sensory aspects are described as biological, using the brains perceptual processing power without a need for learning. They allow cognition without prior knowledge, are resistant to instructional bias, and are valid across cultures [14]. Arbitrary aspects however, are governed by society and culture. Because they are symbols which don't resemble their object [19] they are hard to learn, can be easily forgotten; are capable of rapid change; and are formal in structure, such as in mathematics [14]. In traditional planning and architectural visual communication, many of the visualisations fall into this second category.

2.2 Planning Communication

People who have knowledge on a specific subject, such as planning experts, tend to assume that others have that knowledge too, they overestimate how widely spread that knowledge is and they overestimate the depth of knowledge others may have on that topic [20]. In his book, Rambow examines communication processes within architecture and looks at how both experts and laymen perceive the world around them [20]. He found that there are distinct differences between the way experts and laymen organise information, the former sorting domain specifically, whilst the latter uses descriptive categories. Whilst architects are competent in predicting laymen's knowledge levels and architectural understanding there is a significant visual-semantic communication gap when it comes to two- and three-dimensional thinking and translating; and there are conventional and abbreviation discrepancies. This indicates a third factor stressing the planning situation in cities and metropolitan regions, as people's level of planning knowledge varies. The public body has knowledge ranging from novice to expert. These aspects make planning communication processes about providing the right amount of information to meet knowledge levels, whilst using conventions which can be understood by the majority.

Traditionally architects communicate through their work and communicate predominantly among themselves by use of visual tools, whilst spoken and written descriptions are secondary [20]. Over time various visualisation techniques have developed to express planning information. The most common form are maps, which show physical properties of an area of land or sea and consist of a *'collection of data showing the spatial arrangement or distribution of something over an area'* [9]. Scale, global orientation, the time and a key are important features [21] as maps are abstract due to the prioritisation of clarity and legibility over accuracy when scaled [22]. Most common in planning, maps with a scale greater than 1:5000 are referred to as plans. As two dimensional-representations plans, sections, and elevations represent three dimensional spaces, with the aim to show large amounts of detailed information. This has caused plans to be filled with contextual codes. To counter problems in spatial translation perspective drawings and computer generated images attempt to visualise atmosphere, while detailed drawings provide building instructions for construction workers.

Within the scope of this research three driving groups made up of the various actors involved in planning were determined. The political body makes planning legislation, monitors building codes, regulates development, and plans urban structures to fulfil criteria set by political agendas or people's needs. Planners include all sub-groups in the AEC (architecture, engineering and construction) community, who focus on various aspects of a buildings lifecycle, such as design, planning application, construction or maintenance. Both groups are proficient in planning conventions. The public body however, as the largest group with high cultural diversity and a wide range of planning knowledge, are the people who experience and use architecture, and they are most concerned with how development impacts them and their quality of life.

Formal communication processes are laid out by planning legislation. Planners or authorities must inform the public of planning proposals both prior to and again during planning application to allow for feedback. As a project increases in size and political or social importance, the percentage of the population included is increased. Despite a rising complexity in formal communication processes, the same traditional planning methods are being employed. They include letters informing the public about development proposals, forms detailing area, etc., design plans and physical models. In Germany, law does not require informal communication processes. The aim of these is to involve the public in the design process. Methods are more varied ranging from leaflets to presentations, workshops, discussion and deliberations. The objective is to create local solutions to local problems and achieve public approval. Informal processes often enable higher degrees of participation including consultation, placation, partnership, delegation and control [23].

Based on the conducted research, deficits within planning communication were identified:

Noise. Noise is the unintended addition to a signal created by a "noise source", such as the sound of static on a telephone line, making the encoded and decoded signals different. This means that a message, or planning information, might not be understood in the way it was intended [24].

Convention. Convention describes the rules by which arbitrary signs work and must be learned to be understood. Architectural drawings or the translation of two dimensional drawings into a three-dimensional building are examples of convention and help to counteract noise by making a message more predictable and plans clearer to understand. Whilst planners learn planning convention, not everyone in the political and public bodies do [1].

Access. Access to planning information is a two-fold problem. Firstly, many pieces of planning information are not available in digital form and secondly different aspects of planning information are in different places.

Temporal Displacement. The transition of time can be considered a further problem in current communication processes as different people gain different knowledge at different times. Though it stops information overload it can cause discrepancies in the understanding of a proposal by the different planning bodies.

2.3 Information Visualisation within Games

As mentioned above, visualisation in games is not the same as visual graphics in games. The former provides further information about what is happening to the player within the game world, whilst the latter describes the visual, normally three-dimensional graphics of the game world. In this paper, we consider the former only. Visualisation in games differ from visualisations in general as they need to be *'"useful" and "pleasing" rather than "utilitarian"'* [8] and visualisations within game-play must not be disruptive. Research in this area approaches the topic of information visualisation in games from two opposite fronts. One direction of research looks at the application of visualisation technology in games [8], the other centres around the use of game elements in visualisations [25], [26].

Game specific methods of visualisation demonstrate more sensibility to human perception and are better at avoiding information overload whilst still providing complex information, a concept Bowman et al. agree with [8]. They see the benefit of visualisation technology for games to enable *'better gameplay, easier balancing and debugging, and more enjoyable spectating'* [8]. In their analysis of game visualisation techniques, they aimed to find features *'specific to the intersection between games and visualization technology'* [8], which could benefit the world of information visualisation by promoting mass adoption catering to an existing and motivated user base. Diakopoulos on the other hand believes the benefit of game visualisation to be in their non-linear arrangement and narrative capabilities [25]. For her *'games provide an alternative method for structuring a story, not bound by a linear arrangement but still providing structure via rules, goals and mechanics of play'* [25].

Many authors distinguish between software information visualisation and casual information visualisation within game visualisations. The difference lies predominantly in their target audience. The first is directed at developers and includes log traces, program structure. The second targets the gamers. Pousman et al. define casual visualisation as *'the use of computer mediated tools to depict personally meaningful information in visual ways that support everyday users in both everyday work and non-work situations'* [27].

Bowman et al. go beyond simple definition and identification of game-specific information visualisation, building up a framework within their paper useful to the research questions posed in this paper regarding a comparison to the field of

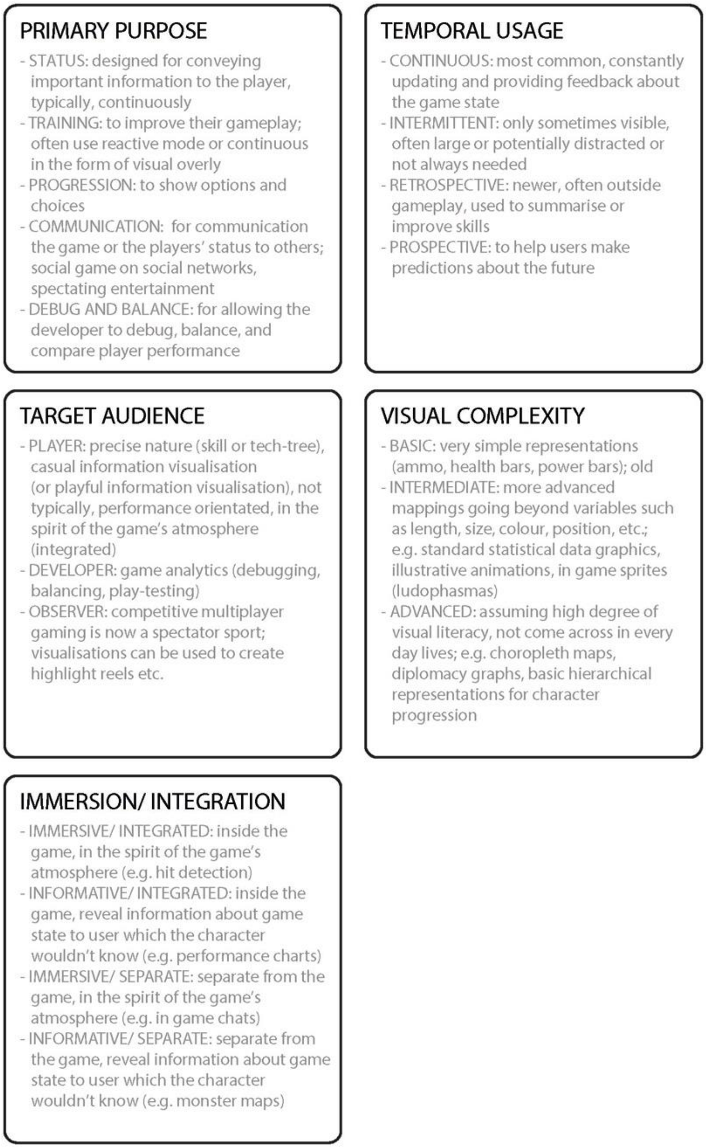

Fig. 3. Summarising the five categories used to classify specific visualisation techniques found in computer games according to Bowman et al. (2012) [8].

architecture and urban planning. Using their analysis of games, they determined five categories as demonstrated in Figure 3: primary purpose, target audience, temporal usage, visual complexity and immersion/ integration. Primary purpose describes the intended use of the visualisation which they divided into status (e.g. health bar), training (visualisation to improve gameplay), progression (displaying options to help with character or level progression), communication (informing other players of status etc.) and debugging (to help developers improve gameplay). Target audience could be players, developers or watchers. Temporal usage describes the amount of time different information is visible. It ranges from continuous, to intermittent, retrospective and prospective. Visual complexity defines how complicated a visualisation is and immersion/ integration specifies if a visualisation is perceived as part of the game, e.g. heads up display, or as separate from it, e.g. skill trees in World of Warcraft. Summarised below are game specific or predominant aspects extracted from the paper, described in a little more detail.

Time. This describes the amount of time information is visible for. Important information such as status bars tend to be continuously visible, whilst other types such as ammunition count are only displayed intermittently when needed. Time also includes retrospective and prospective simulation capabilities.

Dynamic / Static. Closely related to time, this describes how information is highlighted when it becomes relevant by becoming more dynamic at that point. The sudden movement or appearance of the information draws a players' attention.

Layout. The location of different information on a screen determines how important or relevant it is perceived to be. Games which have their gameplay in the centre often have more important information closer to the centre making it more prominent and therefor more relevant.

Immersed / Separate. This describes whether information is integrated within the game, e.g. in a heads-up display, or separate from a game, e.g. information trees etc. Another example of immersed information is blood-spatter in first person shooters which indicate both that the player is being shot at and the direction from which they are being shot from.

Ludophasmas [26]. A term used for ghost cars in driving games where a ghost image of either a player's previous lap, or an opponent's drive path is shown. Here I am also using it to describe elements such as wheel marks rendering optimal racing lines in car games. They express a teaching function.

Multi-User. In multi-player games, different people can often see different information. For example, in multi-player shooters you may only be able to see areas of the playing field which members of your team can see, whilst your opponent will see other areas. Similarly, if one player had the option of using night-time goggles, he would receive different information to his team-mates.

3 Comparison

Based on the framework proposed by Bowman et al. (Figure 3), a comparison between games information visualisation and planning information visualisation was conducted. Looking at the five categories, several observations were made [8].

3.1 Primary Purpose

Status. Visualisations are used in games for different purposes. Displaying status to convey important information about a character's condition, the state of play or the play situation creates a frame of reference for a player. In games, it is typical that this type of information is displayed continuously and updating regularly providing feedback about the game state.

Displaying the most important information about a planning proposal, the main contacts and the stage of the project is also a common practice in planning communication. This information is presented continuously, but not automatically. It is updated but the regularity is dependent on the party providing the information. The aim is to create a frame of reference of the stage and state of the project.

Training. Games use visualisations to help a player improve. The training techniques are employed either retrospectively through video summaries, or through reflective modes, or practice runs and levels; or continuously in the form of visual overlays using effects such as Ludophasmas.

In architectural education, ongoing architects participate in multiple practice projects, some wholly fabricated situations and others with real world application. Outside of architectural practice the use of legends, simulations, and visual diagrams are implemented to help facilitate understand and communicate underlying thought processes within the different planning stages.

Progression. In games progression is linked to development, for example character development (World of Warcraft – Skill Tree) or building strategy development (SimCity, Anno1602). To demonstrate options and choices, a player's progression is visualised, for example by implementing visual skill and technology trees.

In planning maps are used to visualise city development showing building zones, allowing people to see what can be built where. The progression through design stages may be visualised.

Communication. When talking about communication it is possible to distinguish between in game communication and of game communication. In their paper Bowman et al. [8] focus on visualisation to communicate information about a player's status or to communicate game information on social networking platforms.

Most planning visualisation is to communicate planning information and decisions. Plans, sections, elevations, perspectives, visualisations, simulations, etc. are all created to communicate abstract ideas or explore a design notion. Whilst architecture is shared on social networking platforms, the target audience is mostly field specific.

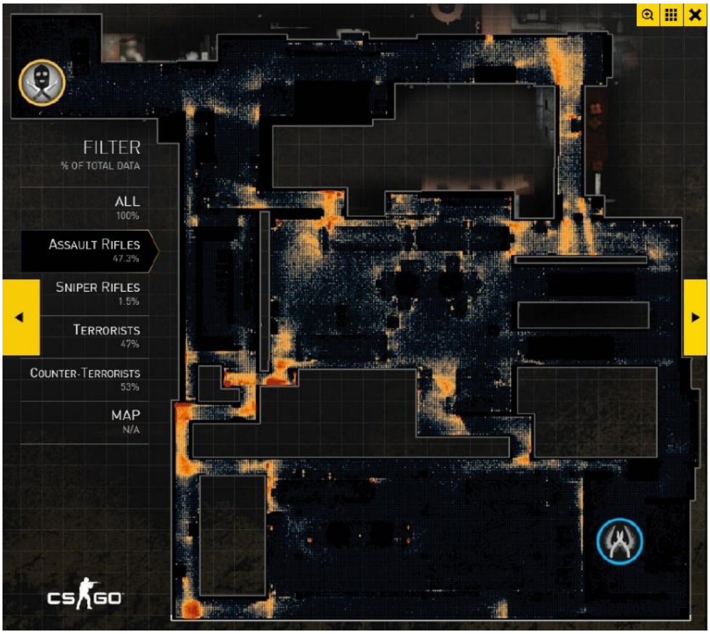

Fig. 4. A heat map showing the death zones on a Counter Strike Global Offensive mission as an example for a player performance comparison [28]

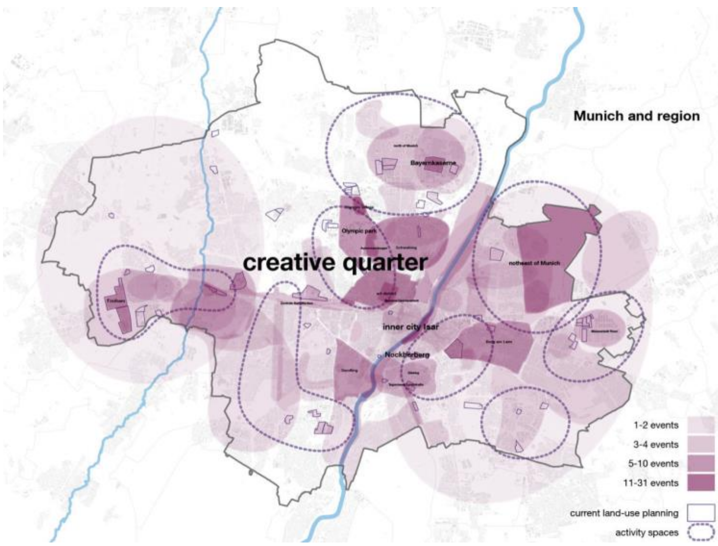

Fig. 5. A heat map showing the spatial pattern of a recent public debate in planning in the city of Munich, Germany. An example of player performance comparison in Planning [29]

Debugging/ Balancing. In games software information visualisation is used to aid developer's debug and balance games as well as compare player's performance (Figure 4).

Possible correlations within urban planning are visible within public participation processes (Figure 5) in early planning phases, where the aim is to identify and prevent problems at later stages, which are often accompanied by higher costs and planning delays.

3.2 Target Audience

Bowman et al. distinguish between three main groups: players, developers, and observers. Different visualisation techniques dominate the different target audiences [8]. Player specific visualisations communicate distinct or casual information. They are often in keeping with the style and atmosphere of the game and their primary purpose is giving the user feedback, skill improvement, in-world awareness and the communication of achievements and progress. Developer specific visualisations provide information for debugging, balancing, player performance evaluation, and play testing, in other words, for analytics. They also use visualisations to draw inspiration from player behaviour. Competitive multi-player games have become a spectator sport, with observers who watch other players play games [8]. Observer specific visualisation promotes observer enjoyment and player performance analysis facilitating peer-to-peer learning.

The specifications for actor groups in architectural planning processes mirror the specifications specific to target audience groups in games - player, developer or observer.

Planners can be compared to developers, as their primary purpose is the development and implementation of a suitable design solution. In planning, we can say that most visualisations are made to communicate ideas within the planning community in the planning world. They represent design stages and fulfil an explorative function or act as instructions. In educational settings, they may be used for skill improvement. In this sense, they are like the debugging and play testing functions used by developers. But they do not function on the player performance or game analytics levels. Players are comparable to users, the public and stakeholders as they both have wide ranges of game or planning knowledge and form the most heterogeneous groups. With the promotion of public participation, visualisation for this group of target-audience is increasing. It serves the purpose to give and receive feedback to and from users, promote planning world awareness and communicate proposals, achievements and progress. It is unclear how the observer group would relate to the planning world. In terms of visualisations being included to make watching players play games more entertaining, a comparison to media documentation could be draw. If the idea of visualisations is to make observers more aware of how and why players are playing the way they are, or to make the players actions more obvious and clear, or perhaps to help predict player's outcomes, then a comparison to the political bodies and decision-makers is more plausible.

3.3 Temporal Usage

The most common form of visualisation in games is continuous. This is the case within architecture too, however whilst in both the information is continuously there, in games it is also being continuously updated. Relevant information which is not always needed or if a visualisation is large or potentially distracting, it is only displayed when needed within games. As much of the information presented within urban planning is not in digital form, information is either considered important enough to be put on a plan, or not important enough to be mentioned. Intermittent information presentation is considerably easier within a digital context. In planning, the consequence is that lots of important information is spread out over many different media platforms. Games display retrospective and simulative information to summarise gameplay, to improve skills or to enable users to make predictions about the future. Simulation is a commonly used tool in planning, to help predict planning problems and to visualise solutions. Retrospective information is visualised case specifically for individual planning projects, to establish a fundamental understanding of the situation.

3.4 Visual Complexity

Visualisations have different levels. This is true both for games and architecture. They range from simple or basic visualisations, through more complex intermediate representations demonstrating relationships between different information, to advanced mappings requiring high levels of perception and visual understanding. It can be argued that this element of the Bowman et al. framework is neither game specific nor planning specific, but is part of the topic of visualisation in general. With ample Literary representation, this aspect goes beyond the research within this paper.

3.5 Immersion/ Integration

Immersion and integration describe how immersed a visualisation is in the game and if it is part of the game application or not. If a visualisation is inside game-play and in keeping with the game's atmosphere, such as in-game hit-detection, it is considered immersive/ integrated. If it reveals information to the player about character or game state it is considered informative/ integrated. If it is separate from game-play but in keeping with the atmosphere of the game, for example an in-game chat, it is considered immersive/ separate. If it is separate from the game and reveals information on character or game state, then it is considered informative/ separate, for example monster maps or skill trees. Within planning this distinction is less defined. Working off Förster and Schönwandt's theory of separate real and planning worlds, we can speculate that there are architectural visualisations which show both information concerning the planning world, such as a floorplan, as well as information regarding the real world, where it is located on the globe. In this respect, the immersion/ integration aspects would function similarly within planning where one could distinguish between information in the planning and the real world.

4 Discussion and Outlook

Within the comparisons section the game world and planning world were compared to each other, based on the framework presented by Bowman et al. [8]. We can see that there are many parallels between how visualisations are used to display information between these two disciplines, however their main use of visualisation is directed at different target audiences. From the literature review, we can say that the gamer fraction of the population is more invested in improving their spatial understanding of the game world and more motivated to improve their game-play and are therefore able to understand a lot more information, people who do not play. In architectural spheres, this is a problematic aspect as the public body often chooses not to understand planning information, resulting in rationally ignorance [30]. Within planning participation there are an increasing number of examples where the processes are gamified to counter these aspects [31]. The hypothesis drawn here is that the way in which visualisations are constructed determines how easy it is to go from novice to expert. It is based on the observation that gamers find it quicker and easier to become experts within games due to their motivation, than the public does when attempting to understand planning information. Games help players adapt their behaviour to observe different information.

One significant difference between the way visualisations are implemented within games and within urban planning is their temporal factor. Whilst both use continuous visualisation and simulation functions, games use intermittent information and retrospective technologies more effectively. Architectural communication tools, such as plans, are usually static and therefor show all necessary information at once. The temporal use of information within gaming visualisation provides a frame of reference for depicting large amounts of detailed and complicated information without overloading. They also demonstrate how information can be highlighted through techniques such as movement, colour and distance from centre. Retrospective and prognostic capabilities provide huge potential in areas of variant simulation and progression monitoring.

Furthermore, inspiration could be drawn from established games such as World of Warcraft who successfully display separate information outside direct game play, such as skill trees. In this way planning legislation, could be made more legible, accessible and understandable for both planners and the public by presenting connections between different legislation paragraphs and documents.

When considering the purpose of visualisation in the two fields we can draw the conclusion that they are applied more diversely within games than in planning and that there are game specific visualisation practices which could benefit traditional planning ones. Aspects little used within planning information visualisation include teaching and training aspect outside the planning sphere; demonstrating choices and options more clearly, especially in public participation procedures; utilising social networks more effectively and promoting social engagement, particularly outside the planning sphere; and analysing planning statistics, comparing performance, and 'debugging' to allow planning problems to be highlighted.

The immersion/ integration aspect holds potentials in planning practice, as well as a possible approach to a question posed within the scope of the larger research project surrounding this paper in finding a definition for gamification within planning: how are information visualisation and gamification connected? The differentiation between game world and real world is a similar model to the differentiation between the planning world and the real world, even if the models were not established within the same context. In both we see that visualisation occurs to target one or the other, or to translate information from one into the other. Developers use visualisation within the real world to depict game world happenings. Similarly, planners prepare visualisations to communicate ideas based in the planning world, in real world participation processes.

Bowman et al. are not the only people to suggest this divide within games. In their search for a definition of gamification, Deterding et al. see this distinction as an important factor. For them games which extend beyond entertainment in the private home or games which have salient features extending beyond the spatial, temporal or social boundaries of game-play are terminologically outside the game world. Gamification is the *'the use of design elements characteristic for games in non game contexts'* [4] or *'designing for gameful experience'* [4] and is terminologically located within the game world. But how does this help define whether information visualisation is an aspect in gamification? Both the real world and the game world use different information visualisation techniques, so information visualisation, by Deterding et al., cannot be an element of gamification. However, in this paper we see that there are visualisation techniques characteristic for games, which can be employed within non-game contexts. Deterding et al. define game elements as *'a set of building blocks or features shared by games that are characteristic to games'* [4]. This research also questions the definition of gamification as it is currently employed in industry, something Deterding himself has done in a recent contribution to a publication on the relationship of urban planning and games design [32]. Within this paper, the author proposes the term could be broadened to include narrative aspects [25] and learning from established, pleasing, interactive and effective visualisation techniques.

The research conducted was based on a literature review and functions as an aspect within a larger research project considering the benefits of gamification in planning. Whilst there is little literature on information visualisation in games there are potentials to been gained from further research both in literature, but also in practical application, in this field and its relationship with planning visualisation. Although it remains unclear how exactly information visualisation and gamification relate to each other, it is clear that certain visualisation techniques are game specific and that they aid storytelling and goal orientation. The knowledge gained in this review will be implemented, along with other elements researched within the larger urban planning project, to examine the effects of game elements in implemented prototypes to improve architectural communication.

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Automatic Generation of Semantic 3D City Models from Conceptual Massing Models

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Abstract. We present a workflow to automatically generate semantic 3D city models from conceptual massing models. In the workflow, the massing design is exported as a Collada file. The auto-conversion method, implemented as a Python library, identifies city objects by analysing the relationships between the geometries in the Collada file. For example, if the analysis shows that a closed poly surface satisfies certain geometrical relationships, it is automatically converted to a building. The advantage of this workflow is that no extra modelling effort is required, provided the designers are consistent in the geometrical relationships while modelling their massing design. We will demonstrate the feasibility of the workflow using three examples of increasing complexity. With the success of the demonstrations, we envision the auto-conversion of massing models into semantic models will facilitate the sharing of city models between domain-specific experts and enhance communications in the urban design process.

Keywords: Interoperability, GIS, City Information Modelling, Conceptual Urban Design, Collaborative Urban Design Process

1 Introduction

In the early stages of urban design, designers often prefer the use of conceptual massing models for design exploration because massing models are easy to create and modify. The use of massing models enables designers to visualise and receive timely feedback on their designs. Designers will explore multiple designs, further develop a few and discard unpromising designs. The use of massing models minimises modelling efforts or “sunk cost” on the discarded designs. These massing models are usually in geometrical formats such as Collada, Wavefront and DXF. The disadvantage is that massing models do not have semantic information, which hinders the sharing of models between domain-specific simulation applications and experts. CityGML is a standard format that documents semantic 3D city data for facilitating data sharing [1]. Designers can model their designs in cityGML format to facilitate model sharing, but this requires them to specify the semantic information. As a result, modelling their design in CityGML increases the modelling effort and the "sunk cost" of discarded design models.

The usefulness of the cityGML model is it acts as the main data exchange format for sharing models with other domain experts. Domain-specific experts can visualise the model by directly importing it into a 3D Geospatial Information System (GIS) application. The 3D model will be useful for performing analyses [2] to develop the design further. The standardisation of the exchange format will streamline the process of sharing models. This paper proposes a workflow to automatically generate semantic 3D city models from the conceptual massing models. The generation process automatically identifies city objects such as buildings, terrains and land-use plots, and converts the massing model into a minimal cityGML model consisting of explicitly defined Level of Detail 1 and 0 (LOD1 and 0) city objects.

1.1 Existing Approaches

The most straightforward method is to construct the massing model within a modelling application that has CityGML modelling capability. These are usually GIS-based applications developed for managing large GIS data set, examples of which are ArcGIS [2], Autodesk Infraworks 360 [3], Autodesk Map 3D [4] and Bentley Map [5]. However, urban designers usually work on a smaller scale and thus prefer modelling in Computer-Aided Design (CAD) applications such as SketchUp and Rhinoceros3D for their more flexible and advance 3D modelling capabilities. Thus, this paper focuses on facilitating the latter; transition of geometric models authored in CAD applications into semantic models for sharing among domain-specific experts. There are two main existing methods for generating a semantic 3D city model from a conceptual massing model: 1) import of massing models into modelling tools that support cityGML export or 2) the use of visual scripting to customise the conversion from massing to cityGML.

The first method imports the conceptual model into a 3D modelling application that supports cityGML modelling. Examples of these applications include the CityEditor plugin for SketchUp [6] and RhinoCity plugin for Rhinoceros 3D [7]. In this method, designers either model the massing design in the 3D application or import the model into the 3D modelling application, explicitly declare the semantic information of each geometry and export it to cityGML format. For example, in CityEditor the declaration is based on SketchUp's geometry group, where each geometry group must be declared as a semantic object. The main disadvantage is that the semantic declaration process is inevitably workflow specific and to manually declare each geometry's semantic content can be a time-consuming and laborious task when the designer has multiple design options.

The second method is to use visual scripting to customise the conversion. Designers will create their customised procedure using a visual scripting application to convert their massing models into cityGML. One such application is FME desktop application [8], which provides readily deployable functions to facilitate setting up the conversion procedure. For example, an urban designer models his design in SketchUp and then translates the geometric data from SketchUp to CityGML by setting up a visual script in FME desktop. FME desktop provides functions to both reads and writes data from the SketchUp file into CityGML. The designer's task is to read his massing model geometries, separate the geometries into their respective semantic objects and write them into CityGML schema. The task requires him to be familiar with the FME desktop's functions and the cityGML schema. The main disadvantage is the high complexity involved in setting up the procedures. These procedures require designers, most of whom are novices in computer programming, to be familiar with modifying and adding semantics onto geometries and translating them into a specific schema using programming methods. Although visual scripting has been shown to facilitate the learning of programming methods among design students, it has also been shown that the visual scripting quickly becomes inadequate [9, 10] and confusing [11] for large and complex design tasks.

2 Method

We developed a workflow to automatically generate a cityGML model from a massing model by adapting the workflow from our previous building-level research [12]. The workflow focuses on city objects typically present in massing models: buildings, land-use plots, terrain and road networks. The automated workflow consists of the four main steps shown in Fig. 1: input model, execute analysis rules, execute template rules and retrieve model.

In the first step of the workflow – input model – the model contains the massing of a city model. The massing models can be modelled in any 3D modelling application, provided the buildings are modelled as closed poly surfaces, terrain and land-use plots as open poly surfaces, and road networks as polylines, which is how designers usually create massing models. This method does not require extra modelling effort from designers as it leverages existing modelling conventions. The polylines and poly surfaces from the model are then sorted into a topological data structure as edges and shells. An edge is defined by a line or curve bounded by the starting and ending vertexes. A surface is defined by a closed sequence of connected edges. A shell is defined by a collection of connected surfaces. A closed shell has connected surfaces that form a watertight volume without holes.

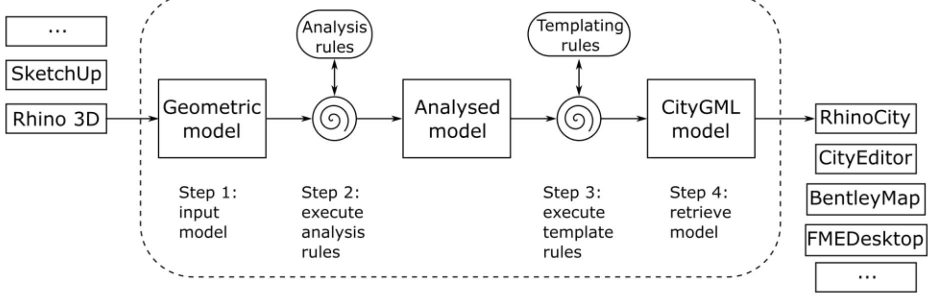

Fig. 1. Proposed workflow for automatically generating CityGML model from massing model

The second step of the workflow – executing analysis rules – starts with analysing the massing model and generating an analysed model with geometric relationship attributes. These attributes are inferred from the size, orientation, and geometrical relationship between topologies in the massing model according to the analysis rules. For example, the shells are analysed and issued a unique identification with attribute `is_shell_closed = True/False`. In order to understand the relationship between topologies in plan, the edges and shells are projected onto the XY plane and analysed. Containment relationships are determined from the analysis. For example, if the topologies are inside one or more other shells when projected to 2D, then attributes are created to capture this information, namely `is_shell_in_boundary = True/False`, `shell_boundary_contains = True/False` and `is_edge_in_boundary = True/False`.

The third step of the workflow – executing template rules – starts with the analysed model and generates the cityGML model. The template rules are matched against the attributes of the analysed model, and if a geometric topology matches the rules, it will be converted into a city object and added into the cityGML model. Designers can customise the template rules according to the type and scale of their urban design. Example rules are as follows:

- If a shell has attributes `is_shell_closed = True`, `is_shell_in_boundary = True`, and `shell_boundary_contains = False`, then a building is generated.
- If a shell has attributes `is_shell_closed = False` `is_shell_in_boundary = False`, and `shell_boundary_contains = True`, then a terrain is generated.
- If a shell has attributes `is_shell_closed = False`, `is_shell_in_boundary = True`, and `shell_boundary_contains = True`, then a land-use plot on the terrain is generated.
- If an edge has attribute `is_edge_in_boundary = True`, then roads are generated.

In the last step, the CityGML is retrieved and shared among domain-specific experts to be further developed.

3 Implementation

The method described above is implemented as four Python classes in a Python library called Pyliburo [13] (*https://github.com/chenkianwee/pyliburo*). The Python classes rely on Pyliburo's modelling kernel for analysing the geometric relationship between the topologies and the CityGML writer for reading and writing CityGML. For this implementation, the massing model is in the Collada format. Each conversion can be represented by a `Massing2Citygml` class, which reads the Collada file and stores each geometric topology as a `ShapeAttributes` class. The analysis rules and template rules are implemented as abstract classes in Python, BaseAnalysisRule and BaseTemplateRule, to facilitate reuse and extensibility.

Fig. 2 illustrates the relationships between the four classes using a Unified Modelling Language (UML) class diagram. In the diagram, the Massing2Citygml class has a one-to-many relationship (1 to N) with the ShapeAttributes and BaseTemplateRule classes. When an instance of Massing2Citygml exists, it can be associated with an unlimited number of ShapeAttributes and BaseTemplateRule classes, as it is necessary to append multiple ShapeAttributes and BaseTemplateRule classes to Massing2Citygml in defining a conversion. The same relationship applies to the BaseTemplateRule and BaseAnalysisRule classes, where multiple BaseAnalysisRule classes are required to define a BaseTemplateRule. The details of each class and their relationships are discussed below.

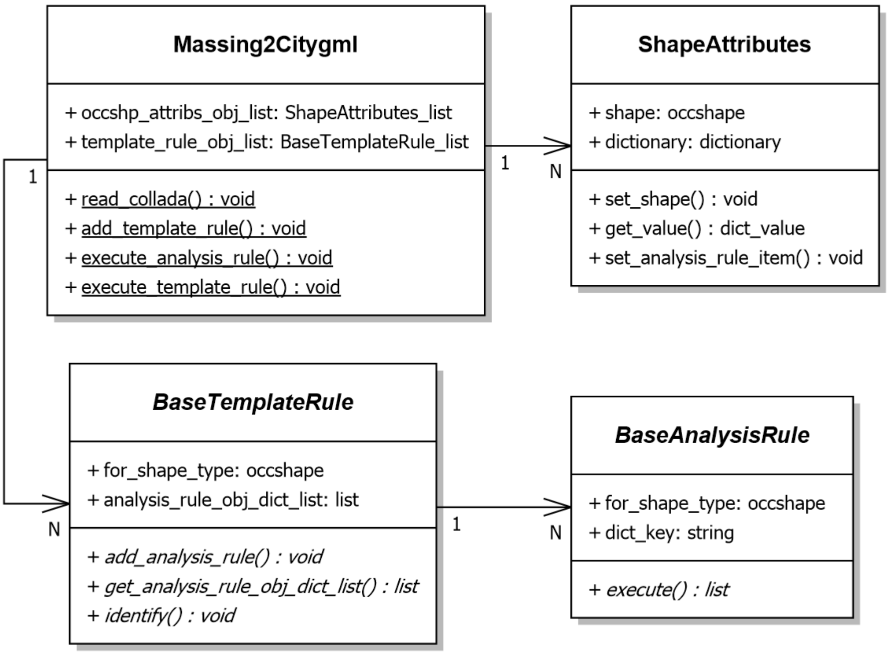

Fig. 2. UML class diagram of the relationships between the four classes

3.1 Massing2Citygml Class

The Massing2Citygml class represents any massing-to-CityGML model conversion. To set up a conversion process, users must set up a series of analysis rules (section 3.3) and then configure the analysis rules for each template rule (section 3.4). Users add the template rules into the Massing2Citygml class after it is configured through the add_template_rule method. The class will execute the analysis rules using the `execute_analysis_rule` method and the template rules using the `execute_template_rule` method to identify the city objects and write them to a CityGML file.

3.2 ShapeAttributes Class

The `Massing2Citygml` class reads the Collada file using the `read_collada` method, converting the geometries from the file to a topology and storing it as a `ShapeAttributes` class. The `ShapeAttributes` class stores each topology from the massing model as an `OCCShape` class as defined in the modelling kernel (PythonOCC). Any additional attributes of the `OCCShape` are stored as a dictionary. The method `set_shape` adds an `OCCShape` and `get_value` access the attributes stored in the dictionary. The `ShapeAttributes` class is the data exchange format between the other three classes.

3.3 BaseAnalysisRule class

The `BaseAnalysisRule` abstract class represents any analysis rule used for analysing and generating geometric relationship attributes for a massing model. As mentioned in the example rules in section 2, we have implemented four analysis rule classes; `IsShellClosed`, `IsShellInBoundary`, `ShellBoundaryContains` and `IsEdgeInBoundary`, based on the `BaseAnalysisRule` abstract class. We will describe the `IsShellClosed` implementation to illustrate the abstract class.

The `IsShellClosed` class has attributes `for_shape_type = OCCShell` and `dict_key = "is_shell_closed"`. `OCCShell` is the topology class to be analysed by the analysis rule and is as defined in the modelling kernel, PythonOCC. The `execute` method requires one input parameter `occshp_attribs_obj_list`, which contains a list of the `ShapeAttributes` instances from the massing model. The `execute` method loops through all the `ShapeAttributes` instances that are shells and assesses if they are open or closed shells. Once determined, it will append the geometric relationship attribute `is_shell_closed = True/False` to each `ShapeAttributes` instances. The topological attribute must be either true or false; this is enforced through the `set_analysis_rule_item` method in the `ShapeAttributes` class. The method then returns the `occshp_attribs_obj_list` with the topological attribute.

3.4 BaseTemplateRule Class

The `BaseTemplateRule` abstract class represents any template rule used for identifying a city object. As mentioned in section 2 example rules, we have implemented four template rule classes: `IdentifyBuildingMassings`, `IdentifyTerrainMassings`, `IdentifyLandUseMassings` and

IdentifyRoadMassings, based on the BaseTemplateRule abstract class. We will describe the IdentifyBuildingMassings implementation to illustrate the abstract class.

The IdentifyBuildingMassings class has attribute for_shape_type = OCCShell. The identify method requires two input parameters, occshp_attribs_obj_list and the citygmlwriter object from Pyliburo. The identify method loops through all the shells and assesses if they satisfy the geometric relationship attribute conditions set in the analysis_rule_obj_dict_list, a list of dictionaries documenting the analysis rules and their corresponding attribute conditions for identifying the city object of interest. The class provides flexibility for users to define their own analysis rules and its corresponding attribute condition. To identify a building object as specified in section 3, one will add and specify the analysis rules and corresponding attribute condition IsShellClosed = True, IsShellInBoundary = True, and ShellBoundaryContains = False, using the add_analysis_rule method. The identify method then retrieves the dictionary that specifies the analysis rule objects and its corresponding attribute conditions using the get_analysis_rule_obj_dict_list method and writes the shell as a building city object.

4 Examples

We demonstrate the feasibility of the automated workflow on three examples. Two simpler examples illustrate how the rules operate and one complex use case illustrates the potential of the workflow. We used SketchUp for modelling the simpler cases and Rhinoceros 3D for modelling the complex case. Using the four Python classes, we wrote a Python script for the conversion, basing it on the analysis and templates rules described in section 2. The source code of the script and the example files can be obtained from GitHub (*https://github.com/chenkianwee/pyliburo_example_files/blob/master/example_scripts/collada/convert_collada2citygml.py*).

A snippet of the source code of the conversion script is shown in Fig. 3. The script requires only two inputs: the Collada file and the file path for the generated CityGML file. First, we initialise the three analysis rules classes; IsShellClosed, IsShellInBoundary and ShellBoundaryContains. Second, we specify the corresponding geometric relationship attribute conditions of each analysis rule class IsShellClosed = True, IsShellInBoundary = True, and ShellBoundaryContains = False and append it to the template class. Third, we append the configured template class to the Massing2Citygml class.

```
input1 = Collada_file
input2 = CityGML_filepath
# 1.) set up the analysis rules
is_shell_closed = IsShellClosed()
is_shell_in_boundary = IsShellInBoundary()
```

```
shell_boundary_contains = ShellBoundaryContains()
# 2.) set up template rules
id_bldgs = IdentifyBuildingMassings()
id_bldgs.add_analysis_rule(is_shell_closed, True)
id_bldgs.add_analysis_rule(is_shell_in_boundary, True)
id_bldgs.add_analysis_rule(shell_boundary_contains,
False)
# 3.) add the template rule in the massing2citygml class
massing_2_citygml = Massing2Citygml()
massing_2_citygml.read_collada(input1)
massing_2_citygml.add_template_rule(id_bldgs)
massing_2_citygml.execute_analysis_rule()
massing_2_citygml.execute_template_rule(input2)
```

Fig. 3 Snippets of the conversion script with the two inputs highlighted in bold

The generated cityGML model is validated by Val3dity [14] and the CityGML schema validator [15]. Val3dity checks and reports geometrical errors of the 3D topologies in a CityGML model. The CityGML schema validator checks and ensure a CityGML model follows its schema definition. A valid CityGML model does not contain any geometrical or schematic errors.

4.1 Example 1

The first example is a simple case; it has a flat terrain, 44 land-use plots, 313 rectangular building extrusions and a road network of 56 edges as shown in Fig. 4a. The example contains a total of 3930 surfaces. We modelled the example using geometry groups as suggested in the SketchUp manual [16]. Extruded buildings, land-use plots, terrain and road networks are modelled as separate geometry groups. Each group is translated into a mesh when exported into Collada. Meshes in Collada contain both surfaces and lines, and meshes that contain surfaces are essentially shells. As a result, building extrusions, land-use plots and terrain geometry groups in SketchUp are automatically exported as closed shells and open shells respectively. The network lines are also automatically exported as edges in Collada. The exported Collada file is triangulated to ensure the geometries are properly translated, as we have experienced inaccurate export of complex geometries, such as those in example 2 and 3, with the non-triangulated option.

Lastly, satisfying all the requirements as mentioned in section 2, the Collada file is converted into a CityGML model as shown in Fig. 4b. Fig. 5 shows the difference between a building extrusion documented in Collada (Fig. 5a) and CityGML (Fig. 5b) after the conversion. The main difference is the building extrusion is explicitly declared as a building object in CityGML, while it is only documented as a mesh in Collada. This is also the case for all the other identified city objects; land-use plots, terrain and roads, in which their semantic information is explicitly declared in the CityGML file.

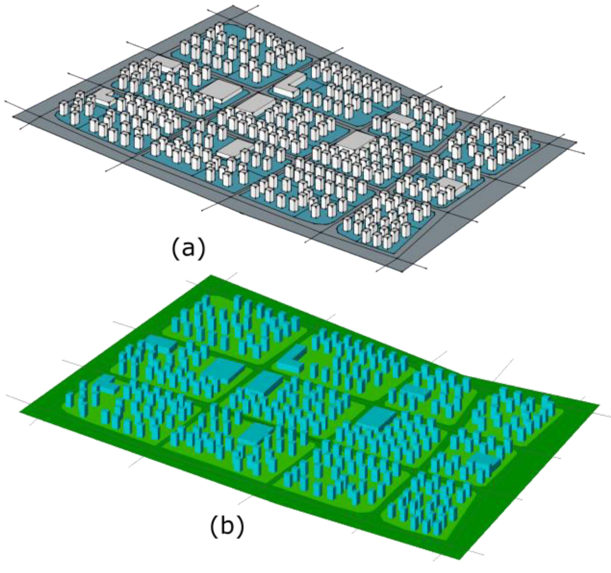

Fig. 4. Example 1 (a) SketchUp massing model (b) Converted CityGML model from the massing model

Fig. 5. (a) Building extrusion exported as Collada from SketchUp (b) Converted CityGML building extrusion with explicit building semantic information.

4.2 Example 2

The second example is a more complex case; it has an elevated terrain, 59 land-use plots, 453 building extrusions and a road network of 1125 edges. The added complexities are the TIN (Triangulate Irregular Network) mesh of the elevated terrain consisting of 4961 triangulated surfaces (Fig. 6a) and the non-rectangular building extrusions (Fig. 6b).

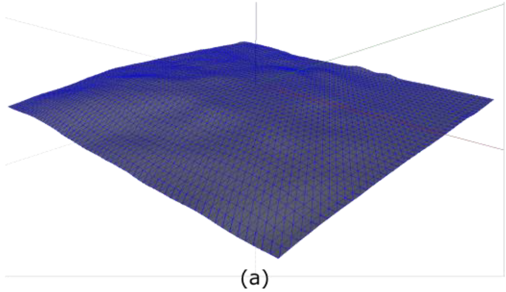

Fig. 6. Added complexities of example 2 (a) TIN mesh of the elevated terrain (b) Examples of non-rectangular building extrusions

All the geometries are modelled according to the recommended SketchUp modelling workflow (Fig. 7a). The example as shown in Fig. 7 contains a total of 37,794 surfaces. The conversion script converted the exported Collada into CityGML (Fig. 7b). The script was able to successfully identify the open shell terrain of 4961 surfaces and non-rectangular extrusions of 76 surfaces, and convert them into the CityGML object as shown in Fig. 8 and Fig. 9.

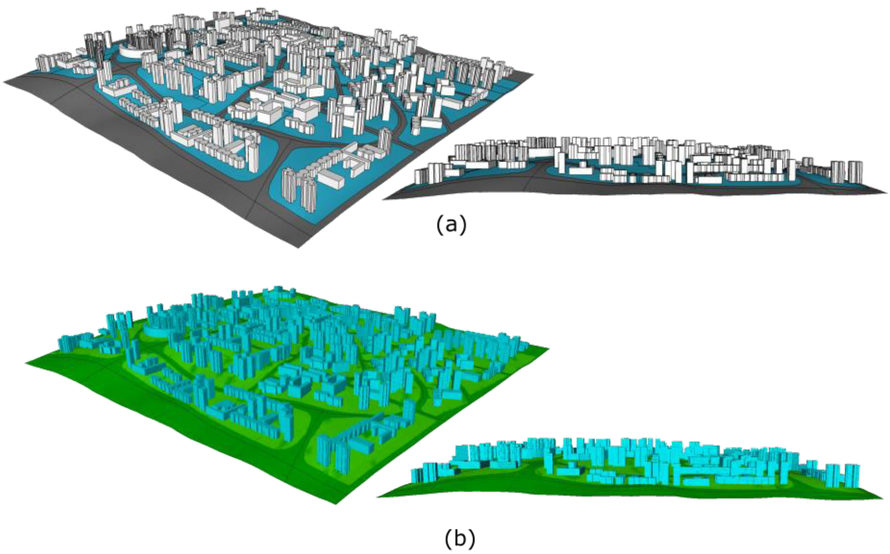

Fig. 7. Example 2 (a) SketchUp massing model with elevated terrain and non-rectangular extrusions (b) Converted CityGML model from the massing model

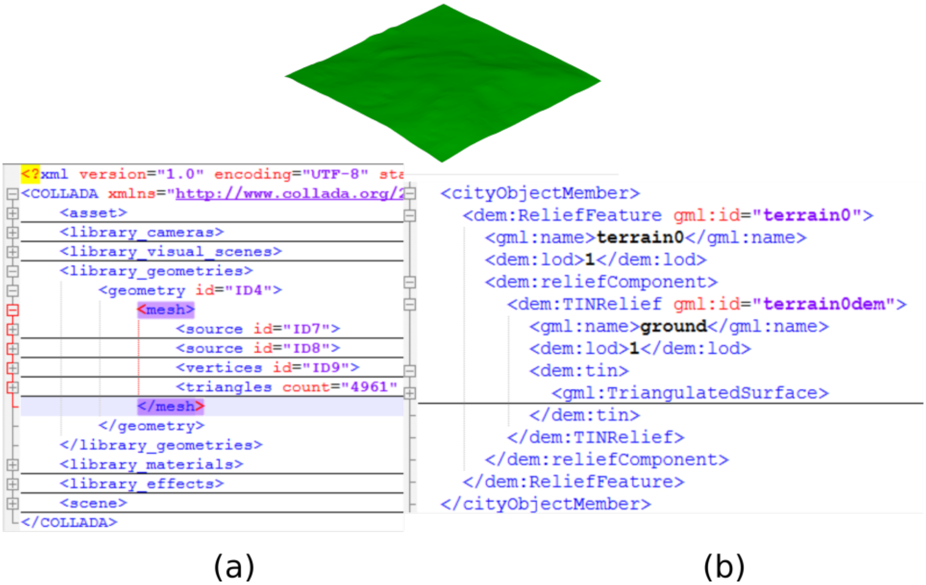

Fig. 8. (a) Terrain shell of 4961 surfaces exported as Collada from SketchUp (b) Converted CityGML terrain with explicit terrain semantic information

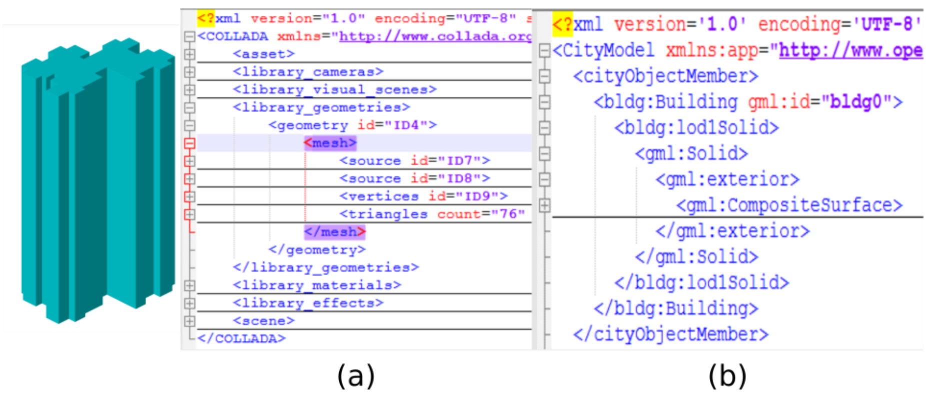

Fig. 9. (a) Non-rectangular building extrusion of 76 surfaces exported as Collada from SketchUp (b) Converted CityGML non-rectangular building extrusion with explicit building semantic information

4.3 Example 3

The last example is the most complex case of all; it has an elevated terrain, 60 land-use plots, 174 buildings and a road network of 1512 edges. The complexity of this example is that each building is a complex solid consisting of hundreds of thousands of polygon surfaces (Fig. 10). SketchUp's push/pull modelling technique [17] is not suitable for modelling such complex solids. We used a NURBS modelling application, Rhinoceros 3D, and modelled the geometries according to this application's recommended modelling workflow. The loft command was used extensively for modelling the twisting and slanting towers (Fig. 10a). The join command was then used to join all the lofted surfaces together to form a closed shell. For more complex geometries that are made up of multiple complex solids (Fig. 10b), the boolean union command was used to fuse multiple solids into a single solid.

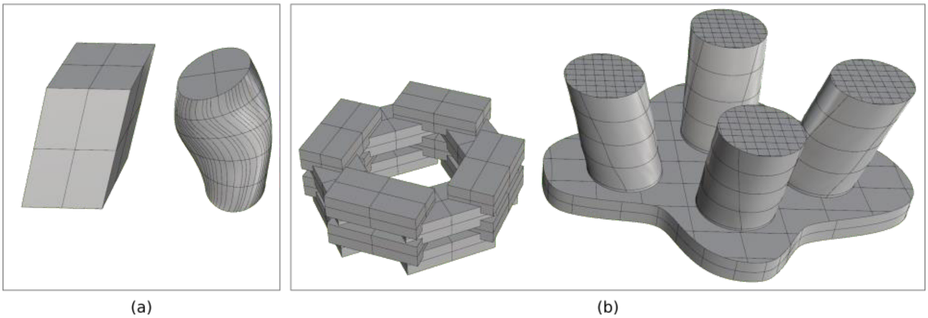

Fig. 10. Complex building solids from example 3 (a) twisting and slanting tower constructed with loft and join command (b) building consisting of multiple solids fuse into a single solid with the boolean union command.

Unfortunately, Rhinoceros 3D is only able to export the building, land-use plot and terrain surfaces and is not able to export the network edges into the Collada format. The workaround is to first export the surfaces from Rhinoceros 3D into SketchUp through the .3ds format and then continue to model the network edges in SketchUp as shown in Fig. 11a. The geometries are eventually exported as Collada and converted into CityGML using the conversion script as shown in Fig. 11b. The example contains a total of 255,953 surfaces. The script was able to successfully convert all the complex building solids into CityGML building objects. Fig. 12 shows an example of a twisting tower of 2960 surfaces and Fig. 13 an example of a building that is made up of multiple complex solids of 3270 surfaces that were converted into CityGML building objects.

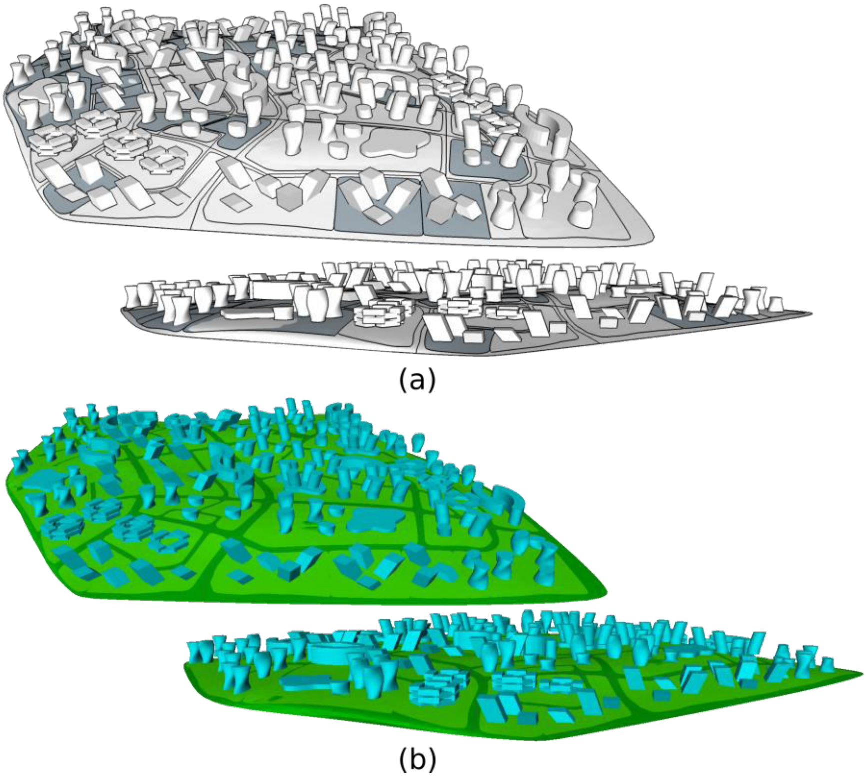

Fig. 11. Example 3 (a) SketchUp massing model with elevated terrain and complex building solids (b) Converted CityGML model from the massing model

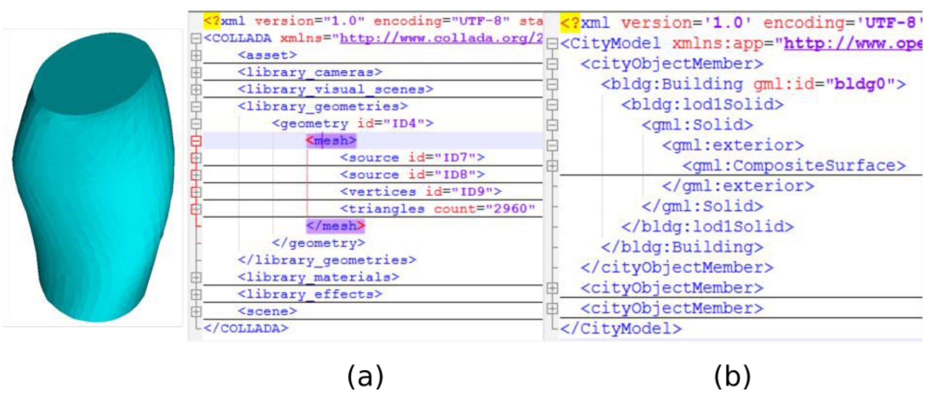

Fig. 12. (a) Complex solid geometry of 2960 surfaces constructed with Rhinoceros loft command and exported to SketchUp then to Collada (b) Converted CityGML complex solid with explicit building semantic information.

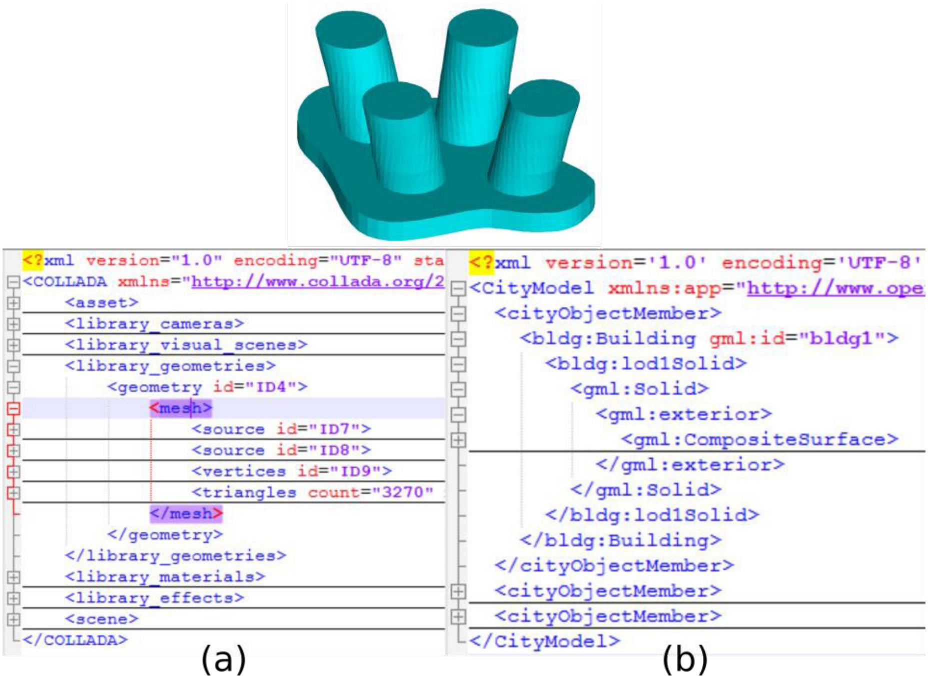

Fig. 13. (a) Complex solid geometry of 3270 surfaces constructed with Rhinoceros loft and boolean union commands and exported to SketchUp then to Collada (b) Converted CityGML complex solid with explicit building semantic information.

4.4 Discussion

The auto-conversion of the massing models to cityGML in examples 1-3 takes 1, 14 and 145 minutes respectively, on a workstation laptop with an i7 processor and 16GB RAM. The complexity in example 3 demands substantially more time for the conversion as compared to examples 1 and 2. However, 145 minutes of computational time is a considerable improvement compared to the required time for manually remodelling the cityGML model. Moreover, it is not common to model in such complexity in the early design stages; we foresee most applications will have the complexity of examples 1 or 2. As the Python library is still an early prototype, further improvement will be made to speed up the conversion process for complex examples. The working prototype will be open and free for usage and feedback (*https://github.com/chenkianwee/pyliburo/blob/master/massing2citygml.py*).

For designers with no programming background who follow the recommended modelling workflow of the respective 3D modelling applications, we have introduced a configuration that only requires two inputs for the conversion and demonstrated its feasibility with the three examples. We envision that the auto-conversion workflow would be used in conjunction with our previous research that generates a 3D semantic city model from open data online [18]. Based on the workflow introduced in [18], designers can acquire all the available data online for reconstructing the existing project site into a CityGML model and use it for the massing design stage. Unlike the conversion from a geometric to a semantic model where there is a need for inferring semantic information, all the geometric data is present in the semantic model. Thus, the CityGML model of the existing site can be easily converted into the geometric model and imported into any 3D modelling application for use in the massing design stage. The massing model will be constructed based on the site model. Essentially, with a streamlined workflow based on an open-standard city model, we hope to enhance communication between experts and facilitate the urban design process.

Currently, the auto-conversion method can only identify four types of city objects; buildings, terrain, land-use plots and roads. However, the library's flexibility and extensibility, described in section 3, allows designers with a programming background to easily configure or create new analysis and template rules catering to their own modelling workflow. One can easily reconfigure the current analysis and template rules for identifying exceptions. One such exception is that land-use plots demarcated for recreational use do not have to contain buildings; to identify such land-use plots one can easily add another land-use template rule with existing analysis rules, `IsShellClosed = False, IsShellInBoundary = True, and ShellBoundaryContains = False`.

When the existing palette of rules is not sufficient for identifying city objects of interest, Pyliburo provides the building blocks, a modelling kernel and a CityGML writer, for creating new rules. For example, one can identify LOD1 road networks by modelling roads as shells instead of edges. In this scenario, one can model the roads as open shells that are contained within a terrain shell and not containing other objects. This only requires the designers to implement a new template rule to identify LOD1 roads, while reusing the `IsShellClosed = False, IsShellInBoundary = True, and ShellBoundaryContains = False` analysis rules to identify the shells as roads.

Similarly, for identifying other transportation infrastructures such as tunnels and bridges, designers will have to decide the modelling procedure for such infrastructures. Tunnels can be modelled as closed shells that are below the terrain and bridges as closed shells that are floating above the terrain. This will require the designer to implement a new set of analysis rules and template rules. First of all, designers have to implement two analysis rules; `IsShellUnder` and `IsShellFloating`. To implement `IsShellUnder`, project the shell upwards; if it hits another shell, it means the projected shell is placed under another shell. Similarly for `IsShellFloating`, project the shell downwards; if it hits another shell and has a distance from the shell, it means the projected shell is floating above another shell. Then append these analysis rules to the template rules: `IsShellClosed = True` and `IsShellUnder = True` for identifying tunnels and `IsShellClosed = True` and `IsShellFloating = True` for identifying bridges.

5 Conclusion

This paper shows the feasibility of the workflow for automatically generating a semantic 3D city model, cityGML, from a conceptual massing model. The workflow does not require extra modelling effort from designers while modelling their massing design, as it leverages existing modelling workflows. The auto-conversion requires only two inputs, the massing model for the conversion and the file path to store the generated cityGML model. It eliminates the time-consuming and laborious task of remodelling massing models into cityGML models so that urban designers can focus on design rather than modelling technicalities. The cityGML model documents partial data from the early design stages in a standard format that can be readily viewed and modified by other 3D GIS applications, thus streamlining the process of sharing models between domain-specific experts. We envision this would facilitate communications between experts in an urban design process.

Further improvements of the auto-conversion include the development of an auto-correct feature for the massing geometries and a Graphical User Interface (GUI) for the library. First, for the conversion of complex geometries consisting of thousands of surfaces, it is demanding for the designers to ensure that each surface is error-free. We would like to implement an auto-correct feature to address this issue. Initially, we need to integrate the Val3dity library for identifying invalid geometries. According to the error identified, we will then develop algorithms using the modelling kernel from Pyliburo to fix the geometries. By doing so, the workflow will be more designer-friendly.

Second, we propose the development of a GUI for the library so that designers who are non-programmers are also able to change the analysis and template rule configurations. We propose developing a parameter tree GUI similar to feature-based modellers such as CATIA. In the parameter tree GUI, the analysis rules are nested within a template rule and the template rules within a `Massing2Citygml` conversion; one can readily remove or append rules to configure the conversion.

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Urban Data Mining with Natural Language Processing:

Social Media as Complementary Tool for Urban Decision Making

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Abstract. The presence of web2.0 and traceable mobile devices creates new opportunities for urban designers to understand cities through an analysis of user-generated data. The emergence of "big data" has resulted in a large amount of information documenting daily events, perceptions, thoughts, and emotions of citizens, all annotated with the location and time that they were recorded. This data presents an unprecedented opportunity to gauge public opinion about the topic of interest. Natural language processing with social media is a novel tool complementary to traditional survey methods. In this paper, we validate these methods using tourism data from Trip-Advisor in Andorra.
"Natural language processing" (NLP) detects patterns within written languages, enabling researchers to infer sentiment by parsing sentences from social media. We applied sentiment analysis to reviews of tourist attractions and restaurants. We found that there were distinct geographic regions in Andorra where amenities were reviewed as either uniformly positive or negative. For example, correlating negative reviews of parking availability with land use data revealed a shortage of parking associated with a known traffic congestion issue, validating our methods. We believe that the application of NLP to social media data can be a complementary tool for urban decision making.

Keywords: Short Paper, Urban Design Decision Making, Social Media, Natural Language Processing

1 Introduction

Compelling arguments for the use of bottom-up social opinions to inspire urban designs can be found in influential books such as "The Image of the City" (Lynch, 1960), "Death and Life of Great American Cities" (Jacobs, 1964), and "City is not a Tree" (Alexander, 1966). A large scale survey of public opinion for this purpose, however, was difficult in the 1960s because it relied on time-consuming traditional ethnographic tools such as surveys and interviews. Presently, modern geo-located data mining techniques can be deployed.

Compared to the traditional methods, such as sampled survey, NLP with social media is not only more cost-effective, but furthermore highlights urban issues on a microscopic scale. Instead of a random sampling, the comments from social media are issue-driven and spontaneous by nature. Compared to traditional methods, our approach provides a more objective perspective of subjective perception from mass. The result will not be limited by survey designers' knowledge or biased by their preconceived mindset.

This project aims to complement traditional ethnographic tools by mining social media data for the purpose of better understanding cities. These techniques are applied to analyze tourism data from Andorra, a small country between Spain and France. Our goal is to show how mining social media data for urban patterns may lead to useful recommendations to Andorran tourism authorities. We investigate how Andorra is perceived by tourists by analyzing social media. Specifically, we analyze a total of 68,500 Andorra-related tourist reviews obtained from Trip-Advisor (TripAdvisor, 2016).

We used "Natural language processing" (NLP) with Trip-Advisor to determine the sentiment of the users towards the hotels, restaurants, and attractions in the city of Andorra La Vella, the capital city of Andorra. By analyzing the words used in the review, this project extracts the topics most commonly associated with good and bad reviews, thus giving a greater sense of how the tourist experience can be improved for each Andorran attraction. This pinpoints problems and opportunities for Andorran urban designers and planners to focus on.

2 Previous Work

The origins of natural language processing sentiment analysis can be found in previous work such as "Sentiment Analysis and Opinion Mining" (Liu et al., 2012) which used sentiment analysis to examine the text of online movie reviews to automatically detect opinions about the various movies. Following this paper, others have begun to use sentiment analysis to examine other product reviews. Our approach is to apply it to urban design decision making.

3 Data and Methods

Our data analysis and urban decision making workflow involves 7 steps, summarized in Fig. 1. The steps are described below.

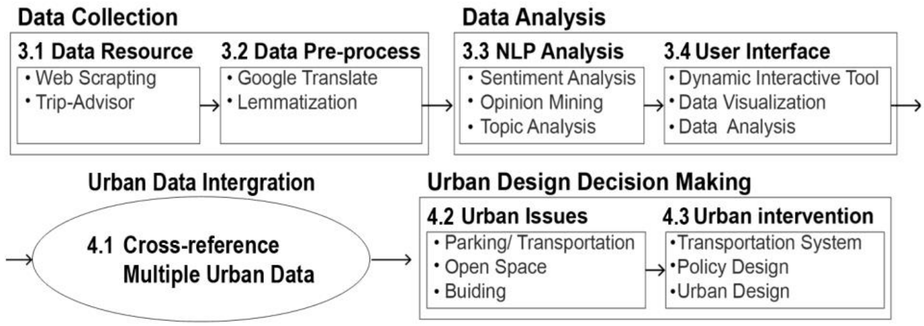

Fig. 1. Data analysis and urban decision making workflow

3.1 Data Resource: Web-Scripting Trip-Advisor

The first step of our analysis pipeline was to extract the relevant review information from each review for the Andorran destinations of interest. On Trip-Advisor we focused on three primary categories of tourist destinations: restaurants, hotels, and attractions. A web-scraper (a program which automatically obtains web content at large scale) was employed to extract the name, address, rating, and review attached to each of these destinations and record them in table format. From these re- views, we would identify sentences that describe urban issues, such as parking, restaurants or shopping. We used a script to parse the data from website based on the structured web format. Reviews were in multiple languages. Each review was translated into English, using Google Translate API, in order to enable subsequent language analysis. We are not using rating as part of the criteria, because it is not specific enough for the topic.

3.2 Data Pre-process: Translation and Lemmatization

Having standardized each TripAdvisor review page into English, the next step in our analysis pipeline was to simplify the page enough to enable NLP analysis by 1) extracting root words, and 2) removing superfluous words. This was done in several steps.

First, reviews had to be "tokenized", that is, broken into single words using the Natural Language Processing Toolkit (NLTK) tokenizer (http://www.nltk.org). Sentences such as "the parking is awful" were broken into its individual words ("the", "parking", "is", and "awful").

Second, each word detected was "lemmatized", by extracting their root word. The purpose of this step was to decrease the number of words that have to be analyzed by equating words like "run", "runs", "ran", and "running" into their respective single root word "run".

Next, the 200 most common words in the English language such as "the", "is", "are", "a", etc. were detected and deleted from the review pages, thus preventing these simple and frequent words from obscuring the more important and relevant words in the text that are actually important for understanding the topic matter. Noun phrases were next detected in the text using NLTK libraries.

3.3 NLP Analysis: Sentiment and Topic Analysis

This step helps to understand if a review is "positive" or "negative" for a related urban topic. We classified the reviews based on "sentiment". Based on NLTK libraries, we detected words that have a "positive" sentiment, and words that have a "negative" sentiment, within the reviews of each tourist destination. Each sentimental word was attached to its neighboring noun (which serves as the particular subject/topic), and the collection of sentiment-noun pairs were collected. For example, the sentiment-noun pair "beautiful lake" was collected.

Based on the sentiment analysis, an interactive visualization was created to enable user to have a comprehensive perspective of all Trip-Advisor destinations for La Vella. It allows for a heat map break down of reviews, sentiment, and relevance for all specific topics examined, as well as a breakdown by language of reviews to estimate the demographics of visitors to each destination.

3.4 User Interface: Dynamic Interactive Data Visualization and Analysis

The key technological development in this project was the production of a searchable visualization summary of all the Trip-Advisor locations to be used in the Andorra CityScope model. It includes a heat map of reviews, sentiment, and relevance to any searchable topic definable by a key word (e.g. "street", "parking", "shopping", etc.). It can also provide a breakdown by review language (Spanish, French, Russian, etc.), to further analyze the demographics of visitors to each specific attraction in Andorra. In addition to being searchable, each location has a popup card that displays information such as rating, summary of review, sentiment, and most popular keywords.

Fig. 2 shows an example of a search conducted in the user interface, searching for key word "street", in Spanish reviews. The degree of popularity of locations is indicated by regions colored from green (less popular) to red (most popular) with restaurants (red dot) and hotels (blue dot).

Fig. 2. HEAT map for search of key word "street" in the Spanish review

Fig. 3 shows the same search on key word “street”, but with the added condition to display the *sentiment* of the reviews, to show which locations were positively (green) and negatively (red) experienced by Spanish visitors.

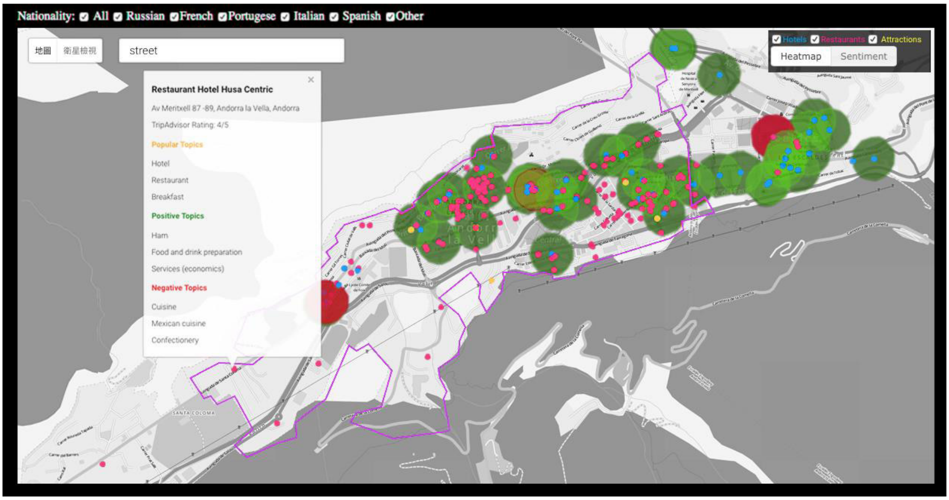

Fig. 3. Map for Sentiment analysis search of key word “street” in the Spanish reviews

4 Result: Data driven Urban Design based on Sentiment Analysis

4.1 Urban Data Integration

We now demonstrate how our User Interface is a valuable tool for urban design decision making. Before we can identify the urban issues, we usually need to cross-reference and integrate multiple urban data, including quantitative and qualitative ones. In this case, we compare the Trip-advisor sentiment map to a land use map.

4.2 Urban Issues

There are two districts, the old city center area and the new pedestrian district, that have a particularly high concentration of negative reviews by searching key words which is most related to traffic issues - “street”, “traffic”, and “parking” (Fig. 4 below, red circled areas). We immediately note a strong correlation between the areas of the city that are most negatively reviewed, and areas that have a lack of parking (Fig. 5 below). This is a novel observation that is a direct result of our data mining.

In this way, sentiment analysis points out issues of importance to the urban designer. Most tourists in Andorra visit by car, and if the city supply of parking facilities does not meet the demand, it invariably has a negative effect on city tourism, and reduces the likelihood that people will want to visit or stay in Andorra.

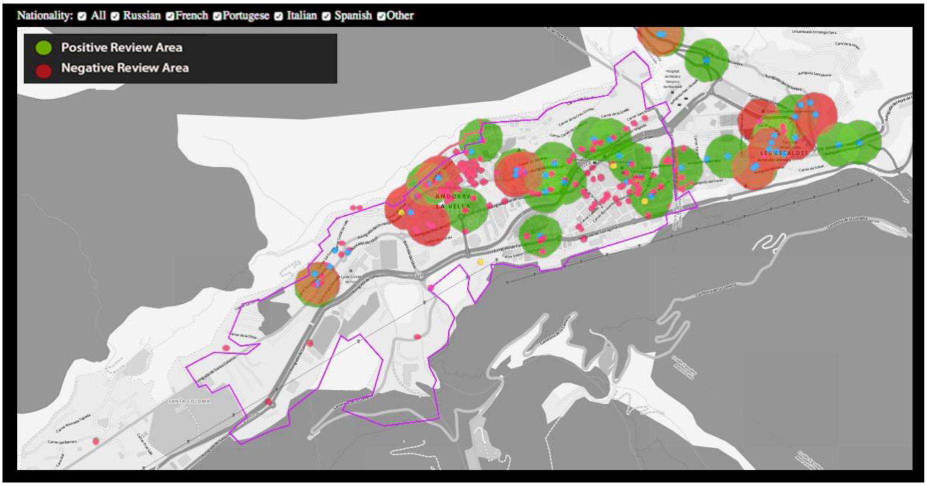

Fig. 4. Sentiment map for positively (green) and negatively (red) reviewed streets by searching key words “street”, “traffic”, and “parking”, with areas that are concentrated with negative reviews circled in red

Fig. 5. Availability of parking (blue), plotted with negative review-concentrated areas of the city circled in red

4.3 Urban Intervention

Social media data may provide urban designers bottom up information to make decisions about where their future design improvements should focus on. In this case, urban designers may need to alter the parking facilities around the old shopping centers or renovate the area.

In parallel with the parking problem, we figure out that there is another more general problem regarding transportation systems. After searching the key word "transportation", we got both positive and negative entries on the heat-map. We then zoom into the areas that have more negative entries, and click on each of them to examine what the original review is about. The negative reviews include "too many cars", "do not have bus stop", "narrow road", etc. Through this method, we are able to identify the urban issues through users' point of view. In this case, we realize that with increasing car usage, the traditional road system in Andorra Le Vella does not meet road usage demand. One can address both of these problems simultaneously. One possible solution is to increase the public transportation system for intra-city network connections, which would help alleviate the overall traffic condition.

5 Conclusion

Our analysis of social media data revealed the most positively and negatively reviewed tourist locations. By comparing the regions to the land use map, we identified a prevalent issue of parking in the city. Urban decision makers may benefit from this new approach of the data source compared to the traditional methods, such as sampled survey. NLP with social media is not only more cost-effective, but also it provides an insight on the urban issues by examining spontaneous reviews, rather than survey answers guided by the survey designer. We suggest that our approach of combining social media "big data" with natural language processing to detect patterns of sentiment is a useful new methodology for the urban designer and planner, and can give data-driven insights that would have been hard to collect otherwise. We wish that our work will inspire more related research or applications

6 Future Work

In the current research, we successfully used NLP with social media to identify the parking problem in Andorra and to understand the causal reason. The same approach could be use by urban planners or designers in broader ways. Here are some possible applications:

- Land use – to understand if there is a good balance between residential and employment spaces in a certain area.
- Transportation – to analyze the composition and experience of different traffic modes: biking, working, driving and taking public transportation. It provides a great guide for improving the urban transportation infrastructure.

- Open space – to understand the perception of the public urban environment: if we need a park and, if so, where is the optimal location.
- Third places – if there is any complaint about a lack of restaurants, grocery stores, etc.; if there are enough cultural facilities, such as a museum or library.
- Healthcare – to examine the quantity and quality of healthcare resources, such as hospitals, pharmacies, and places to have physical exercises.
- Security – to understand how safe the neighborhood is.
- Education – if there are enough education resources like schools and day-care centers.

To enable the new applications mentioned above and to improve the precision and comprehensiveness of the methodology, future work will be conducted as follows:

- Trip-Advisor data analysis will be compared to government GIS data to validate our spatial observations.
- Analysis of other types of social media (Twitter, Flickr, Facebook, Instagram, etc.) will be conducted to reduce sampling bias in our data from analyzing only one type of social media.
- Trip-Advisor data analysis will be overlaid with Call Detail Record (CDR) data to understand the mobility patterns of tourists.
- Computer vision will be employed to detect the activities and the image of cities in social media pictures.
- Stakeholders will be able to conduct real-time monitoring or intervention using NLP with social media in circumstances such as during massive events or nature disaster.

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Interactive Urban Synthesis

Computational Methods for Fast Prototyping of Urban Design Proposals

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Abstract. In this paper, we present a method for generating fast conceptual urban design prototypes. We synthesize spatial configurations for street networks, parcels and building volumes. Therefore, we address the problem of implementing custom data structures for these configurations and how the generation process can be controlled and parameterized. We exemplify our method by the development of new components for Grasshopper/Rhino3D and their application in the scope of selected case studies. By means of these components, we show use case applications of the synthesis algorithms. In the conclusion, we reflect on the advantages of being able to generate fast urban design prototypes, but we also discuss the disadvantages of the concept and the usage of Grasshopper as a user interface.

Keywords: Procedural grammars · Artificial intelligence in design · Urban synthesis · Generative design · Grasshopper plugin · Cognitive design computing

An Experimental Methodology for Urban Morphology Analysis

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Abstract. The paper presents results of a research conducted in 2015 and 2016 at Lodz University of Technology. It proposes a purpose and context fit approach towards the automation of urban data generation based on GIS tools and New Urbanism typologies. First, background studies of methods applied in urban morphology analysis are revealed. Form-Based Code planning, and subsequently Transect-Based Code are taken into account. Then, selected examples from literature are described and discussed. Finally, the research study is presented and the outcomes compared with more traditional methodology.

Keywords: GIS · Urban morphology · Spatial analysis · Decision support systems · Urban design · Data analytics · Modelling and simulation

CIM-St

A Parametric Design System for Street Cross Sections

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Abstract. City environment is very much determined by the design of its streets and in particular by the design of its cross section. This paper shows a street cross section design interface where designs are controlled by an ontology and a parametric design system. The system keeps its semantic structure through the ontology and provides a design interface that understands the computer interaction needed by the urban designer. Real time visual analytics are used to support the design decision process, allowing designers to objectively compare designs and measure the differences between them, in order to make informed decisions.

Keywords: Parametric design · Ontologies · Compound grammars · Street cross section · Urban design systems

Building Performance Studies

Shape the Design with Sound Performance Prediction

A Case Study for Exploring the Impact of Early Sound Performance Prediction on Architectural Design

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Abstract. Acoustics is typically considered only late in developed design or even post occupancy, if at all, for specification of finishes and furnishing, and typically with a remedial mindset. In this paper, the role of sound performance as a design driver in increasing the speech privacy of a semi-enclosed meeting space in an open plan interior is studied. Sound performance prediction is applied as an imperative input to inform the meeting space design. The design is the second iteration in an evolving series of meeting spaces, and therefore has benefited from both subjective experiments and objective measurements performed with the first meeting space prototype. This study promotes a design method that offers a strong relationship between the digital simulation of sound performance and design development. By improving the speech privacy of a meeting space by means of purely form, geometry and design decisions, the significance of architecture in tuning the sound performance of a space is investigated.

Keywords: Sound Performance Prediction, Sound Simulation, Meeting Space, Architectural Design

1 Introduction

With the recent trend of using simulation techniques in processes of designing, acoustics has always received less attention from both designers and software developers in comparison to the other design parameters such as light and energy. One probable reason is the complexity of sound wave behavior and human sound perception.

Although there has been much improvement in acoustic simulation and computational techniques in recent decades [1], architects barely apply sound performance prediction as a design driver in the early stages, except for the design of concert halls and auditoriums. In the best scenario, sound performance is thought of as a self-contained aspect of a design, with no influence on the other design imperatives, and it is considered and analyzed only in the final phases of the design.

Often, the result of sound performance analysis doesn't cause a major modification in the final design and geometry but only serves as a representation of a promising output of a project. Even if the result is not encouraging, it simply implies that space needs further treatment after construction. This counters the purpose of prediction, which is to improve the acoustic performance of a room before it is built [2]. This is to say that architects approach acoustics in a remedial mode of practice after either the design completion or building construction [3].

This study integrates the acoustic analysis as a design driver in an architectural design process. The aim is to highlight the significance of sound performance prediction in the design progression, particularly in spaces that require sound considerations as fundamental to the use of space. Meeting rooms are one of those spaces that need specific acoustic considerations to provide an acceptable level of speech privacy and speech intelligibility. A semi-enclosed meeting room is selected as the design case study in this research to address the lack of speech privacy as one of the most prevalent complaints reported in the open plan interiors.

Moreover, the research investigates and develops a design method that offers a strong relationship between digital sound simulation and parametric design. It combines the results of the previous subjective analysis with simulation prediction to inform the geometry and shape the space. The project has benefited from the experimental studies conducted in the first prototype of a semi-enclosed meeting space and therefore subjective analysis was actively involved in the design process together with acoustic simulation techniques. This novel work-flow has enabled us to obtain feedback from subjective experiments, notably in regards to human auditory perception, when digital modelling has provided limit answers.

2 Project Background

The motivations for initial investigations were the field observation at Sagrada Familia Church in Barcelona when it was opened to the public in 2010. The very first human sound experience of the space was a diffused sound field, which was ascribed to the scattering effects of doubly curved hyperboloid cells in the nave walls [4]. Following the hypothesis, a 1:1 prototype of a hyperboloid wall was built and analyzed in SmartGeometry 2011 [4] to confirm the sound scattering attribute of the hyperboloid geometry.

With promising results obtained, the research extended further to investigate the impact of diffused sound fields on increasing the speech intelligibility of small spaces. A semi-enclosed meeting space composed of hyperboloid modules was designed, named FabPod and situated in an open plan office at the Design Hub, Royal Melbourne Institute of Technology (RMIT) University in Melbourne, Australia. The non-rectangular walls and highly articulated cells with hyperboloid geometry in FabPod aimed to achieve a less echoic, resonant space and consequently more speech intelligibility (Fig.1a) [5]. At this stage, the focus of the research was tuning the sound

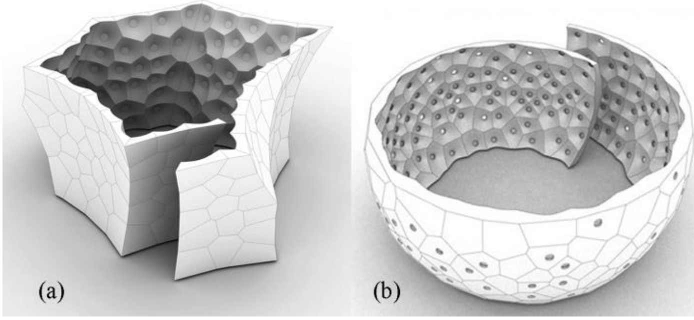

Fig. 1. (a) Meeting space final design, convex form. (b) proposed concave form

performance of the pod's interior through surface articulation. Underpinning the FabPod's overall geometry was the fabrication limitation and construction logic for having planar hyperboloid intersections. This could be achieved by intersecting various circles to produce a convex form that is aesthetically more preferred than a concave shape (Fig.1b).

Upon completion of the 1:1 prototype, further measurements and experiments were performed in the FabPod I to evaluate the pod's sound performance from both objective and subjective views. Improved speech intelligibility inside the meeting pod was confirmed with acoustical measurements [6], while in the preliminary speech privacy measurements, the FabPod I could not meet the criteria of a private space [7]. In addition to the measurement processes that conformed to international acoustic standards [8], two distinctive subjective experiments were performed adopting an architectural rather than engineering approach. The first subjective experiment aimed to verify the sound simulation prediction with the human auditory experience in the pod [9], while in the second subjective experiment the impact of sound diffusion field and improved speech intelligibility on speech privacy of the space was investigated.

A cross validation technique was applied during the first experiment with human participants to verify the results of the Odeon (Room Acoustic Software) simulations. That is, the field measurements performed during the experiment were compared with previous standard acoustical measurements. The consistency between the two objective measurements established reliable grounds for the architectural subjective setup and verified the human perceptions of privacy. Subsequently, simulation results were further congruent with human sound perception in the space, which provided a platform for predicting the sound performance of the second generation of the design, FabPod II, with sound simulation software, Odeon [9].

In the second subjective experiment, human sound experience substantiated the significance of sound field diffusion in tuning the acoustic environment, yet the improved speech intelligibility did not affect participants' vocal effort and consequently did not influence the speech privacy. This experiment included a thorough investigation of the speech intelligibility of the space and its relationship with human vocal effort and speech privacy, which is beyond the scope of this paper. But it is vital to mention that the experimental outcomes indicated that the direct sound is the primary sound energy that governs a face-to-face conversation in small meeting rooms; therefore, improving the speech intelligibility of a small space beyond a certain point, although perceivable by human ears, should not be the priority. This experimental finding altered the focus of the research in designing the second design iteration for the pod from increasing speech intelligibility to increasing speech privacy, and also from surface articulation design to the overall geometry of the space.

With the above research background, the FabPod II development as presented in this paper followed a series of already established design proposals to create an innovative design to fulfill fabrication process, sound performance, and architectural aesthetic requirements.

3 Sound Simulation

Physical modelling and scaled physical modelling was widely adopted and applied for more than 60 years before digital acoustic simulations provided a more powerful and time-saving alternative [10]. Developed digital modelling techniques for sound prediction provide an opportunity for architects to integrate the sound phenomenon considerations in the early stages of design. Yet, the validity of the results and the degree of consistency with human auditory perception is still in question. In addition, the limitations of such simulations should be recognized and acknowledged in the design process, as discussed below.

3.1 Simulation Technique

Acknowledging potential sources of errors such as Computer Aided Design (CAD) model approximation, material data and algorithmic details [11], for this case study the room acoustic software Odeon has been adopted as the software of choice. Odeon uses a hybrid room acoustical model which combines both ray tracing and image source methods and has limited practicality in simulating surface articulation. The validity of the software results and its consistency with the human auditory perception have already been verified by the subjective experiment and objective measurements performed by the authors in the first generation of the design [9].

Moreover, Insul, sound insulation performance predictive software has been used to determine the sound transmission reduction through the structure and material. Further details of the Insul simulations are beyond the scope of this paper, however, the data produced by this software was imported into Odeon to fully integrate the impact of both material and structure into the digital modelling prediction. This method has been developed to improve the simulation predictive results for FabPod II since the effect of transmission loss had not been considered in the initial simulations of FabPod I.

3.2 Simulation Parameters and Specifications

The research aimed to address speech privacy, one of the most common problems of open plan spaces. Therefore, the results of this study might be informative in general for all types of open plan offices. But, since this is practice-based research, context is therefore required. The first iteration of the pod is situated in an open plan working space in the RMIT Design Hub and the second prototype will be situated in the same building but on a different floor level. The office is 55 x 10 x 3.30 m high with three entirely glassed walls and one painted concrete wall. The acoustic specifications for all surfaces are illustrated in Table 1. For eliminating the impact of materials in simulations, all of the pod surfaces were assigned a 20% absorbent material.

Table 1. Absorption coefficient (α) of the open interior surfaces

Frequency (Hz)	*125*	*250*	*500*	*1000*	*2000*	*4000*	*8000*
Ceiling	0.30	1.00	1.00	1.00	1.00	0.97	0.97
Floor	0.00	0.05	0.05	0.10	0.05	0.00	0.00
Glass	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Wall	0.10	0.05	0.06	0.07	0.09	0.08	0.08

Interpreting the sound simulation outcome requires the selection of appropriate parameters. For many years the Reverberation Time (RT), regardless of the space characteristics, was the primary parameter for analyzing sound performance [12]. Since the initial part of the decay curve, that is significant for speech intelligibility, is not included in the RT, the human speech perception, therefore, cannot be fully represented in small spaces. Instead, a more recent parameter, the Speech Transmission Index (STI), has been developed to describe the quality and the amount of the speech understood in the space. The STI is a value between 0 and 1. Odeon calculates the STI by applying the indirect method in compliance with the international standards ISO 9921 and IEC 60268 [13].

The target of the design is to achieve minimum STI in the open working area while maintaining the required speech intelligibility in the pod, where more conversations and meetings are taking place. Less STI in the open office areas offers less speech comprehension, which delivers more speech privacy for occupants holding a meeting in the pod. In addition, more speech privacy brings less distraction and more productivity in the open office.

4 Architectural Design Development

The back and forth process between architecture and acoustics together with feedback obtained from the first prototype consequently shaped the composition of architectural design. In this section, following the interaction between sound interpretation and geometric rules, a continuous improvement in speech privacy of the open plan space can be noticed.

While acoustic simulations provide both visual and numeric results, for this paper, a grid colored map of STI has been selected as a preferable architectural method of presentation.

4.1 Geometric Investigations

Preliminary design for the second prototype simply followed the convex form derived from aesthetic preferences in the FabPod I but in two different iterations. Two overall enclosed surfaces were presented in the initial phase of the design. Both geometries stemmed from a funnel shape that has a smaller area in the plan relative to the ceiling with the walls gradually diverging towards the top.

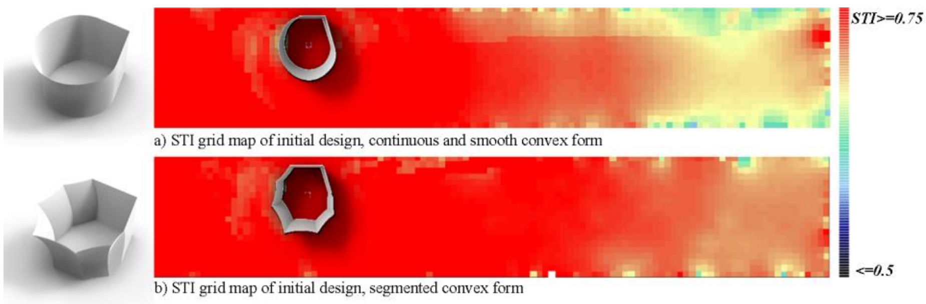

Fig. 2. Odeon simulation results for two iterations of convex geometry

The results of the simulation for the first two iterations are illustrated in Fig. 2. The STI grid map of the working area suggests that both geometries failed to provide a minimum privacy requirement of the space. A supplementary cumulative distribution graph shows that quite 100% of the working area has the STI above 0.6 which is the maximum threshold for providing poor speech privacy (Fig. 3). This can be explained through the nature of the funnel form which may assist the sound waves in propagating out from the pod and beginning to spread in the open interior in a shorter period of time.

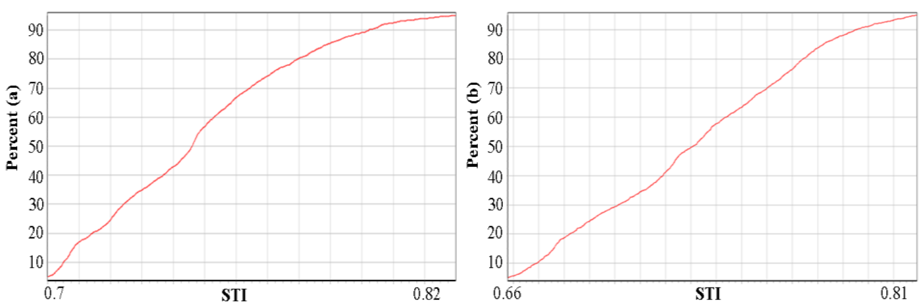

Fig. 3. Cumulative distribution graphs a) segmented convex pod, b) continuous convex pod

Although both forms with similar volume and curvature were almost unsuccessful in fulfilling the privacy requirement, it is clear from the Fig.2 that a convex form with a smooth and continuous structure performs better than the segmented shape with intersection lines. The negative curvatures inside the pod in these two iterations appear to be the most problematic cause of decreasing speech privacy. Therefore, the degree of the curvature might be one of the most important factors which highly influence the sound behavior in the space. The ratio of pod's top edge area to floor area seems to be another determinant factor.

At this stage of the design, it was hypothesized that the characteristics of the general structure, degree of the curvature and ratio of the top to floor area needed further investigation and consideration for feedback into the design.

In order to undertake a comparative analysis to study the three above-mentioned parameters of the hypothesis, a geometric system including intersecting spheres, smooth surfaces and boolean operations was established. With this system, both discrete and continuous forms can be generated using the same parameters in terms of size, curvature and composition (Fig. 4).

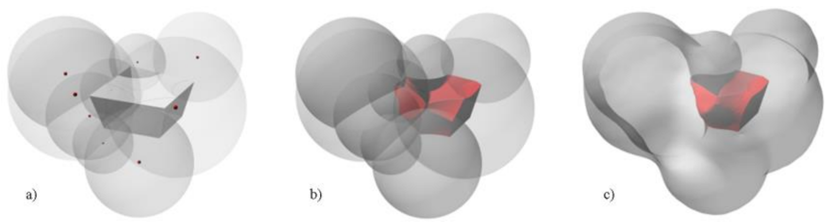

Fig. 4. Geometric system a) intersecting spheres, b) boolean operation, c) smoothing

First Set of Comparative Shapes: Diverging Shape and Curvature Degree

For investigating the impact of concave geometry and diverging form two identical geometries were developed. The forms consist of convex parts which clustered in a concave form. Therefore, the overall compositions read as a concave shape.

Comparing this set of geometry with the initial design highlights the advantage of diverging form over the converging structure (Fig. 5).

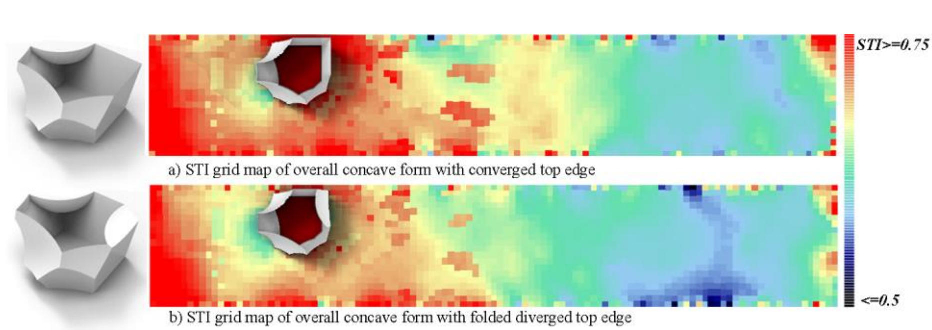

Fig. 5. Odeon simulation comparison, Set I

The only difference between the two pods in the comparison in Fig. 5 is the folding part on the ceiling edge which changes the pod's curvature. As illustrated in the STI simulation results, the slight alteration not only decreases the sound transmission to the immediate surroundings but also offers effective improvement at multiple locations across the whole office area. This modification provides STI below 0.6 for at least 20% of the working area, which is a 10% improvement relative to the other geometry.

Second Set of Comparative Shapes: Smoothing the Intersection Lines

In the process of refining the geometry in response to the sound performance, the intersection lines in the second form above (Fig. 6b) was converted to a smooth, continuous form to further investigate the effects of surface alteration.
As indicated in Fig. 6, the outcome is promising in terms of increasing speech privacy. One possible reason might be attributed to the increasing reflections inside the pod when the structure is more joined and unified. The extended reflections keep the sound energy inside the pod for a longer period of time and only releasing the energy into the open interior after significant sound energy decay.
The cumulative distribution function graph shows an improvement of 12% in the total area having the STI below 0.6, compared to the previous geometry.

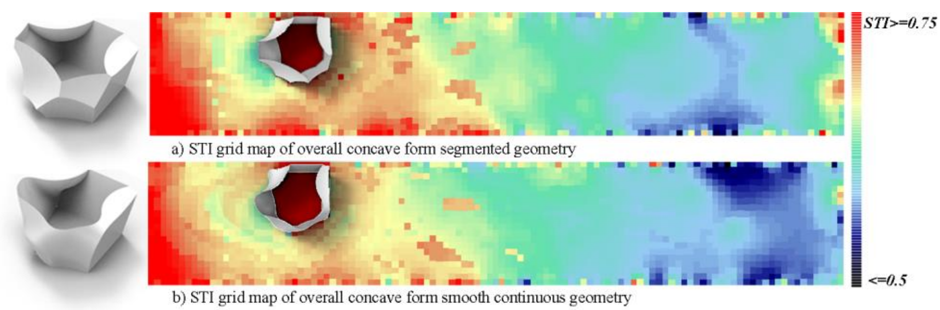

Fig. 6. Odeon simulation comparison, Set II

Third Set of Comparative Shapes: Reducing the Ratio of Ceiling to Floor Area

In this section, the first geometry from the first set of comparative shapes was simply flipped upside down to invert the ratio of the top edge to the floor area. Comparing the two simulations readily suggests a dramatic increase in speech privacy of the space (Fig. 7). The efficiency of the latter pod in terms of sound performance can be explained by having more control on the sound rays' paths, impeding sound propagation and reflecting sound waves back into the pod.

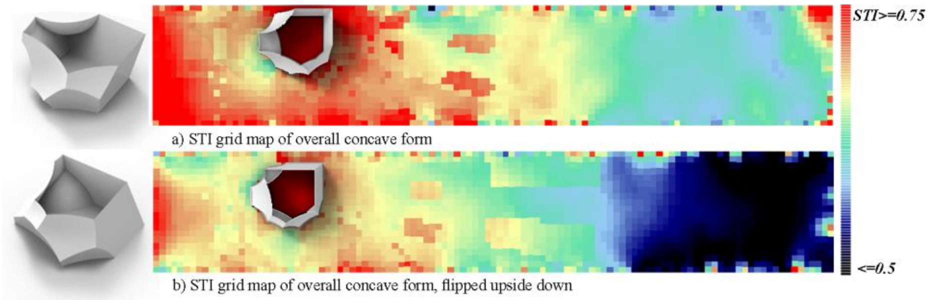

Fig. 7. Odeon simulation comparison, Set III

4.2 Tectonic System Development

A digital fabrication and construction system was developed in parallel with the sound performance exploration as one of the primary aspects of architectural design. The 3-way interaction between the architectural design, fabrication development and sound performance analysis provides the possibility of offering practicable geometries and structures. The feasibility of the workflow was verified by both digital and physical prototyping (Fig 8, 9). The digital prototype at this stage is an illustration of a balance between the sound performance, constructability and architectural design.

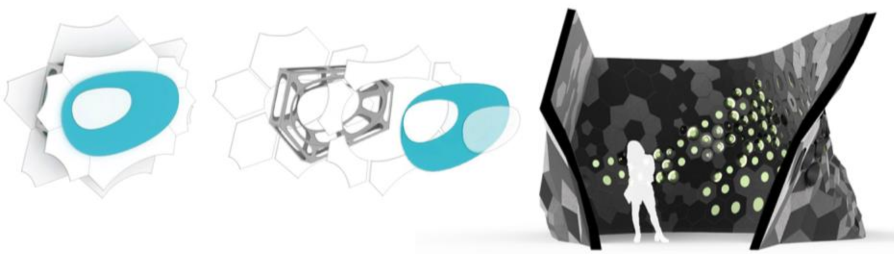

Fig. 8. Digital prototyping parallel to acoustic analysis

Fig. 9. Physical prototyping parallel to acoustic analysis

The construction system has been developed with a lightweight thin modular steel metal structure. Individual cells are custom cut in sheet metal and folded in a cellular arrangement for increasing structural strength and stacked together to provide the overall system framework that can be covered later with acoustic panels. This construction technique allows the system maximum flexibility, which can be readily adapted to various forms while maintaining the modularity for further extension and mass production in manufacture. Also, the system can be adapted to local conditions and fit into different project briefs. Furthermore, a thermal formed CNC (Computer Numeric Controlled) trimmed conoid is used to create aperture to provide light and visual connection between the internal and external spaces.

To develop the construction work-flow parallel to the design progress, several prototypes for modules were produced which ultimately had a great impact on the architectural design. One of the most influential constructed elements was the aperture.

It was decided to fit two apertures on a single conoid to cut down the material waste (Fig. 10). Also, for reducing the number of cells the operational volume of the robotic arms was maximized which directly affected the conoids' size.

As Fig. 10 illustrates, each of the two unique apertures in different sizes is calculated and mapped onto one standard thermal formed conoid. This fabrication process increased the size of the apertures dramatically and prompted larger steel modules (Fig. 11). As a result of fabrication constraints, the cell size limits the application of surface articulations and therefore calls for a new design composition with less geometric complexity.

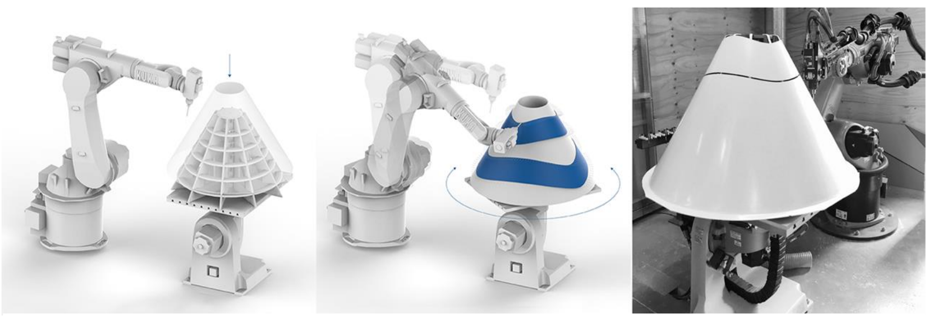

Fig. 10. Map two conoids on one large cone in the trimming process

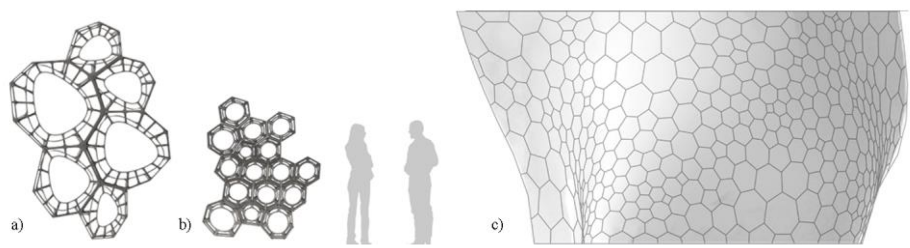

Fig. 11. Conoids size alterations, a) new cells, b) former cells, c) cells mapped on last iteration

4.3 Design Decisions: A Trade-Off Architectural Solution

Responding to both acoustic needs and fabrication constraints simultaneously requires a new parametric design that delivers a novel architectural solution to all the individual parameters.
For achieving the highest possible speech privacy whilst addressing the construction requirements, two primary design decisions were considered targeting a new formal composition:

- For facilitating the planarization, construction, and assembly process, a combination of both discrete and continuous geometry is suggested. Although the notion of continuity appeared to be one of the sound performance parameters, a compromise in the new design offers a better architectural solution.
- A double layer structure is proposed to address both acoustically well-performed interior concave surfaces and an aesthetically preferred exterior convex shape.

New Geometric System

In redesigning the geometry, a new method of intersecting tori rather than spheres has been adopted for three primary reasons:

- A torus has two internal and an external curvature. The radius of each curvature can be modified individually and therefore offers greater freedom in the design process and brings an inherent simplicity for construction. This includes an ease in assembling and dismantling when splitting the pod into separate tori.
- For achieving a geometry with the better sound performance the internal tube curvature can be adjusted while a gentle exterior curvature helps avoid potential construction problems. The double curvature of the torus is a particularly effective strategy for a double layer structure. It assists in providing enough flexibility to control the distance between the layers.
- Another advantage of the double curvature in the torus geometry over the sphere is the significant reduction in the unpleasant sound reflections at one focal point. This is specifically beneficial in improving the speech intelligibility of the space.

A double layer skin is developed with a grasshopper script with an exterior diverging structure and interior converging shape (Fig. 12).

The double skin geometry was simulated in Odeon to verify the sound performance of the system and to rank the iterations in order of improved speech privacy. It can be seen from Fig. 13. that the design process of iterations followed an upward trend in increasing the speech privacy. There is a dramatic improvement in the speech privacy of the open interior from the first initial design with 100% of the space having full speech intelligibility to the final iteration, where almost 55% of the space has STI below 0.6.

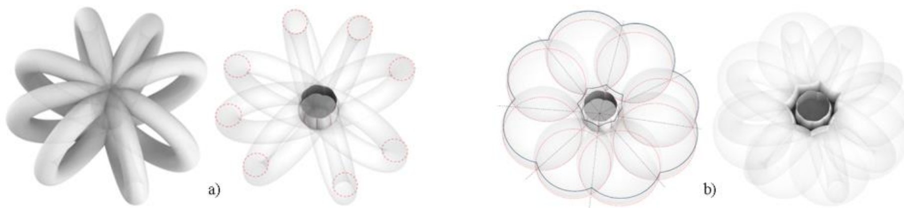

Fig. 12. a) Internal layer, intersecting tori, b) external layer, intersecting hemispheres

5 Conclusion

This study investigated the impact of architectural design in improving the sound performance of semi-enclosed subspaces within an open interior. Acoustics can be applied as a design driver at early stages of design and the interaction between auditory analysis and other design imperatives such as fabrication constraints can play an active role in shaping the architecture. In the design process of a semi-enclosed meeting space in an open layout interior, as a case study in this research, a speech privacy improvement of approximately 55% was achievable purely by the means of architectural geometry. This improvement can be further increased by applying acoustic solutions such as absorbent materials. Moreover, the results of this study might be informative generally in terms of geometric rules for semi-enclosures in open interiors to increase the speech privacy and therefore productivity.

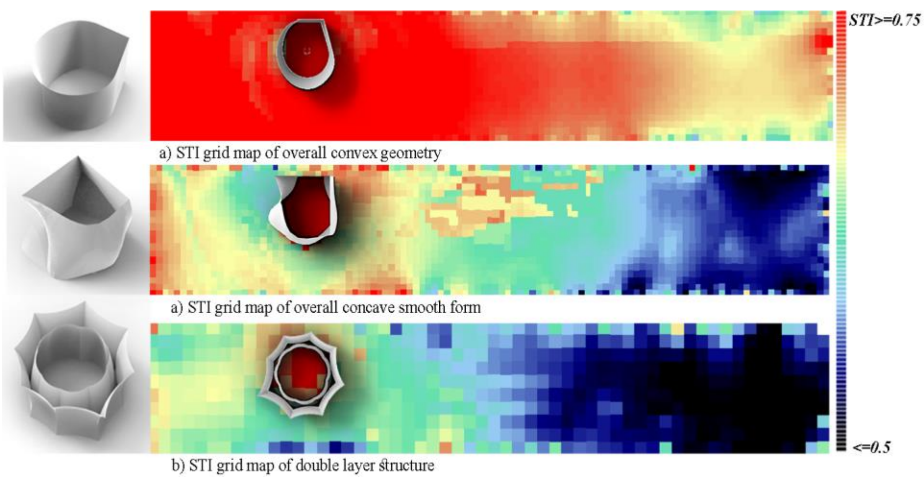

Fig. 13. Increased speech privacy in the design progression from top to bottom

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RhinoRstab

Introducing and Testing a New Structural Analysis Plugin for Grasshopper3D

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Abstract. This paper presents a new open-source structural analysis plugin for Grasshopper – RhinoRstab. The plugin bridges data between the worldwide established software: Rhinoceros3d and Dlubal RSTAB. The basic idea behind the approach is to create an interactive workflow between the architectural design on the one hand and a structural analysis tool on the other hand. In contrast to RhinoRstab, other analysis tools for Grasshopper predict the structural behaviour independent of its structural capacity. Thus, additional standalone software is necessary to verify the analysis of these plugins subsequently. To test the validity of this new tool, it is compared to a similar application, namely Karamba (a widely used structural analysis plugin for Rhinoceros/Grasshopper). Both tools are tested in different scenarios. The study shows that for some elements in a structural system and some calculation methods RhinoRstab and Karamba results differ strongly. However, regarding the runtime, Karamba operates faster than RhinoRstab.

Keywords: Automation, Structural Analysis, Structural Design, Optimization

1 Introduction

With parametric design gaining currency among structural engineers, information exchange between architectural designs and structural analysis software receives major interest as a design tool [1]. This paper presents a plugin for the workflow of a dynamic inter-process communication between the architectural design and structural analysis software. It combines already existing software and uses their advantages as reliable design and structural calculation tools. The plugin RhinoRstab connects the 3D graphical software Rhinoceros/Grasshopper [2] and the structural analysis program RSTAB by Dlubal [3].
With regards to similar and already existing applications, the Rhino [4] and Rhinoceros/Grasshopper communities offer different solutions for structural analysis. These plugins are able to be executed during the design process, providing a deeper understanding of the structural performance influenced by alterations of the

Erratum

The scientific paper ”RhinoRstab - Introducing and Testing a New Structural Analysis Plugin for Grasshopper3D” contains the assertion that ”. . . for some elements in a structural system and some calculation methods RhinoRstab and Karamba results differ strongly.”. In order to prove their case, the authors compare the results of two structural calculations performed with both programs. **The reported differences in the calculation results are however caused by modelling errors, methodical errors and inaccuracies on the side of the authors of the paper. The corresponding assertions and conclusions in the paper are therefore wrong.**

The paper fails to mention that the pro-student version of Karamba 1.2.2 was compared with RStab version 8.05.0030 (henceforth RStab8 for short). **Also the paper makes wrong assertions regarding the features of Karamba 1.2.2.**

Here a detailed account of the errors contained in the paper:

- In the paper the results of the calculations of structure 1 are wrong because of these modelling errors:
  - In the RStab8 calculation under ”Calculation Parameters” the option ”Activate stiffness factors of materials” was enabled. This makes RStab8 divide the materials Young’s Modulus by the partial safety factor of the material. Since RStab8 uses a partial safety factor of 1.1 for steel, enabling this option increases the calculated displacements by 10% relative to the unfactored case.
  - The structure consists of elements with circular hollow cross sections (CHS) of diameter $57[mm]$ and wall thickness $4[mm]$. In Karamba 1.2.2 the shear areas A_y and A_z are calculated according to the standard textbook formula for a CHS: $A_y = A_z = 2 \cdot A/\pi$ which results in a value of $4.24[cm^2]$. RStab8 uses a value of $3.31[cm]$. This causes deviations in the cross section forces for very short members like those along the upper boundary of structure 1 which have a length of roughly $0.5[m]$.

  Setting the shear areas in Karamba 1.2.2 to those of RStab8 and disabling the stiffness reduction in RStab8, the following differences in the calculation results are observed. The percentages refer the maximum deviation found in all elements to the corresponding mean value of the Karamba and RStab results:

  - Support forces: 0.0001%
  - Maximum normal forces in members: 0.006%
  - Maximum shear forces V_z in members: 0.8%
  - Maximum moments M_y in members: 0.15%
  - Maximum deformation: 0.0003%

The results deviations presented in table 1 on page 132 of the paper are therefore wrong.

- In the paper the results of the calculations of structure 2 are wrong because of these modelling errors:
  - Like for structure 1 a stiffness reduction of 10% was imposed on all materials in the RStab8 calculation.
  - The geometry of the structures calculated with RStab8 and Karamba 1.2.2 was not identical: due to geometric inaccuracies there were two gaps in the Karamba model. In the RStab-model these were not present because the authors of the paper used different tolerance settings in Karamba and RStab for joining neighboring nodes.
  - The comparison of the results from second order theory between RStab8 and Karamba 1.2.2 neglects a difference in the way both programs take account of the normal force N^{II} which causes the second order effects: according to the RStab8 manual RStab8 uses the mean value of the normal forces in a beam as N^{II} whereas Karamba 1.2.2 uses the minimum normal force. This is documented in the Karamba 1.2.2 manual. The latter procedure gives results which lie on the safe side.

    In order to make a valid comparison between second order results of Karamba 1.2.2 and RStab8 one has to divide the beam elements of the structure into small segments so that the difference between N^{II} as calculated in RStab8 and Karamba 1.2.2 becomes negligible. In case of elements where the cross section forces change sign, and the gradient of the cross section force is small, the method of comparing the difference of the results to the corresponding mean value becomes meaningless for judging the correctness of the structural analysis: Tiny variations in the results then cause large relative deviations. Therefore the method for comparing the results of RStab8 and Karamba 1.2.2 by calculating relative deviations is invalid and has a pronounced influence in case of second order structural calculations when small beam segments are used.

Setting the shear areas in Karamba 1.2.2 to those used in RStab8, disabling the stiffness reduction in RStab8 and using the geometry with the gaps for RStab8 and Karamba 1.2.2 the following differences in the calculation results are observed. The percentages refer the maximum deviation found in all elements to the corresponding mean value of the Karamba and RStab results:

- Th.I, support forces: 0.0002%
- Th.I, maximum normal forces in members: 2.7%
- Th.I, maximum shear force V_z in members: 0.02%
- Th.I, maximum moments M_y in members: 0.04%
- Th.I, maximum deformation: 0.3%

  - Th.II, support forces: 3.9%
  - Th.II, maximum deformation: 2.4%

  If each beam is divided into 20 segments the following relative deviations result for the calculation according to second order theory:

  - Th.II, support forces: 0.19%
  - Th.II, maximum deformation: 0.14%

  The results deviations presented in table 2 on page 133 of the paper are therefore wrong.

- On page 129, first paragraph, it is stated that Karamba 1.2.2 creates only stress resultants. This is not the case. Besides stresses and other properties resultant cross section forces, local cross section forces, displacements can be retrieved from beam elements.

- On page 130, section 2.2, first paragraph, it is stated that in Karamba 1.2.2 the selection of predefined cross sections is limited to a smaller range than in RStab8. This is not the case. In version 1.2.2 the cross section library of Karamba comprises roughly 6600 different cross sections. The cross section library can be easily extended by the users and has therefore no limit on the potential number of predefined cross sections.

- On page 131, section 2.2, first paragraph, it is stated that "... Karamba is not proven by any construction standards".

  - In case the authors mean that Karamba 1.2.2 does not contain procedures for designing structural elements according to building codes then this is not correct: Karamba 1.2.2 contains assessment and optimization tools based on Eurocode 3 for steel structures.
  - In case the authors mean that the results of Karamba 1.2.2 are not verified then this is not correct: Karamba 1.2.2 comes with a selection of widely used benchmark examples with comparisons to results known from literature.

- In section 3.3 of the paper the authors draw several comparisons between the results of Rstab8 and Karamba 1.2.2. These comparisons are wrong.

- In section 4.1, first paragraph, it is stated that "... Karamba, in turn, only shows structural behavior but does not demonstrate its actual structural capability". This is wrong: Karamba features assessment and optimization tools based on Eurocode 3 for steel structures. It also lets the user retrieve (besides other result properties) cross section forces and moments for beams and principal stresses and Van Mises stresses for shells.

- In the same paragraph it is stated that "... Karamba also lacks of options to superimposition results.". It is not mentioned in the paper that Karamba 1.2.2 offers the option of load superimposition.

- In the same paragraph it is stated – with respect to the results of Rstab8 and Karamba 1.2.2 – that ”. . . it can be observed that the result of the single elements show great differences (up to 71% in structure 1 and 74% in structure 2)”. This is wrong.
- In the same paragraph it is stated – with reference to Karamba 1.2.2 – that ”. . . as it only shows one result per element, it is not clear where the result force is acting on the element and if it represents the maximum value.”. This is wrong. In case of beams Karamba 1.2.2 lets the user retrieve a user defined number of results (displacements, cross section forces,. . .) on equidistant points of the beam axis.
- In the same paragraph it is stated – with reference to Karamba 1.2.2 – that ”. . . It also does not distinguish between strong and weak axis of a cross section, and therefore only provides the resultant for both axis.”. This is wrong. Karamba 1.2.2 distinguishes between the strong and weak axis of a cross section and provides not only resultants of the cross section forces but also their components in the local element coordinate system.
- **For the reasons described above, the result comparisons in table 1 and table 2 for tree structure 2 in appendix 2 on page 136 for the components of the support forces are wrong.**

parametric design. This structural observation has relevance, especially for complex structures such as the ones created by parametric modelling approaches. During the conceptual design phase this observation is useful for a behavioural estimation and optimisation of structural elements. Besides RhinoRstab one of the most popular parametric plugins is Karamba, which strength lies within the usage in an early design stage [5]. Since this tool creates only stress resultants, accurate structural calculations are required to verify the results subsequently. In this further step the structure is determined according to Building Codes, such as DIN, Eurocode, International Building Code, etc. Different researches show that additional, standalone structural analysis software is used to verify the results of Karamba [6]. Furthermore in the later design stages of projects with higher degree of complexity the usage of certificated program in structural performing is required [1].
A direct connection between Grasshopper and a verified structural analysis software such as RSTAB would therefore eliminate the needs to verify the results in another standalone program and thus allow a more flexible usage throughout all design stages. As the structural design and the calculation happen within the same software-environment, the possibility of a straightforward structural optimising is no longer limited to the early design stage, but could influence more advanced design phases as well. Linking the two software components would therefore result in more reliable design concepts already in early phases, more flexibility throughout all design stages, as well as a great reduction of time and workload for all project participants. In this paper such a connection is established by a new plugin RhinoRstab. It provides a quantitative benchmark based on a structural analysis of spatial structures and discusses the advantages and disadvantages of the software plugins, RhinoRstab and Karamba.

2 Structural Analysis Tools for Grasshopper

The majority of structural analysis tools for Grasshopper is based on Finite Elements as RhinoRstab, Karamba [5] and Millipede [7]. As well as RhinoRstab, all other calculation tools consist of common Grasshopper utility elements and are fully embedded in its friendly interface. The embedding into Grasshopper allows a direct link between the parametric model, the finite element calculator and also optimisation algorithm.
Derived from the notion to create a benchmark for RhinoRstab the plugin is compared with Karamba, following the basic function: specification of material and cross-section properties, support definition, first and second order analysis, and result visualization methodology. Paragraphs 3 and 4 describe the benchmarking on spatial structures, which showing the detail results.

2.1 RhinoRstab: an Open-Source Plugin

RhinoRstab [8] is an open-source developed plugin connecting *RSTAB* and *Grasshopper3D* through the *RS-COM* interface provided by *Dlubal* [9]. To create an interactive workflow between these programs, the plugin is designed in such a way that the workspace is embedded in the *Grasshopper* environment. Using its convenience of a visual programming language, the whole structural analysis process such as support definition, force application and the actual calculation can be controlled in *Grashopper3D* without switching between programs.
Forming the RhinoRstab-plugin, it is separated in different components. One of the three major members is the export tool, which transfers the parametric model from *Rhinoceros* to *RSTAB* including specifications of the structural members regarding support conditions, material and cross section. Another main component is the analysis tool. Exporting the load definition to *RSTAB*, the tool starts the structural analysis and imports the outputs back to *Rhino*. The result-component provides the choice of visualising different analysis results such as the deformation, internal forces and support reactions. Fig. 1 presents all different plugin components.

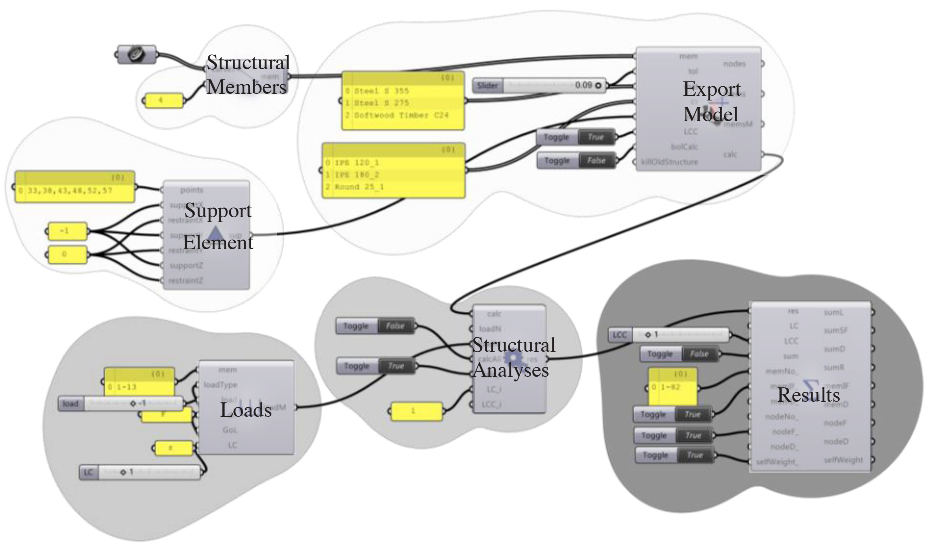

Fig. 1. Illustration of RhinoRstab Plugin Elements

2.2 Comparison to Karamba

Comparing the application of *Karamba* and *RhinoRstab,* both plugins are similar to use. The plugins provide element libraries, including material and cross sections. Where RhinoRstab provides a full selection of international standardized materials and cross-sections, the selection of Karamba is limited to a smaller range.
However, the main difference from *RSTAB* to *Karamba* lies within the calculation, or more precisely in the verification of the results. The significant difference is that the

analysis issued by *Karamba* is not proven by any construction standards. In contrast *RSTAB* enables a user to choose from different international building codes and thus provides a verified proof of stability. *RSTAB* allows a more elaborated and detailed calculation in terms of buckling, 2nd order analyses, dynamic calculation, etc.
Depending on the outcomes of the structural analysis, it may lead to an alteration of the initial design. Thus it is important to provide reliable analysing results in an early design phase. The presented plugin aims at the realization of that goal. Pointing out the difference between the analysis of *Karamba* and *RhinoRstab*, the comparative study shall present an evaluation of the results concerning accuracy and runtime.
In order to provide a detailed comparison of both programs, in the following the plugins are tested in different scenarios such as the structural analysis of structural systems. The parametric models are defined with variable form and cross section parameters following the aim to create an optimized structure.

3 Analysis and Benchmarking of Spatial Structures

In the following two scenarios the analysis of treelike, spatial structures is presented. The design of the first structure (Fig. 2) is kept rather simple in order to prove the authenticity of the results by comparing the software analysis with manual calculations. The second structure demonstrates the usage of both tools analysing a more complex construction. Structure 1 is analysed following theory first order. The theory considers stresses in a simplified manner, analysing the structure as an unformed system. Structure 2 is analysed according to theory first and second order, where theory second order also considers the deformation of the system.

3.1 Analysis of Structure 1

Structure 1 consist of 62 steel rods of different length, from 2.96 to 4.50 meters. Its structural elements are S275 steel profiles, type RO 57x4 | DIN EN 10220_1. Allocating the most convenient position of the trunk, the fixed support is placed in such a way that all moments equal zero. The geometry of structure 1 is shown in Fig. 2.

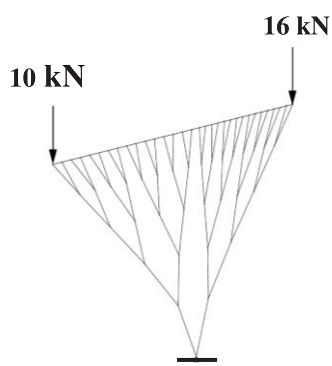

Fig. 2. Tree Structure 1

The first part of the calculation does not take the self-weight into account, in the next step the analysis is repeated also considering the self-weight of the structure.
In Appendix1 the results of the structural analysis are displayed. It shows the support forces of the structure. In addition Table 1 demonstrates the runtime of both plugins and the coefficient of determination R^2, which point out how strongly the results of both calculations correlate. Whereby a R^2 of 1.0 represents identical results and 0.0 indicates no result correlation at all. Furthermore the results of each structural member was analysed and compared. The maximal deviation of each result field was determined regarding the mean value of both programs. In Table 1 the maximal deviation is shown proportional and by its real value.

Table 1. Runtime & Statistical Analysis of Structural Calculations

Software	**Assemble + analysis + results [ms]**	**Total runtime [ms]**		
RhinoRstab	320ms + 675ms + 77ms	1072ms		
Karamba	2ms + 6ms + 56ms	64ms		
Theory		**R^2**	**max result deviation**	
1^{st} order	support-forces	1.000	0.00	0.00
1^{st} order	max. normal-forces in members	1.000	13.2%	0.09kN
1^{st} order	max. shear-forces in members	0.999	58.6%	0.04kN
1^{st} order	max. moments in members	0.986	71.8%	0.03kNm
1^{st} order	max. deformation	0.909	4.8%	78.21mm

3.2 Analysis of Structure 2

The second example shows the structural analysis of a pavilion supported by several treelike pillars (Fig. 3), which consist of 68 rods and 14 beams. The load of the roof gets transferred into the beams, which result in point-loads on the end of each pole (Fig. 3, right). As the whole structure is made of steel S275, the pillars consist of RO 82.5x7.1 | DIN EN 10220_1 profiles.

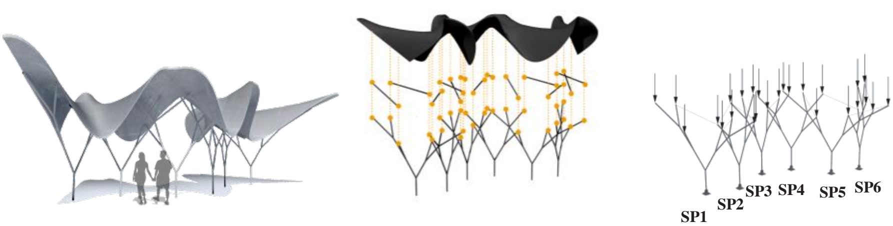

Fig. 3. Perspective of the tree structure 2 (left), exploded view (middle) and structural model (right)

The structure is analysed concerning its internal strain, stresses and support forces, following theory 1st and 2nd order. In Appendix2 the results of RhinoRstab and Karamba are presented , including the self-weight, sum of vertical loads, the total load and its support forces in X, Y, and Z direction. In Table 2 the runtime performance of both programs is demonstrated followed by an estimation of results similarities. Additionally to the coefficient of determination R^2, the single results of Karamba and RhinoRstab were analysed and compared. The max deviation of each result field (i.e. maximal normal forces) is shown proportional and by its actual value. The value was calculated, regarding the mean value of both programs.

Table 2. Runtime & Statistical Analysis of Structural Calculations

Software	Assemble + analysis + results [ms]	Total runtime [ms]		
RhinoRstab	329ms + 775ms + 112ms	1216ms		
Karamba	83ms + 153ms + 156ms	392ms		
Analysis	**Statistical analysis of**	**R^2**	**max. deviation**	
Th.1st order	support-forces	0.994	52.0%	0.07kN
Th.1st order	max. normal-forces in members	0.992	61.7%	0.032kN
Th.1st order	max. shear-forces in members	0.876	65.8%	-0.70kN
Th.1st order	max. moments in members	0.819	74.0%	0.26kNm
Th.1st order	max. deformation	0.867	6.2%	10.15mm
Th.2nd order	support-forces	0.994	58.5%	0.08kN
Th.2nd order	max. normal-forces in members	0.993	74.1%	0.24kN
Th.2nd order	max. shear-forces in members	0.935	54.3%	0.627kN
Th.2nd order	max. moments in members	0.782	70.0%	2.09kNm
Th.2nd order	max. deformation	0.877	6.5%	14.05mm

3.3 Results

Analysing structure 1 and 2, both programs show in general similar results, as the coefficient values R^2 are mostly around 0.9. The biggest difference for structure 1 lies in the estimation of the maximum deformation with a value of 0.9. Analysing structure 2, the largest difference lies in the results of the second order analysis of moment forces, with 0.782. As the R^2 value evaluates the result in a general way, the individual result values were examined more precisely. This observation shows that despite a high coefficient of determination great deviations exist. The maximum deviation of structure 1 lies in the structural analysis of moment forces with 71.8%. This value is regarding the mean value of both software results. Examining the results of structure 2, the maximum deviation lies in the first order analysis of moment forces

with a value of 74%. In the second order analysis the results of the normal forces show a maximum deviations of 74.0%.
Concerning the runtime of both plugins, Karamba performs the structural analysis quicker than RhinoRstab, 16 times faster in structure 1 and 4 times faster in structure 2.

4 Conclusion and Further Works

In this paper a new structural analysis plugin for Grasshopper is introduced, in which a dynamic inter-process communication between the software Grasshopper and RSTAB is created. Subsequently the RhinoRstab plugin is compared with Karamba, creating a benchmark for the performance of both plugins.

4.1 Conclusion

The functions of RSTAB provide, among other things, dimensioning tools for each building materials and thus is usable for the verification of the results. Karamba, in turn, only shows structural behaviour but does not demonstrate its actual structural capability. Karamba also lacks of options to superposition results, it only offers the choice of either a single or all load cases. This load treatment is rather unfortunate in proper structural analyses, as it presents an important part of the general analysis. Concerning the numerical comparison of the software, it shows that both programs create different results. Though the structural analysis of the plugins provide in general similar results, analysing the results more precisely, it can be observed that the result of the single elements show great differences (up to 71% in structure 1 and 74% in structure 2). A reason for the different results can be that the result output of Karamba is imprecise. As it only shows one result per element, it is not clear where the result force is acting on the element and if it represents the maximum value. It also does not distinguish between strong and weak axis of a cross section, and therefore only provides the resultant for both axis. Comparing both programs the results of RhinoRstab were customised to the result output of Karamba. Another great differences lies in the runtime of both plugins. Karamba performs faster than RhinoRstab and is therefore very suitable for quick alterations, such as performed in optimisation processes. Whereas the strength of Karamba lies within the runtime, the advantage of RhinoRstab is the quality of the analysis. RhinoRstab provides large object libraries and allows very detailed settings concerning structural analysis and result visualizations.

4.2 Further Works

Further works target the improvement of the RhinoRstab plugin for optimisation purposes, finding the most suitable form and cross section for a structure. As optimisation processes usually require a rapid alteration of model properties, the aim

is it to optimize the operation time of RhinoRstab, by simplifying extensive calculation processes.
In the current state of the plugin, the type of parametric models is limited to space-frame structures. In order to analyse plates, walls, shells, etc. it is favourable to base the analysing tool on 3 dimensional finite elements. Additional extension of the plugin‘s abilities target on linking it to the finite element calculator Dlubal RFEM [10], following the same strategies as introduced in the interactive workflow between Rhino and RSTAB.

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Appendix 1

Table 1. Analysis of Tree Structure 1

		F_V [kN]	F_H [kN]	M [kNm]	Comment
1.1	Manual calculation	26.00	0.00	0.00	self-weight not considered
1.1	Karamba	26.00	0.00	0.00	self-weight not considered
1.1	RhinoRstab	26.00	0.00	0.00	self-weight not considered
1.2	Karamba	38.46	0.00	0.00	self-weight considered
1.2	RhinoRstab	38.46	0.00	0.00	self-weight considered

Appendix 2

Table 1. Theory 1st Order Analysis of Tree Structure 2

	Self-weight of structure [kN]		**Sum of vertical point loads [kN]**		**Total load [kN]**	
	Rhino-Rstab	Karamba	Rhino-Rstab	Karamba	Rhino-Rstab	Karamba
	23.228	23.229	48.593	48.593	71.821	71.822
	F_x [kN]		**F_y [kN]**		**F_z [kN]**	
SP1	-0.100	-0.090	0.244	-0.270	22.018	22.670
SP2	0.838	0.930	-0.381	-0.410	8.292	7.860
SP3	0.190	-0.060	-0.200	0.430	5.596	4.260
SP4	-0.272	-0.280	-0.034	0.060	5.604	6.950
SP5	-0.887	-0.620	0.247	0.460	8.2841	8.090
SP6	0.231	0.130	0.124	-0.280	22.026	22.000
Σ	0.000	0.010	0.000	-0.010	71.821	71.830

Table 2. Theory 2nd Order Analysis of Tree Structure 2

	Self-weight of structure [kN]		**Sum of vertical point loads [kN]**		**Total load [kN]**	
	Rhino-Rstab	Karamba	Rhino-Rstab	Karamba	Rhino-Rstab	Karamba
	23.229	23.229	48.593	48.593	71.821	71.822
	F_x [kN]		F_y [kN]		F_z [kN]	
SP1	-0.632	-0.460	0.229	0.060	20.711	21.540
SP2	1.083	1.070	-0.369	-0.580	11.307	10.390
SP3	0.507	0.170	-0.207	0.250	3.892	2.900
SP4	-0.520	-0.620	0.164	0.070	3.890	5.390
SP5	-1.068	-0.810	0.414	0.480	11.303	10.980
SP6	0.629	0.650	-0.230	-0.280	20.719	20.620
Σ	0.000	0.000	0.000	0.000	71.821	71.820

Computational Decision Support for an Airport Complex Roof Design

A Case Study of Evolutionary Optimization for Daylight Provision and Overheating Prevention

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Abstract. This study focuses on generating geometric design alternatives for an airport roof structure with an evolutionary design method based on optimizing solar heat gain and daylight levels. The method incorporates a parametric 3D model of the building, a multi objective genetic algorithm that was linked with the model to iteratively test for various geometric solutions, a custom module that was developed to simulate solar conditions, and external energy simulation environments that was used to validate the outcomes. The integral outcome was achieved through an iterative workflow of many software tools, and the study is significant in dealing with several space typologies at the same time, taking real-life constraints such as applicability, ease of operation, construction loads into consideration, and satisfying design and aesthetic requirements of the architectural design team.

Keywords: Evolutionary algorithms, daylight and energy performance, multi-objective optimization

1 Introduction and Motivation

This paper presents a case study in which geometric design alternatives for an airport roof structure were generated with an evolutionary design method based on optimizing solar heat gain and daylight levels. Our method incorporates a parametric 3D model of the building, a multi objective genetic algorithm that was linked with the model to iteratively test for various geometric solutions, a custom module that was developed to simulate solar conditions, and external energy simulation environments that was used to validate the outcomes.

While simulation methods for energy performance mostly allow for the testing of specific design scenarios, evolutionary methods iteratively generate and test several scenarios, presenting a range of optimal solutions to the designer. The benefits of the use of evolutionary algorithms for multi-objective optimisation in architectural design have been extensively studied [1–4], and several case studies that utilize such approaches can be found in literature [5–9].

Similar to the study presented in this paper, a number of these studies are concerned with geometric optimisation of roof structures [1, 2, 6]. As design objectives, many consider reduction of energy consumption while attaining sufficient natural daylight for illumination, and their methods incorporate trade-off decisions between these generally conflicting objectives [1, 2, 4–6, 8]. While it is a common approach to link a parametric model, a simulation engine and a genetic algorithm within the workflows of similar studies [1–3, 9], our presented method integrates a custom module that simulates solar rays for critical hours to test seasonal extreme conditions and a genetic solver already avaliable as a plugin for the parametric modeling environment utilized. Among the few studies that take into consideration the spatial functional requirements of the buildings as cases presented [1, 6] (sports building), [3, 7, 9] (office building or spaces), our study is uniqe in that it considers specific daylight and solar radiation conditions required for spaces of varying functions within the airport complex (offices, cafes, indoor landscape elements, walkways, parking lots).

Along with these uniqe aspects, the work introduced here is a real-world study carried out for a building under construction in Cukurova, Turkey. We propose a replicable workflow for design problems where geometric alternatives are to be explored for optimisation of daylight and solar gains using parametric modelling and evolutionary algorithms.

2 The Case Study

This study was commissioned by the architectural design team of an airport project, to support the design decision process for the roof shell.

The airport was designed in a coastal, hot-summer Mediterranean climate. The complex consists of two independent buildings: The main one is the terminal building that accomodates terminals, a hotel and a carpark, with a footprint of 150.000 sqm (Fig. 1). The second is a single storey building with a footprint of 20.000 sqm that houses CIP and VIP lounges (Fig. 3 and Fig. 4). The building is under construction at the time of the submission of this paper.

Fig. 1. 3D visualization showing the two buildings (from design team's website)

Fig. 2. Schematic plan of the main building

In both buildings, the roof was designed to be supported by a concrete shell that spans over separate building blocks. The semi-open spaces between the two blocks required openings above to allow sufficient daylight in; and these openings posing the issue of overheating risk was the nexus of the environmental dilemmas our team faced.

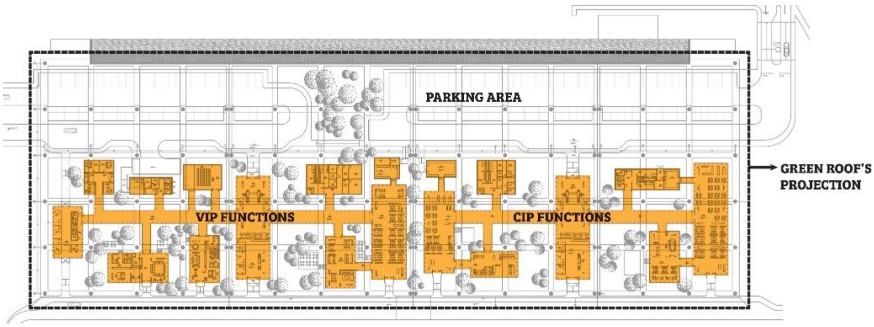

Fig. 3. Schematic plan of the secondary building

The roof had already been designed by the architecture team as a grid shell, within which regions had been determined to be opened by the use of four different concrete modules, designed with varying perforation levels (Fig. 4).

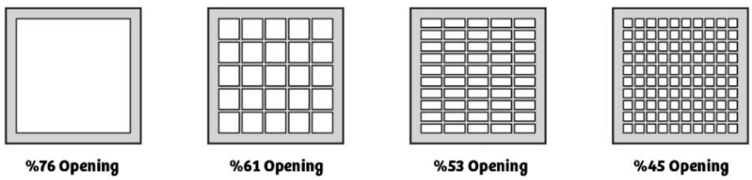

Fig. 4. Modules and their opening ratios

The objectives of our study were to;

1. Minimize energy consumption of active cooling particularly during hot seasons,
2. Provide sufficient natural daylight for interior and transitional spaces while preventing over-illumination and sun patches,
3. Take into consideration additional environmental stimuli such as rain and wind, particularly in the car park area,
4. Achieve these by primarily using the modular roof elements that were approved by the design team and were to be easily manufactured.

When the climate data was analysed, it was clear that preventing overheating was the main objective as direct solar radiation amounts were quite high. Based on global illumination and diffuse radiation levels, providing adequate amount of daylight did not seem to be a predominant problem. For these reasons, the optimisation process was based on a model of solar rays, in order to simulate direct sunlight, ergo solar radiation. While the *quantity* of natural daylight was usually not an issue, the *quality* needed to be controlled, therefore the daylight performance of generated roof geometries were simulated.

3 Methodological Procedures

Preliminary studies determined that three different evaluation methods were required for different areas of the building:

1. The main building's roof, the part that covers the terminal and hotel areas,
2. The main building's roof, the part that covers parking lots, and
3. The secondary building's (CIP/VIP building) roof (Fig. 5).

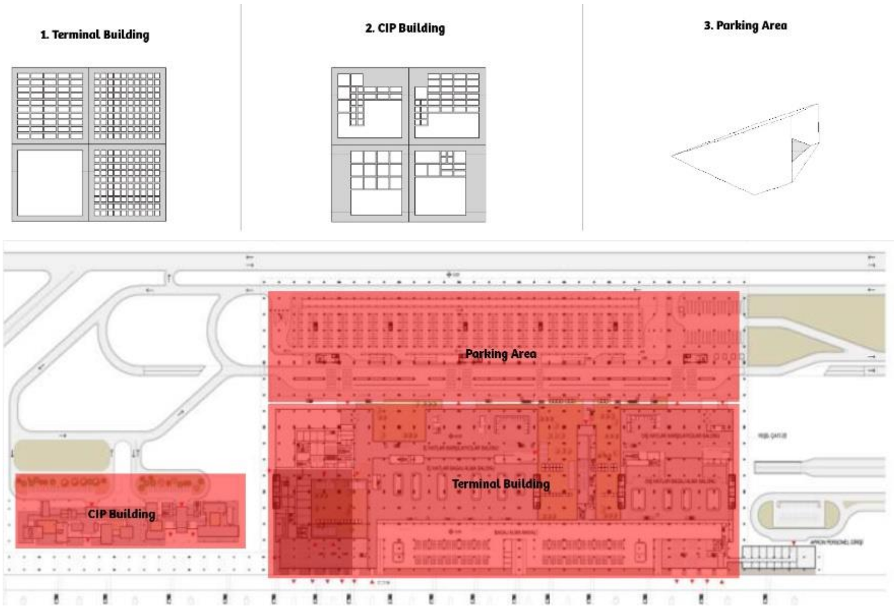

Fig. 5. Schematic plans showing 3 different areas of study

At the previous stages of design it was already decided by the design team that the shell structure was to be constructed with a 16m x 16m grid. Perforations deployed to optimize sunlight were to be configured through an arrangement of modules of this size, already designed by the architecture team.

In the CIP area, as the spaces underneath the shell is much smaller, the resolution of 16m x 16m was not sufficient. In this part of the roof structure, to provide an optimized solution, we proposed to use different opening ratios within a single module.

While the required perforation percentages for each area were determined by an initial basecase simulation run without any roof structure at all, the distribution of openings to provide the necessary perforation levels were calculated by the genetic algorithm.

The genoms provided to the GA for each of the three parts of the building studied were different due to the varying requirements. In the main building's terminal and hotel areas, the four different module options (0, 1, 2, 3) for each 16m by 16m grid cell constituted our discreet variables. For the parking area, an angle of extrusion for all the shading surfaces that changed at intervals of 5 degrees between 0 and 360 degrees (0, 5, 10,…355) were our discrete variables. For the CIP area, the perforated (1) and non-perforated (0) grid cell for each of the 100 cells in each 10m by 10m module were our discrete variables. A grading system that took into account all the spatial requirements was developed, which was then fed into the algorithm as the fitness formula. This grading system is to be further explained in the next sub-sections.

3.1 Roof over the Terminals and the Hotel

The complex has two separate roof surfaces that light needs to penetrate through; the larger main roof and the roofs of the blocks underneath. This requires a strategic positioning of the openings in the upper roof to selectively let the light in, also considering the greatly varying incident angles of wanted/unwanted sunrays (Fig. 6).

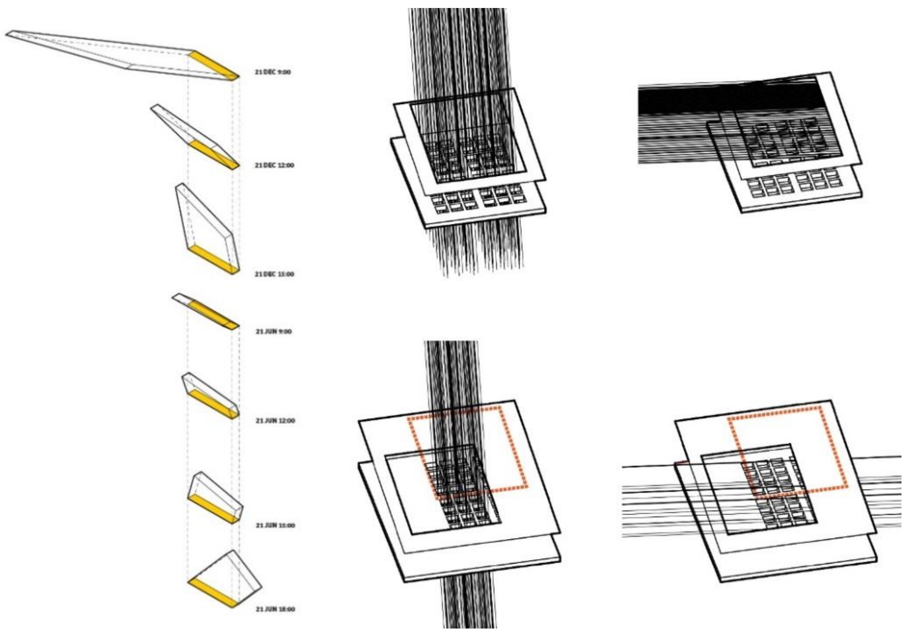

Fig. 6. Reflection of sunrays on the roof on different times & placing the openings strategically

Base-case solar radiation simulations (without any roof at all) were run for each level, both for summer and winter conditions in order to understand how the masses of each block affect each other and the open spaces in between. These simulation results showed how much sunlight the areas *could* receive. Another investigation was mapping the differentiating spatial typologies (offices, hotel, terminal, cafes, etc.); which showed how much sunlight the areas *needed* to receive. Overlapping these, the areas and their corresponding roof parts were divided into different zones, and each zone was assigned a percentage of perforation that would transform the available sunlight into what was required.

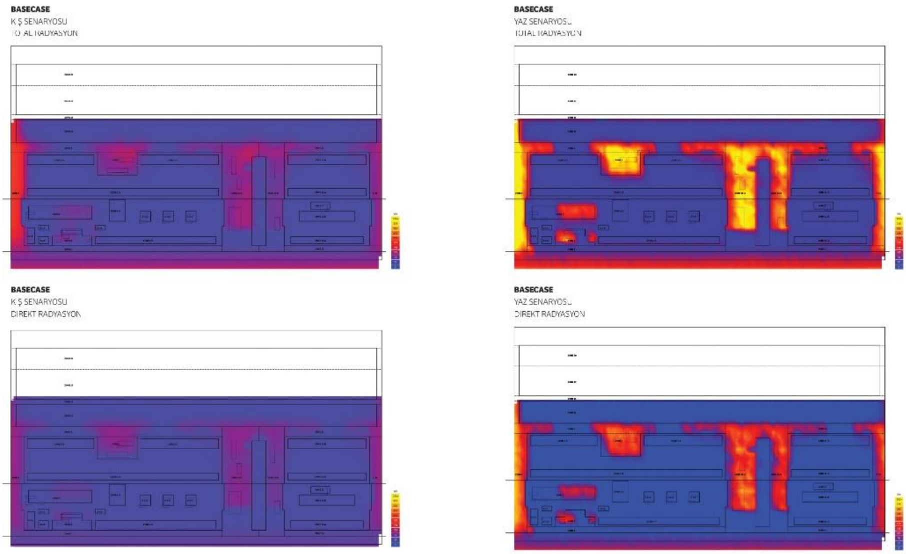

Fig. 7. A sample from base-case simulations

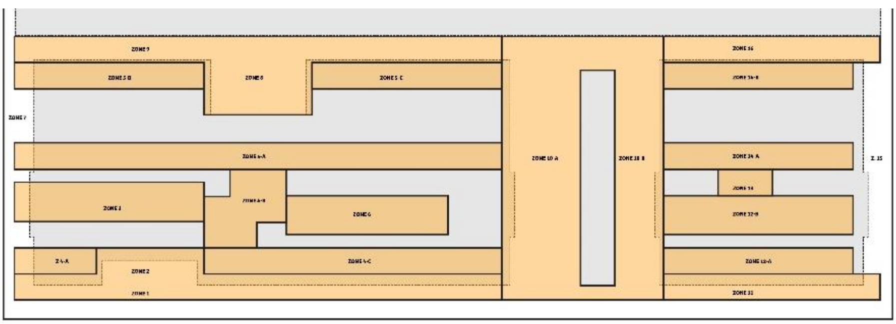

Fig. 8. Zoning the roof

A grading between -2 to 2 allowed for defining the most and least desirable times for direct sunlight to be received by each zone based on functions of spaces (Table 1). The genetic algorithm was run on one zone at a time. Within given tolerances the algorithm produced many different results, each approaching the goal with slight variations.

Table 1. The grading system

		Bonus/penalty factors for spaces based on time and day						Weights factors for genetic algorithm	
		Hotel Facade	Terminal Facade	Office Facade	Cafe/Lounge Facade	Active greenery	Ground	Bonus/penalty factors	Perforation requirement (%)
June 21st	09:00	1	-1	-2	-2	1	0	50%	50%
	12:00	-1	-1	-2	-2	-1	0		
	15:00	-1	-1	-2	-1	0.5	0		
	18:00	0	0.5	-2	0.5	1	0.5		
December 21st	09:00	1	1	-1	1	2	2		
	12:00	0	1	-1	1	2	2		
	15:00	1	1	0	1	2	2		
	18:00	-	-	-	-	-	-		

In the algorithm we utilized for this part of the roof:

1. Our discrete variables were the four types of concrete modules (0,1,2,3),
2. Each case consisting of a configuration of varying modules within one zone was an individual,
3. The fitness criteria were formulated, based on the grading system (Table 1) providing negative and positive coefficients for the amount of desired and unwanted light rays, and total percentage of perforations in each case.
4. Octopus genetic solver [10, 11] was used with in the Grasshopper [12] visual programming environment in Rhinoceros3d [13] software. Octopus was chosen as it allows for the multi dimesional visualisation and analysis of results, each dimension representing independent objective functions. The solutions are represented as points on this 3d graph, the position of each result demonstrating its proximity to satisfying each of the criteria (Fig. 10). The three fitness criteria corresponding to the 3 dimensions of the results graph in our study are as follows:

$$DP - \frac{\sum_{i=0}^{n} p_i}{n} \tag{1}$$

Where DP = desired perforation percentage per area, n=number of 16x16m cells populated with modules for the main terminals and the hotel, p= perforation percentage of each cell

$$-1 * \sum_{i=0}^{n} c * r_i \tag{2}$$

n= the number of regions per different time frames with different coefficients in the grading system, c= the coefficients determined by the grading system, r= number of solar rays that fall onto each region with different coefficients assigned to them in the grading system. Only, the rays falling onto the landscape elements are excluded here since they are taken into account seperately in a third fitness function.

The octopus genetic solver always tries to minimize the results, therefore this equation is multiplied by -1.

$$-1 * \sum r \qquad (3)$$

Where r = solar rays that fall onto the landscape elements.

1. The genetic solver was expected to pick successful patterns leading it to establish a set of pareto-optimized solutions. A brute force calculation of running all possibilities was impossible due the large number of possibilities. There are 50 openings only in Zone 10. 5 module option in all 50 openings would lead to a solution space of 550 (1.2089258196146292e+24) options.
2. In the genetic solver the greenery has been solved as an independent dimension. Altough it was preferable to get direct light on the interior landscape elements it was not vital for the performance of the building, keeping in mind that the landscape design was not completed during the study. When indoor landscape elemens were included in the overall grading system, it was observed that the genetic algorhytm achieved numeric success by only focusing on providing light on the landscape elements.

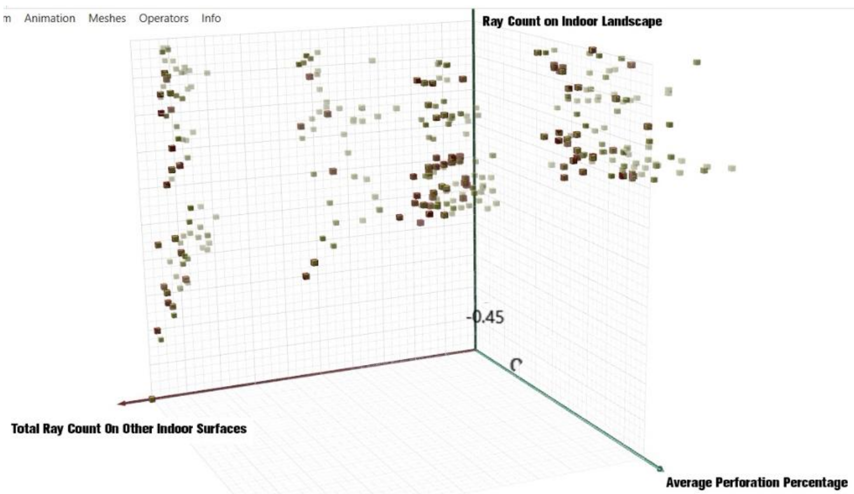

Fig. 9. Genetic Algorithm Pareto-Optimized Solutions

The evolutionary optimisation was run with a population size of 30 and 50 generations for each zone. The final selection of generated geometry was done manually. Octopus was choosen mainly due to its ability to remember previous iterations and its ability to navigate through multi dimensional results visually. Fig. 9 shows the relation between opening levels and numeric success of the grading system.

Best generated roof design proposals were tested in Ecotect [14] and Radiance [15] softwares, and compared with basecase runs on each level of the building for validation (Fig. 10).

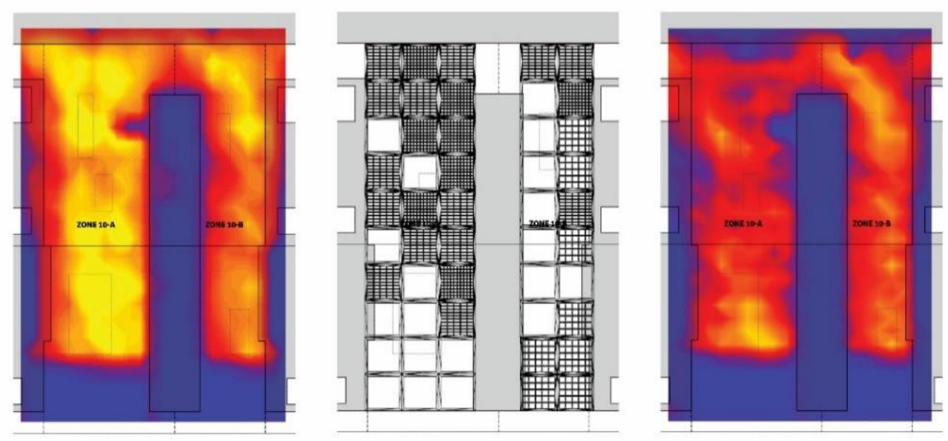

Fig. 10. Control simulations

3.2 Roof over the Parking Lot

The parking lots being unconditioned areas without any envelope changed the performative priorities of the roof drastically due to any openings in the roof making it prone to rainwater directly. Additionally, achieving sufficient daylight levels throughout the year became more substantial than the risk of overheating. A new methodology was developed in order to evolve light wells with closed surfaces in the water-flow directions while letting maximum winter light in and preventing over-illumination and heteregonuous sun patches on the ground in summer.

The idea of light wells had already been conceptually concieved when this study started. The expected performance criteria from the wells were: (1) to prevent direct rainfall, (2) while doing so, to satisfy the natural daylight requirements. In order to prevent rainfall, a slanted geometry was in question, therefore the geometrical limits to the wells were due to constructability rather than aesthectic. Due to the tricky process of removal of molds from a slanted well, the angle and height limits were set. These limits have been transfered to Grasshopper environment as the upper and lower bounds of number sliders. The results were validated through Radiance for daylight levels and distribution at the end of each iteration.

The study not only focused on the geometry of a single well, but also included how the wells were to be arrayed on the roof. At this stage of the study, the civil engineering team had to calculate the additional loads the proposed wells were causing, and this was one of the parameters our team had to take into account.

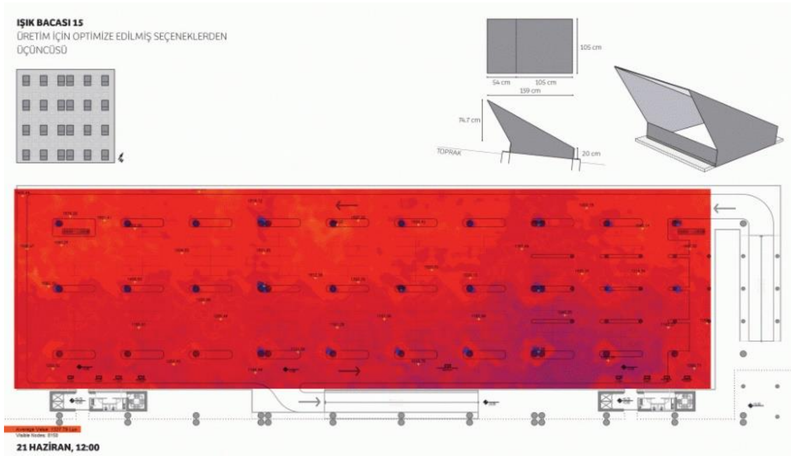

Fig. 11. One of the generated light wells and daylight simulation

In the algorithm:

1. The light wells are slanted extrusions of a given base opening and an independently slanted cutting plane to be aplied on the extrusion.
2. The optimization was run in a separate shoe box test, in order to see if the resulting daylight levels and distribution were within comfort band.
3. The fitness criterion used for the parking area optimization are as follows:

$$-1 * \sum_{i=0}^{n} c * r_i \quad (4)$$

n= the number of regions per different time frames with different coefficients in the grading system, c= the coefficients determined by the grading system, r= number of solar rays that fall onto the ground with different coefficients assigned to them for each time frame in the grading system.

3.3 Roof of the Secondary Building

Due to the secondary building consisting of smaller blocks and in-between areas under the roof, a higher resolution study for the perforations was needed and the optimization was done by a perforation grid of 1m x 1m (Fig. 12).

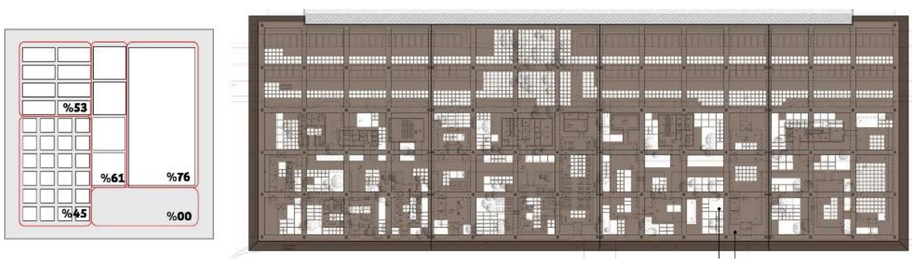

Fig. 12. Roof patterns generated by 1mx1m perforated grid

The fitness criteria for the CIP area consists of the same formulation (1), (2) and (3); with a modification in formula (1) as follows:

$$DP - \frac{\sum_{i=0}^{n} p_i}{n} \tag{1}$$

where DP = desired perforation percentage per area, n=number of 10x10m cells populated with varying modules for the CIP, p= perforation percentage of each cell.

4 Results and Observations

The decision making process in the study was intricate, iterative and multi-faceted. The integral outcome was achieved through an iterative workflow of many software tools, with an effort to prevent getting lost in translation regarding both the communication with the design team; and also in the use of many digital mediums.

Several studies have utilized evolutionary optimisation in the design of building envelope structures [1–3, 7–9], however the case we present is unique due to specific requirements and approaches utilized in the solution of the optimisation problem. Multiple different climatic conditions for multiple space typologies were considered including cafes, lounges, terminal areas, offices, a hotel, car parking and areas of indoor landscape; scattered in a complex 3D mass. To formulate these requirements into fitness criteria, a grading system was developed for each space typology adapted from CIBSE Guides for thermal and lighting requirements in different types of spaces [16–18]. Rather then linking a climatic simulator to the genetic solver, the solar rays that were simulated for eight specific hours in the duration of a year were utilized for efficiency of time and computing power. The project was a real-world case, therefore the study was carried out in coordination with a design team and required consideration of additional aspects usually disregarded in academic studies. These included aesthetic choices by the design architect, applicability, production cost, and ease of operation. Additionally, our workflow incorporated a final stage where we re-simulated performances of a number of manually selected geometries amongst the pareto-optimal solutions and made informed decisions to chose the most appropriate for the rest of the design. Finally, while it is common for architects to collaborate with several engineers in similar studies, it is rare to incorporate landscape architects. The optimisation parameters included the placement of active greenery as it was important to the designers to have live trees and foliage under the roof. For these reasons, the project is significant within applications of multi objective genetic algorithms in design optimisation, and is known to be first of its kind in Turkey.

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A Mathematical Model Linking Form and Material for Sound Scattering

Design, Robotic Fabrication and Evaluation of Sound Scattering Discs: Relating Surface Form to Acoustic Performance

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Abstract. This paper presents empirical research into the acoustic performance of randomized robotically fabricated patterns. Randomness is introduced as degrees of variations in code, both supported by quasi-predictable variations in a computational process, and the select changes through multiple variables in precise robotic fabrication that extend the spectrum for manufacturing diversity in micro-geometries that can change the acoustic response of space. Through physical acoustic testing of scale model 1:10 prototypes in a scale model reverberant box, and consecutive re-modelling of sound discs based on root mean square and depth comparison, a tendency for acoustic behaviours both for scattering and absorption could be demonstrated that relates low spatial frequency magnitude of surface modulation closely to scattering coefficient in a limited case study of six samples. As a result, the study presents a mathematical model that links form and material for sound scattering.

Keywords: Acoustic Micro-Patterns, Design Robotics, Scattering Coefficient

1 Introduction

Relationships between sound and architectural space are complex because sound wavelengths span a very large range (1:1000), and are significantly large on an architectural and human scale. As a result, not only is sound propagation in rooms immensely complex, but also human perception of sound is remarkably rich and varied. The macro-geometry or overall form of a space, such as flat or curved or intersected walls, and the micro-geometry of surface patterns influence the way in which sound is projected back into space and is heard. Specifically, micro-patterns can contribute significantly to sound absorption, reflection, or scattering into different directions.

The integrative systemic bridge between parametric design and acoustic analysis could offer control over acoustic phenomena produced by complex spatial geometries, aiming at a sound produced by the spatial geometry itself, as opposed to amplified sound in common public spaces, work spaces, or spaces for performative arts. Through empirical tests of complex pattern geometries, mathematical models linking form and material to acoustic response can be derived, which allows the production of a space with a distinct ‘sound coloration’, based on a framework for a spatial syntax that integrates acoustic performance. From a signal processing perspective, space can be thought of as an acoustic filter; that is, the effective use of architectural design can concentrate and rarefy sound in time and frequency domains. To enable design for this, a mathematical connection between acoustics and architecture is required.

Consequently, this paper describes research into randomized patterns in order to identify tendencies for the acoustic performance of non-periodic surfaces. It describes an interdisciplinary collaboration between computational and generative design, acoustic analysis and simulation, and advanced robotic manufacturing, aimed at novel paradigms for surface geometries that change the acoustic response of space.

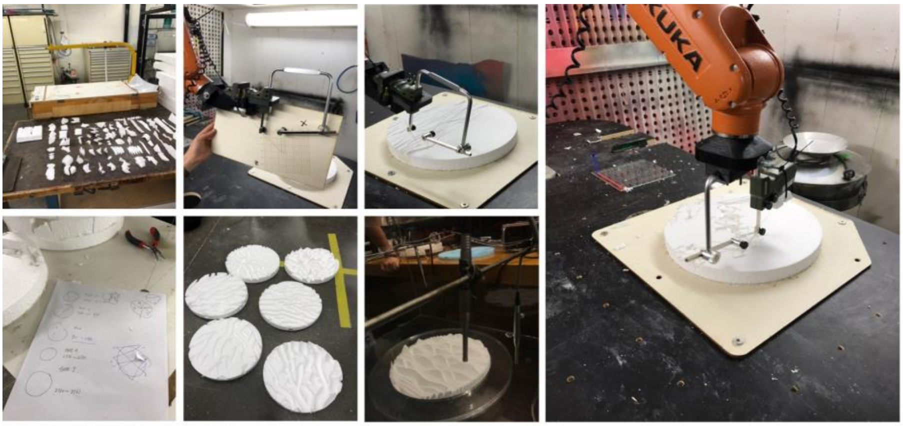

Fig. 1. Analogue subtractions, robotic hot-wire cut, pattern series, acoustic testing in reverberant box, KUKA KR 6 work-cell (CodeToPro2016)

To this end, randomness can support a highly controlled design process for sound scattering patterns; by introducing non-periodicity in complex geometries and design robotics, thus resulting in expanded pattern archives for acoustic effects. While robotic manufacturing enables precision for 1:10 scale model prototypes (such as the fast prototyping for acoustic scattering), design robotics and manipulations of toolpaths, end-effectors and code sequence can expand the range of available physical samples, and distinguish acoustic performance relative to surface qualities, as is discussed. In the following, the paper reports on the robotic fabrication and physical acoustic testing of a case study series of micro-acoustic patterns, and then discusses the continued reverse engineering of select samples in order to derive data for modeling, providing a potential basis for design.

2 Case Study Series: Randomness in Robotic Pattern Multiples

2.1 Methodology and Approach

A series of 35 samples, sound discs with modulated scattering surfaces, were produced so as to generate and test a range of non-predictable patterns for acoustic performance (see Fig. 1). Random variations were robotically fabricated by use of multiple criteria; such as the pattern, end-effector shape, and toolpath variation, as described in the following. Patterns further investigated included our previous research into robotic fabrication of micro-acoustic patterns [1,2,3], with a focus on relationships between the depth range of the relief in the surface pattern and the frequency range for high scattering values. These depart from modulated surface differentiation such as Hexagons, Wave and Batten patterns [4,5]. These patterns result instead from series of lines that result from simple rule-based descriptions, and have common use in computational design.

First, different patterns were scripted in GH Grasshopper (a plug-in to McNeel Rhino/visual scripting method), modeled on biomimicry or mathematical codes (Turing Patterns, L-/branching systems, Dynamic Flows, Swarm/Agent behavior, examples here Fig.2a and 2b). This introduced a level of variation or randomness into the overall surface for acoustic and esthetic reasons, in order to maximize the frequency spectrum for scattering, and to avoid using a regular periodic pattern (which is less efficient in sound scattering/behaves spatially differently).

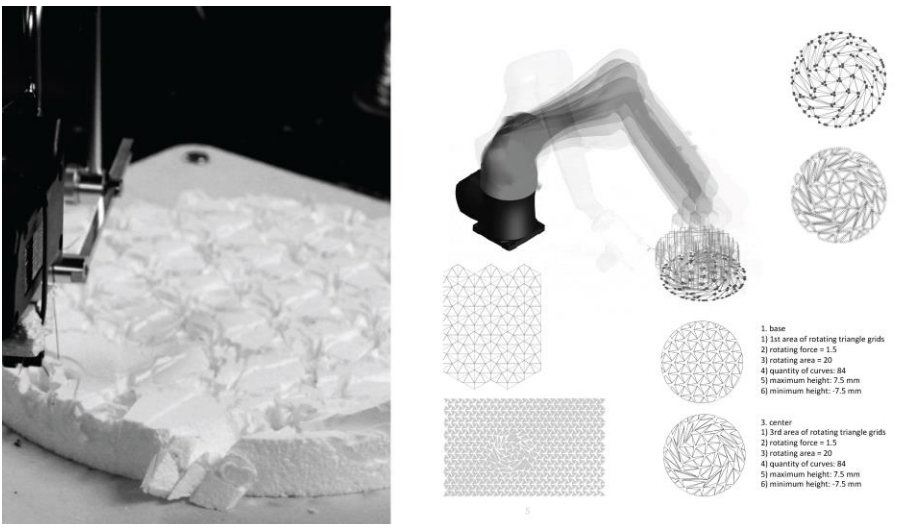

Fig. 2 a. Scattering surface pattern and robotic tooling with changes in periodicity (Xuhui Alphonse Lin, CodeToPro2016).

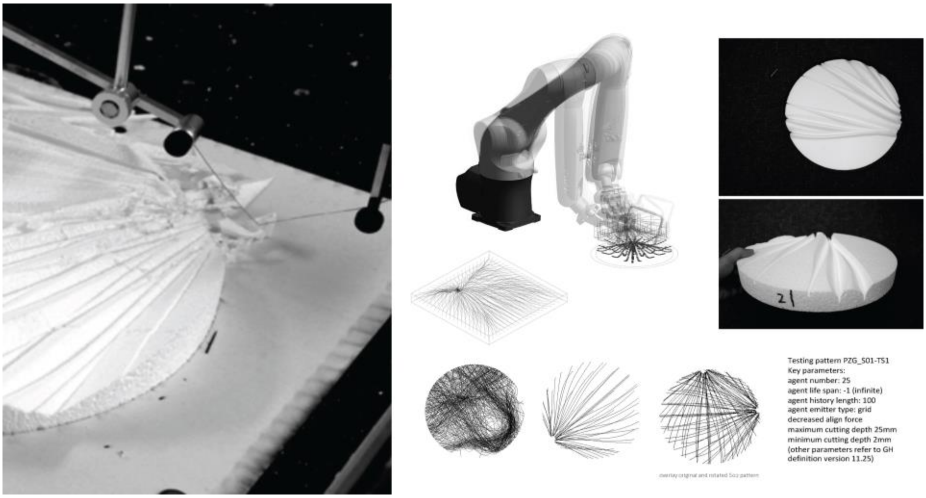

Fig. 2 b. Simplified robotic tooling path relative to agent based behaviour from singular origin point (Guoliang Pat Zhen, CodeToPro2016).

These patterns were then used for a geometry base of a disc with 310 mm diameter, 40mm material depth and 19mm potential surface depth, based on two standard equations with a height ≥ 1/16th of diameter [5]; and a d < 찍貫 (wavelength of sound: 貫, depth of the structure relative to surface area must be greater than half the wavelength) [6]. Then, pattern scripts were simulated in KUKA|prc (a plug-in to McNeel Rhino/robotic simulation), with a translation of singular lines into isocurves, in order to check density of pattern, and the variation of depth across each line, and multiple pathways of cutting motion (see Fig.3). In the robotic setup, a hot wire cutter was mounted on a KUKA KR 6 robot arm as an end-effector, and patterns were cut in industrial EPSF Styrofoam. In order to vary results, different wire profiles (v, u and o-profiles) were used as end-effectors.

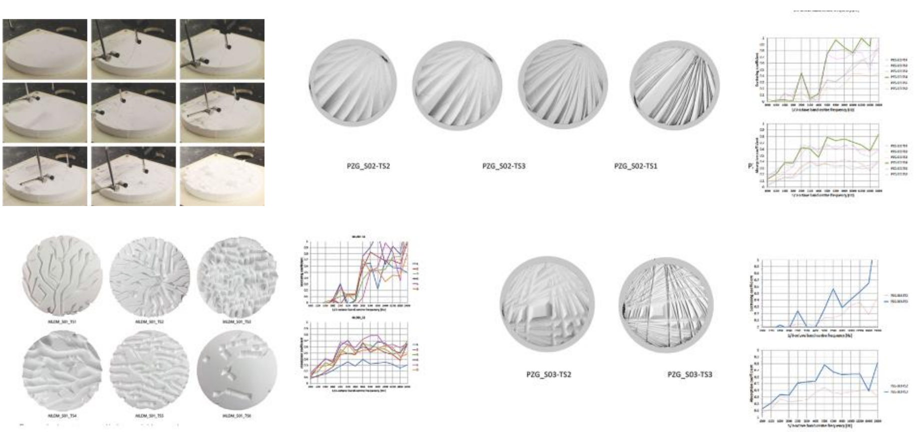

Fig. 3. Robotic prototype series based on generative design. MLDM, L-System series, Michel Luis de Melo (left), and PZG, Flocking Flowl series, Guoliang Pat Zhen (right), CodeToPro2016.

Variations of patterns series were developed by introducing randomness to the robotic process, so as to increase the range of surface differences across the series for acoustic tendencies, by: a) varying the density and/or overall surface area to be cut away, in a percentage over 3-4 test discs; b) relative depth of toolpath for decreasing/increasing the valley depth, thus potentially changing scattering; c) introducing a different wire form with an undercut, thus potentially increasing absorption, and d) control over script for robotic fabrication/subtractive cutting as full or partial stage.

2.2 Physical Acoustic Measurements: Results of Micro-Acoustic Patterns

Following the parametric modeling and robotic scale model production, physical evaluations were undertaken, with the aim of identifying empirical relationships between physical parameters and acoustic result. The acoustic reflective properties of the surfaces were measured as scattering coefficients and random incidence absorption coefficients, by using a scale model reverberant room (a reverberant box with an internal volume of 0.284 m^3, with a measurement procedure was based on ISO 17497-1, see Fig. 4). Each disk was placed on a turntable, and synchronously averaged impulse responses are obtained for different source and receiver positions from the material sample (using a long duration 'maximum length sequence' test signal, with AARAE software, [7]. The acoustic performance is measured as apparent reverberation time: with and without the sample; and in stasis and rotation, yielding a spectrum of random incidence scattering coefficients. This physical acoustic analysis was produced by calculating the mean scattering coefficient and centroid in the 2 kHz – 20 kHz range across different series of sound discs (Fig. 5). Sample PZG-S02-TS6 showed the highest mean scattering coefficient of 0.63, and relatively high absorption coefficient of around 0.65. Characteristic for this particular prototype were deep undercuts, and linear smooth surfaces, which led to the working hypothesis that larger area of smooth surfaces of varying angles potentially increase scattering, and deeper valleys increase absorption. Deep undercuts both created a relative large amount of flat surface area, and deep valleys at the same time. This result is in the following subject to further evaluation, as is the ratio between size of the undercuts and certain frequency's wavelength, which require further investigation in regards to the scattering and absorption performance.

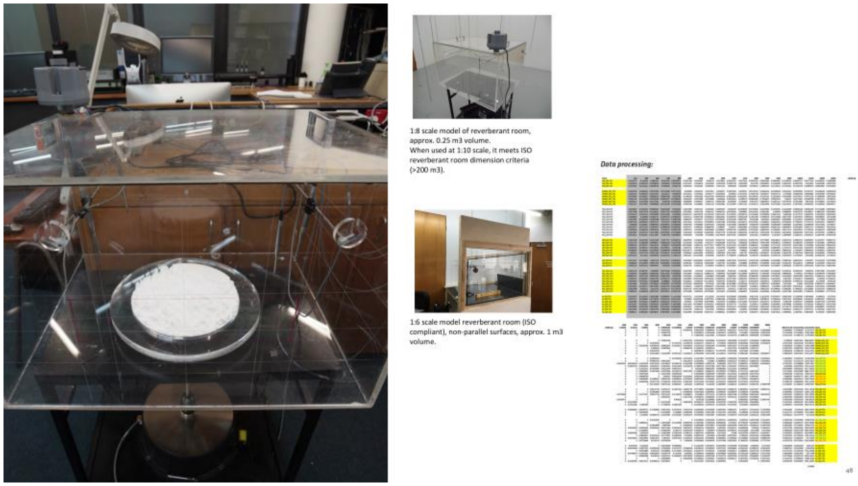

Fig. 4. Scale model reverberant room (right, mid) and scattering data (left) from scale model prototypes.

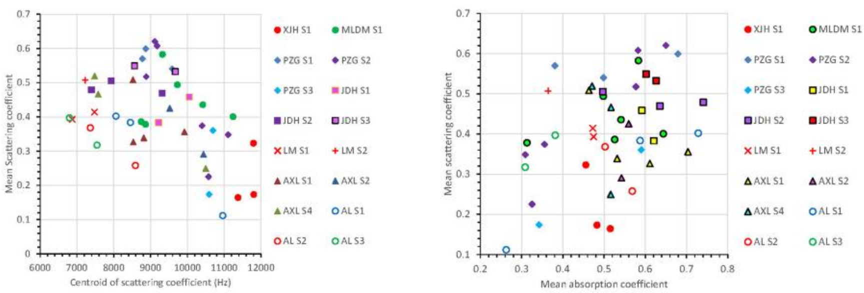

Fig. 5. Acoustic Results for tested micro-pattern sound discs, with centroid of scattering (left) and mean absorption coefficient (right).

2.3 Discussion, Constraints, and Next Steps

As a preliminary result, key constraints and benefits for investigating the fabrication and performance of micro-acoustic patterns were demonstrated. In terms of fabrication, robotic randomised manufacturing offered large scope for variability for sound discs; and a maximum depth of valley could be continuously achieved across the surface. In terms of acoustic analysis, similar densities of valley patterns cause similar acoustic behaviour; a periodic spatial design of surfaces produces a periodic scattering spectrum with regular visible peaks (whereas non-periodic pattern organisations tended to yield a smoother curve). General evaluations of removed material (percentage of waste) could not yield significant results for further tendencies. Most importantly, scattering and absorption highly efficient surfaces could be produced through slight change (robotic tooling lines combined with wire profile). Through pattern generations within multiple criteria (parametric modelling to scale model production to physical simulation), the acoustic reflective properties of surface patterns delivered tendencies for scattering performance, with a larger spectrum of scattering-effective acoustic micro-patterns produced in a robotic subtractive process. Yet, a more detailed review of surface properties and acoustic behaviour was required, leading to the next phase.

3 Reverse Engineering: Deriving Acoustic Tendencies

While the aim of this first analogue series had been to find an empirical relationship between a physical parameter and acoustic result, further approaches were required. These include the differentiation of ratio between surface area, depth of cut and pattern frequency; through measurement/ integration of the 1) of surface area of the disc, which can be expressed as a ratio to the flat disc prior to cutting; the 2) root-mean square (RMS) depth of the surface (subtracting mean depth); or the 3) circular FFT power spectrum around the surface (at various radii) as the most detailed approach. These criteria were explored in a digital simulation of the previous series, as is discussed in the following.

3.1 Surface and Depth Comparisons and Analysis

In order to conduct further acoustic simulations and to evaluate the previously tested, most successful sound discs (PZG-S02-series, based on generative agent system), accurate 3D representations of the physical models were required, based on close examination of the surface properties. Surfaces thus were simulated through modeling in GH Grashopper and KUKA|prc, based on the original lines of the robotic toolpath, and by use of the precise wire-frame tool dimensions and shape (v and def-v, u-shallow and u-steep, y-shapes, see Fig. 6).

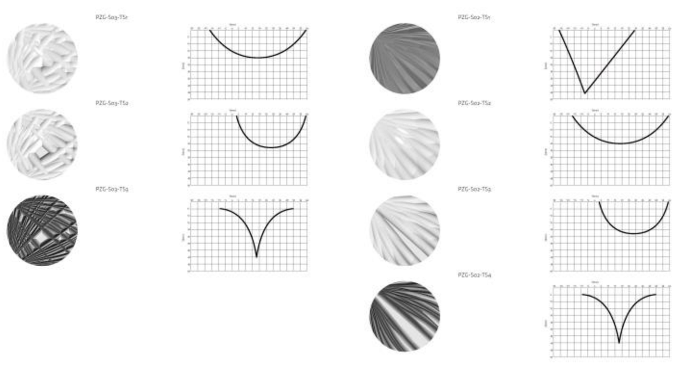

Fig. 6. Re-engineered acoustic pattern series based wire-profiles, toolpath and depth as simulation (agent based, single origin, left/double paths, right/single path)

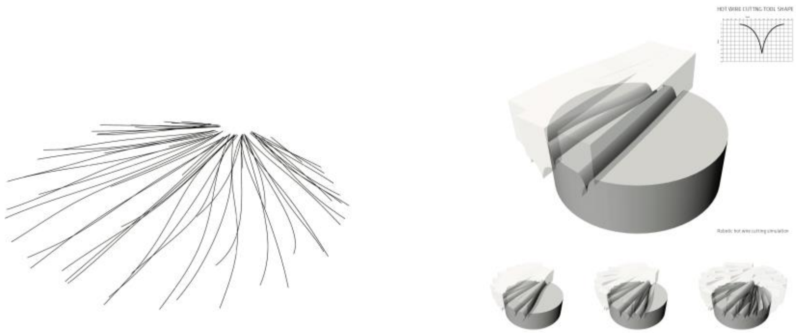

Fig. 7. Agent-based modeling setup for macro pattern toolpath, with agent emitted from random location, no attractor points or obstacle in environment (GH, left), and simulation of the robotic hotwire subtraction process (KUKA|prc, right).

Through re-modelling by extrusion and Boolean operations that replicated the pattern configurations and robotic tool path, the samples could thus be differentiated for the ratio between surface area, depth of cut and pattern frequency (Fig. 7). This allows further analysis through detailed comparisons of the surface properties in order to achieve the closest approximation between analogue model and digital simulation:

Surface Area Comparison. The first calculation compared the original surface area of the uncut disk to the finish surface area of the cut disc. This provides a ratio or mass applicable for comparison purposes, but remained too unspecific for detailed depth of valley descriptions and thus acoustic performance.

Volume Comparison. The second calculation measured the volume of material removed by comparing the cut surface to the uncut surface. This provides an indication of material wastage and removal, which is relevant for fabrication.

For consecutive calculations, more precise measurements were delivered by calculating surface depth of each sample with superimposing a point grid for single point depth; and radii for mean depth frequency (Fig. 8):

Root mean squared (RMS). The third calculation evaluated the cutting depth across the surface and calculates the square root of mean squared of this data. The Root mean squared or RMS value is used as the best measure of the effective value, in this case of the surface depth. Its mathematical value is computed by taking the square root of the average (mean) of the squares of a set of randomly varying depth observed at regular intervals (outer, inner and middle rings) for a pattern disc, which gives each disc a recognizable depth and thus acoustic profile. Here, the cutting depth is evaluated by projecting a grid of sample points across the cut surface as an even grid, with approximately 1885 sample points were evaluated for depth.

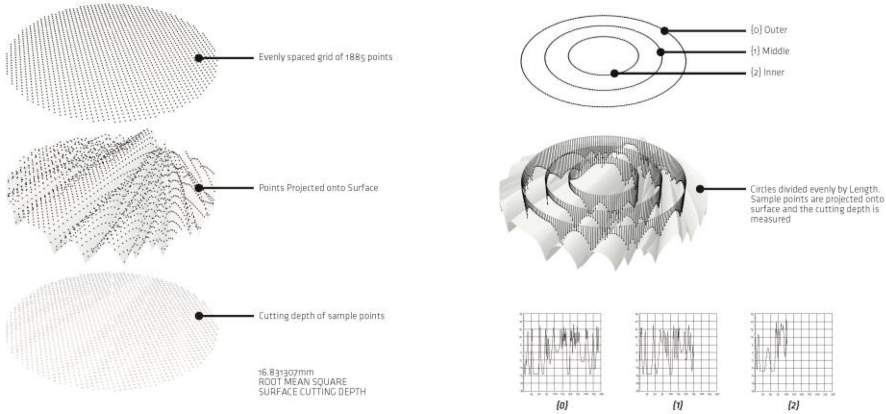

Fig. 8. Root Mean Squared RMS comparison with point blanket (left), and Depth-Depth Mean with radii set at intervals (right)

Depth - Depth Mean. The fourth calculation then measured the cutting depth of a series of divided radii, which are projected onto the cut surface and calculates the mean for each radius. Radii were set at A=50, B=83 and C=116mm with A=314, B=523 and C=733mm perimeter values. The depth value measurements were taken at approximately 3mm intervals along the circle perimeter. The mean is then subtracted from each of the values and this data is plotted as a graph. This provides an indication of the mean depth frequency.

In a limited case study of series with six samples (PZG-SO2), the surface designs were re-engineered to form a profile with exact depth points and valley dimensions (see Fig. 9). This provided differentiation of ratio between surface area, depth of cut and pattern frequency; through measurement and integration of disc surface area, root-mean square (RMS) and depth of the surface (subtracting mean depth); and circular FFT power spectrum around the surface (at various radii). Samples could thus be evaluated, prior to robotic prototyping and the physical acoustic validation. The acoustic surface analysis then follows then the same logic as physical acoustic measurement, with a spectrum analysis around circles that trace the path of the sample as it rotates in the acoustic measurement procedure. This optimizes the parametric design of scattering surfaces by moving fast from prototyping to final validation stage. And while non-physical computational acoustic modeling (such as using boundary element method or finite element method) is computationally intensive in respect to useful design loops, such shortcut indicator of scattering can provide a large advantage. Most importantly, direct design loops between design, fabrication and acoustic evaluation thus become possible.

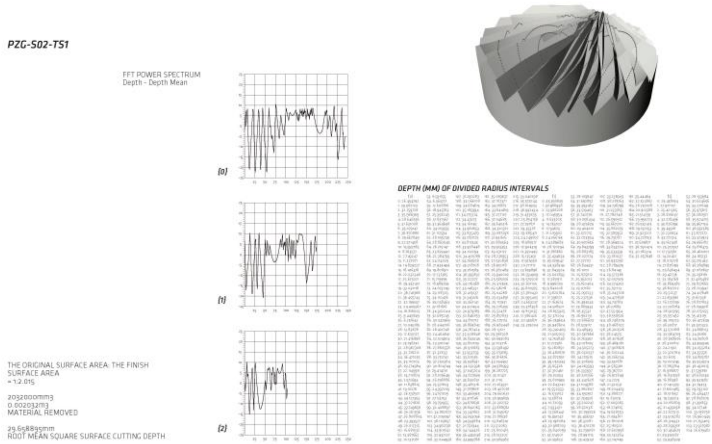

Fig. 9. Sample of resulting virtual simulation of six acoustic samples of a series (PZG-SO2). This delivers exact measurements of surface depth which are used for virtual acoustic evaluation of scattering performance.

3.2 Relating Form to Scattering Coefficient

The relationship between physical form and scattering coefficient is complicated because scattering may be caused by a combination of wave-related effects (interference and diffraction) and small scale specular reflection (mainly at high frequencies, from curved or angled surfaces). Computational modeling of sound wave interaction with a complex surface is non-trivial, and generally takes substantially more effort and time than fabrication and physical acoustic measurement. Nevertheless, in general a more complex surface might be expected to yield greater scattering, and there are various ways of indicating this. The simplest might be the amount of material removed from the blank sample, assuming that more cutting might be associated with greater scattering. While this is easy to measure, it has an obvious flaw of being insensitive to the roughness of the sample's surface (e.g., a flat surface could result from the removal of material, which would yield no scattering). For the six samples considered here there is near-zero correlation between material removed and scattering coefficient ($r = 0.06$).

The increase in surface area of a sample, compared to the flat sample, is likely to be a better, albeit crude, indicator of scattering. Surface area can be expressed as a ratio with reference to the original flat circular face. For the six samples considered here there is a correlation coefficient of $r = 0.60$ between surface area ratio and scattering coefficient, which concurs with this hypothesis, but only as a weak indicator.

A more robust, indicator of scattering might be the root mean square (rms) amplitude of the surface. Before calculating root mean square ($\hat{z}$), we first subtract the mean surface depth, $\bar{z}$, because the mean depth will have no effect on scattering, whereas fluctuations around it will. This is expressed in equation 1, where z is the set of depth values and n is the number of data-points.

$$\tilde{z} = \sqrt{\frac{\sum(z\text{-}\bar{z})^2}{n}} \qquad (1)$$

The correlation between $\hat{z}$ and scattering coefficient is r = 0.85 for the six samples tested. A limitation of the RMS indicator is that it is insensitive to the spatial relationships between z values across the surface. An alternative that is sensitive to spatial relationships is to perform spectrum analysis of the surface, which decomposes the surface to a series of sinusoidal waves over a range of spatial frequencies. The magnitude spectrum, Z, can be derived from the absolute value of the fast Fourier transform (FFT) of a set of surface depths (equation 2). This set of depths could be approached in various ways, but in this study the values are read around a circle – which is particularly apt considering that the scattering coefficient is measured by rotating the sample. In this study three circles were used with radii of 116, 83 and 50 mm

$$Z = |FFT(z)| \qquad (2)$$

Again, the mean surface depth, which is represented by the first spectrum component, is of no interest and can be neglected (or zeroed by subtracting the mean prior to conducting the Fourier transform). As can be seen in figure 10, the magnitude spectra of the samples have most modulation at low spatial frequencies. The power spectral centroid provides a single value summary of spectral balance, and is calculated following equation 3, in which f is spatial frequency. Centroid values are between: 7.6 and 13.2 in the outer circle; 5.3 and 12.6 in the middle circle; and 1.9 and 6.2 in the inner circle.

$$f_{centroid} = \frac{\sum Z^2 f}{\sum Z^2} \qquad (3)$$

There is a high correlation between the mean magnitude of the low spatial frequency components and the scattering coefficient (e.g. taking the mean of components 2-16, which correspond to harmonics 1-15, of the outer circle yields a correlation coefficient of r = 0.97 with scattering coefficient), as illustrated by figure 11. A similarly high correlation is achieved in the middle circle using components 2-9 (harmonics 1-8). The inner circle does not provide such a good predictor of scattering, which is understandable considering that it represents less of the surface, and that the center part of the disc moves less during rotation than the outer part. The fact that the optimum spatial cut-off frequency is lower in the middle circle than in the outer circle suggests that the distance moved, rather than the angle rotated, influences scattering. Relating this to the scale of sound waves, the 15th harmonic of the outer circle has a wavelength corresponding to sound at about 7 kHz, while the 8th harmonic of the middle circle has a wavelength corresponding to sound at about 6 kHz.

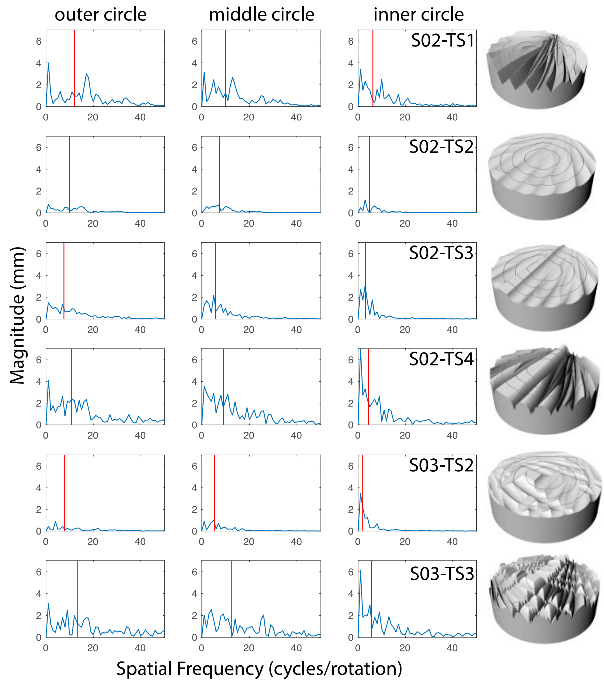

Fig. 10. Spatial magnitude spectra of the six samples measured around three circles (outer, middle and inner). Power spectral centroid (which can be thought of as the mid-point of the spectrum's power) is shown as vertical red lines.

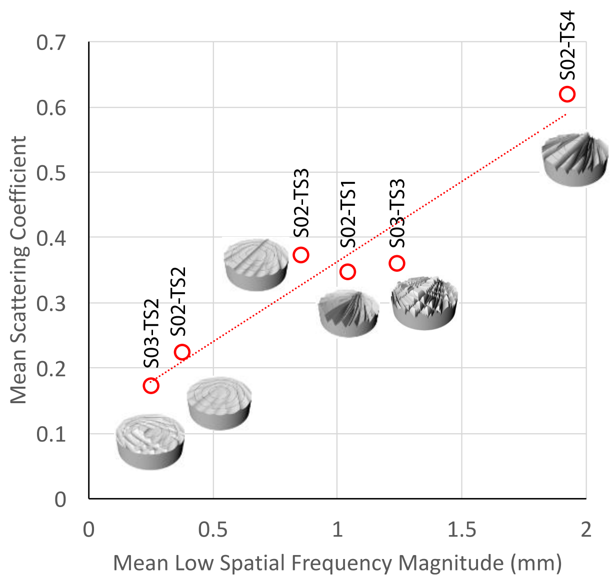

Fig. 11. Relationship between the spectrum magnitude (components 2-16 of the outer circle) and scattering coefficient (mean of 1/3-octave bands from 2-20 kHz) for the six samples, yielding a correlation coefficient of $r = 0.97$.

4 Conclusion

This study has explored the relationship between physical form and acoustic scattering of surfaces, finding that the low spatial frequency magnitude of surface modulation relates closely to scattering coefficient in a limited case study of six samples. The approach taken to surface analysis follows the logic behind the acoustic measurement: spectrum analysis is done around circles that trace the path of the sample as it rotates in the acoustic measurement procedure. Results suggest that, with further refinement, scattering surface design could be approached in the spatial frequency domain, or that prototype designs could be evaluated quickly using this technique prior to fabrication and acoustic validation. As has been discussed, this provides a substantial opportunity for speeding up parametric design of scattering surfaces by moving the slow physical part of the process from the design loop to the final validation stage. Non-physical alternatives involving computational acoustic modeling (such as using boundary element method or finite element method) are currently too computationally intensive and cumbersome to incorporate into a useful design loop, and so this shortcut indicator of scattering can provide a large advantage.

The concept of spatial spectrum analysis for scattering surface design has some history in the seminal designs by Schroeder, such as the quadratic residue diffuser (QRD) [8] and maximum length sequence (MLS) diffuser [9]. Both of these are designed to have a flat magnitude spectrum up to the Nyquist frequency established by discrete element (or ‘well’) width, with the flat spectrum being seen as likely to provide even scattering over the design frequency range. A broader scattering frequency range is achieved by the QRD due to the greater range of surface depths.

Following the work described in this study, a larger systematic study is envisaged examining relationships between parameters that describe surface form and acoustic scattering. The present study used three circles for surface analysis, but it would be a minor extension of this technique to analyze the whole surface. With more test samples, it would be possible to examine the relationship between the scattering coefficient spectrum and surface spectrum. These and other developments of the present study would allow a large speed-up of novel scattering surface designs.

Acknowledgements. This paper is part of ongoing research into acoustic performances of architectural surfaces. The authors would like to thank the team for CodeToProduction2016 for their engagement (Michel De Melo, Juanhua Alphonse Li, Xuhui Lin, Anson Li, Gulling Pat Zhen, Jarrod Haynes). The research was supported by a 2015 SEED grant and a 2017 research grant from School of Architecture, Design and Planning, The University of Sydney. Robotic fabrication with support of the DMaF Lab by Dylan Wozniak-O巽석onnor, Rod Watt and Lynn Masuda.

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Body Patterning: A Model for Responsive and Interactive Building Envelope

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Abstract. Patterns in nature, either the cells forming the skins of living organisms or the sand forming the dunes, are in a constant change. Given that, pattern cannot only be seen as an absolute image of a whole formed by units, but it can also be seen as a process, which is controlled by stimuli affecting the outcome both visually and functionally in the architectural context. In this paper, the changes on the bodies of color and form changing living organisms are implemented to the building envelope as a dynamic process of adapting to the environment in terms of interaction. The bio-system is implemented to the envelope in terms of morphological, functional, and behavioral properties of particular living organisms. The proposed model is discussed in terms of adapting its environment by sensing and responding.

Keywords: Biomimicry, Pattern, Chromatophoric Architecture, Building Envelope.

1 Introduction

A long history of creating a recognizable order exists in design, which is called as pattern or occasionally ornament. These terms have been controversial so far, as Picon asserts that since Renaissance, architects have seen the ornamentation as an insignificant property than the organization of the whole building [1]. Besides, the exclusion of the pattern from the scene of the architecture had reached a peak with Modernism whose motto 'form follows function' made the pattern unnecessary within the built form. Since Alexander implies that production of building can be called as the assembly of patterns, the rejection of pattern from architecture has superseded by the idea that the pattern is a contributor to make architecture more profound [2]. However, regardless of these discussions in the architectural scene pattern as a formation appears from micro scale to macro scale as a transition between matter and energy in nature.

The very special type of the pattern formation occurs on the body of color and form changing organisms such as cephalopods as an adaptive process. This formation is called body patterning. The skin of these organisms works as an interface between inner and outer body. The building envelope also works as an interface by enhancing the interaction of the building with its environment as well as providing the inner comfort. The building envelope is usually a static element, which cannot adapt the changing environment. Given that, the dynamic envelope that responds to stimuli has become a key issue to create an interactive and responsive skin.

This paper is about the implementation of dynamic body patterning of particular living organisms to the building envelope in terms of adaptation. The adaptation process is triggered by stimuli - sun, human movement, and visual changes in the environment. In Section 2, biologically inspired design will be explained as a methodology for this paper. In Section 3, the differentiation between pattern and ornament will be discussed by focusing on sensing and identity. Next, body patterning as a bio-system and man-made system will be examined. In Section 4, the changes on the bodies of particular living organisms are implemented to the building envelope as a dynamic process of adapting the environment in terms of camouflage (blending with its environment) and interaction. Finally, the outcomes will be discussed in terms of sensing and responding in the adaptive building envelope.

2 Biologically Inspired Design

Nature has been an inspiration to solve problems, which is called as biomimicry. Biomimicry is defined as "the conscious emulation of life's genius that is long tested by evolution" [3]. It is used as a method in several fields such as engineering and medicine and as well as architecture. However, when emulating the biological mechanisms to architecture, certain abstractions of natural mechanism should be needed from the early design process. Given that, the process can be defined as the biologically inspired design because of the analogical relation between natural and man-made systems.

Biologically inspired design (BID) has three properties such as adaptability, multi-ability, and evolvability [4]. In the proposed model, the focus is on adaptability of living organisms as a response to the ever-changing environment. The implementation of adaptation strategies of bio-systems occurs in several ways such as morphological, functional, and behavioral [5]. Morphological adaptation in nature is related to the appearance of the organism such as form and color. Functional and behavioral adaptations are defined as an organismic or systemic response to the stimuli [5]. However, functional adaptation is a chemical process such as CAM photosynthesis while behavioral adaptation is a physical such as concealment of cuttlefish.

The morphologic, functional, or behavioral properties are implemented from nature to the design by employing two different approaches, which are solution-driven, and problem-driven approaches. Searching other ecosystems or organisms for a defined problem is called problem-driven approach and analyzing specific ecosystems or organisms for adopting the found relations or behaviors into the design is called solution-driven approach [6]. The solution-driven approach is adopted in this paper in order to form the pattern based dynamic envelope, which adapts its environment by enhancing the inner comfort and interacting with its environment.

Regarding pattern in architecture, the inspiration of nature oscillates between imitated and functional morphology. Arslan and Gönenç Sorguç assert that the imitation of the organisms' form has usually been encountered in architecture as a kind of visual expression [7]. For example, the pattern of neural networks is repeated in façades of the different buildings in order to create a complex expression. Thus, detailed analysis of the morphology becomes a key issue in order to enhance the functionality of the building envelope as well as visuality of it.

3 Patterning and Ornamentation on Bodies

Pattern can be defined as the sequence or frequency emerging from the repetition of a unit. However, identical units are not necessary for being a pattern. For example, all the seashells have different lines on their outer surface, which cannot hamper to distinguish the seashells from other organisms. Several categorizations of pattern exist, but none of them captures the whole. Pickover suggests three categories that are the patterns of representing nature, mathematics and symmetry and human art by implying that any of the patterns can be tagged with another category than the suggested one [8]. In this paper, we define two main categories such as nature and man-made patterns by combining the mathematics with human art.

In nature, pattern formations can be categorized as bubbles, waves, bodies, branches, breakdowns, fluids, grains, communities etc. [9]. For example, the bubbles tend to make the minimum surface, while the living organisms try to adapt to their environments by forming their pattern of molecules or cells. Every single entity within a pattern creates a complex whole, which sometimes creates a visual appealing ornamentation, especially in the living organisms.

In man-made realm, there are several subcategories of pattern, which depend on the discipline. For architecture, Alexander defines three sub-categories that are the urban, building and construction, which can be used for creating a design pattern [2]. Some of the patterns represent topological relations between entities such as spatial patterns. Some of them work for the embellishment such as decorative patterns in order to create an appealing look. Moreover, decorative patterns such as Islamic patterns have aesthetic values additional to geometrical properties of units, which help to tile a surface or construct a 3D form like Muqarnas.

Pattern has certain mathematical relations of elements and functional properties, which define the organization of the whole, while ornament has aesthetic properties, which are not necessarily because of function. Moreover, pattern and ornament differ in terms of *symbolic meaning* [10]. Gleiniger asserts that the pattern theory is a rational phenomenon, and the ornament theory is a sensorial and meaningful phenomenon [10]. Rationality of pattern comes from the mechanism behind the outcome, the rules, or relations that form the final pattern. Sensory of ornament comes from the *enrichment* [11] of the pattern as an addition to the rationality of it. Enrichments appeal the senses with additional static or dynamic properties upon the organization of units (pattern). As it is shown in Fig.1, body ornamentation can be defined as the enrichments of sensing and identity upon body patterning. *Meaning* in

Gleiniger's explanation of symbolism is replaced with identity due to properties of body ornamentation in nature [10]. Body ornamentation ensures sensing the environment and responding to it as well as giving identity to the organism.

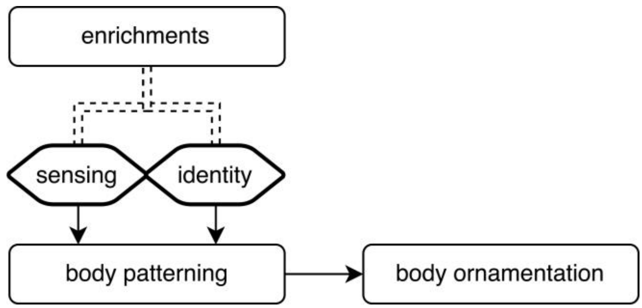


Fig. 1. The relation between body patterning and ornamentation

By re-examining the nature, regarding pattern alternation on bodies of living organisms has shown body patterning occurs both functionally and visually. Moreover, body ornamentation usually occurs especially in birds for attracting mates, which is an example of *extended phenotype* [12] addition to the morphogenetic pattern formation of birds. According to Dawkins, phenotype is not confined to biological processes within the body and extended to embody all effects that a gene has on its environment [12]. Thus, both in animals and humans have the extended phenotype regarding body ornamentation as an extension to their own skin. The body patterning is analyzed in two sections as bio-system and man-made system.

3.1 Body Patterning as a Bio-System

As a pattern formation's sub-category, the very special kind of pattern changes occurs on the skin of animals, which have the ability to change the form and the color of their skin. Body patterning is mainly related to the communication between living organisms as well as adaptation to environmental changes. Moreover, their interactive skin gives an identity to the organism. For example, cephalopods, which have sophisticated skin adaptation system in both color and form adapt perfectly to the environment thanks to its multi-layered skin. According to Packard, the body pattern of cephalopods is comprised of the chromatophores, reflecting cells and skin muscles [13]. The most prominent element of body patterns are chromatophores cells due to their colors and they appear on the specific region of the body [14]. The chromatophores vary in color and filter the light to define the color of skin by inflating and deflating, which is shown in Fig. 2. If the chromatophores inflate, they color the skin to their own colors by filtering the reflected light. If they deflate, the light, which comes through the skin, is reflected as white color by reaching leucophore cells. Iridophores produce iridescent colors. These pigment-like cells work as muscles and ensure two functions such as *concealment and communication* [14].

By inflating and deflating, they block each other and create several patterns on the body of the organism.

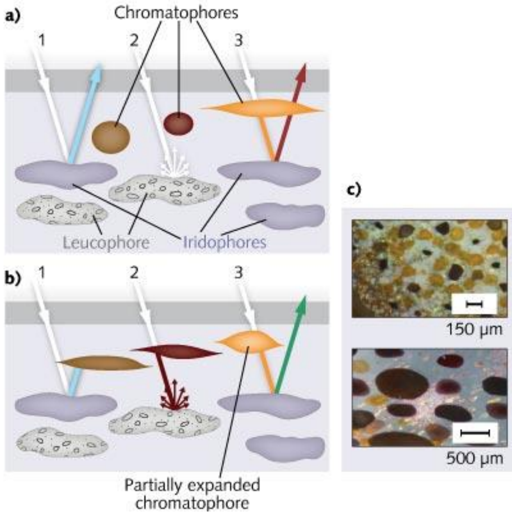


Fig. 2. The layered system of the chromatophores of *Cephalopod* [15]

Another example for the pattern formation on bodies is the skin of Antarctic krill. The skin has several muscle-like pigments, which can inflate and deflate in order to change the color and overall pattern of the skin (Fig. 3).

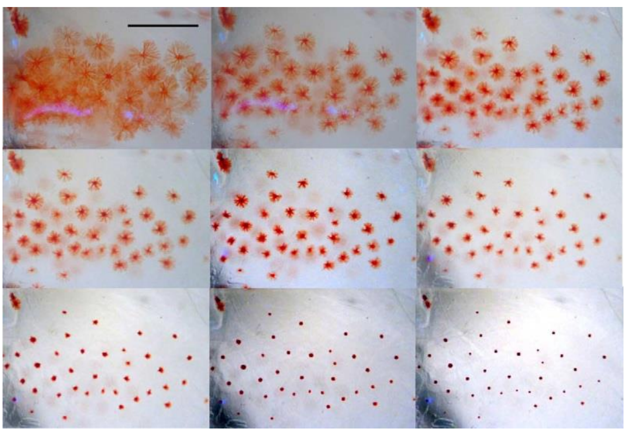


Fig. 3. The mechanism of Antarctic Krill's skin [16]

3.2 Body Patterning as a Man-made System

Unlike other organisms, human does not have peculiar body patterning to attract the attention or simply protect himself from climatic changes. Thus, people in tribes cover their skin with ornaments to emphasize their position among others, sometimes for rituals and conceal themselves for protection. Ornaments might be applied on body in order to transfer social messages in a community as an example of the interaction. They show the already gained social status or act as an interface for the communication of given social identities [17]. These ornaments generally consist of geometrical elements repeated all over the body. They have symbolic meaning as ornament and they follow a geometric rationality as pattern. The symbolic meanings of the body ornaments are comprised of idealized representations of persons of different ages, gender specific representations [17], group affiliations, marital status, social standings, or levels of wealth etc. [18]. Like in nature, ornamental enrichments upon repeated units occur in body patterning on human bodies. This early version of body ornamentation is followed by fashion design that is out of the scope of this paper.

Body patterning can be translated to the building envelope as an order of units in the context of architecture. The organization of units in a pattern is defined by the rhythm of the elements. This rhythm can be classified as regular and irregular regarding whether the grasping the period of the pattern or not. Both of them can be used to tile a surface or strengthen linear materials such as rope by weaving. Unlike the static organization of units, the dynamic organization is used to control inner comfort or animate the data.

4 A Model For Bio-Inspired Interactive and Responsive Building Envelope Based On Pattern

The environment of the building visually changes due to the rapid urban development in recent years. On the other hand, we live in a digital world, many information passes through visual displays. Thus, building skin should have the ability to both blend and interact with its surroundings by becoming an interface or media façade. When we search for such interfaces in nature, we see that several organisms such as chameleon and cuttlefish have adaptable skins. By employing the methodology of biologically inspired design mentioned above, the proposed model transfers the functional morphology of the cuttlefish's skin as well as the behavior of it in terms of responding stimuli. Changing patterns on the body of living organisms, which are utilized as both the concealment and accentuation elements, is implemented to the building façade, envelope, or installation.

4.1 The Implementation of Pattern Formation of Skins

Living organisms adapt to their environments according to stimuli. Their skin adaptation systems are affected especially by light, interaction with other organisms and visual changes in the environment. These stimuli are transferred to the proposed model as parameters, which affect the overall formation of the building envelope.

The pattern formations of skins are implemented according to three parameters of evolution and adaptation of living organisms such as morphological, functional, and behavioral [5]. Morphological bio-system is transferred as layered skin, which behaves as a display by using pneumatic modules instead of muscle-like chromatophores. The stimuli, which affect the bio-skin, are light, interaction with living organisms and visual changes in the environment. These stimuli are implemented as the sun, interaction with people and visual change in the environment, respectively. While keeping the light and visual change stimuli the same, the interaction between organisms is transferred as human interaction within the space due to its habitability as a building envelope (Fig. 4).

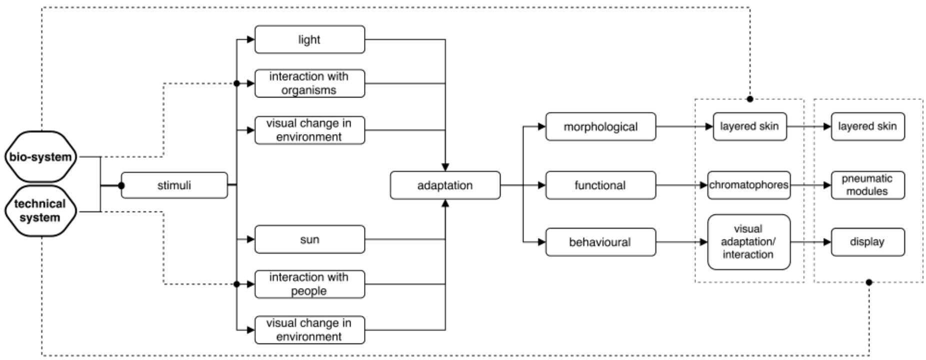


Fig. 4. The implementation diagram of proposed system

By implementing the properties of particular organisms' skin, an interactive pixelated building envelope is proposed by using double-layer of pneumatic units, which generated from a hexagonal grid. A unit is generated by selecting the medians of the hexagon. For the first layer, mediums of the 1, 3, 5 edges are selected and for the second layer vice versa. These selected edges form the one pneumatic module of the system as an implementation of chromatophores of the skin of color-form changing organisms (Fig. 5). The pneumatic units control the light by inflating and deflating as well as responding visually to the environmental changes and human movement by using LED, which is placed within each module.

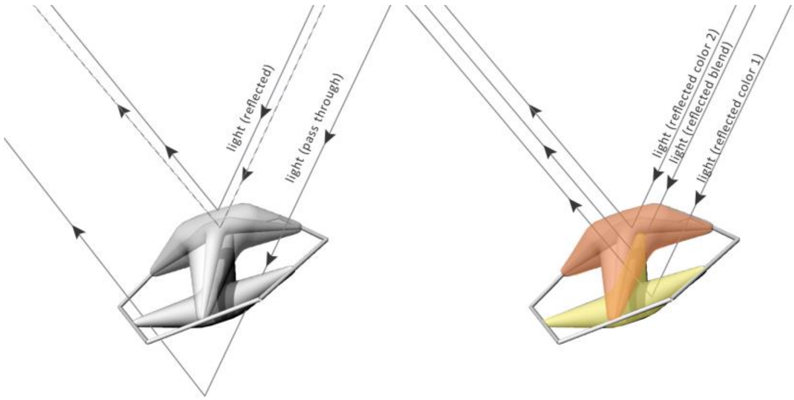


Fig. 5. The behavior of the double-layered modules in terms of light transmission.

Modules can be activated separately by being affected by different stimuli. Modules create a pattern when they form the envelope, façade, or installation upon a regular grid. The building envelope application of the system is mainly discussed in the paper.

4.2 The Pattern-based Responsive and Interactive Envelope

To generate the model, double-layer hexagonal grid, which is called hexagonal honeycomb is chosen to place the modules (Fig. 6). These two layers are interwoven and have the ability to change in color and form by using pneumatic, and LED systems like in the chromatophore cells of cephalopods. Several protrusions can be achieved by changing the distance parameter between layers as it is shown in Fig. 6.

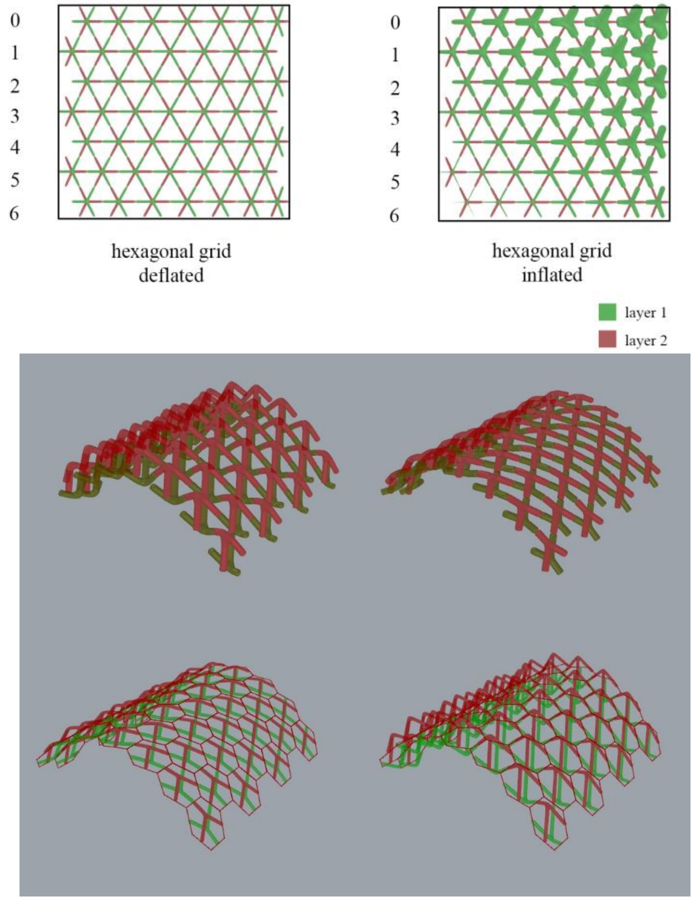


Fig. 6. The double-layer grid system, which is derived from hexagonal grid

The envelope responds to the sun, human movement, and visual changes in the environment. Pneumatic cells control the light transmission in the envelope according to the sun vector. Cells are inflated to protect the interior of the envelope from the direct sunlight. Thus, the seasons and the location of the envelope directly affect it. Moreover, the human movement within the envelope affects the body patterning by reflecting warm or cold colors according to the location and density of people. If the density of people increases in particular area, the modules reflect warm colors at that area, vice versa. The visual change in the environment also affects the envelope's formation and color by decoding pixel information of real-time data (Fig. 7).

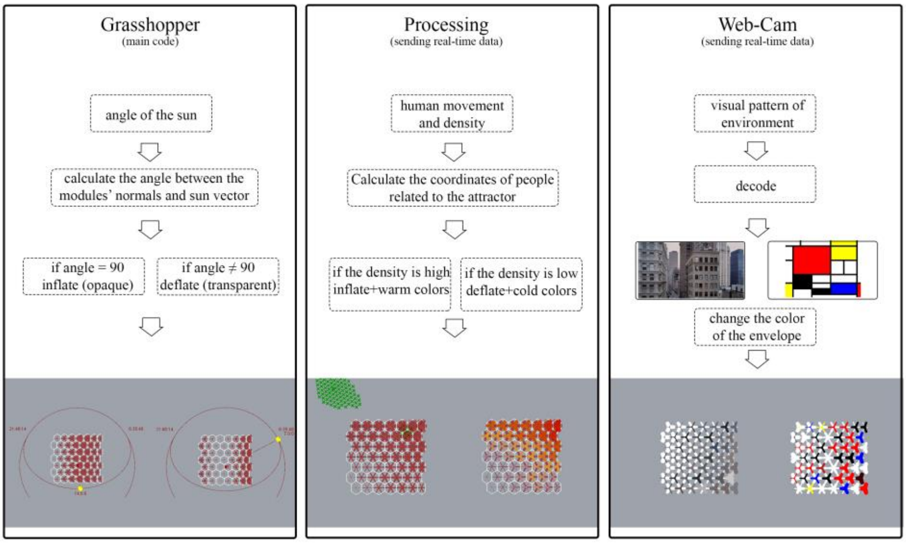


Fig. 7. The diagram, which shows the algorithm of the model

Data transmission between mediums is shown in Fig. 8. Any surface, which is created in or imported to Rhinoceros, can be used as an initial form. The initial form can be 2D or 3D surface. Next, the sun, human movement and visual change in the environment are represented in Grasshopper as vector, X and Y coordinates, and pixel, respectively. The angle between sun vector and surface normal is used for controlling the light transmission and heat. Moreover, the distance between the coordinates of the people and envelope is employed to control the inflation and deflation integrated with color as a signaling system. Human movement is transferred from Processing. Visual data of the environment is gathered from Webcam. Pixel data, which is collected via Webcam, affects the color matrix of LED system.

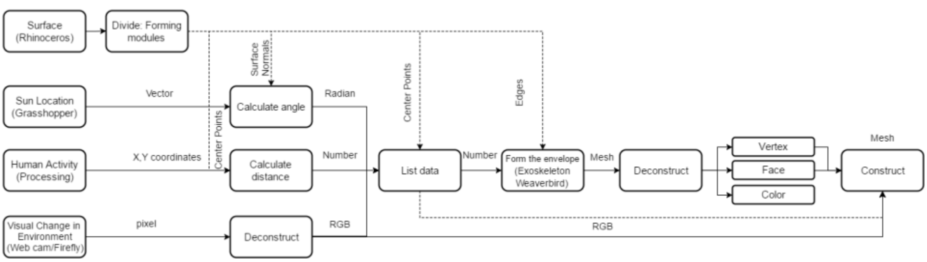


Fig. 8. The data transmission between mediums

Sun vector, which depends on the location, the date and time affect the envelope by triggering the inflation, if the sun angle is close to the 90° and deflation if the angle is not close to 90° (Fig. 9). The light transmission is hampered by inflation and allowed by deflation. Moreover, color changes can be integrated with the inflation-deflation system. For example, bright colors can be used in hot climates in order to increase reflection and reduce heat gain.

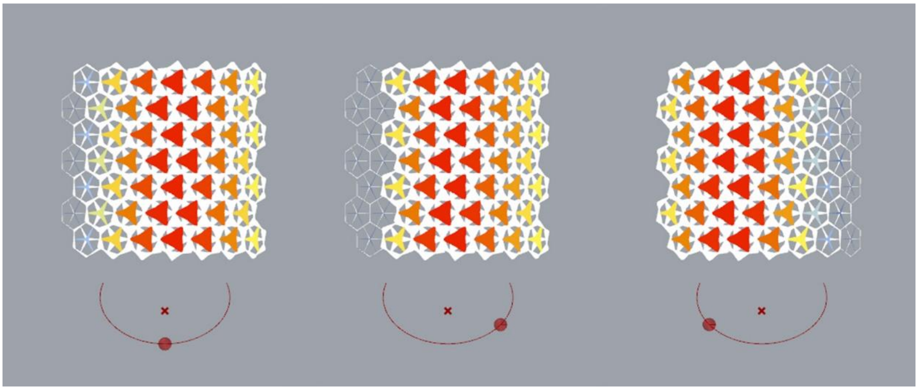


Fig. 9. The body patterning of the envelope according to the position of sun

Human movement and density within the envelope is represented in Processing with particles, which follow the attraction points by adapting the code for this model [19]. The user can control the location and number of attraction points. The changes of information are directly transferred to Grasshopper via ports (Fig. 10). The red points in Rhinoceros represent the number and location of people, which interact with the envelope. Points are synchronized with the Processing.

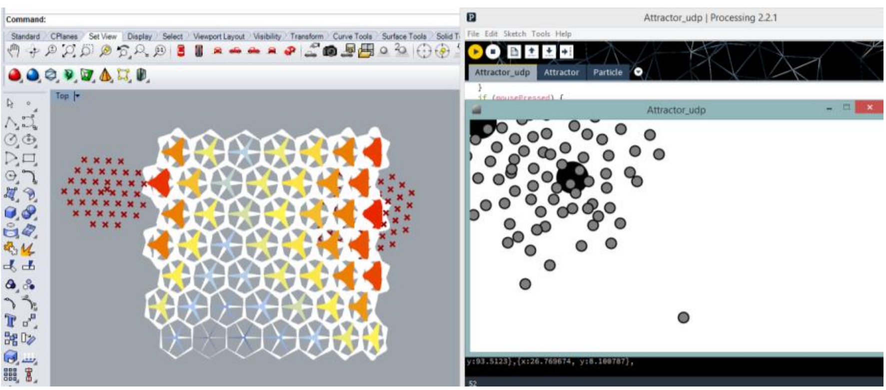


Fig. 10. The body patterning of the envelope according to the human movement

Visual changes in the environment are captured via Webcam. Firefly add-on in Grasshopper is used in order to transfer the captured image's RGB values to the model. Seasons as well as silhouette related changes in the environment directly affect the overall look of the envelope (Fig. 11).

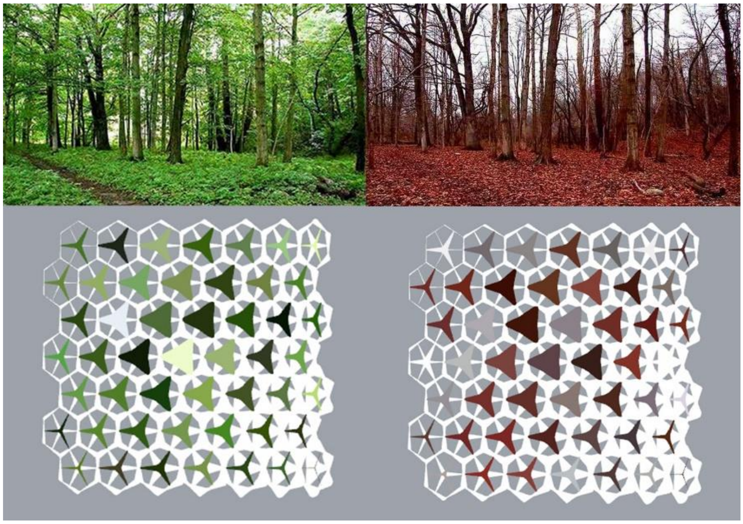


Fig. 11. The body patterning of the envelope according to visual changes in the environment

Combinations of the three stimuli – the sun, human movement, and environmental changes create many possibilities in terms of interior space and exterior appearance of the interactive and responsive envelope (Fig. 12).

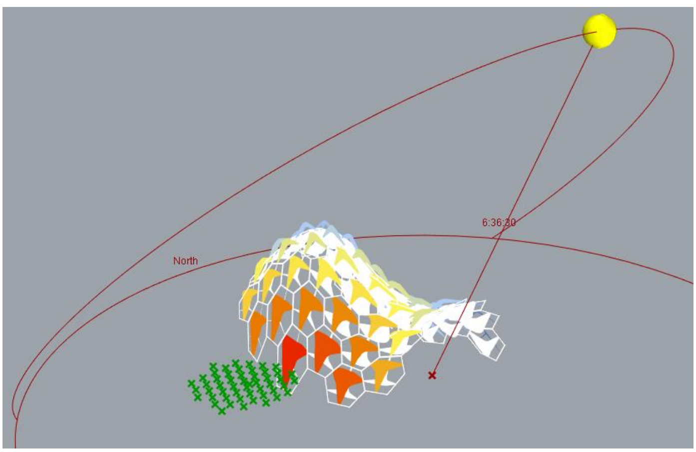


Fig. 12. The combination of stimuli affecting the envelope

4.3 The Outputs of the Model and Potentials

The model can be used to generate building envelope, façade, or installation from macro to micro scale in design. Pneumatic modules can be produced by using PVC, which is activated by air pressure. After producing the modules, they are replaced upon a hexagonal grid to form the envelope. Arduino can control the actuation with the light and movement sensors. The visual pattern of the environment and human movement can be used for the pneumatic actuation. The data, which is read as pixels, affects the inflation/deflation process by controlling air pressure with Solenoid valves within Arduino.

Three different application of model as a building envelope is shown in Fig. 13. In Fig. 13a, the pneumatic modules, which act like a textile, can be used with scaffolds due to stability. In Fig. 13b, the pneumatic modules are attached to a hexagonal structure with joints. In Fig. 13c, the whole system is produced as a pneumatic textile with PVC materials, which can take shape of a proposed form. Constant air should be provided to this type of system in order to take its shape and be stable. Changes within the envelope create the different kind of spaces affecting the senses.

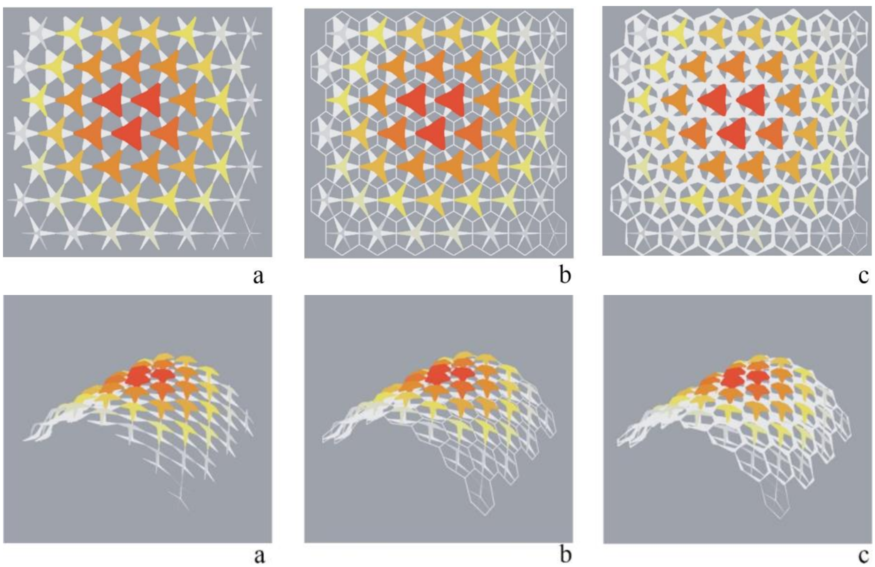


Fig. 13. The variations of the building envelope produced with the model

The façade application of the model can ensure the heat and light optimization in new buildings as well as old ones. Moreover, it can be used as a permanent or temporary display on building façades. Old buildings can visually blend with the environment thanks to the pigmented system. In micro scale, the model can be used as a kinetic installation in a space by employing the human interaction of the model. The model can be modified in the interior application for optimizing sound absorption or reflection in terms of performance.

Variations of the model are shown in Table 1. The type of stimuli and relation to the bottom or top layer of pneumatic grid affect the overall body patterning as well as the function of the skin such as the envelope, façade, or installation.

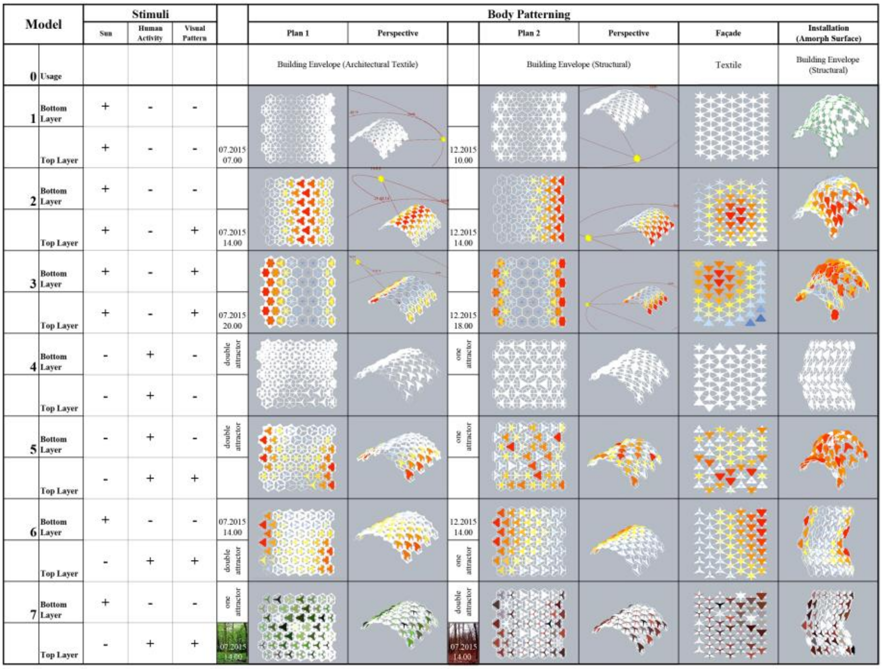
5 Discussion and Results

The body patterning mechanism of color and form changing organisms is adapted to the proposed model in terms of morphological, functional, and behavioral properties of the organisms by employing BID (Biologically Inspired Design) approach. Body patterning is defined as the rational organization of units, while body ornamentation with color and form changes is defined as the enrichments on the repetitive structure by sensing the stimuli and ensuring the identity of the envelope. The enrichments can be seen as *extended phenotype* [12], which ensures adaptation of the organism to its environment.

The variations are obtained owing to the sun, human interaction, and visual change in the environment. The sun orientation of the model yields to sustainable architecture with heat gain and light optimization. The optimization of the light and heat gain will be analyzed in the future research. The human interaction provides a dynamic relationship with the inhabitants of the building while defining a surface of communication with its environment. Moreover, the human and environmental interactions create *data animation* [20] on the building envelope regarding *chromatophoric architecture* [20], which is defined as a 3D grid of pixels. The use of color as an animation of social data shows how groups of people come together and behave [20]. However, further research is needed for analyzing the movement patterns of people interacting with the envelope. Thanks to the color adaptation of the model; it blends with its surroundings. Combinations of these agents can create microclimates in the interior of the pattern-based envelope by expressing the senses of inhabitants, which is transformed to the color data. This also works as a signaling system as in nature, which can be defined as media façade in terms of architecture.

Understanding the adaptations of living organisms leads to defining the building envelope as an expression, negotiation, and performance entity aside from dividing interior and exterior. Thus, the building envelope is not seen a static element and is seen as a system which can be transformed according to several stimuli like in nature. The building envelope becomes a responsive and interactive skin, which adapts changes in the environment with the pneumatic and pigmented system. Further research is necessary for the production of the pneumatic system and interaction circuits to test whether the proposed model works as expected. Given that, the model is a part of an ongoing research in terms of the production of the proposed system.

Table 1: The variations of proposed model.



Model		Stimuli				Body Patterning						
		Sun	Human Activity	Visual Pattern		Plan 1	Perspective		Plan 2	Perspective	Façade	Installation (Amorph Surface)
0	Usage					Building Envelope (Architectural Textile)			Building Envelope (Structural)		Textile	Building Envelope (Structural)
1	Bottom Layer	+	-	-								
	Top Layer	+	-	-	07.2015 07.00			12.2015 10.00				
2	Bottom Layer	+	-	-								
	Top Layer	+	-	+	07.2015 14.00			12.2015 14.00				
3	Bottom Layer	+	-	+								
	Top Layer	+	-	+	07.2015 20.00			12.2015 18.00				
4	Bottom Layer	-	+	-	double attractor			one attractor				
	Top Layer	-	+	-								
5	Bottom Layer	-	+	-	double attractor			one attractor				
	Top Layer	-	+	+								
6	Bottom Layer	+	-	-	07.2015 14.00			12.2015 14.00				
	Top Layer	-	+	+	double attractor			one attractor				
7	Bottom Layer	+	-	-	one attractor			double attractor				
	Top Layer	-	+	+	07.2015 14.00			07.2015 14.00				

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Remembrane:
A Shape Changing Adaptive Structure

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Abstract. This paper presents a research on adaptive kinetic structures using shape memory alloys as actuators. The target of the research is designing and building an efficient kinetic structural system that could be potentially applied at an architectural scale. The project is based on the study of tensegrity and pantograph structures as a starting point to develop multiple digital and physical models of different structural systems that can be controllably moved. The result of this design process is a performative prototype that is controllable through a web-based interface. The main contribution of this project is not any of the presented parts by themselves but the integration of all of them in the creation of a new adaptive system that allows us to envision a novel way of designing, building and experiencing architecture in a dynamic and efficient way.

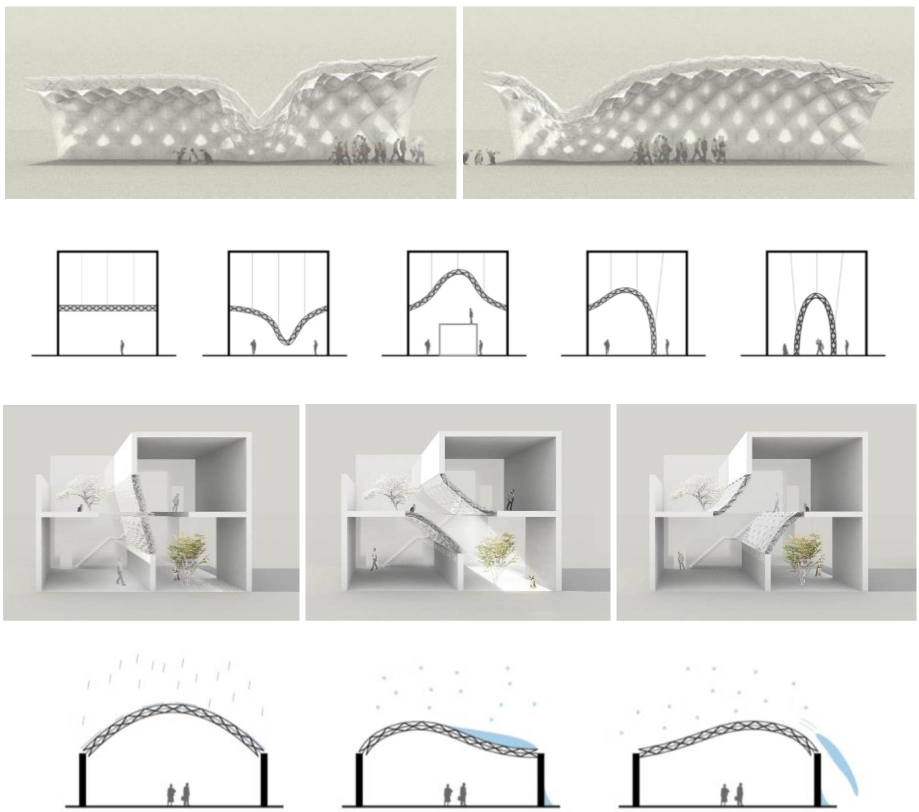
Keywords: Responsive Structures, Kinetic Structures, Adaptive Systems, User Interaction, Structural Optimization

1 Introduction

Understanding the significant need of generating the production of responsive construction systems, the scope of the paper is to present a case study on computed matter, exploring shape memory adaptive structures to be applied at architectural scale. The project implements shape memory alloys, digital content, fabrication and user interfaces to set up an intelligent responsive structural system that can be applied in different architectural scales. Shape memory alloys are not new and have been extensively used previously for a number of kinetic prototypes. The novel aspect of the present research is the overlapping of computational design and simulations, physical computing and user interfaces in the implementation of dynamic systems (user-environment) in the architectural scale.

Remembrane is an exploration of applying shape memory alloys to create a big scale adaptive kinetic pantograph-tensegrity structure that could adapt to environmental changes and be easily controlled by users through a user-friendly interface. The research focus has been placed on the structural design following the material properties and allowing users to be the ultimate decision makers of the performance of the structure. The developed prototype investigates the use of springs made of Nitinol (a shape memory alloy) as linear actuators. The project avoided from the beginning the use of centralized heavy motors to move the system and focused on developing a distributed system of lightweight actuators (nitinol springs) embedded into the structure that allow a much more precise control of the shape and a much more energy efficient movement.

The interaction with the structure and the different ways of controlling it have also been an essential aspect of the project. Easy manual control of the shape and automatic autonomous performance of the system had to be combined in order to achieve a truly intelligent and efficient interaction. Both ideas were at the starting point of the design of the user interface. The final prototype of the research is a real scale performative kinetic structure. The prototype has been deliberately left without a specific function in order to allow us to envision an endless number of potential applications: from adaptive partition solutions to environmentally responsive roofs, to morphing facades and changing urban elements (Fig. 1).



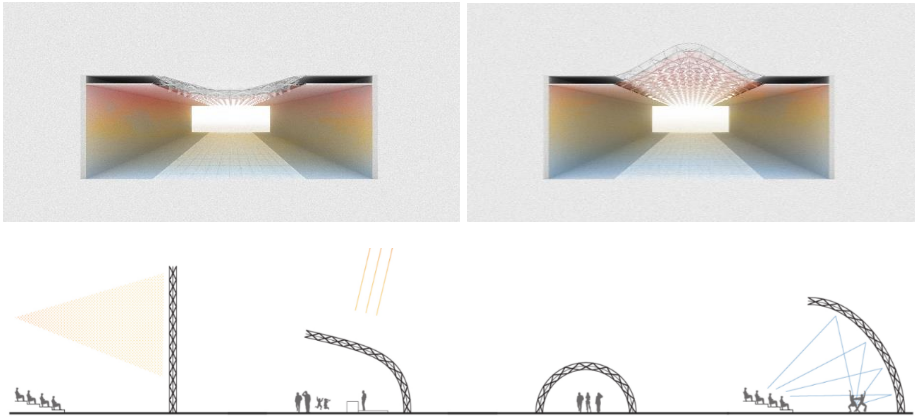


Fig. 1. Different applications of adaptive structures

2 Background

Kinetic and adaptive structures have been part of the architectural discourse for decades, but recent technological advancements have made them much more feasible. From academic research to real built structures motion has now become an integral part of architectural design.

The adaptive affordances of kinetic structures have been debated in architectural research for more than a decade (Senagala, 2005). The issues of automation and control have been proved instrumental in the development of kinetic, responsive and adaptive structures and their contribution towards a 'smart architecture'. A wide variety of strategies in construction and automation of kinetic, robotic and complex systems mechanisms has been employed to achieve transformability and adaptability in engineering and architecture (Sanchez del Valle, 2005). Under this scope digital prototyping and simulation has always been a key component in the development of these strategies. Moreover, the issues of user control and interaction have also been rigorously studied and proposed as inevitable components of human perception and engagement with dynamic structures and architectural spaces (Michael & Allyn, 2012). In this study, we are proposing a novel adaptive system that aims to incorporating all of the above. Specifically, the project implements a kinetic mechanism, i.e. shape memory alloys, digital content, fabrication and user interfaces to set up a responsive structural system that can be applied across different architectural scales.

As mentioned, kinetic structures are not new in architecture. They have been envisioned and developed for decades and can be categorized according to their typology, motivation, type and mechanical analysis of the kinetic mechanism (Ron & Weissenbock, 2013). Various structural, behavioral and physiological adaptation agendas have been employed for a variety of design objectives, including environmental control, energy generation, conservation and transport and usage principles as well as material property based changes per component (Biloria &

Sumini, 2009). As mentioned, the proposed system has been deliberately proposed without a prescribed application as it is envisioned as an open-ended system that aims to be the basis for future applications of kinetic structures based on shape memory alloys.

Shape memory alloys are certainly not novel technology as they have been commercially available for decades, however their use in architectures is not very widespread although there has been a number of studies that has demonstrated their potential in architectural applications. Nickel Titanium Shape Memory Alloys have been implemented in small scale prototypes to demonstrate their ability to configure and reconfigure spatial volumes (Villalon, 2007). Our study uses Nitinol springs in the form of a lightweight distributed system of actuation of a larger scale structure. Nitinol springs have also been implemented for the investigation of surface movement through controlled and repeatable deformation of a composite structure of an art installation demonstrating their potential in further application of architectural scope (Esquivel et al, 2013). Shape memory polymers (SMP) have also been implemented in small scale prototypes in lightweight deployable structure and have also demonstrated the potential of shape-changing materials in architectural scale and scope.

As previously stated the main contribution of this project lies on the integration of all aforementioned aspects of fabrication, control and automation for the development of an open ended kinetic system that can form the basis of further architectural applications

3 Methods

3.1 Actuators

The first development step was to test different actuators and assess them in terms of their resistance, lifespan and light-weightness. Shape memory alloys (in particular Nitinol) were the selected solution because they are relatively powerful and lightweight. These two characteristics make them very suitable for an actuation system that is embedded into the structure and distributed throughout its different parts. Nitinol wires are flexible at normal air temperature and they go back to a “saved shape” when heated above the transformation temperature (70 ºC for the used wires). This transformation process can be used to create an actuator and enhanced by shaping the wires into springs. To save a specific shape, the Nitinol wire has to be fixed in the desired position and heated between 400ºC and 800ºC for around 5 min and immediately cooled down (Fig. 2).

Several experiments were carried out to test the material resistance and strength in order to optimize the structure and its movement. Moreover, a proper heating system had to be developed to optimize the reaction time as well as to avoid material damages, trying to make the solution reliable and stable. The tests proved the material capacity to lift certain weight when heated. All the experimentations were carried out with the same environmental conditions and interpolated to obtain a reliable dataset.

Fig. 2. Nitinol – shaped into springs, stretched and reshaped by heat

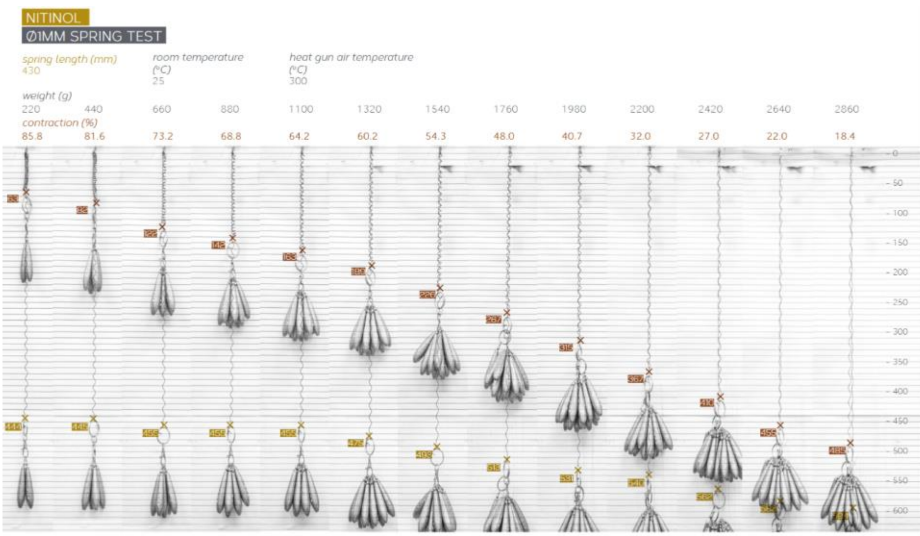


Fig. 3. Nitinol springs strength test

The results underline a relationship of direct proportionality between spring's shrink and loads (Fig. 3). However, tests have highlighted how unstable the material is if not properly heated. Therefore, to avoid any material damages, a proper and controlled heating system had to be designed. Activating Nitinol using DC current with the proper amount of electricity allows a homogeneous and precise heating. However, DC current could easily overheat and damage the Nitinol wire. To limit these potential material damages a Pulse Width Modulation (PWM) circuit was developed. Using PWM has several advantages: it turns the current on and off to the wire very quickly and this power oscillation allows to keep heating the wire while avoiding damage to the material's crystalline structure. Moreover, by modulating the "oscillation" period, the shrink time can be easily controlled.

After several tests and physical models, springs made of 1 mm thick Nitinol were used for the prototypes because they presented appropriate strength for the scale that was being studied. The electronic circuit designed to control these Nitinol wires was composed by an Arduino board and four transistors that controlled the amount of current released in each Nitinol wire (Fig. 4). In the final prototype a 14V power supply was used and each transistor released 4,67A to its corresponding Nitinol line (made of four 650 mm long and 1.0 mm thick cables, shaped as springs).

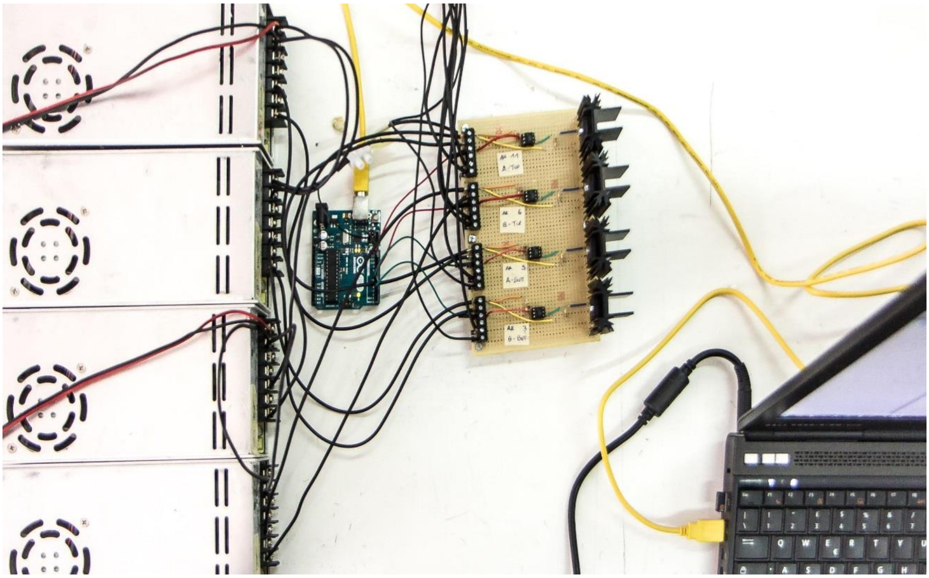


Fig. 4. Electronic circuit

3.2 Structure

After studying the properties of Nitinol and understanding its advantages and limitations as an actuator, the actual skeleton of the structure had to be explored. Therefore, the next step was a series of tests focused on geometric principles and structural systems that allow kinetic behaviour. Each system design iteration was simulated to understand and predict its behaviour. The software that was used was *Kangaroo*, a plug-in for *Grasshopper* for *Rhinoceros 3D*. Most of the explored systems can be understood with an analogy to the human body in which the structure itself, the bones, consist of rigid elements (bars) and the muscles, the Nitinol wires, take care of the movement.

There are 2 structural/geometrical principles that were further studied and served as a base for the final design of the system: pantographs and tensegrities. The pantograph mechanisms are able to expand or compress in a vector perpendicularly to the actuating vector. Pantographs are made of crisscrossing sticks and their main advantage is their capacity to achieve big expansions with a small actuation movement. They are also lightweight structures and they introduce the idea of deploy ability (Fig. 5).

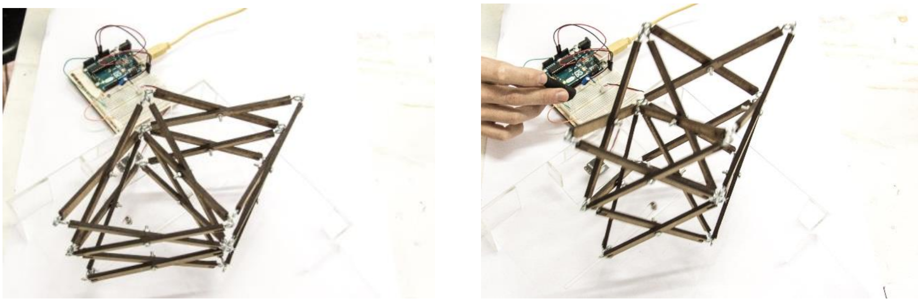


Fig. 5. Pantograph inspired structure – actuation with a motor

Tensegrity structures are systems in which tensile and compressive elements are harmoniously working in complement towards equilibrium. They are visually recognizable with the individual compressive elements held into its place in space by tensile elements that form a continuous network. The integrity of the structure is taken care by the tensile members and not the compressive ones. Therefore, tensegrities are light and, on paper, efficient if its assembly complexity is ignored. Tensegrities are easily convertible to kinetic structures by replacing some of the tensile elements (cables) by linear actuators.

Both pantograph and tensegrity principles have been used for the development of a vast variety of structural systems that can be divided into two main groups: the linear systems and the surface systems (space frames). The linear systems behave like towers that can bend in any direction (like a finger) by locally controlling the actuators (Fig. 6). The linear systems are relatively easy to move and control but they cannot be directly applied as an architectural structure, they always need to be part of another system.

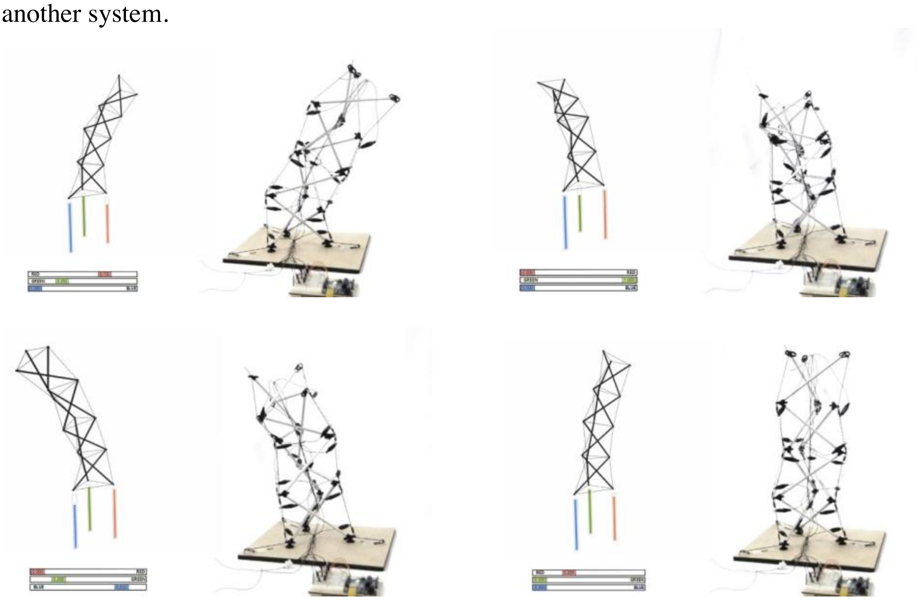


Fig. 6. Pseudo-tensegrity prototype controlled by a digital interface

The surface systems are space frame structures that can be shaped in many different ways (Fig. 7). Surface systems are much more interesting for an architectural application than the linear ones because they can become by themselves architectural elements (partitions, facades, roofs, canopies etc.). They are able to adopt an endless number of shapes and positions to adapt to environmental conditions and user's needs (Fig. 8). Some of the surface systems that were digitally tested presented the ability to bend in multiple directions (double curvature) (Fig. 9). However, a single curvature behaviour was chosen as the most appropriate one to develop in order to avoid an overly complex structure.

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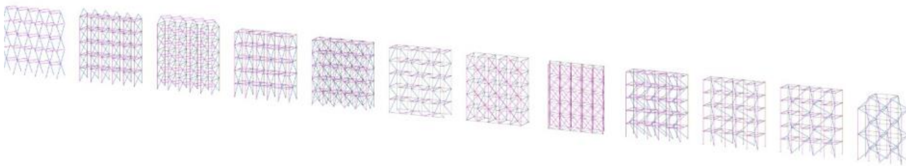

Fig. 7. Pseudo-tensegrity prototype controlled by a digital interface

Fig. 8. Digital simulations of a pseudo-tensegrity space-frame structure with control of local cables

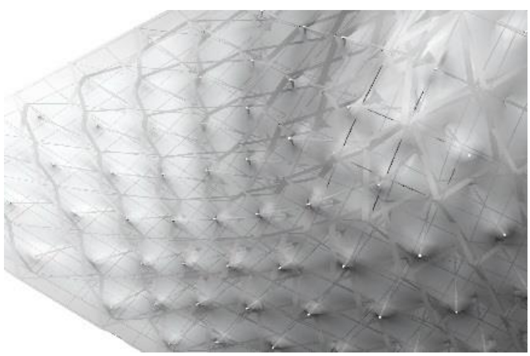

Fig. 9. Surface system with double curvature

3.3 Remembrane 1.0

The geometrical system that presented the best performance was a diagrid pantograph with pseudo-tensegrity principles. Wood pieces with flexible plastic joints and a diagonal network of Nitinol springs were the main components of the prototype (*Remembrane 1.0)* (Fig. 10). The bending of the surface is provoked by the contraction of the Nitinol springs when they are heated. This first prototype was a significant step in the study, however, there were four main aspects that had to be improved or developed: improving the actuation and creating a locking system, reducing the weight of the structure, designing and building a skin and programming a user interface.

Fig. 10. 1st performative prototype – *Remembrane 1.0* – base skeleton and nitinol springs

The actuation system was improved by placing the Nitinol actuators in vertical lines and adding a diagonal network of tensioned coil springs and cables that help stabilize the structure (Fig. 11). The diagonal network also allows to lock the structure in any position thanks to a locking mechanism integrated within the structural components. When the system is locked, a piece of folded plastic (polypropylene) pushes two small elements that block the diagonal cables connected to the structure. A small Nitinol spring is connected to the element that blocks the cables. If the Nitinol is heated, it contracts and moves the plastic pieces, releasing the cables and allowing the whole structure to move freely (Fig. 12). Thanks to the locking system the Nitinol springs do not need to be constantly electrified to maintain a certain position and the system becomes much more efficient in terms of energy consumption and movement control.

The expansion of tensioned coil springs is proportional to the system movement: the more the structure bends, the stronger the force these springs apply to the system (Fig. 13). This force counters gravity and helps to stabilize the entire structure. Consequently, the actuators need less force to move the structure. In fact, the final solution uses 41,26% less Nitinol than the previous versions, and 75% less energy.

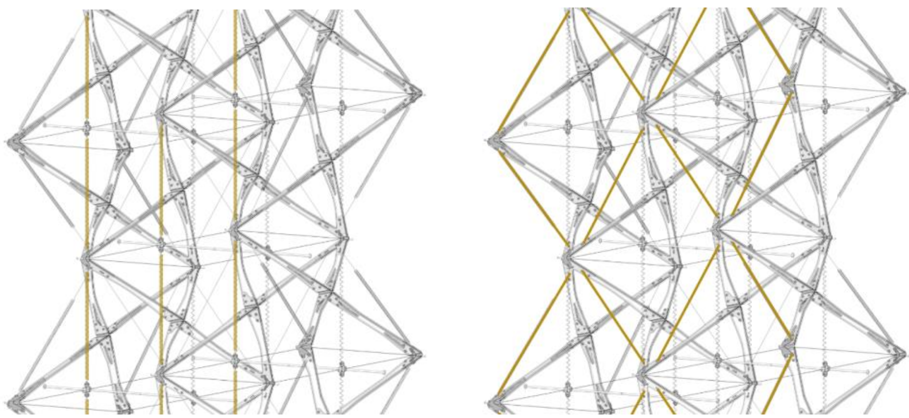

Fig. 11. Actuating Nitinol springs (Left) & Cables with tensioned coil springs (right)

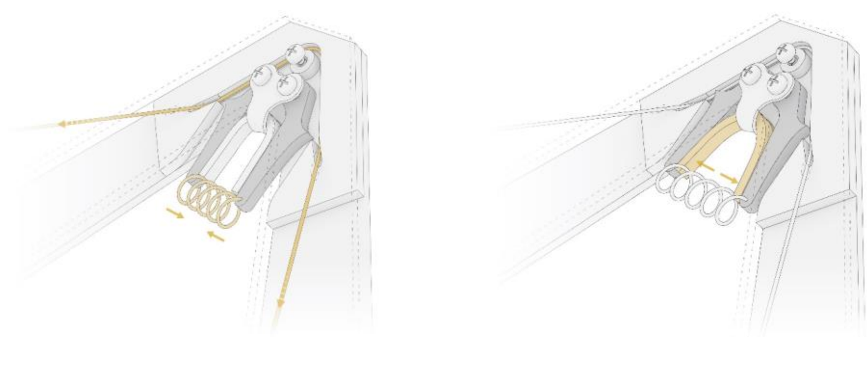

Fig. 12. Local stabilization device using Nitinol to release friction

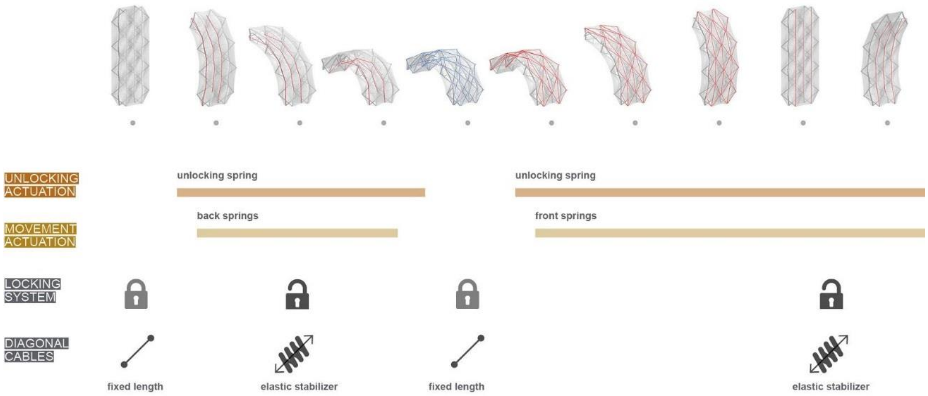

Fig. 13. System devices coordination for movement and stabilization

3.4 Structural Optimization

The structural optimization has been an essential step to maximize the lightweight performance of the structure. In order to minimize the system weight without modifying its strength, a topological optimization process has been carried out. This analysis has generated an important mass reduction (about 52%). To perform the structural analysis, *Karamba*, - a parametric structural engineering plugin for *Grasshopper* for *Rhinoceros3D* - has been used (Fig. 14). Thanks to this tool, the structure has been checked from a structural point of view, and the shape of each element has been informed according to the software results, minimizing the material quantity and improving the general system behavior (Fig. 15).

By reducing the structure weight, Nitinol springs need less force (and electricity) to move the structure. Moreover, each joint has been informed by the analysis optimizing its shape and minimizing deformations (Fig. 16).

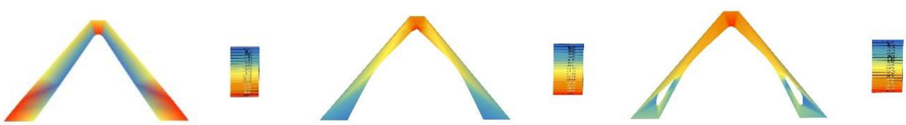

Fig. 14. Analyzing structural component for optimization

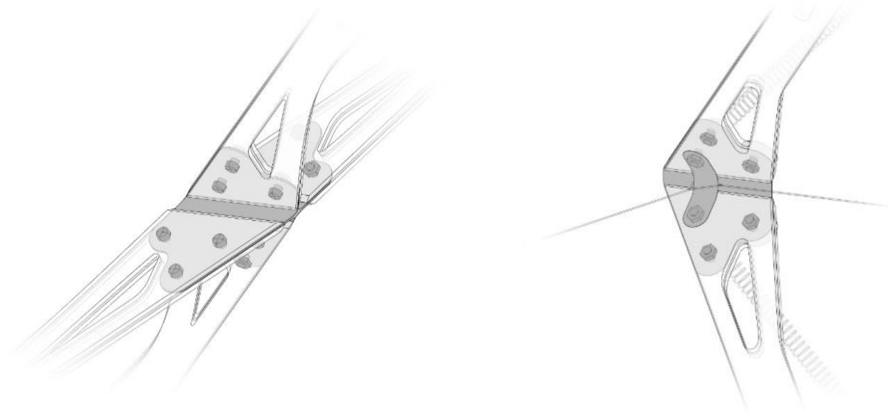

Fig. 15. Structural components after optimization with reduced material

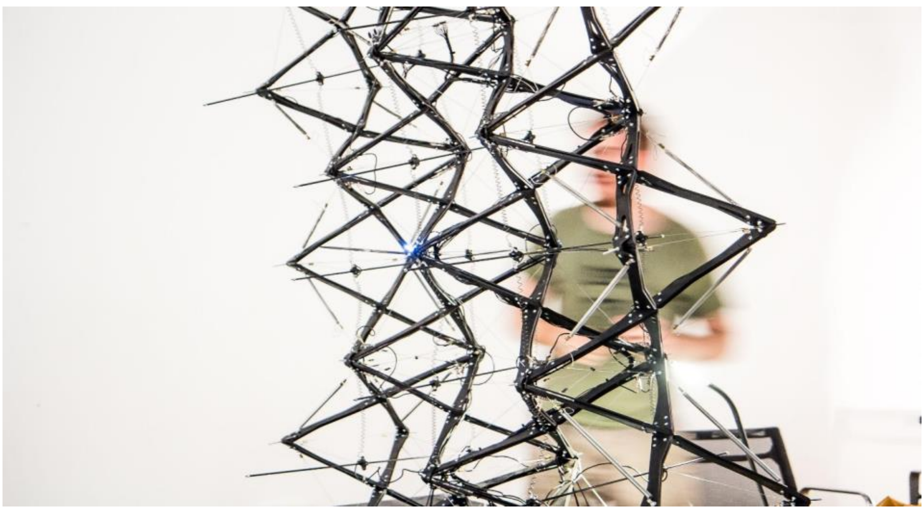

Fig. 16. Remembrane 2.0 - base structure with actuators and wirings

3.5 Skin

The structure has been mainly developed as skeletal system, conjunctionally with flexible joints and Nitinol springs acting as muscles pulling on them. As a complex assemblage of multiple components, a skin was necessary to contain the whole within one visual entity; a continuous surface as an architectural boundary, and to protect the mechanics from exterior elements such as water, corrosion and physical contact (Fig. 17). The protection goes in the other way to protect the users from the sharp components, the electrical current running through the wires and the heat generated to actuate the Nitinol springs.

It is an added skin over a lightweight skeleton; choice of material or system can be flexible, according to the use of the structure. However, the chosen material was a thin sheet of silicone, which is known to withstand heat, harsh chemicals, electric current, and resist to a great expansion, since the structure is meant to be deformed and transformed several times. It also offers a great translucency to allow the light to pass through, if its use is to create a space requiring natural light. The industry offers silicones with different transparency and elasticity, which make it an interesting choice, but also quite experimental for our application.

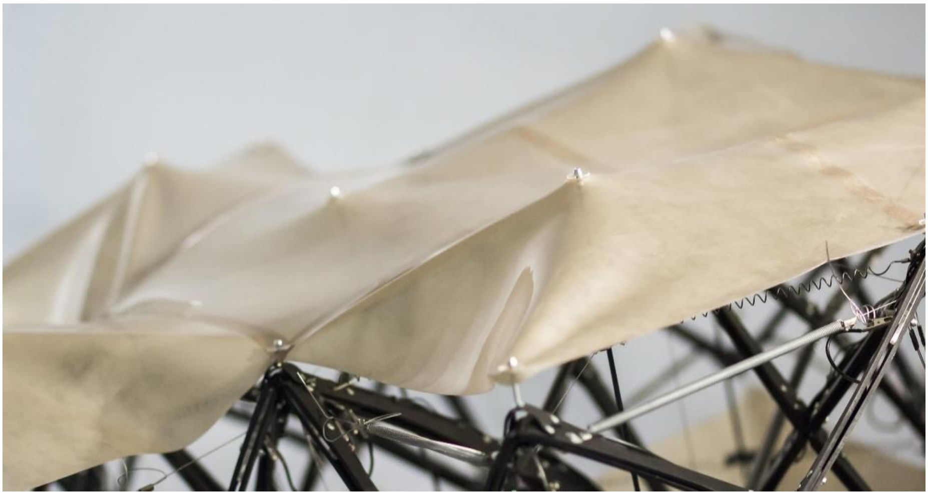

Fig. 17. Elastic skin as layer of protection

The elastic membrane is attached to the pantograph joints while floating bar components push the skin towards outside, creating a morphing tensile landscape on the surface and emphasizing the tensegrity character of the structure. This allows stabilizing the structure by adding extra surficial tension. Using this principle and these bars being longer than the thickness of the structure, the overall skin is already under moderate tension while straight. This bar system becomes helpful especially when the structure bends; one side of the skin experiences more tension than the other. The tensioned side pushes the floating bars towards the other, less tensioned, side hence soothing forces avoiding wrinkles on one side and hypertension on the other side in order to avoid the risk of skin rupture (Fig. 18).

Fig. 18. Damping system for tensile skin using bars

3.6 User Interface

The interaction between the users and the *Remembrane* is one of the most important parts of the project. A truly innovative responsive kinetic system has to be easily controllable but also intelligent enough to make its own decisions. In order to achieve that, a complex interaction system had to be designed. The system has two possible ways of interacting: interface mode (the user sends orders through the user interface) and sensing mode (the structure reacts to the sensors' inputs) (Fig. 19).

To make this complex interaction as easy as possible a user-friendly web based interface has been designed. A web application has the huge advantage of being accessible by any device that can support a web browser. This means that any computer, smartphone or tablet can be used to run the user interface and no special software or hardware is needed. The interface has been developed in order to not only send orders to the prototype but also to visualize the information measured by the sensors installed on the structure (Fig. 20). Therefore, there is a bidirectional communication with the *Remembrane*. Four different scripting languages have been used to develop the application: Html, Css, JavaScript and Processing.

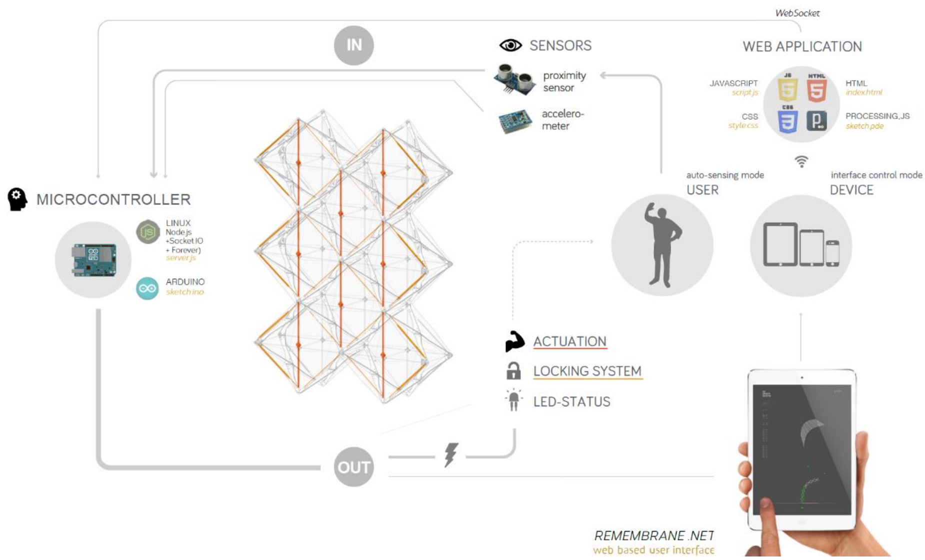

Fig. 19. Data input and output cycle through several agents

To physically interact with the structure a microcontroller was needed. The microcontroller acts as an intermediate between the web application and the prototype. The most extended and easy to use microcontroller is the Arduino and among all the Arduino models the Yun was chosen because it can connect to the internet using wifi and, therefore, it allows to interact with the web application wirelessly. The actual interaction with the *Remembrane* takes place at the input and output pins of the microcontroller. The input signals come from 2 proximity sensors (one in each side of the structure) and 1 accelerometer that measure the inclination. The output signals go to the network of actuators, to the locking / unlocking system and to the 2 LEDs that show the status of the structure.

The Graphic User Interface has been carefully designed to allow an easy and efficient interaction between the user and the *Remembrane*. It is based on interactive graphics that make the whole communication process very intuitive. The most important element of the interface is the interactive 2D diagram. It can be reshaped just by touching the screen of a tablet/smartphone (or clicking and dragging on a computer) and it automatically sends the necessary information to shape the structure in the same way (Fig. 22). The 2D diagram is complemented by 2 other elements: a visualization of the real inclination of the structure measured by the accelerometer (Fig. 21) and a visualization of the distance to obstacles measured by the 2 proximity sensors. The 2D diagram is, therefore, a tool to send instructions but also a tool to understand the current state of the prototype. The button under the diagram is used to lock or unlock the structure. On top of the 2D diagram there is a 3D previsualization of the structure. On the top left corner of the interface there is a button that allows the user to switch between interface control mode and sensing mode. In the interface-mode the structure reacts only to the instructions sent through the interface. On the other hand, in the sensing mode, the prototype performs autonomously according to the sensors' inputs. In fact, it behaves according to a set of rules that have been pre-programmed. The final prototype has a very basic set of rules: when the proximity sensor detects that something is very close, the structure bends to the opposite side (Fig. 23). This simple behavior has the purpose of illustrating some kind of autonomous behavior that could be further developed. On the left side of the user interface there are different numbers that are continuously updated. These values are the data from the sensors and the length of all the actuators of the structure.

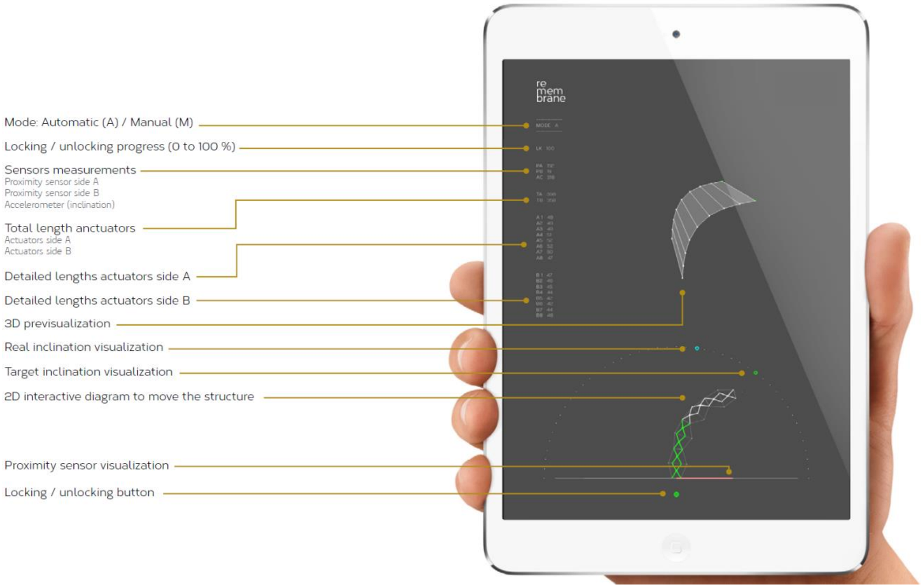

Fig. 20. User Interface on a wireless device

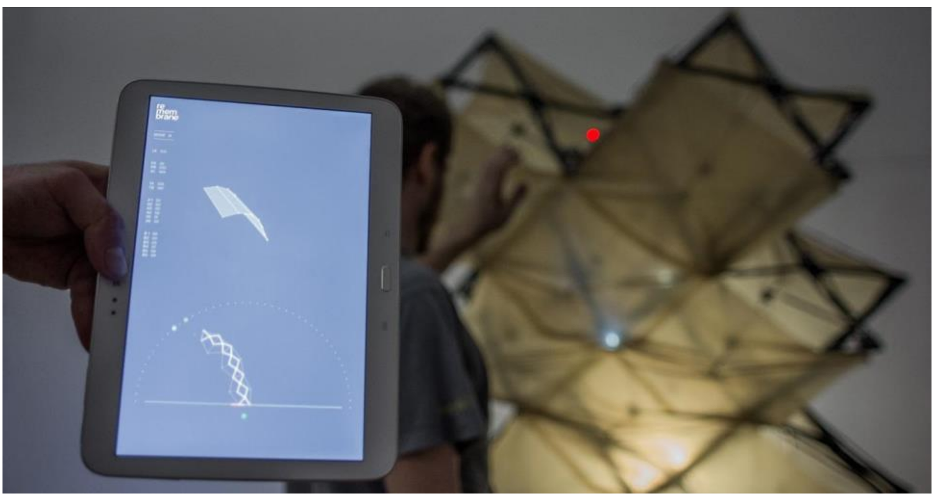

Fig. 21. User Interface wirelessly indicating current curvature

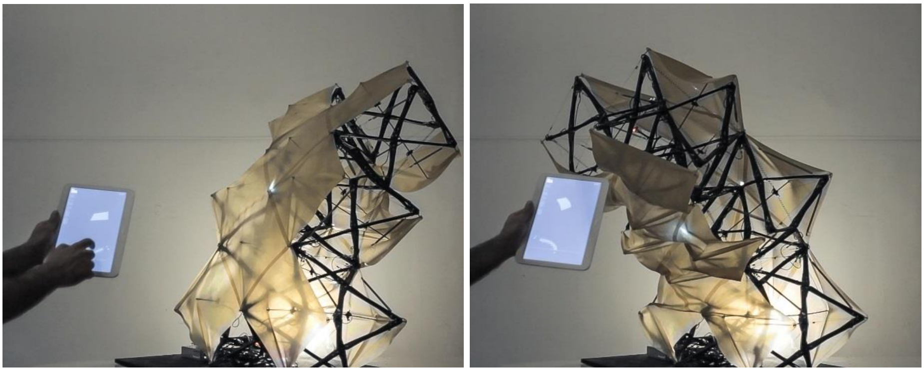

Fig. 22. Wireless control via user interface

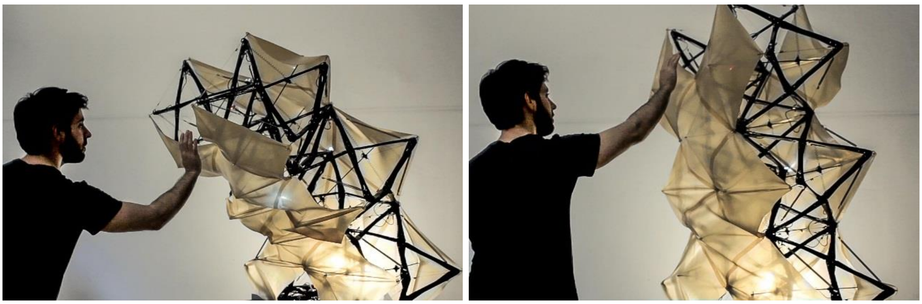

Fig. 23. Autonomous response via proximity sensor

4 Results and Discussion

All the digital and physical explorations have led to a better understanding of the possibilities and the limitations of the systems that have been designed. Lightweight responsive kinetic structures based on pantograph and tensegrity principles with a distributed system of Nitinol actuators have been proven to be feasible. Moreover, the final version of the *Remembrane* has become not only a performative kinetic prototype, but also a demonstration of new ways of user interaction and an exploration on basic autonomous performance. However, the *Remembrane* prototype presents two important weaknesses that could limit its further development into architectural elements.

The first big limitation is the use of Nitinol as actuator. Nitinol is definitely an appropriate material for lightweight linear actuators. However, in the architectural scale, Nitinol presents two major disadvantages: it needs a big amount of electricity to reach the temperature in which it actuates and it has significant restrictions in terms of strength when using small sections. Another important aspect to reconsider is the number of elements of the prototype. After every test that was carried out many problems appeared. In general, the problems were solved by refining the existing components but also adding more elements to the structure. The result has been a highly complex prototype (Fig. 24).

Fig. 24. Remembrane 2.0 in action

5 Conclusion

This study ends with a strong belief in the future of lightweight responsive kinetic structures. We envision that they are the evolution of the current architecture and they will radically change the way that spaces are experienced. These structures have evident advantages in terms of energy performance and adaptability to the needs of the users. Furthermore, there is already available technology to create interactive structures with embedded artificial intelligence. However, it is absolutely necessary to understand the limitations of the systems and materials that have been tested in order to set the basis for future research on adaptable kinetic structures.

New ways of heating the Nitinol springs should definitely be explored. A passive system using the solar radiation in a controlled way to heat the Nitinol wires is surely an interesting future research line. The limitation in terms of strength of the Nitinol springs could be solved by increasing the section of the wires. However, the current cost of big Nitinol wires makes them unsuitable for real architectural structures. Nevertheless, it is not unreasonable to think that in the near future Nitinol will become much more affordable and it will be a common material in the construction industry.

As mentioned before, the big amount of elements in the final system is one of its major weaknesses. The challenge now is not to keep adding complexity but to simplify the whole system to the point that the same performance is achieved with less and simpler components. Continuing this research following the stated guidelines would surely lead to a better and more energy-efficient kinetic structure to be applied in the construction of the architectural spaces for the contemporary world.

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Neighbourhood Shading Impacts on Passive Adaptive Façade Collective Behaviour

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Abstract. The past decade witnessed a shift in adaptive facades from energy-intensive complex systems to material-based actuated facades. The latter, however, were only developed with limited control in shape memory alloy applications, and more generally designed as independent components. The perception of the component within a system as a self-regulating entity was shown to widen the behavioural response and intelligence of an adaptive system in several projects. On the other hand, its range of impact and integration as a design factor were not targeted at full breadth in the literature. The study's objective was to investigate the incorporation of neighbourhood shading behaviour of a shape memory alloy-actuated façade component on the entire system. Based on a designed adaptive component, the research identifies the shading impact on the actuators' incident solar radiation as well as its hourly and seasonal range, and thus encourages a better prediction of collective behaviour.

Keywords: Solar Morphing Envelopes, Neighbourhood Shading, Collective Behaviour, Adaptive Facades.

1 Introduction

The past decade witnessed a shift in adaptive facades from energy-intensive complex systems to material-based actuated facades [7, 8, 14]. The latter, however, were generally developed for binary movements and limited control in shape memory alloy[1] (SMA) applications, and more generally designed as independent components.

The AIR Flower project, for instance, defined a composition of separate elements, and for which the resulting façade behaviour is similar to a system using a centralized actuation mechanism for all the components within the same orientation [16]. The

[1] Shape memory alloys are smart materials which exhibit shape memory effect and super-elasticity properties when they undergo lattice phase transformations from a strong high temperature phase (austenite) to a softer low temperature phase (martensitic). [1, 3, 4, 10, 11]

latter is an approach that was implemented in Harvest Shade Screens where one SMA spring activated the rotations of all louvers within one panel for cost effectiveness and resource efficiency [6].

The perception of the component within a system as a self-regulating entity was shown to widen the behavioural response and intelligence of the system, an approach implemented by the three other projects. Piraeous Tower facade's sine-wave geometry was produced by the vertically located SMAs to elliptical openings of a continuous stretched material and showed a dependence between individual component responses and the aggregate impact. Shading neighbours delay component actuations, in addition to the gradient effect they achieve due to the material flexibility thresholds [2]. Similarly, the Self-Adaptive Membrane and Adaptive Skins projects' system nature gave rise to movement patterns [5, 15]. Self-shading, although not purposely accommodated for in the design, constituted an essential aspect of the overall behaviour and a collective impact of individual differences. On the other hand, its range of impact and integration as a design factor were not targeted at full breadth in the literature.

The objective of this study was to investigate the incorporation of neighbourhood and self-shading behaviour of a shape memory alloy actuated façade on the adaptive system in its entirety as well as the components design in terms of behaviour and performance. This explores impacts on the generation of actuation patterns that are not based on uniformity. Based on a designed adaptive component, the research identifies the extent of the self-shading impact on the actuators' incident solar radiation as well as its hourly and seasonal range and explores the pattern variance instilled by the collective generative behaviour.

2 Methodology

To investigate the impacts of neighbourhood shading on a material-based adaptive façade collective behaviour, the evaluation of neighbourhood shading cases was carried out and compared. The strategy and implementation process of this research are detailed in the following sub-sections including the climatic context, the case study shading geometry, the simulation environment, the computational strategy, and the evaluation method.

2.1 Climatic Context and Case Study Shading Geometry

A south-oriented façade was evaluated for the purposes of the study to provide an assessment environment that accommodates for the largest shading variations. The location of the façade was identified as Cairo, capital of Egypt, for which the case study shading geometry was designed and which is characterized by being a hot arid climate with a clear sky for the majority of the year [12]. The case study adaptive component [9] consists of an origami-based geometry of 400mm by 400mm that is actuated by four shape memory alloys located at four corners. These can produce nine distinct forms, illustrated in Fig. 1, through linear movements up, side and/or down. These were designed to be placed side by side to generate a grid of shading.

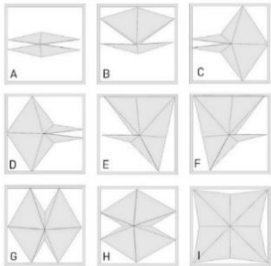

Fig. 1. Nine Forms Generated by Origami-Adaptive Component [9]

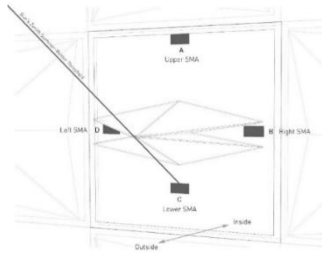

Fig. 2. 4-SMAs Location within Shading Component [9]

2.2 Simulation Environment

A digital model was developed in Rhino3D modelling software along with its parametric plugin Grasshopper for simulating origami movements with forces tailored to the four shape memory alloy limitations and automating the simulation process. An analysis grid of 100mm by 100mm, located 100mm behind the shading geometry, was used to represent the building surface for the incident solar radiation simulation. Each SMA irradiation was identified by the average of four analysis points based on their specific locations within the component, illustrated in Fig. 2. For each of the studied cases, a solar irradiation analysis was performed through Ladybug[2], using Radiance engine, for a selection of 40 hours acting as the representative sample of the year. The latter was defined as hours from 08:00 to 17:00 on the equinoxes and solstices. Two distinct set of data were collected from the simulation: the solar irradiation on the building surface and the four SMAs incident solar radiation values; used for the corresponding evaluation of the neighbourhood shading performative and behavioural impacts, distinctly shown in Fig. 3.

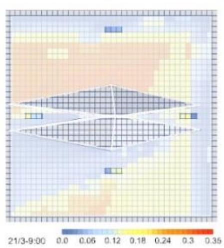

Fig. 3. Solar Irradiation Analysis (Building Surface and 4-SMAs) [9]

[2] Ladybug is an open source plugin utilised for environmental performative assessments and visualisation using data extracted from EnergyPlus weather files [13].

2.3 Computational Strategy

To grab an understanding of the shading impact of all geometries during all times, incident solar radiations had to be computed for all possible combinations. Since each panel have the possibility of nine geometrical options, a sample grid of 9x6 for instance, would mean 9^{54} possibilities for the adaptive shading skin and a much higher number for any larger grid. The computational irrationality of carrying out that number led to the definition of shading to be considered as a product of only its four direct neighbours, resulting in a case reduction to about 60,000 possibilities.

These possibilities represent all possible configurations of any grid size. The Von Neumann neighbourhood approach, as shown in Fig. 4, can be justified by the low probability of shading's farther reach.

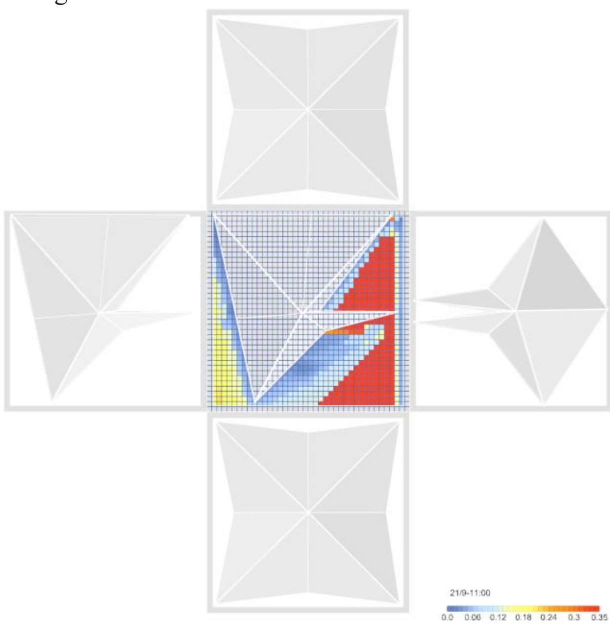

Fig. 4. Component Neighbourhood for Shading Impacts

The incident solar radiation values for these configurations were computed, stored for analysis, and used in analysing shading patterns.

2.4 Evaluation Method

The shading impact was evaluated using an impact factor defined as the percentage change between the incident solar radiation of the base case (non-deployed geometry with no neighbours) and each neighbouring case. A comparative assessment of the impact factor of the 4 neighbouring geometries on each one of the 4 SMAs for each of the 40 hours under study was carried out.

3 Results and Analysis

The integrated system's neighbourhood and self-shading impact factor was calculated for each set of neighbours and each SMA as an average of the 40 hours and illustrated in Fig. 5 below. All the results were represented in a table hierarchy where the upper sided hierarchies are defined respectively as upper neighbours with a sub-hierarchy of right neighbours, and lower neighbours with a sub-hierarchy of left neighbours.

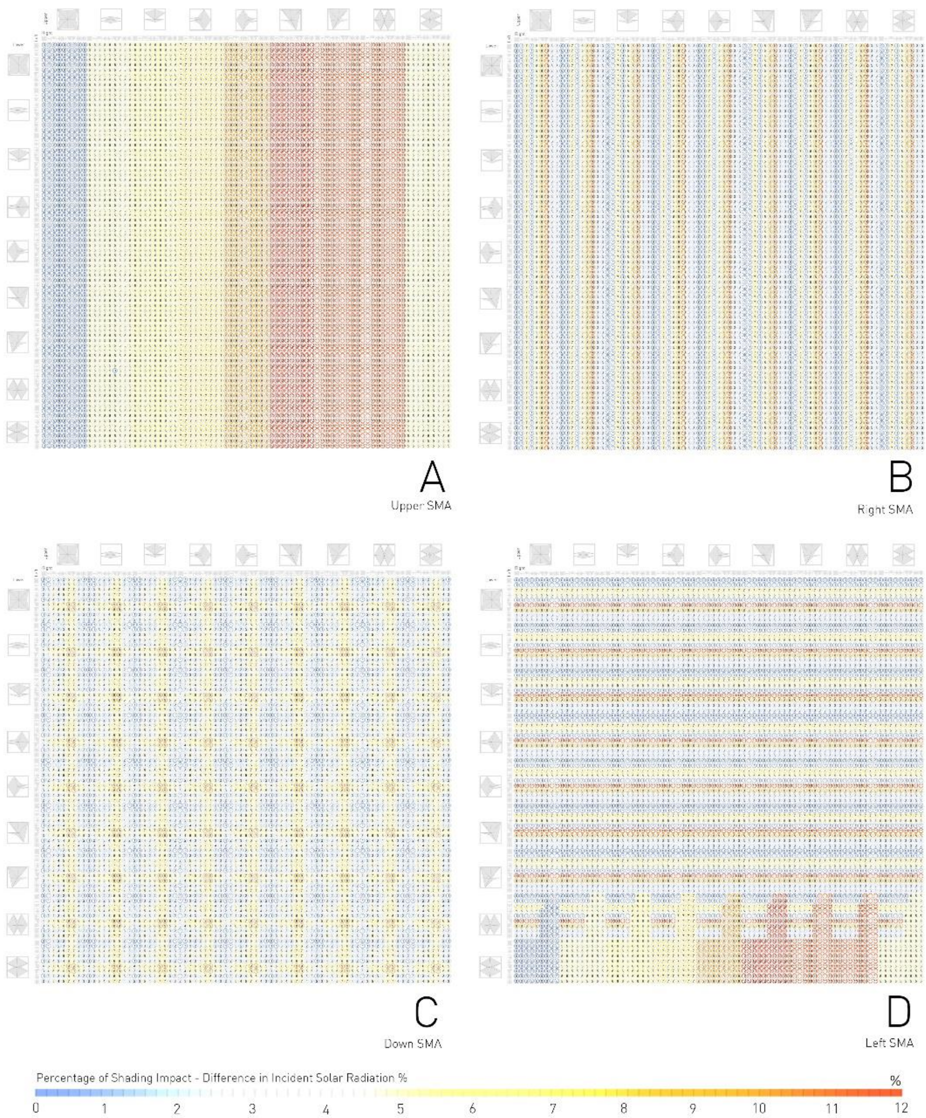

Fig. 5. Average Shading Impacts of all Neighbours per SMA

An observed pattern of impacts was distinct for each SMA, where the upper, right, and left SMAs were only impacted by their corresponding neighbour, the lower SMA by the right and left neighbours, with zero impact from the lower neighbour. The impacted cases were further explored on an hourly basis, identified below in Fig. 6 in which zero impact conditions were eliminated.

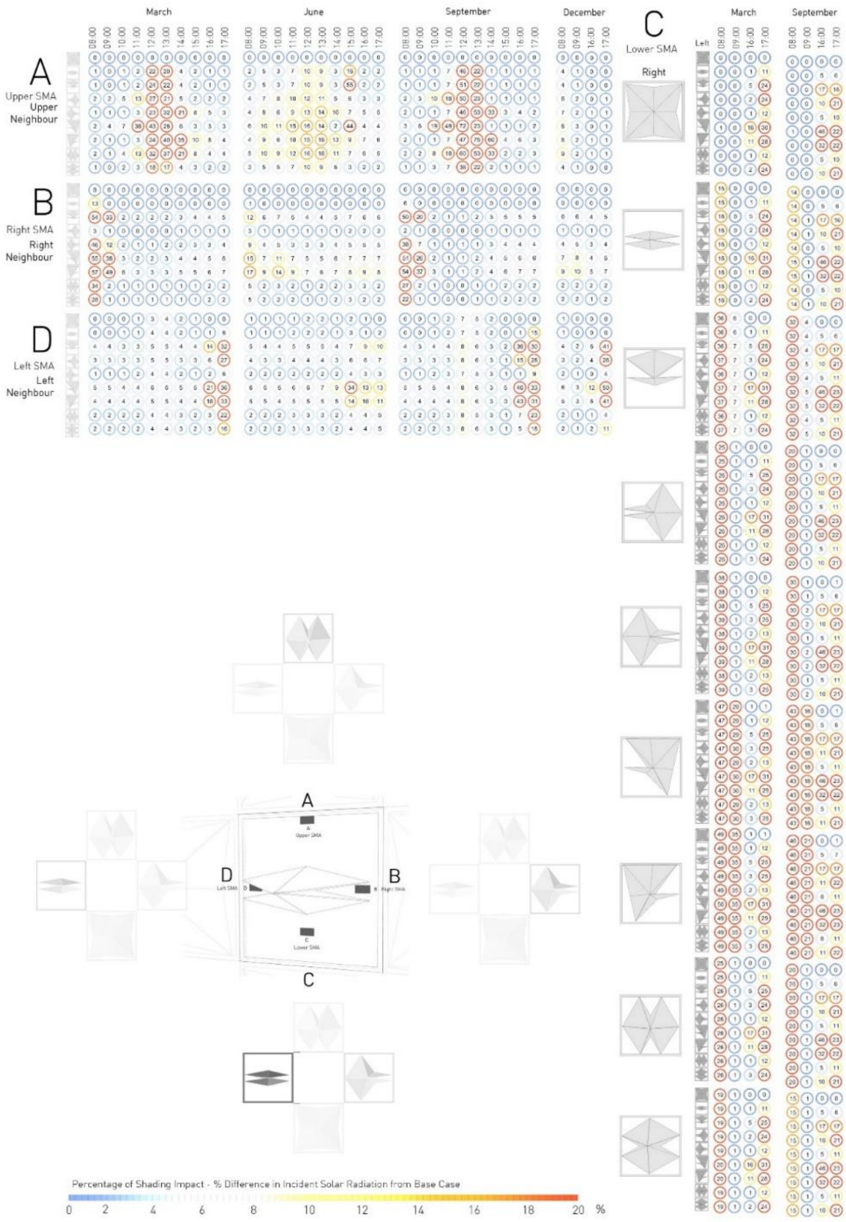

Fig. 6. Hourly Shading Impact Percentage of All Cases of Significance

The relation between the shading impacted cases, identified as the cases achieving a percentage change greater than 10%, geometry configurations and time was highlighted through dividing the positive cases by ratio for each hour and each month. An illustration of the geometry's ratio of impact throughout time was developed as shown in Fig. 7 and Fig. 8.

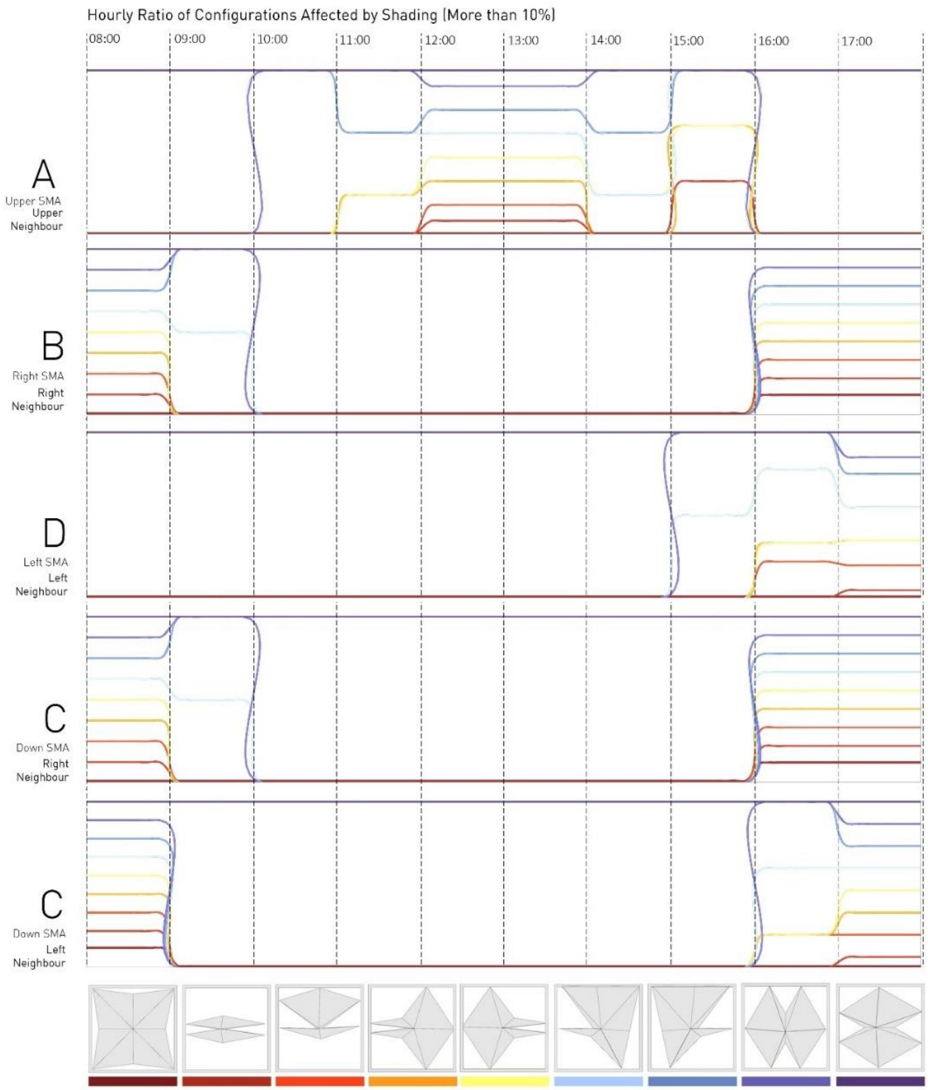

Fig. 7. Shading Impacted Cases - Hourly Ratios

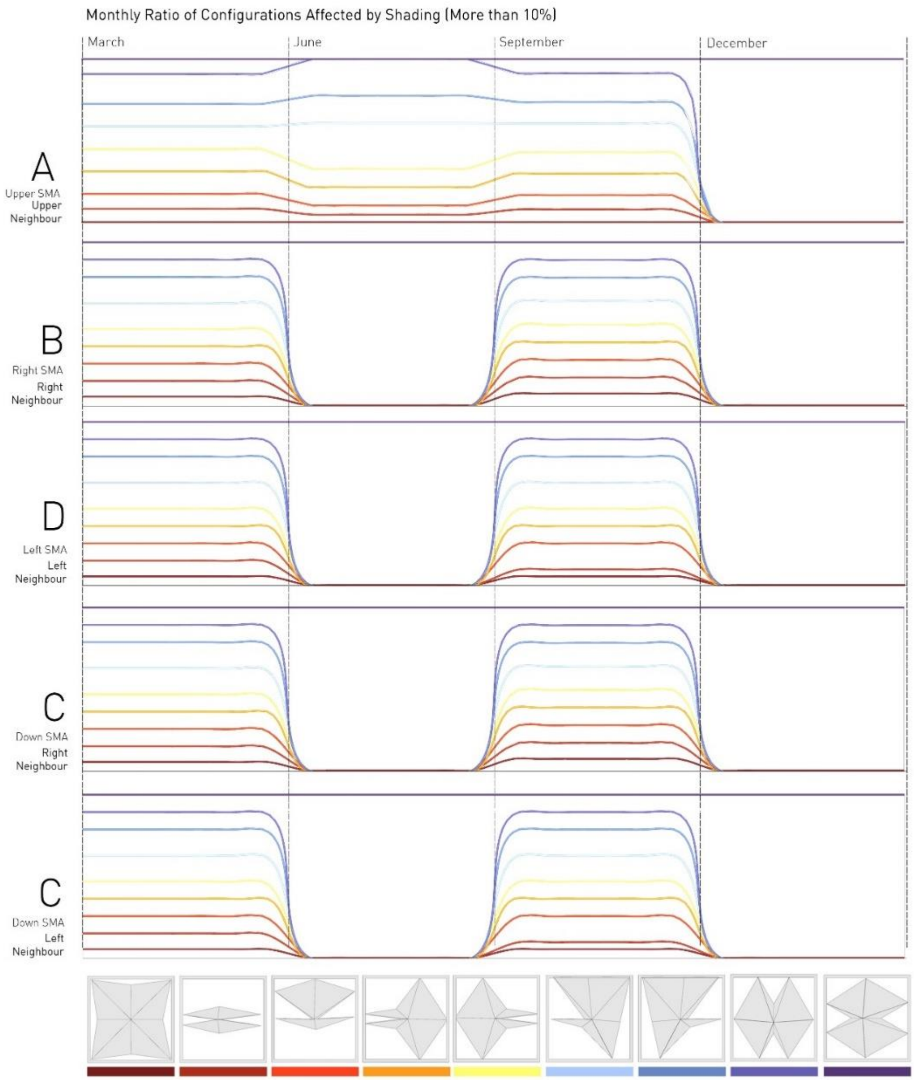

Fig. 8. Shading Impacted Cases - Hourly Ratios

These diagrammatic illustrations of cases with high shading impacts identified the significantly different shading impacts and allow for a distinct time-based and geometry-based separation of cases. For hours ranging from 10:00 to 15:00, the only influential actuator, for instance, was the upper one, affected only by its upper neighbour; while all other neighbours and SMAs were completely unaffected during this period, in contrast to being highly affected during early and late hours of the day.

During December, no shading impacts were found, which can be explained by the lower sun positions. The geometrical configuration showed as well diverse shading influences, however not as highly distinct as the time-based differentials. The right and left neighbours' geometrical configurations showed mirror impacts for early and late hours of the day.

The shading's effect extent was as well observed through its performative impact: the incident radiation on the building surface, shown in Fig. 9. It should be noted that due to the 10cm gap between the shading component and the building surface, the illustrated impact on the building façade constitute a greatly attenuated expression of the actual effects on the four SMA solar incidence.

Fig. 9. Neighbour Shading Impact on Incident Radiation on Building Surface

For the same recorded hours, different shading patterns were observed with varying neighbouring geometries, where specific geometries achieved greatest differentials in the mornings, others in the afternoon, with a more general combinatory effect for the upper SMA during mid-day. Although the impacts were restricted to a limited range of hours, it reached up to 75%, a radiation difference of $300\ Wh \cdot m^{-2}$. The latter results in a pattern differential of great relevance to performance and behaviour of the SMA-adaptive solar shading and of subtle but interesting generative nature.

4 Discussion

The system's neighbourhood and self-shading impacts showed differentials and the potential for some degree of generative behaviours in the designed system. The Von Neumann neighbourhood definition used for improving computational time efficiency for irradiation calculations allowed for a decrease in the number of simulated configurations to 60,000 cases. The lower shading impacts of other façade portions constituted the basis for this compromise in identifying comprehensive shading patterns. Within the evaluated cases, the lower neighbour showed no impacts thus allowing for further reductions in computational time and a quicker design-testing loop to about 6,500 cases (10% of the original configurations).

Recorded incident solar radiation on the four SMA and the building surface allowed for the identification of the most impactful geometries as well as the time and seasonal factors impact. Shading impact factors ranged from 0% to 75%, 0 to $300\ Wh \cdot m^{-2}$. The lower SMA was the actuator with the highest percentage change due to being the only actuator influenced, not by one, but two different neighbours (the right and left neighbours). The largest shading impacts were found during the late mornings and late afternoons, for the right and left portions, while mid-day hours were highly impacted upper portions. December showed no impacts, June minor impacts in contrast to March and September months which had the highest with a steady distribution among geometrical forms.

The flattest geometry, the opaquest configuration, showed a no effect on its neighbouring shading components. The periods from 09:00 to 11:00 and 14:00 to 16:00 were the hours in which each geometrical configuration showed a different proportional contribution to shading. The performative influence of shading was observed to be significant and highly affected by the geometrical neighbourhood configurations, which reflects the necessary consideration of designed geometries and behaviours for higher performing facades. Significantly identified at specific time periods, the self-shading dimension can show interesting and subtle changes in a façade's behaviour.

The integration of that characteristic into the design of the system component could allow for higher performance and better system predictions. An understanding of the time-based and geometry-based influences analysed in this research provide an opportunity for designers to carefully consider only relevant cases of shading thus reducing significantly computational time and promoting a more efficient and informed design-behaviour-performance testing cycle.

The scope and limitations of this study constitute a necessary dimension for the proper interpretation of results. Firstly, the solar irradiation was simulated based on a digital simulation using Cairo's weather data file for a south-oriented façade with no obstructions using recommended simulation resolution. A calibration using real life measurements could be a further step towards additional validation of results. Secondly, the 40-hour representative sample reflected the year's peak changes rather than the continuous climatic behaviour. Thirdly, the solar irradiation here is studied in isolation of other climatic factors such as wind, humidity and sky coverage which can have an impact on the adaptive component's behaviour. On the other hand, the brute force method of testing all cases, with the limitation of Von Neumann neighbourhood, provided the means to effectively evaluate both the individual impacts of geometries, neighbours, SMA locations and time on the shading factor, as well as their aggregated effect.

5 Conclusion

Among the greatest challenges of designing material-based actuated responses is their sole reliance on the material's behavioural response to certain climatic and situational factors which can be hardly controlled. Slight contextual differences lead to significant behavioural changes and thus should be accommodated for, to achieve desired formal and performative outputs. This shall not be presented as a constraint as much as it should be as an opportunity of exploring the material capacities to self-regulate a system, based on an understanding of its logics and structure, for either performative or non-performatives goals. A global design of an adaptive façade is thus preferred over an isolated component design due to the latter's inability to accurately represent responses highly affected by the self-shading dimension, one that was capable of creating an impact factor of up to 75%.

By comprehending the neighbourhood shading impacts, the computational intelligence of natural collective systems can be promoted through careful informed design decisions for an adaptive system, studied here in the case of shape memory alloys (SMAs). These decisions include the geometrical form, scale, proportions, and orientations of the shading, as well as the location of the actuators relative to the component and its neighbours. Despite the context- and geometry-specific nature of the study, shading impact behavioural and performative outcomes can be transferable on general terms to similar hot arid climates for the time-based impacts as well as partially considered for similar geometrical forms. However, they cannot be utilized for facades oriented differently due to the strict difference in solar angles and exposure.

Future design studies in the field of material-based actuated adaptive facades should thus aim to integrate neighbourhood shading on component design decisions as well as efficiently focus its effect on the relevant time periods and sun-geometry shading angles. Performative thermal façade implications should be utilized for informing design decisions rather than acting as a passive factor; and other façade functional and environmental objectives can be additionally studied to identify their relationship with neighbourhood shading behaviour. The aspiration is for a highly performative zero-energy adaptive architecture that is self-regulating by an instilled computational collective intelligence.

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Investigating the role of Entropy in Design Evaluation Process

A Case Study on Municipality Buildings

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Abstract. The concept of entropy, which can be used to measure physical disorder, has been rediscovered by Shannon to measure the irregularity in information. Entropy measurements are made by considering one or more factors. Specific features such as color, shape, element type, height, material related with architectural compositions can be considered as factors and the amount of information carried by the building depending on one or more of these factors can be measured. In this study, it is questioned whether there is a relationship between entropy values of municipal building competition projects, which are measured in relation to the factors, and the building is considered successful by the competition jury. In order to conduct this examination, the entropy values of the projects, which respected to the same architectural program and won various awards in the project competitions were calculated. Before making comparisons, measurements were made according to solid-void ratios on the plan layout, the shapes of closed and discrete spaces, and the distribution of functions. A discussion was made on the usability of entropy method in the design phase, which gave solid and precise results according to the results of the comparisons.

Keywords: Entropy, Architectural Competition, Municipality Buildings.

1 Introduction

1.1 Aim and Methodology

The rapid development in information and communication technologies has triggered the emergence of innovative design and analysis methods. New techniques and technologies provide a better understanding of the spatial and topological qualities of built environments. It is possible to compute and visualize the various types of information embedded in built environments or buildings using methods such as entropy. Entropy can also be used as an objective measurement method for meaningful comparison of different abstract or concrete architectural compositions.

This study aims to question whether there were optimum entropy values for a certain architectural program such as municipality buildings through architectural competition projects. The second aim of the study was to investigate whether there was a relationship between the achievement of the project in the competition and the calculated entropy value of the project. In order to fit the measurements to be made within the scope of the study to a specific standard, the buildings were first remodeled in computer environment then entropy calculations of each project were made on same 3 factors.

Within the scope of the study, 9 municipality building projects that have attended to 3 national architectural project competitions in Turkey were selected for entropy calculations. According to the quantitative entropy values obtained from measurements based on solid-void, shape and color(function) factors, different municipality buildings were compared and the findings were explained.

2 Main Concepts of Entropy and Basic Entropy Equation

Although the entropy concept was introduced to measure physical disorder, it was rediscovered by Shannon and Weaver [1] to measure the irregularity in information in 1949. To be able to make an entropy measurement, it is necessary to have factor and levels related to the factors. For instance, the letter sequence "AAAAAAA" consists of 7 units. The only factor encountered in the example line is the "letter". In addition, the only level of this factor is the letter "A". All the units forming the sequence point to the uniformity and entropy takes the value of zero. On the other hand, when all units such as "ABCDEFG" are different, the level as much as units is encountered. Total diversity is dominant in this case and entropy has the highest value [2].

The basic equation that can be used to calculate the entropy is shown in Figure 2. In the equation, H correspondence to the entropy calculated according to a factor and is calculated in terms of bits; *p* is the level of probability of a factor occurrence. [2-3].

EQ1: $$H_{factor} = -\sum_{i=1}^{nlevels} p_i \log_2 p_i$$

Fig. 1. Basit entropy equation [4]

In the example, string with ten elements made of letters were randomly generated with four elements (A, B, C, D). When the end product was ABBCCCDDDD, there was one A, two Bs, three Cs and four Ds in the string. In this case, the probability of finding the letters in the series was 1/10, 2/10, 3/10 and 4/10, respectively. The entropy value of the letter sequence was calculated as H = 1,84 bits via summing these probabilities in the order in place of the pi in the equation [4].

One of the difficulties encountered in entropy measurement studies are that the calculation has been performed based on multiple factors, all independent of each other. Where the factors are independent of one another, the total entropy equals the sum of the entropy values measured for each factor.

Letter A

$$-\frac{1}{10} log_2 . \frac{1}{10} = 0{,}33 \text{ bits}$$

Letter C

$$-\frac{3}{10} log_2 . \frac{3}{10} = 0{,}52 \text{ bits}$$

Letter B

$$-\frac{2}{10} log_2 . \frac{2}{10} = 0{,}46 \text{ bits}$$

Letter D

$$-\frac{4}{10} log_2 . \frac{4}{10} = 0{,}53 \text{ bits}$$

$$0{,}33+0{,}46+0{,}52+0{,}53=1{,}84 \text{ bits}$$

Fig. 2. Calculating the entropy value of a letter array

3 Measuring the Entropy of Architecture

Meaningful comparison of different buildings may be possible using a standard measurement method such as entropy. In this paper, we examined two studies that have different approaches to entropy calculations.

In his study, Crompton[3] focused on the question of whether the amount of information contained in the building carries a meaning. According to Crompton, the entropy of a structure consisting of repeated pieces can be found by measuring the entropies of the pieces and the entropy of a structure is the average of the amount of information measured in bits for parts.

In the Crompton [3]'s article, the building's information content was measured by modeling the building with LEGO blocks. The entropy values of the parts were calculated according to the frequency of usage between the LEGO parts produced until 2010. LEGO models can have high or low entropy values relative to ordinary or unique parts they contain. According to calculations, entropy values per piece of buildings well known in the architectural literature varies from 6 to 10 bits [3].

	Pieces	H
Falling Water	811	6.8
Empire State	78	6.8
Sears Tower	70	7.2
Hancock Tower	69	7.5
Guggenheim	210	7.6
Seattle Needle	57	10.3

Fig. 3. Entropy calculations of LEGO Architecture sets [3]

In Figure 3, entropy calculations of LEGO Architecture sets of 6 different 20th century buildings were made by Crompton. Yet the two Frank Lloyd Wright's building models are much smaller than others in scale, they are more complicated than the towers. According to Crompton[3]'s findings, the vocabulary of modern architecture can be elegant and simple; however, it plays a minor role in the growth of complexity. Crompton also claims that, as days go by in cities, architecturally interesting and unexpected buildings and parts of these buildings are encountered. In this case, many new cases increase the entropy of cities and structures [3].

Against the Crompton's approach [3], which explains that entropy of a structure can be calculated by considering the entire LEGO space, Stamps [6] claims that the information content of the building can only be calculated from the LEGO parts that make up the building. According to Stamps [6], counting only the different parts of a building is a more appropriate approach to calculate entropy.

Stamps [6] created a LEGO set containing 884 pieces while developing the method in the study. LEGO parts have two features as shape and color. For parts in the LEGO884 language, shape entropy and color entropy were calculated as 4.27 and 3.17, respectively, and the overall entropy of the set was calculated as 7.44 bits. LEGO100 set was formed with 100 pieces randomly selected from 884 pieces. The average entropy of the LEGO100 set was calculated as 1.87 bits per piece.

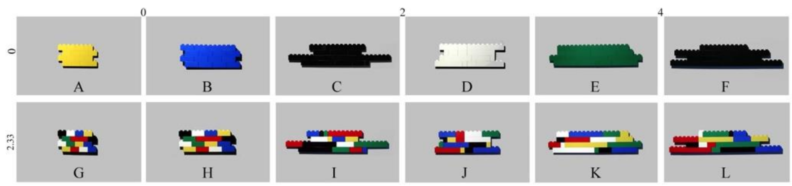

Fig. 4. Experimental design with LEGO bricks [6]

As illustrated in Figure 4, 12 LEGO models had 7 different shapes and 6 different colors. Entropies of 12 produced models vary between 0 bit and 6.23 bits. Stamps in his study [6] investigates the relationship between perceived diversity and entropy measured on the model. Stamps [6] showed the 12 LEGO models to participants and asked them to sort LEGO models from monotonous to diverse. As a result, while the correlation between color entropy and perceived diversity was r = 0.969, the correlation between shape entropy and perceived diversity was r = 0.015. As a result, visual diversity can be estimated by measuring the entropy of the parts and by calculating the total entropy.

4 Case Study: Measuring the Entropy of Municipality Building Projects

Previous approaches emphasize that entropy is a method that can be used to analyze both abstract compositions and built environments. In Crompton's work, all calculations made through Lego models are only related to a single factor that is shape of the parts. On the other hand, Stamps make the entropy calculations of abstract compositions are based on color and shape factors, in the evaluation phase the factors are considered separate and independent from each other. In both studies, it is clear that there are no certain weights considered among the factors during calculations.

In the proposed model, entropy calculations are made according to 3 different factors. The first two factors, which are solid-void ratio and shape of perceived distinct spaces of the building, can be examined in all kind of building typologies. In this study, the third factor, color is used to represent the functional distribution in the building.

The proposed model first investigates whether there is an optimum entropy value for a specialized building typology. Prior to begin calculations, the design brief and architectural programs for 3 competitions were obtained and examined. In brief and architectural programs, the requested functional distribution and solid-void ratios are given to the architects who participate to the competition. These two ratios and the entropy values of all chosen projects were calculated for each factor. In the competition brief, instead of specifying the shapes of required spaces, the sizes of these spaces are specified in square meters. For example, edge lengths 3 to 8 meters or 4 to 6 meters can form a space of 24 square meters. In this case, it can be said that there is no definite information about the shape of the spaces in the competition brief. For this reason, it is not possible to calculate the optimum shape entropy. In this study, because of the limited content of the competition briefs, factors such as facade shape, facade color, height or solid-void ratio of facade excluded

The model also measures the various entropy values of buildings that have been successful and unsuccessful in architectural competitions and questions the relationship between success/achievement and entropy value. In the scope of the research;

-Bornova Municipality Building (2015)
-Efeler Municipality Building (2016)
-Inegol Municipality Building (2016) competitions were examined.

It is aimed to select 3 projects for each competition, to investigate different approaches for the same program and accordingly whether there are different entropy values. Factors such as solid-void ratio, building style, façade shape, building shape, window shape, scale, color, silhouette, material and articulation about which many studies conducted in the literature can be measured with entropy. In the study, the entropy of the buildings was measured by utilizing the modularity, form and color(function) characteristics that are the most basic features of a municipality building.

4.1 Solid-Void Entropy

The solid-void entropy is calculated by counting the solid and void cells in the floor plans remodeled on a grid. Firstly, according to the areas given in the brief of the competition, the optimum entropy calculation was made according to the solid-void ratios required by the organization committee of the competition. Afterwards, solid-void entropy was calculated for 3 projects from 3 different competitions. As a result, it was seen that project with the entropy closer to optimum entropy value was the most successful projects in the case of Bornova Municipality.

Table 1. Solid-void entropy values of projects from Bornova Municipality Competition.

	Solid	Void	Total
Optimum Value	10550 m2 (cells)	7450 m2 (cells)	18000 (cells)
	10550/18000 = %58,61	7450/18000 = %41,39	%100 (ratio)
	log2(58,61/100).(58,61/100).(-1)	log2(41,39/100).(41,39/100).(-1)	
	H= 0,452 bits	H= 0,527 bits	H=0,979 bits
First Prize	9178 m2 (cells)	6516 m2 (cells)	15694 (cells)
	9178/15694 = %58,48	6516/15694 = %41,52	%100 (ratio)
	log2(58,48/100).(58,48/100).(-1)	log2(41,52/100).(41,52/100).(-1)	
	H= 0,453 bits	H= 0,527 bits	H=0,979 bits
Mention Prize	8804 m2 (cells)	8434 m2 (cells)	17238 (cells)
	8804/17238 = %51,07	8434/17238 = %48,93	%100 (ratio)
	log2(51,07/100).(51,07/100).(-1)	log2(48,93/100).(48,93/100).(-1)	
	H= 0,495 bits	H= 0,505 bits	H=1,000 bits

As seen in Table 1, the solid-void entropy value of the project with first prize is exactly the same with the optimum value given in the brief. The solid-void entropy value of the mention prize winner project is unrelated to the optimum value.

Table 2. Optimum Solid-void entropy values of Efeler Municipality Competition.

	Solid	Void	Total
Optimum Value	10620 m2 (cells)	4100 m2 (cells)	14720 (cells)
	10620/14720 = %72,15	4100/14720= %27,85	%100 (ratio)
	log2(72,15/100).(72,15/100).(-1)	log2(27,85/100).(27,85/100).(-1)	
	H= 0,340 bits	H= 0,514 bits	H=0,853 bits

Table 3. Solid-void entropy values of projects from Efeler Municipality Competition.

	Solid	Void	Total
First Prize	8949	4821	13770
	8949/13770= %64,99	4821/13770= %35,01	%100
	log2(64,99/100).(64,99/100).(-1)	log2(35,01/100).(35,01/100).(-1)	
	H= 0,404 bits	H= 0,530 bits	H= 0,934 bits
Mention Prize	8666 m2 (cells)	5416 m2 (cells)	14082
	8666/14082= %61,54	5416/14082= %38,46	%100
	log2(61,54/100).(61,54/100).(-1)	log2(38,46/100).(38,46/100).(-1)	
	H= 0,431 bits	H= 0,530 bits	H= 0,961 bits
Not Awarded	9048 m2 (cells)	3444 m2 (cells)	12492
	9048/12492= %72,43	3444/12492 = %27,57	%100
	log2(72,43/100).(72,43/100).(-1)	log2(27,57/100).(27,57/100).(-1)	
	H= 0,337 bits	H= 0,513bits	H= 0,850 bits

Different from Bornova Municipality Building Competition, the entropy of the winner of the first prize in Efeler Municipality Building Competition does not correlate with optimum value. On the other hand, the results of calculations also show that a non-awarded project has the closest entropy to the optimum entropy value.

4.2 Shape Entropy

Before starting shape entropy calculations, the volumes that construct the buildings were redrawn as closed polygons and polygons with same sizes are clustered. After, the entropy values of each volume were calculated according to the usage frequency of the used parts in the whole building. By summing the entropy values of all the parts(volumes), the total shape entropy of the building was calculated(Table 4). This type of approach differs from the Stamps's work [6], which creates abstract designs with its own LEGO vocabulary, as well as from Crompton's study [3], which construct the building with a predefined LEGO set. In this study, shape of the parts are obtained from the analysis on buildings.

The equal distribution of the parts with same size can be construct the building that results with the maximum shape entropy. However, the equal distribution, shape and size of each piece will lead to meaningless spaces in building scale. Therefore, it is not possible to mention an optimum value for shape entropy. In the calculations made, it is seen that the shape entropies of the buildings are different according to both in all building and on the floor plans.

Table 4. Calculated Shape Entropy of the Mention Prize Winner Project in Efeler Municipality Building Competition

Size of volumes	**Number of parts**	**Entropy per piece**	**Total shape entropy**
4x6	95 pars	1,86	176,36
4x8	93 parts	1,89	175,50
4x4	35 parts	3,30	115,39
3x4	39 parts	3,14	122,49
2x3	30 parts	3,52	105,58
6x8	9 parts	5,26	47,31
8x8	5 parts	6,10	30,52
3x3	6 parts	5,84	35,05
3x6	10 parts	5,10	51,04
2x8	9 parts	5,26	47,31
8x12	2 parts	7,43	14,85
6x24	1 parts	8,43	8,43
2x2	6 parts	5,84	35,05
6x6	1 parts	8,43	8,43
3x8	1 parts	8,43	8,43
2x4	2 parts	7,43	14,85
14 types	**344(total)**		**996,59**
Avarage shape entropy of the building			**996,59/344 = 2,90 bits**

The project information given in Table 4 has 2.90 bits average shape entropy while the all building is constructed only with 14 different volumes. Besides, the project that won the first prize in Efeler Municipality Building Competition used 45 different shapes in various numbers to create the building and has 4.68 bits shape entropy.

4.3 Color Entropy

The colors of the parts were used to express the functions of the spaces on the floors of the buildings were analyzed. Entropy can be calculated according to the proportions of the functional distributions of the spaces located on the floor as well as calculating the distribution of colors in an abstract composition. There are five very common functions in the brief and assignment of the projects examined. These functions can be listed as; offices, meeting rooms, service, archive and circulation. Buildings with the same number of functions can be compared in terms of functional distribution (color entropy). For example, in a building with 8 functions (colors) 3 bits are the maximum entropy value that reached as a result of equal distribution of functions. However, there are no instances where all functions are uniformly distributed in the buildings.

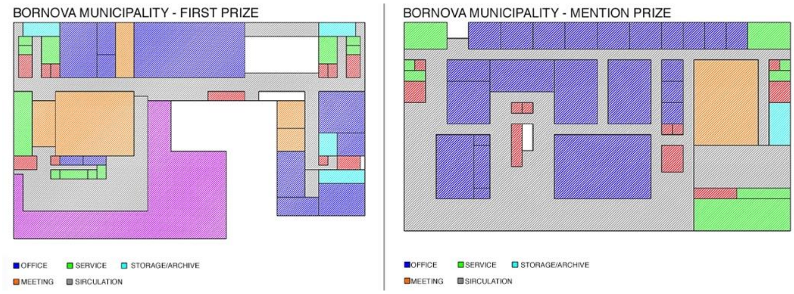

Fig. 5. Coloring different Bornova Municipality Projects according to the functions

Table 5. Calculated Color Entropy of Bornova Municipality Project Competition

	office	meeting	service	archive	circulation	total
Optimum Value	7540	935	1495	580	7450	18000
	7540/18000	935/18000	1495/18000	580/18000	7450/18000	
	%41,89	%5,19	%8,31	%3,22	%41,39	%100
	log2(41,89/100).(41,89/100).(-1)	log2(5,19/100).(5,19/100).(-1)	log2(8,31/100)(8,31/100).(-1)	log2(3,22/100).(3,22/100).(-1)	log2(41,39/100).(41,39/100).(-1)	
	0,53 bits	0,22 bits	0,30 bits	0,16 bits	0,53 bits	1,73
First Prize	%48,73	%8,13	%5,30	%3,38	%35,17	%100
	log2(48,03/100).(48,03/100).(-1)	log2(8,13/100)(8,13/100).(-1)	log2(5,30/100).(5,30/100).(-1)	log2(3,38/100).(3,38/100).(-1)	log2(35,17/100).(35,17/100).(-1)	
	0,51 bits	0,29 bits	0,22 bits	0,17 bits	0,53 bits	1,73
Mention Prize	%40,70	%11,19	%8,31	%0,44	%39,35	%100
	log2(40,70/100).(40,70/100).(-1)	log2(11,19/100)(11,19/100).(-1)	log2(8,31/100).(8,31/100).(-1)	log2(0,44/100).(0,44/100).(-1)	log2(39,35/100).(39,35/100).(-1)	
	0,53 bits	0,35 bits	0,30 bits	0,03 bits	0,53 bits	1,74

The optimum color(function) entropy of Bornova Municipality Building Competition is calculated as 1,73 bits according to the brief. The total entropy of the first prize winning project is also calculated as 1,73 bits. However, the optimum entropy values of various factors and values obtained from winner of first prize differ from each other. For instance, the optimum entropy value of the service function is calculated as 0,30 bits, on the other hand the service function of first prize carry 0,22 bits of information.

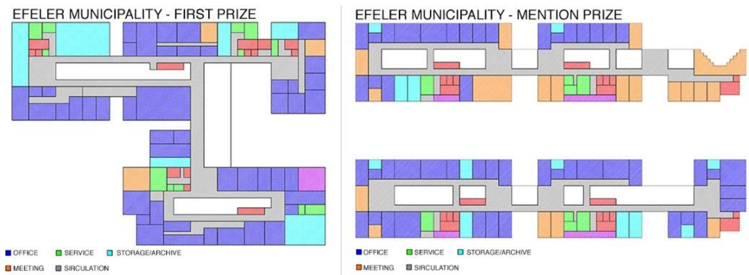

Fig. 6. Coloring different Efeler Municipality Projects according to the functions

Table 6. Calculated Color Entropy of Efeler Municipality Project Competition

	office	meeting r.	service	archive	circulation	total
Optimum Value	7490	1230	640	1260	4100	14720
	7490/14720	1230/14720	640/14720	1260/14720	4100/14720	
	%50,88	%8,36	%4,35	%8,36	%27,85	%100
	log2(50,88/100). (50,88/100) .(-1)	log2(8,36/100). (8,36/100). (-1)	log2(4,35/100). (4,35/100). (-1)	log2(8,36/100) (8,36/100). (-1)	log2(27,85/100) (27,85/100) .(-1)	
	0,50 bits	0,30 bits	0,20 bits	0,30 bits	0,51 bits	1,81
First Prize	%46,83	%4,21	%5,36	%10,05	%33,55	%100
	log2(46,83/100). (46,83/100) .(-1)	log2(4,21/100) (4,21/100). (-1)	log2(5,36/100) (5,36/100). (-1)	log2(10,05/100) (10,05/100) .(-1)	log2(33,55/100) (33,55/100) .(-1)	
	0,51 bits	0,19 bits	0,23 bits	0,33 bits	0,53 bits	1,79
Mention Prize	%39,44	%13,56	%5,30	%6,43	%35,28	%100
	log2(39,44/100). (39,44/100) .(-1)	log2(13,56/100) (13,56/100) .(-1)	log2(5,30/100) (5,30/100). (-1)	log2(6,43/100). (6,43/100). (-1)	log2(35,28/100). (35,28/100) .(-1)	
	0,53 bits	0,39 bits	0,25 bits	0,22 bits	0,53 bits	1,93
Not-Awarded	%45,60	%4,78	%3,06	%2,84	%17,91	%100
	log2(45,60/100). (45,60/100) .(-1)	log2(4,78/100) (4,78/100). (-1)	log2(3,06/100) (3,06/100). (-1)	log2(2,84/100). (2,84/100). (-1)	log2(17,91/100). (17,91/100) .(-1)	
	0,43 bits	0,25 bits	0,19 bits	0,18 bits	0,50 bits	1,55

Calculated optimum color entropy of Efeler Municipality Building is 1,79 bits. The calculations show that first prize winning project has the closest value to the optimum, whereas mention prize winner project and not-awarded project has values of 1,93 and 1,55 bits.

Table 7. Calculated Functional Distribution/Color Entropy of İnegöl Municipality Architectural Project Competition

	office	meeting r.	service	archive	circulation	total
Optimum Value	5030	600	504	440	2646	9220
	5030/9220	600/9220	504/9220	440/9220	2646/9220	
	%54,56	%6,51	%5,4	%4,77	%28,70	%100
	log2(54,56/100).(54,56/100).(-1)	log2(6,51/100).(6,51/100).(-1)	log2(5,4/100).(5,4/100).(-1)	log2(4,77/100)(4,77/100).(-1)	log2(28,70/100)(28,70/100).(-1)	
	0,48 bits	0,26 bits	0,23 bits	0,21 bits	0,52 bits	1,69
First Prize	%49,80	%7,19	%6,46	%2,58	%33,97	%100
	log2(49,80/100).(49,80/100).(-1)	log2(7,19/100)(7,19/100).(-1)	log2(6,46/100)(6,46/100).(-1)	log2(2,58/100)(2,58/100).(-1)	log2(33,97/100)(33,97/100).(-1)	
	0,50 bits	0,27 bits	0,26 bits	0,14 bits	0,53 bits	1,69
Mention Prize	%47,82	%9,52	%6,36	%2,03	%34,27	%100
	log2(47,82/100).(47,82/100).(-1)	log2(9,52/100)(9,52/100).(-1)	log2(6,36/100)(6,36/100).(-1)	log2(2,03/100)(2,03/100).(-1)	log2(34,27/100)(34,27/100).(-1)	
	0,51 bits	0,32 bits	0,25 bits	0,11 bits	0,53 bits	1,73
Not-Awarded	%45,94	%6,89	%6,06	%9,78	%30,55	%100
	log2(45,94/100).(45,94/100).(-1)	log2(6,89/100)(6,89/100).(-1)	log2(6,06/100)(6,06/100).(-1)	log2(9,78/100)(9,78/100).(-1)	log2(30,55/100)(30,55/100).(-1)	
	0,52 bits	0,27 bits	0,25 bits	0,33 bits	0,52 bits	1,88

The value calculated as the result of the distributions given in the brief of the examined municipal buildings was considered as optimum value and the entropy value obtained from the functional distribution of buildings was compared with the optimum value. As a consequence, the closeness of the entropy value to the optimal value has been associated with the success of the building in the competition.

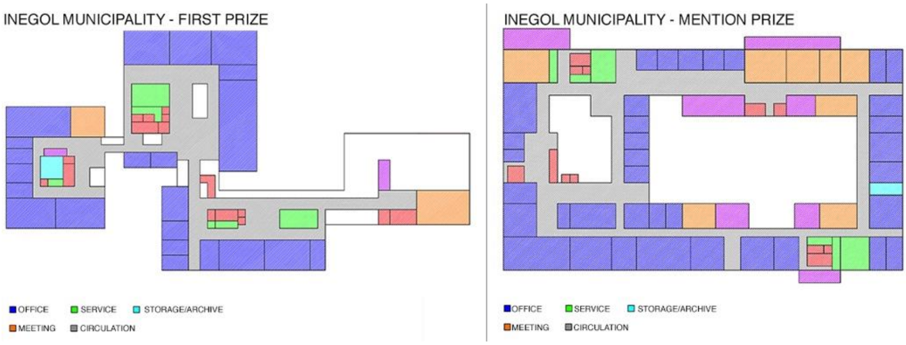

Fig. 5. Coloring floor plans of 2 projects according to the functions

Table 8. Graphical representation of results based on entropy calculations

5 Conclusion and Discussion

Stamps [6] has studied the relationship of singular or multiple factors to visualize complexity and its effects. Stamps also emphasizes that using the right variety of visual complexity is an important aspect of design in place of disordered or monotonous situations. Crompton [3] makes comments on modern and contemporary building shapes depending on the amount of entropy measured. Stamps measures the entropy of design factors such as façade color, window shape, roof shape and height of buildings in his works and produces designs with the desired entropy value using multiple factors. But up to now studies have not examined the relationship of a building with entropy and an specialized architectural typology. In this study, the relation between the entropy value calculated on the data in the brief/architectural program and the success achieved in the competition by the designed building was examined.

Many factors are encountered in the process of designing a building. One of these factors is brief/assignment. Although the theme of the three examined competitions was the design of the municipal building, optimum values for solid-void and functional distribution(color) entropy vary in the briefs for buildings. According to the results of the study, only the required entropy value in the given brief is not sufficient for evaluation the project as successful. Furthermore, it is not possible to obtain information that the monotonous or disordered building is closer to win a prize. When the floor plan is considered to be a canvas of color, the expected complexity can be produced with color patches representing the required size and function. Although this composition produced satisfactory amount of the expected value of entropy, regulation such as content and function cannot be ignored in the design and arrangement of functions represented with colors will not be logical. In this study, the factors such as shape, solid-void ratio and function are examined independently from each other, but all calculations are made with using the same method and equation.

The use of entropy method results in objective and invariable results. Apart from physical features of the building, besides measuring the building itself, many factors encountered such as the relationship with the environment and the environmental conditions. However, jury evaluation is a subjective decision-making environment. Designing with entropy could have been successful if assessments were to be carried out on a check board by holding numerical values and evaluating certain criteria individually.

From all these results, it can be said that a strict calculation method cannot be used solely to evaluate the success of the architecture. In this context, entropy can be used as an input in design; however, it seems that designing only according to entropy cannot produce designs that can be considered successful. When achievement of a building was observed, it is seen that qualitative ones are more dominant than quantifiable and non-quantifiable factors values by entropy.

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Solar Collection Multi-isosurface Method

Computational Design Advanced Method for the Prediction of Direct Solar Access in Urban Environments

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Abstract. Direct solar access and daylight requirements contribute significantly when it comes to shaping the layout and appearance of contemporary cities. Urban planning regulations in Estonia set the minimum amount of direct solar access that existing housing has the right to receive and new premises are required to get when new developments are built. The solar envelope and solar collection methods are used to define the volume and shape of new buildings that allow the due solar rights to the surrounding buildings, in the case of the former, and the portion of the own façades that receive the required direct solar access, in the case of the latter. These methods have been developed over a period of several decades, and present-day CAAD and environmental analysis software permits the generation of solar envelopes and solar collection isosurfaces, although they suffer from limitations. This paper describes an advanced method for generating solar collection isosurfaces and presents evidence that it is significantly more efficient than the existing method for regulation in Estonia's urban environments.

Keywords: Urban planning · Direct solar access · Solar envelope · Solar collection · Computational design · Environmental design

Design Geometry and Form Studies

Kinetic Origami Surfaces

From Simulation to Fabrication

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Abstract. On nowadays social, technological and economic context everything changes constantly so there is the persistent need to adapt at all levels. This research defends that Architecture should do the same through the use of kinetic and interactive buildings, or elements in a building. These elements should allow the building to adapt to changing needs and conditions. This article describes the current state of an ongoing research that proposes the use of kinetic Rigid Origami foldable surfaces to be used as roofs for spaces with big spans and the practical contribution that the Design Studio Surfaces INPLAY has brought to it.

Keywords: Origami Geometry, Parametric Design, Kinetic Architecture, Digital Fabrication, Design Studio

1 Introduction

"*Today's intensification of social and urban change, coupled with the responsibility of issues of sustainability, amplifies the demand for interactive architectural solutions. In the context of architectural need, the attribute of being able to adapt to changing needs is paramount in contemporary society.*" [1]

In the last decades the technological developments regarding computational design and fabrication generated advanced technologies and tools to be used in Architecture.

With these tools the architect has now at his reach the possibility to create buildings that can transform themselves in order to adapt to different needs, functions and ambient or environmental conditions instead of buildings that are static and immutable on their structure requiring to be heavily equipped with thermic, sound and/or lighting systems with all the financial and environmental costs that brings.

The kinetic deployable structures can be one way of responding to such matter.

"*It would seem that deployable structures offer great potential for creating truly transforming, dynamic experiences and environments. Their lightness and transportability allow them to adapt to a society that is constantly evolving and changing. Furthermore, these are reusable structures that make efficient use of* *energy, resources, materials and space, thus embracing the concept of sustainability*." [2]

This research proposes the use of Rigid Origami foldable surfaces to be used on buildings that can change themselves in order to meet the needs of a determined function or ambient/environmental demands. The choice of this kind of geometry is easy to justify, Rigid Origami geometry has very clear rules that fit perfectly a kinetic architectural objective and, in a more emotional way, they are incredibly hypnotic and dazzling structures. These surfaces have self-supporting qualities and, by the application of forces at strategic points, have the power to grow, shrink and adapt to several geometric configurations.

Furthermore the advanced technologies allow the architects to simulate digitally several solutions, or families of solutions, test them and optimize the chosen one before construction. So this research also proposes the use of Digital Simulation tools to test and evaluate the folding of the surfaces for what regards the geometrical and kinetic aims of those surfaces.

Throughout this article it will be classified the types of Kinetic Systems in Architecture (Michael Fox and Bryant Yeh), categories of Deployable Structures (Esther Rivas Adrover), it will be explained the fundamentals of Rigid Origami geometry (Robert Lang and Erik Demaine) and the way that this applied research combined these three areas in a workflow that was used in the Design Studio Surfaces INPLAY to create five prototypes, from conception to construction.

2 Kinetic Systems

In Architecture there has been always the use of kinetic elements embedded in the building, like doors, windows, shutters, etc. Even in a passive way buildings were thought about, from centuries ago, in a manner that allows them to be cooler in summer and hooter in winter or to have windows and solar shadings with a configuration that takes the best advantage of the solar trajectory depending on the time of year or day.

Despite the undebatable importance of these abilities, these are not always enough to make a building operational at all times with the needed comfort for a given situation. A kinetic building, or kinetic elements in a building, enriches the utilization of the building by allowing it to be used in more situations, shelter different events and to adapt to changing ambient or atmospheric conditions.

According to Fox and Yeh [3] the kinetic systems can be classified in three kinds of structures: Embedded, Dynamic and Deployable.

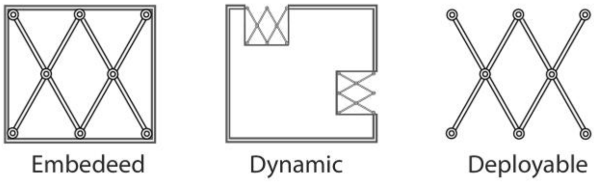


Fig. 1. Types of Kinetic Systems (Source: Fox and Yeh, 2000)

The **embedded** kinetic structures are systems that are integrated in an architectonic whole at a fixed location. Their function is to help control the whole in response to changing conditions. The **dynamic** systems act independently of the architectural whole, like doors, movable walls, etc.

The **deployable** kinetic systems are systems that are easily constructed and deconstructed systems. These structures can have one or multiple functions and their movement can be controlled in six different ways:

Internal Control: have the potential for mechanical movement but they do not have any direct control device or mechanism, they have a constructional internal control that allows it to move by rotating or sliding. It is the case of deployable and transportable architecture.

Direct Control: the movement is done directly by a source of energy such as electrical motors, human action or biomechanical changes in response to environmental conditions.

In-Direct Control: the movement is induced indirectly through a sensor feed-back system. The sensor sends a message to the control device that gives an on/off instruction to the energy source so it actuates the movement. It is a singular self-controlled response to a unique stimulus.

Responsive In-Direct Control: the operation system is quite similar to the last one but here the control device can make decisions based on the received input from various sensors. After analysing the inputs it makes an optimized decision and sends it to the energy source for the actuation of a single object.

Ubiquitous Responsive In-Direct Control: in this type of control the movement is the result of several autonomous sensor/motor pairs that act together as a networked whole. The control system uses a feedback algorithm that is predictive and auto-adaptive.

Heuristic, Responsive In-Direct Control: in this case the control mechanism has a learning capacity. The system learns through successful experiential adaptation to optimize the system in an environment in response to change. The movement gets self-constructive and self-adjusted [3].

The structures that this research refers to would be the Deployable Kinetic Systems with an In-Direct Control, according to Fox and Yeh's categorization.

3 Deployable Structures

The deployable structures have been used for thousands of years, since the nomad man created shelters that could be transported from one place to another and easily assembled and disassembled [4].

These are the main reasons for these structures to continue to be used and even more in the actual architectural context. They are usually light, self-supported and can often be divided into its components parts or be collapsed into a compact volume to be transported from one place to another. When they are used as part of a building they offer the possibility to extend that building or to transform it in several ways.

Esther Rivas Adrover [2] defined the typologies of the deployable structures in Architecture through 30 existing examples of such structures. Esther Rivas Adrover classified two main groups; Structural Components and Generative Technique. The **Deployable Structures** classified as **Structural Components** are deployables that were developed with a structural approach, the structural components of the deployable mechanism are its essence and base of design. The **Generative Technique** concentrates on movement and form inspired by Origami and Biomimetics that can later be developed with several structural systems [2].

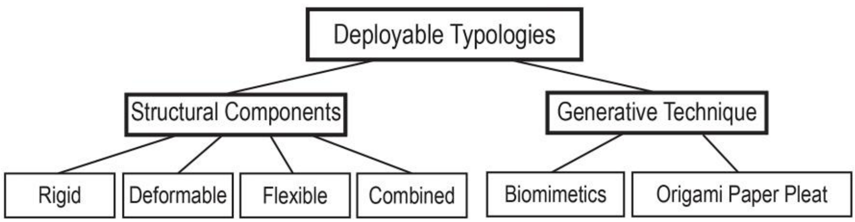


Fig. 2. Deployable Typologies (Source: Esther Rivas Adrover, 2015)

The group of Structural Components can be divided in four subgroups, Rigid, Deformable, Flexible and Combined, and the group of Generative Technique can be divided in two main subgroups, Biomimetics and Origami Paper Pleat. The last subgroup is the only that will be profoundly presented here since it is the subgroup in which this research is placed.

3.1 Rigid Origami

This research proposes a new subcategory within Esther Rivas Adrover's classification under the Origami Paper Pleat group, that is the **Rigid Origami**. In Rigid Origami the final model must be the result of the folding of a single planar sheet, where each face must be plan and have the same area at all times. This means that the material cannot bend, except at the creases, and it cannot stretch either. The creases work as hinges between the flat faces, they have to be straight and cannot change their length during the folding process. Also no face can ever penetrate another face [5] [6].

Rigid Origami can be subdivided into Flat Foldable and Non-Flat Foldable. The flat foldability of a given crease pattern can be determined before the folding by the verification of three fundamental rules stated in the Maekawa's Theorem, Kawasaki Theorem and Two-colourability Rule.

The **Maekawa's Theorem** states that a crease pattern is flat foldable if at every interior vertex the number of valley (V) and mountain (M) folds differs by two.

$$\sum V - \sum M = \pm 2 \quad (1)$$

The **Kawasaki's Theorem** states that a crease pattern is flat foldable if at every interior vertex the sum of the even and odd angles defined by the creases are equal to 180°.

$$\alpha_1 + \alpha_3 \cdots + \alpha_{2n-1} = \alpha_2 + \alpha_4 \cdots + \alpha_{2n} = 180° \quad (2)$$

Fig. 3. Graphic representation of Maekawa's and Kawasaki's Theorems (Source: Authors)

The **Two-colourability Rule** states that for a crease pattern to be flat foldable it must be possible to colour each face of the crease pattern in a way that two faces with the same colour never share a crease.

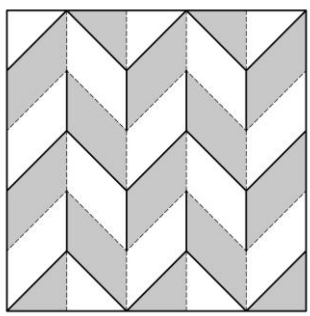


Fig. 4. Example of Two-Colourability Rule with Miura flat foldable pattern (Source: Authors)

3.2 Rigid Origami in Architecture

The present research categorizes the utilization of Rigid Origami in Architecture in three main groups, Static, Deployable Fixed and Deployable Kinetic.

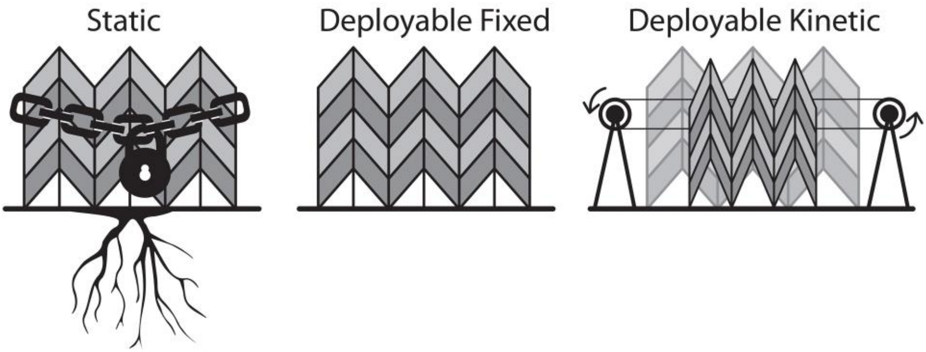


Fig. 5. Groups of Origami in Architecture (Source: Authors)

The **Static Origami** in Architecture happens when a building is constructed with an Origami form but this form remains with the same configuration through time. From the range of states an Origami surface can assume it is chosen only one state to reproduce in a permanent way. This state is chosen due to aesthetical and/or structural reasons since a pleated form has structural qualities that a plan form does not, like the division of the forces that the structure might be subjected to. This research finds this kind of Origami utilization in Architecture as the one that takes less advantage of the main qualities of Rigid Origami, so it will not be presented further here.

The **Deployable Fixed** Rigid Origami structures take advantage of the self-supporting capabilities of Rigid Origami surfaces and of their ability to be folded into a flat, compressed object. These surfaces can be easily assembled and disassembled without the need for additional supporting substructures and, when flattened, are easily transported and stored.

There are several examples of such utilization of Rigid Origami. In 2007 Miwa Takabayashi designed *Packaged*, a small pavilion to use in a Shopping Centre made of corrugated cardboard. *Xile*, 2008, by Mats Karlsson, was a 35 meter long translucent tunnel created to connect two buildings during the design fair *Interieur*. Matthew Malone developed the *Recover Shelter* in 2008, a temporary shelter to be used in emergency situations made with polypropylene. In 2009 the students from the third year of Architecture in the University of Cambridge designed, fabricated and assembled a temporary cardboard pavilion for a banquet at the University gardens. David Penner created the *Corogami Folding Hut* in 2010, a collapsible ice skating change hut, made with doubled wall polypropylene. More recently, in 2014, the students of the University of Southern California made a pavilion in polycarbonate that occupies an area of 15m x 3m and is 3m high. All these examples are able to support themselves without the addition of alternative structural systems due to the rigidity of the main material and the chosen Origami geometry.

The utilization of **Deployable Kinetic** Rigid Origami can be found in a wide variety of situations, from folded solar sails launched into space, medical devices, reconfigurable walls, shading systems, acoustic enhancement and artistic responsive installations.

The use of Kinetic Origami allow the designers to create not only transformable architecture in terms of the configuration of the lived space but make also possible the creation of responsive architecture or architectural elements such as kinetic roofs, or ceiling or wall panels.

The examples presented below are grouped in terms of their geometry, this is if they are **modules** (first) or **surfaces** (second).

Auxetic Origami of Christopher Connock and Amir Shahrokhi from Yale University, 2011, was a structure with sixteen flower like modules that responded to the ambient's levels of light by opening or closing themselves (Fig. 6). In 2011 David Lettellier exhibited *Versus*, two modules of Origami talking flowers placed on opposite walls that reacted to sound and communicated constantly with each other (Fig. 7).

Fig. 6. Auxetic Origami

Source: amirshahrokhi.christopherconnock.com

Fig. 7. Versus

Source: www.davidletellier.net

In 2012 AHR Architects finished the construction of the *Al Bahr Towers* where they used a façade protection system composed by several triangular modules with six faces. These modules protect the building from the sand storms and excessive sunlight (Fig. 8). In 2015 the mechanical engineering students of the Compliant Mechanisms Research Group designed the *Origami Kinetic Sculpture* based on the square twist pattern to be presented at the exhibition "Folding Paper: The Infinite Possibilities of Origami" at the BYU Museum of Art. (Fig. 9)

Regarding the utilization of Kinetic Origami as **surfaces** instead of modules there is a very interesting work by of Otto Ng that in 2010 at the John H. Daniels Faculty, University of Toronto, created *Wallbot*. These were mobile pieces of wall that worked together. It was used the Miura pattern stretching from 1m to 1,5m on each Wallbot that responsed to behavioural patterns and thermic conditions (Fig. 10).

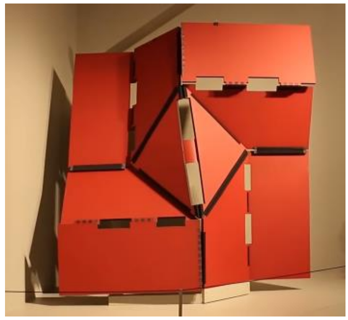


Fig. 8. Al Bahr Towers

Source: Christian Richters, www.ahr-global.com

Fig. 9. Origami Kinetic Sculpture

Source: compliantmechanisms.byu.edu

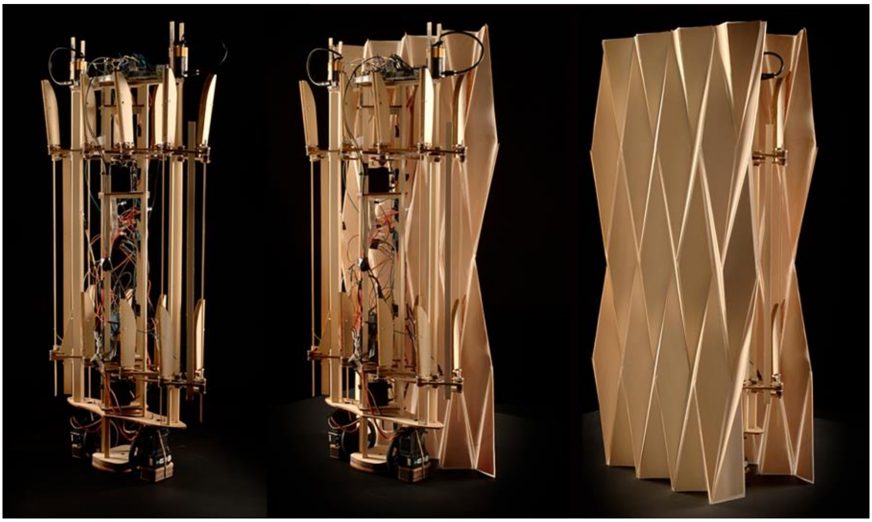


Fig. 10. Wallbot (Source: www.ottocad.net)

Fig. 11. Tunable Sound Cloud

Source: www.fishtnk.com

Fig. 12. Tessel

Source: www.davidletellier.net

Fishtnk created the first version of the *Tunable Sound Cloud* in 2010, a surface that modifies itself in order to enhance the acoustic performance of spaces (Fig. 11). With the same purpose David Lettellier created *Tessel* also in 2010 (Fig. 12). A similar surface, the *Ressonant Chamber*, was developed in 2012 by RVTR in a partnership with ARUP acoustics (Fig. 13).

Fig. 13. Ressonant Chamber (Source: www.rvtr.com)

Cerebral Hut was designed in 2012 by Guvenc Ozel and Alexandr Karaivanov and was an installation made with 11 hexagonal modules of surfaces folded with the Ron Resch Pattern that reacted to the user's brain frequencies with the objective of allowing the users to control it with their minds (Fig. 14).

In 2014 Foldhaus created *Blumen Lumen*, an interactive art installation that uses the Miura pattern to create 10 animatronic flowers that open and close in response to the people around them (Fig. 15).

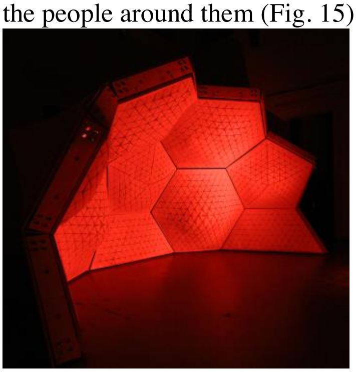


Fig.14. Cerebral Hut

Source: ozeloffice.com

Fig.15. Blumen Lumen

Source: blumenlumen.com

As a sum up of the groups and subgroups that were exposed on the last two sections, and to place the current research, Figure 16 shows Esther Rivas Adrover's classification extended with the branches proposed by this research.

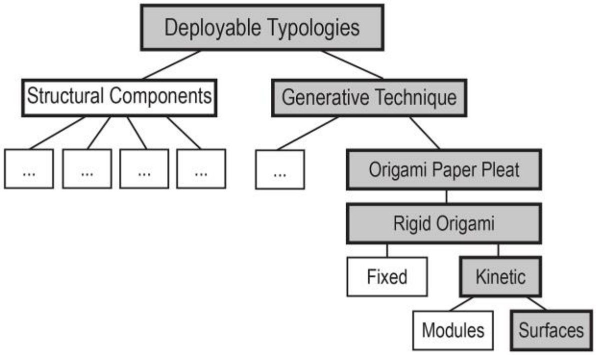


Fig. 16. Deployable Typologies Extended (Sources: Esther Rivas Adrover, 2015 and Authors)

This research places it self along the grey path, its focus are the Deployable structures made with Rigid Origami Kinetic Surfaces. The ultimate goal is to develop a kinetic roof for a space with a big span and build a part of it in a real scale prototype.

From the shown examples there are several conclusions made on this research. It is possible to conclude that when using Rigid Origami to develop kinetic objects the most common approach is to use modules with a small number of surfaces instead of using surfaces with a big number of faces. Probably because it is much more complicated to control an origami surface in a kinetic context. This is one of the contributions this research intends to accomplish, the use of surfaces rather than modules to cover spaces with big spans.

It is also possible to observe that, when using surfaces, the crease patterns more often chosen are the Miura-Ori and the Ron Resch pattern. Probably the two most studied and used patterns of Origami surfaces in Architecture.

4 Digital Simulation

The use of digital parametric tools by Architects enables the testing of several solutions in order to choose the most appropriate for a particular building site or function and to optimize the chosen solution before its construction.

In the particular matter of Rigid Origami folding simulations there is already an extensive work from authors like Robert Lang and Tomohiro Tachi that have the developed softwares available to the public on their websites. Daniel Piker has also several Origami folding definitions available at Grasshopper3d.com and is the creator of Kangaroo and the Origami component on Grasshopper. Then there is the work of Casale and Valenti that use Rhinoceros and Grasshopper to simulate the folding of different crease patterns each one with a different approach depending on the geometry of the pattern [7].

The simulation method used in this investigation is similar to the one used by Casale and Valenti, it uses Rhinoceros and Grasshopper. But these authors create definitions to fold the entire crease pattern at once and at this investigation the method is to define the minimum possible module of the regular tessellation, define the parameters to design the faces that constitute the module and the local rules for their folding.

This way is possible to alter the dimensions of the base module and simulate the folding from the plan state to the completely folded and then reproduce that module with vectorial copies allowing to extend the crease pattern as far as wanted and also change the configuration of the module faces at any point of the folding process.

This method comprises 3 steps:

1 – Analysis of the regular tessellation in order to define the base faces

2 – Simulate the folding of the base faces from the unfolded state to the completely folded state

3 – Generate the complete tessellation through vectorial copies of the base faces

On the developed definitions there is always one point or crease that does not change during the folding. This element behaves has the attachment to the XYZ referential, is the centre of all the transformations.

This method and the resulting definitions have proven to work perfectly and simulate in a rigorous way the folding that happens on physical rigid models with minimum thickness, but they are not suitable for irregular crease patterns.

5 Work Method

This research also intends to develop a method for the design and construction of Rigid Origami Surfaces to be used with kinetic purposes. The method encloses all the main areas previously described and also the materials and digital fabrication areas.

The proposed method starts with the study of the place to intervene. It is necessary to understand deeply the “problem” to solve, the objectives and constraints for the surface that is being designed, the configuration of the available space for the implementation, the desired covered area and the unobstructed height where the surface will move. Furthermore there is the need to know the purpose of the surface and also if it will be exposed to the natural elements, like sun, rain, snow and wind since the geometry of the surface can aide in solving such matters.

From the conclusions taken before it will be possible to decide which crease pattern will suit best the space and function of the intervention. At this point it is proposed the use of parametric tools that can help the designer simulate the movement that the surface will describe from the unfolded to the folded state. After the Digital simulation it is essential to observe the result and to confront it with the initial objectives, if it does not fit the purposes then modifications must be made to the crease pattern or even the choice of a different one.

Once the geometry of the surface is adjusted it is necessary to decide which material, or association of materials, will be used to fabricate it. These materials must replicate the rules of Rigid Origami, they must guarantee that all faces are planar at all times in order to keep the integrity of the simulation and the surface's behaviour in a real context.

The geometry of the surface and the movement that the hinges and vertices describe during the folding process are directly related to the kinetic system. This system must be in sync with the geometry of the surface so it will support it and flow with it as the folding process occurs.

The interaction with the surface must also be settled before the fabrication so any emergent issues may be solved before entering the final step of the workflow.

Finally, the last stage will be the fabrication of the surface. For the fabrication the Digital Simulation made before will be of great importance, with it will be possible to generate the drawing of the planar surfaces to be cut in a CNC milling machine, laser cutter or any other digital fabrication tool.

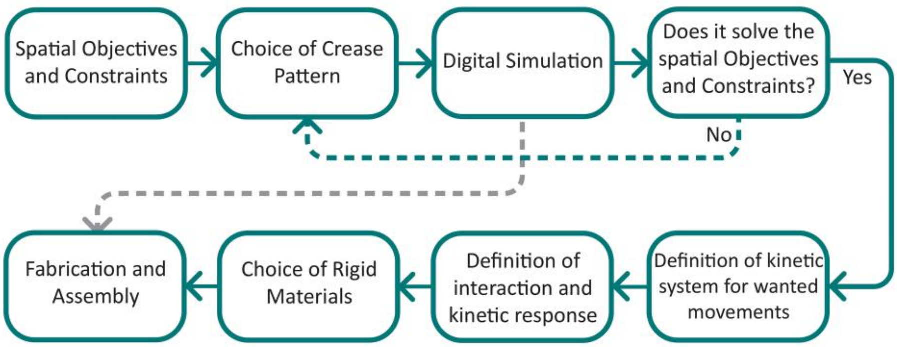


Fig. 17. Work method (Source: Authors)

6 Design Studio Surfaces INPLAY

On 2016 it was organised an event, Design Studio Surfaces INPLAY at ISCTE-IUL, Lisbon, Portugal, that was like a small replica of this research. Each group of students at the design studio had to create a suspended Rigid Origami surface that would move in response to an external stimulus, like light levels or the approach of a person or object. The main objectives of Surfaces INPLAY in relation to this research were to test several issues:

1) the work method

2) suspended surfaces with five different crease pattern's geometries, their capacity of compression and intrinsic possibilities of movement.

3) surfaces made with 0,8mm thick polypropylene, 3mm thick plywood and 160g/m² paper; how to fold these materials

4) linear motion systems, manual or with motors and their relation with the mechanical systems

5) arduíno controlling for the sensors reading and kinetic system operation

This issues were tested on five different prototypes that shall be called A, B, C, D and E from now on. The prototypes where conceived from concept to fabrication by

10 students from Portugal, Italy, Brasil, Canada, Greece and Belgium. The students were mostly PhD students, Architecture students and University teachers. Some of the students had already knowledge on Parametric Design and/or Origami Geometry, but most of them did not, so there were several masterclasses to level the general knowledge needed for the construction of the prototypes.

6.1 Spatial Objectives and Constraints

The space for the implementation of the prototypes was a squared plywood board with 1x1 meter that would be the base for the suspended Origami surfaces and also hold and hide the actuator and all the mechanical system. The only mandatory constraints were 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 free and up to the students, so it was possible to make the rails, holes and attachment points needed for each specific prototype directly on the base. Each board was drawn by each group and digitally fabricated at Vitruvius FabLab..

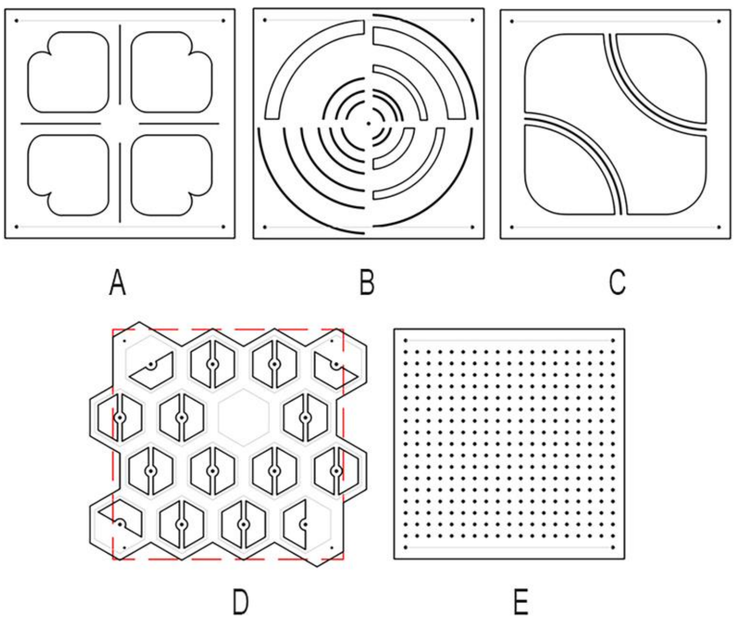


Fig. 18. Prototype bases (Source: Authors)

6.2 Digital Simulation

After the first geometric experiments with paper, paperboard and cardboard, based on the crease patterns presented by Paul Jackson on his 2011 book, Folding Techniques for Designers: From Sheet to Form [8], the students simulated the folding of their crease patterns with Rhinoceros, Grasshopper and Kangaroo and did the necessary adjustments to the geometry of the pattern in order to achieve the proposed effect, as preconized in the work method.

Prototype A was constituted by four symmetrical modules that intended to be four birds that opened and closed their wings in a diagonal movement set with vertical and horizontal moving points of the surfaces.

Prototype B used a parallel pattern with an inflexion in order to create four surfaces that were like a hybrid between a hand fan and a shell. These four surfaces open and close in a radial movement.

The geometry defined for the prototype C had some similarities with the previous one, it was also a shell like surface, but instead of having parallel creases the creases were radial and the faces used to achieve the inflexion on the surface were much less.

Prototype D used the Yoshimura pattern in sixteen helicoidal cylinders. This was the only prototype that used the movement in the vertical direction while all the others structures moved on the horizontal plane.

Prototype E was made with the Ron Resch pattern to create a surface that would act as a fluid when subjected to forces in different points. This was the only Non-Flat Foldable surface, since the Ron Resch pattern does not verify the Maekawa's theorem. The objective of this prototype was to make one unique surface that would have different things happening at the same time, pulling and pushing on different points. Unfortunately the students did not consider the material limitations and the final structure did not behave as initially intended.

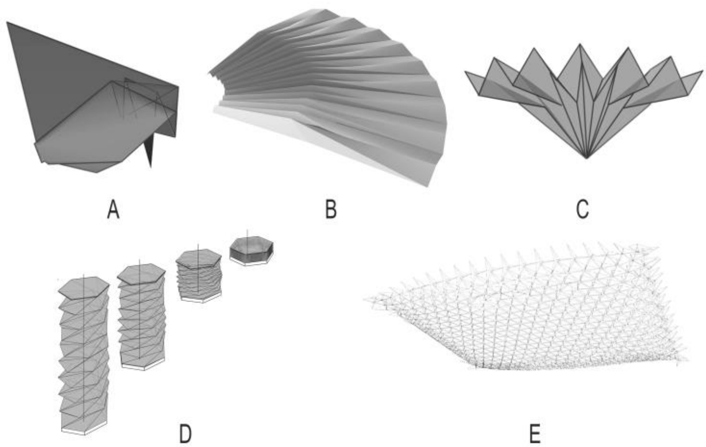


Fig. 19. Digital Simulations (Source: Authors)

6.3 Materials and Digital Fabrication

For the final prototype the available materials were 3mm thick plywood boards, 1mm polypropylene or 160g/m² paper.

The students that used polypropylene did the creases directly on the material with the laser cutter either with dashed lines where the dashes where cut all the way through (A and E) or by engraving the creases on both sides of the polypropylene (B). All these three prototypes had to have the vertices cut away where there would be more forces in action so they wouldn't inhibit the structure's movement.

The "engraving on both sides" method proved to be more efficient than the "dashed lines" method because it cuts away some material over the entire crease, while the dashed lines method obliges to a crushing on the non-dashed parts. The fact that the creases are engraved at their entire length and until half of the material's thickness makes the folding more natural and creates less "crushing" of the material under the crease lines and so inhibits less the folding.

Prototype C used the 3mm plywood and encountered a problem that did not exist on the other prototypes, how to make a surface with thickness fold. To resolve that each face was cut individually at the laser cutter and then stitched to the adjacent faces in a way that only allowed the faces to fold on one way, defining like this the mountain and valley folds.

Fig. 20. Plywood stitching (Source: Authors)

For prototype D it was initially tried to perforate the paper at the laser cutter to make a sort of pre-crease, but it did not work, after a few utilizations the paper would tear apart. So the pattern was simply printed on paper and the folds were made by hand.

These experiences proved that making the creases directly on the polypropylene with the laser cutting machine is a successful way of making Rigid Origami foldable surfaces if the vertices are cut away. It was also possible to observe that the patterns with bigger faces behaved better than the patterns with smaller faces, possibly because this material as the tendency to curve slightly the faces on the areas near the creases.

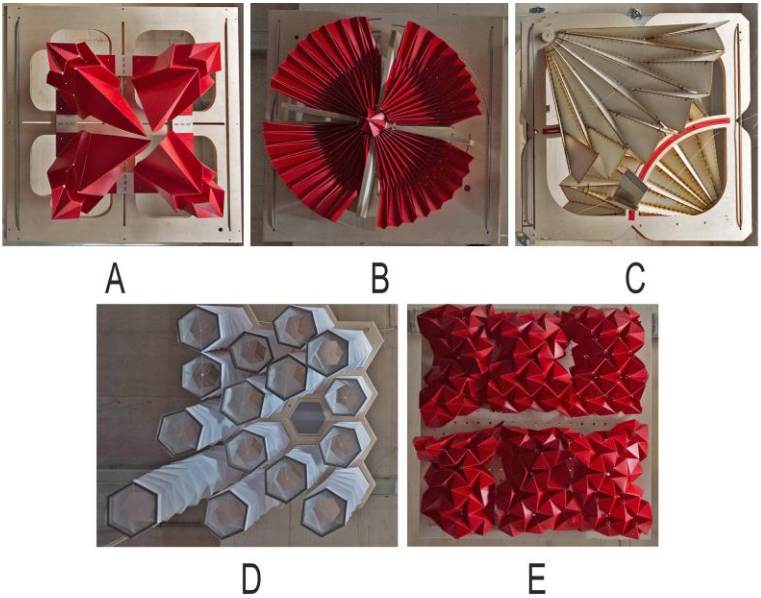


Fig. 21. Prototypes (Source: Authors)

The method to put together the plywood faces by stitching them with nylon thread also proved to be an efficient way of making these surfaces fold.

6.4 Kinetic System

For the kinetic system all groups, except C, used one motor actuator SuperJack of 12’’ (around 30,5 cm). The objective was to use only linear movement.

Prototype A used rails on the plywood base for the moving pieces, like a cross, and had four voids behind the birds where the beak of each bird would always be in touch with the base. On this prototype it was used a mechanism with pulleys and cables that, with the force of one linear motor, made all the lines of movement work in a perfectly synchronised way, with this system all the birds moved at the same time in tri-directional symmetric ways. This prototype did not have fixed points on the geometry, only moving points.

Prototype B was divided in four spaces with circular rails cut on the plywood. Each origami surface was attached to the plywood base on one extreme as the other one was attached to the rotating cross, put in motion by the linear actuator. The movement was rotational and worked like four curtains that open or close at the same time when the motor made a rigid wood cross rotate 90 degrees.

Group C did not use the motor, the movement was achieved when a user pulled the cords to open or close the two module surface. This prototype used the upper and lower parts of the plywood base to place the surfaces, i. e. one was suspended while the other was supported by the base.

Prototype D had the plywood base completely redrawn, the limit shape was completely changed, although respecting the attaching points, in order to place and create an attaching base for each cylinder. To make the cylinders compress and expand it was used the linear motor in an horizontal position that would rotate 8 horizontal wheels with different diameters. These wheels made the cylinders move in a vertical direction at different speeds.

Prototype E had a grid of wholes on the plywood base so it would be possible to choose freely where to attach the cables to the structure's moving points. The linear actuator, placed on the XY plan, made the points of the surface move in Z creating an effect of compression of the surface at some points while at others the effect was of decompression.

It is possible to say that in what relates to the kinetic movement all structures worked perfectly, it is however important to refer that these results where only possible because all the structures started their folding in a slightly folded state. Otherwise, the motors or the manual pull, would have to make tremendous strength to make the surfaces leave the completely unfolded state to a folded one.

It was also possible to verify *in loquo* the capability of compression of each prototype. The real capability of compression differs very much from the folding simulations done on Grasshopper + Kangaroo because for the simulation the faces are considered as without having any thickness and the forces created by each material at the creases region are also inexistent on the simulations.

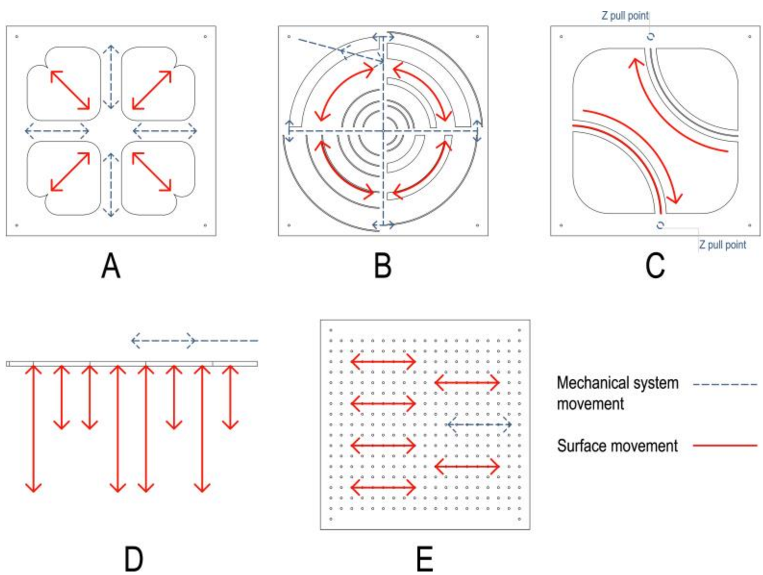


Fig. 22. Prototypes movements (Source: Authors)

The prototype with the best capacity of compression was D prototype because paper was the less thick of all the available materials and also because the Yoshimura pattern has that inherent ability, nevertheless the values of compression range from 10% to 95% because some cylinders never get completely folded, due to the kinetic system design, while others cylinders get maximum compression.

The worst capacity of compression was found on prototype E. The chosen geometry is not flat foldable thus it could never obtain good values of compression, but even so the fact that it does not have fixed points and that the used material was polypropylene did not help to the compression ability.

The other prototypes had values of 60% (A), 75% (B) and 85%(C).

6.5 Interaction System

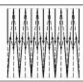
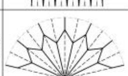
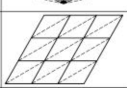
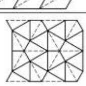
For the interaction system the available sensors were light and distance sensors but it was also possible to use potentiometers to mimic other kinds of interactions. Prototypes A, B, D and E used the distance sensors so their structures moved every time a person, or an object, gets in the range of the sensor. The values of the sensors would be read by the arduíno that would then make the motor work inside a preprogramed range that fitted the surfaces purpose.

Group C explored more the interaction between the object and the user and worked the most the arduíno possibilities. Every time a user opened the C prototype surfaces there was a little "being" inside that would react badly to the intromission making an awful sound and flashing a light so the user would feel obligated to close it again so the "creature" could be comfortable on his cocoon.

6.6 Synthesis

The next table intends to make a compared synthesis on the remarks and results described on the last five sections regarding the prototypes developed at the Design Studio Surfaces INPLAY.

Table 1. Synthesis of results

	Crease Pattern	Is it Flat Foldable?	Fixed Points	Direction of Movement Actuator	Surface's Movement	Material	Creases	Capacity of compression	Behaved as Grasshopper + Kangaroo simulation?	Followed work method?
A		Yes	No	linear at XY plan	Symmetrical to the diagonals at XY plan	Polypropy-lene	On material dashed lines	60%	Yes	Yes
B		Yes	Yes	linear at Z direction	Radial at XY plan	Polypropy-lene	On material engraved	75%	Yes	Yes
C		Yes	Yes	linear at XY plan	Radial at XY plan	Plywood	Stitched	85%	Yes	Yes
D		Yes	Yes	linear at XY plan	Helicoidal at Z direction	Paper	On material by hand	between 10% and 95%	Yes	Yes
E		No (Does not follow Maekawa's Theorem)	No	linear at XY plan	Z direction	Polypropy-lene	On material dashed lines	15%	No	No

7 Conclusions

As stated at the Introduction chapter this research intends to make a contribution to nowadays Transformable Architecture solutions with Deployable Rigid Origami Surfaces by structuring the knowledge on Kinetic Systems, Deployable Structures and Rigid Origami Geometry. It is believed that that goal has been positively achieved.

In addition it is proposed a comprehensive work method that follows every step of the architectural process for this kind of structures, from design to construction. In this process the architect is placed as a constant presence in every stage and has the tools for the decision making with awareness and consideration to those same stages and the ways they influence each other and the final design and construction.

In order to prove the applicability of the suggested geometries and work method it was used the Design Studio Surfaces INPLAY. This Design Studio was of great importance to test in a practical way the work method, the proposed digital simulation tools, Rigid Origami geometry, materials, kinetic and mechanic systems and digital fabrication.

From the developed prototypes it was possible to verify that the fixed points on a kinetic structure can be very important for the surfaces behaviour and capacity of compression but it is also possible to construct them without any fixed points, at least in suspended situations. The geometry of the pattern, the used material and the force of the motors used are also key factors for the range of compression this surfaces can undertake.

It was verified physically the importance of starting the movement with the pattern already slightly folded, in the case of prototype C, for instance, was impossible to make it move and fold if it was not initially folded.

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Teaching Design by Coding in Architecture Undergraduate Education

A Case Study with Islamic Patterns

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Abstract. Computer-aided design has found its role in the undergraduate education of architects, and presently design by coding is also gradually finding further prominence in accord with the increasing demand by students who wish to learn more about this topic. This subject is included in an integrated manner in some studio courses on architecture design in some schools, or it is taught separately in elsewhere. In terms of the separate course on coding, the principal difficulty is that actual applications of the method can rarely be included due to time limitations and the fact that it is conducted separately from the studio course on architecture. However, within the framework of the architectural education, in order to learn about the coding it is necessary to consider it along with the design process, and this versatile thinking can only be achieved by the application of the design. In this study, an elective undergraduate course is considered in the context of design and to yield a versatile thinking strategy while learning the language of visual programming. The course progressed under the theoretical framework of shape grammar from the design stage through to the digital fabrication process, and the experimental studies were carried out on the selected topic of Islamic pattern. A method was proposed to improve the productivity of such courses, and an evaluation of the results is presented.

Keywords: Islamic Patterns, Shape Grammars, Architectural Education, Parametric Design, CAAD.

1 Introduction

The contemporary demand for the inclusion of computer-aided design in courses run in schools of architecture is increasing relentlessly, as a consequence of the fact that students no longer use computer-aided design merely as a representation tool in their design studio projects. The relevant computer-aided design tools have become assimilated into the student's projects in the design stage [1], and this situation changes appreciably the classic design education in the field of architecture. Hence, there are attempts to include novel methods in design education, and efforts are made to determine which of them is the most efficient.

In schools of architecture, computer-aided design is taught in an integrated way in the architecture studio classes, or it is taught as an elective course on this subject, which is included within the architecture curriculum. The main problem encountered in teaching computer-aided design as an elective undergraduate course is that the students are unable to apply their knowledge to actual product design because the architectural design studio is involved in a separate course. It is only possible for students to learn about computer-aided design tools in combination with the particular design by actually applying the methods and also can experience the versatile thinking together with the use of different design tools. Therefore, application-oriented work was considered in the elective undergraduate course taught by this author, with the title “Introduction to Parametric Design”. Here, the intention was to teach the basic visual programming language in the content of the course, in which the theoretical framework of shape grammar was used, and the students were expected to create an Islamic pattern as an application of these principles.

In shape grammars, which enable the creation of innovative designs using computational methods, it is essential that the shapes are used on the basis of a set of defined rules [2] [3]. Different possible emergent design solutions may occur according to the adoption of these rules [4] [5]. These design solutions in shape grammars are generally created using rules such as rotating, reflecting, duplication, scaling, copying, shifting, intersecting and subtracting. If the initial shape is defined as S0 and the application rule is defined as =>, the computation develops as S0 => S1 => S2 => S3 => ... => Sn [6].

Numerous studies have been performed in relation to shape grammars, which are used to create new designs, and also to analyze existing designs, as have been described by Stiny [7], Knight [8], Cagdas [9], Li [10], Duarte [11] and Krstic [12]. Also available are prominent examples [13-15], where shape grammar has been used in architectural education. The use of shape grammar together with encoding in computer is present in the graduate-level course on architectural education [16] or it may be articulated to the design studio in an experimental form [17]. In the present study, which is based on a knowledge of the coding in parametric design, the process followed and the method adopted are discussed in the context of a separate undergraduate architecture elective course. Here, the subject of the application work was Islamic patterns, about which much research [4], [18-22] has been carried out, using the particular advantages brought by the development of the computer technology. As the course progressed, an evaluation was made from the design stage through to the final digital fabrication process.

2 Methodology

The aim of the elective course, "Introduction to Parametric Design" in an architecture undergraduate program, is to teach students how to do basic programming using the visual programming language, which is of increasingly importance in the field. It is, a challenge in its own right to learn the visual programming language in the first place; however, it is considered that the most efficient way to learn it is to create a design product. Hence, during the course, each student is expected to create a design product.

The students, who took this course, had some prior experience with computer-aided design programs such as AutoCAD, Photoshop, and (to some degree) Revit, but not with the use of visual programming language. Accordingly, we commenced the course by teaching 3D modeling in Rhino, and in the following weeks, focused on the basic principles of programming. Subsequently, the production of various scripts was made using Grasshopper (a Rhino plug-in) under the supervision of the instructor. Having understood the visual programming, the students began to produce their own design of an Islamic pattern by means of the principles of shape grammar.

Before starting their design, the students did research on the nature of Islamic patterns using the internet and discovered a variety of such examples, which they examined together with the instructor, who asked them to try to find out how to form the pattern mathematically (rule-based design). Hence, the students had prior knowledge on how to form a pattern by means of shape grammar. Having completed this stage, the students were informed about some detailed studies on Islamic patterns, [18-20] so that they might have some insight into how these fitted into the overall framework of the subject.

During the students production of designs in the course, they were asked to do form-finding [23] studies on specifically Islamic patterns depending on their own set of rules, instead of examining a particular Islamic pattern and reproducing them in a visual programming program with based on rules. Thus, it was provided to be able to discover different forms depending on the rules. This type of method was found suitable to be followed since they define their own rules according to various parameters and shape their forms according to these parameters and create new designs during the production of the form in architectural design.

The students started to produce their Islamic patterns with the use of the basic shapes in Grasshopper. They developed their initial shapes by using such basic geometries as circles and rectangles. Later, they investigated the formation of patterns by defining the different rules regarding the determined initial shape. For example, in the student's work shown in Fig. 1, the initial shape is defined as a triangle formed in a circle, and from which he began to define rules for the production of forms from this initial shape. In this example, the first rule applied to the initial shape is to take a symmetrical mirror, and the second rule is to make an array based on a process of repetition. After this stage was completed, some students were proposed to add a gradual scale with the aid of the closest point component in Grasshopper for creating variations in repetitive patterns.

The instructor suggested that some of the students who started with working in two dimensions could work in three dimensions. For example, Fig. 2 of the student study, the student identified the initial shape as a hexagon. Then the student identified the points on the corners of this hexagon in grasshopper. She also identified new points on the edges of the hexagon. She then created new lines by combining these points and created new hexagons in the initial shape hexagon. Later, she accepted the whole hexagons, created in the initial shape hexagon, as a module and scaled it. In each hexagon in the initial shape hexagon, she placed this scaled module as considering it the new layer in the third dimension. This process was repeated several times, and as a result the form became a three-dimensional form.

In summary, when we simplify the process by removing the components used as tools for making rules applicable in Grasshopper, we see the rules as divide the initial hexagon into hexagons, scale the unit and place as a layer in third dimension, copy, repeat last two rules (scale and copy) (Fig. 3).

The students, who were trying to reach the third dimension, applied this rising method by stratification. The reason may be the direction of basic commands that they learned (Fig. 4). In the study, the student determined the initial shape as triangle. Then, she created a triangular grid with the repeat of triangles and formed the rotated inner triangles by defining the points in the triangles in this triangular grid. Then, she accepted these formed inner triangles as a collective module, and did copying procedure with array polar. Then, she scaled the whole copied and considered to be a layer in third dimension. She applied the scaling procedure again to the formed new layer and so, added the third layer and in the same way, added the 4th layer. In summary, we see the order of the rules as the repetition of the initial shape (triangle), the rotation of the triangles, copy the unit, placing as a layer in third dimension by scaling and repeat last rule twice.

Simultaneous with the students creating their Islamic pattern, the digital fabrication issue was also undertaken as part of the content of the course. Here, the aim was to make the students prepare their patterns in such a way (as scale and material) that the latter can be produced using the machines present at the school. This is because it is important that the students are able to learn versatile thinking along with an experience of the use of different tools in order to achieve the best results. As Kolarevic [24] has said: "*knowing the production capabilities and availability of particular digitally-driven fabrication equipment enables architects to design specifically for the capabilities of those machines*".

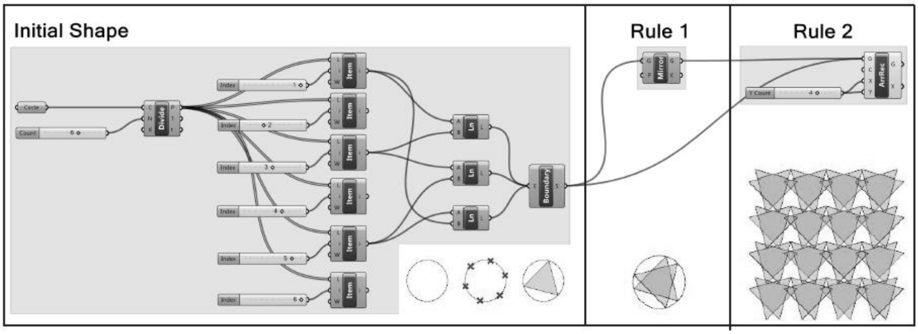

Fig. 1. A student study showing the followed path in the pattern forming stage.

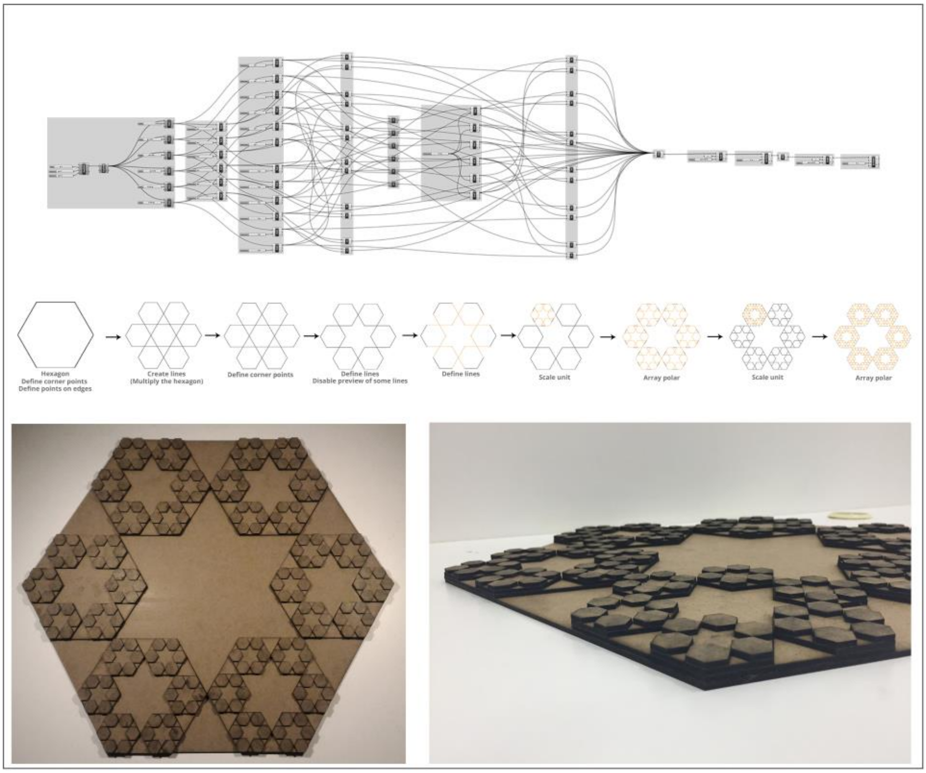

Fig. 2. Student's work of third dimension

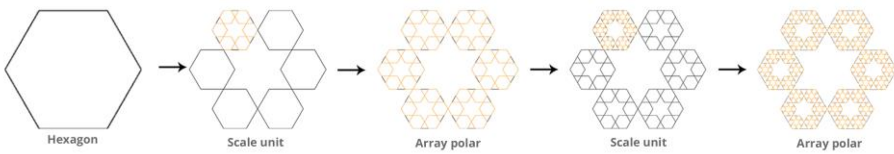

Fig. 3. Set of rules used for the pattern creation in the student's work.

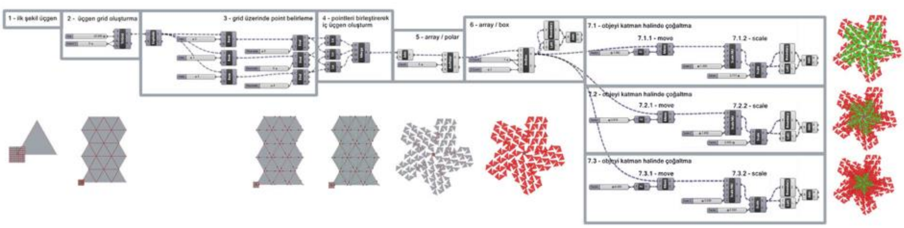

Fig. 4. Student's work of third dimension

3 Results

The use of constructivist pedagogy with well-defined steps, might be one of the answers to an up-to-date problem of designers' reasoning on dataflow programming, because, students tend not to do data flowing on a rule-by-rule basis, when they use the visual programming language program. But, when they start to prepare a definition based on the rules, they begin to create a structure / fiction in their minds. The next rule, that they will define in the visual programming language (by doing visual computation), is based on the form that occurred as the output of a previously defined rule. Consequently, the rules become break points in their definitions, and these break points form the backbone of the students' designs.

The definition of the initial shape (determined by the student) and the rules which are parametric in Grasshopper provide a starting point for emerging forms to be easily differentiated, and the students can quickly and easily produce many alternatives. Accordingly, the students can return to the initial shape or a particular rule in the Grasshopper script and change the value of the related slider to re-define the rule easily, and according to the new rule, can more rapidly produce any other series. As students develop their designs, they have come to the realization that they are especially returning to the breakpoint rules and these rules are actually facilitating the process.

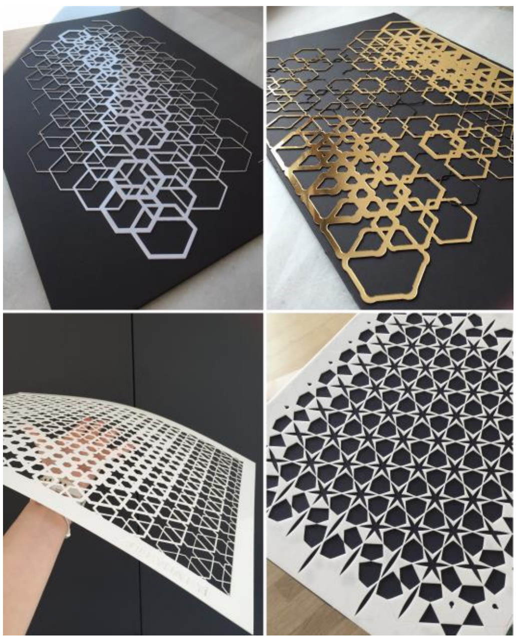

Fig. 5. The models, which were made by using plexiglas material.

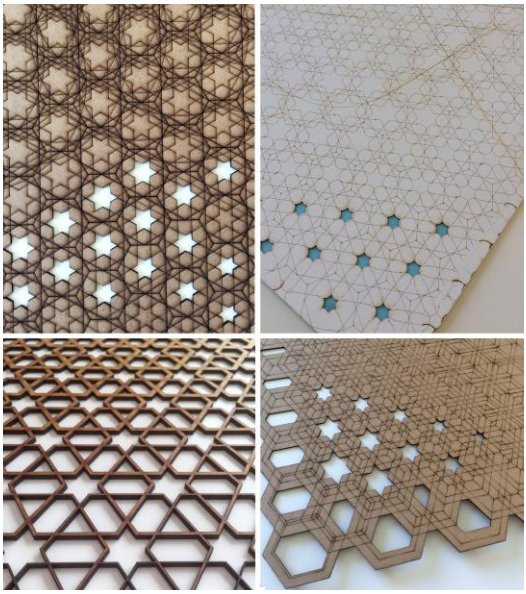

Fig. 6. The models, which were made by using cardboard material and left openings.

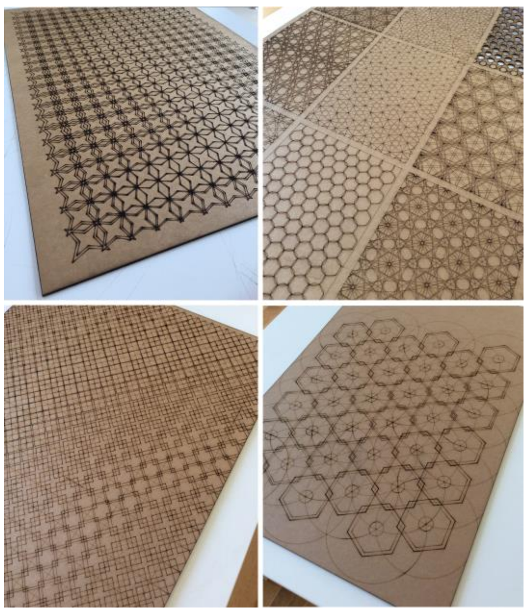

Fig. 7. The models with different geometries, which were made by using cardboard material and produced by doing laser scoring

These series produced belong to the digital sketches, which the students may choose among many alternatives; these sketches also prompt students to explore new ideas. Thus, there is a similarity with the paper-based sketches which are done during the initial process of the project within the framework of classical architectural education. It is also true that in the classical paper-based sketches, the student can arrive at various forms and ideas that cannot be predicted in advance. However, in the parametric design, shape grammar rules are quickly redefined and thus, students can assess the produced alternatives very quickly.

An early experience that students have, in their early years of architecture education, is to create the first digital fabrication of the Islamic patterns that they have made. From the digital fabrication experience, they learn to consider the virtual and the actual models together, and so gain some experience regarding such issues as time management and the selection of materials [25].

At the digital fabrication stage, the students were free to use any material of their choice. Some of them preferred to use plexiglass materials in different thicknesses and colors (Fig. 5), while others decided to leave voids in their created Islamic patterns for openness in the structure. Thus, the students could effectively reveal the contrast of fullness - emptiness (or figure-ground relationship) in their created patterns (Fig. 5 and Fig. 6). Some students preferred to display their products using the laser scoring made on the materials that they used. Thus, those students who opted for digital fabrication, strengthened the representations of their created patterns by expressing different geometries (such as hexagon or circle) with different thickness of lines (Fig. 7).

The instructor cautioned the students in advance about the length of time necessary for laser cutting since they had no prior experience of this technique. This helped them to start the preparation of the digital fabrication stage of their design at a sufficiently long time before the submission deadline, and so they gained experience regarding the time management of the aspect of digital fabrication.

4 Conclusion

In this study, a description is given of an elective course, which has been inaugurated in an architecture degree program and aimed to teach students coding with parametric design. This elective course is taught separately from the architectural design studio, and given the limited amount of time available, it is a great challenge for both the students and their instructor to teach coding efficiently in it. The author teaches this elective course and aims to obtain the most effective results on the basis of learning, together with actual applications. The topic of the application is Islamic pattern, and it was conducted under the theoretical framework of shape grammar.

The design commenced with studies in the virtual environment and proceeded on to the digital fabrication stage. Thus, the students, creating the design with the topic of Islamic pattern, simultaneously learned that it is necessary to act in a coordinated manner, employing the basics of visual programming language, to make a design using the principles of shape grammar and digital fabrication. It is very important that students in the early stages of the architectural education learn that, in the computer-aided design, versatile thinking and the ability to use different tools together are vital. Having become aware of this in the early stages of their course, the students can easily transfer their skills to other projects, which they will design throughout the period of their education.

Computer-aided design has been included in the programs of many architectural education schools. However, different methods should be researched to find the best integration to both education in the studio and in the other courses. Different experimental studies must be carried out to demonstrate which methods are the most effective.

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Spherical Perspective

Notational Drawing System for non-Euclidean Geometry

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Abstract. As a traditional design media, drawing usually has limitations in dealing with non-Euclidean geometrical problem, and therefore is highly challenged by the digital tools in contemporary architecture. This paper offers an explanation of the working mechanism of spherical perspective, an alternative projection instrument, to explore the potential of drawing in digital design scenario. Firstly, the paper reviews how architects notated non-orthogonal geometry by introducing perspective projection into the drawing system of Stereotomy in history. Then based on the conclusion from historical research, the paper develops a design tool, which would be able to translate geometry from orthogonal projection system to spherical one to generate non-Euclidean form. In the end, the paper brings further discussions about the formal and spatial effects brought by this new tool, and its potential and difficulty to be developed into professional design and representation media for architectural practice.

Keywords: Form Study, Spherical Perspective, Projective Geometry, Non-Euclidean Geometry, Notational Drawing

1 Introduction

Architect as a profession, in both historical and contemporary context, is relying on certain medias to conceive and represent space. In the historical context, the medias were usually architectural drawings and their associated projection systems. Depending on their different capabilities, these drawings could be defined as either notational or representational tools [1]. The former were usually employed as abstract machines to conceive and notate building form in virtual space, i.e. plan, section, axonometric; the latter were basically used as visual medias to simulate spatial experience, i.e. perspective. In contemporary, drawings have been highly challenged by the development of 3D modeling and rendering technique in architectural digital turn. And they are usually treated as optional instruments for architectural design, representation and construction. Confronting this situation, the paper aims to explore the potential of drawing in digital environment and to utilize its working mechanism to generate new formal effects.

One fundamental reason of the contemporary situation of drawing would be its limitation as a design media in producing and notating non-Euclidean geometry. And in this paper, we would argue that this limitation is caused by the usually adopted parallel projection system in drawing.

When architecture became an allographic art in Alberti's time, drawing set was invented for the first time to separate design and construction. Architects was able to design in virtual space by using notational drawings firstly, and then the drawing set would be delivered to building site to instruct the real construction without the presence of the architects themselves [2]. The separation between design and construction required high fidelity in the translation of geometric information from 2D drawing to 3D building. And it is the employment of parallel projection that ensured the correlation between drawing and object in a highly precise way. In this situation, because what could be constructed was highly depending on whether it could be notated by a set of drawings, the mechanism of parallel projection started to have strong limitations on building form.

In his book *Projective Cast*, Robin Evans elaborated the limitation of notational drawing on the classical building form through the lens of the working efficiency of design [3]. In the tradition of architectural profession, the design process was usually interpreted as being operated in an imaginary cube of "architecture working space" (Fig. 1). In this space, plan, section and elevation was imagined as being distributed onto each face of the cube and correlated by invisible parallel projection lines. Based on the relation between drawing set and object, Robin Evans developed a particular theory explaining the orthogonal feature of classical building form. As he stated in his text,

'It is easiest to deal with three types of drawing if they are perpendicular to each other, and it is easiest to align the principal surfaces of a project with the surfaces on which it is drawn; in consequence, a building will be a box in a box of pictures. So planar, rectangular form is economical too, within the confines of the technique.'[3]

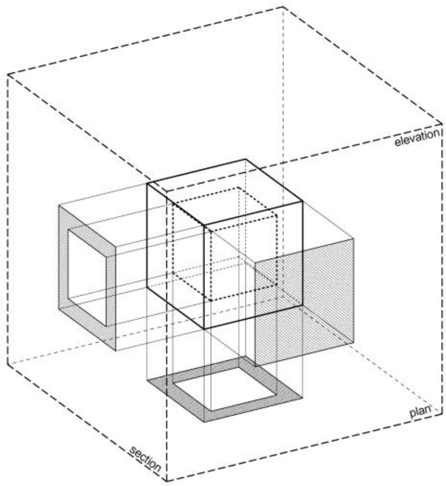

Fig. 1. Imaginary cube of "architectural working space". Drawing by the author

If we expand our scope to contemporary architectural practice, we could also find demonstrations for Evans' argument. The architects, who still use drawings as design generator, usually prefer to use certain types of drawing as the dominant media to conceive form. And as the side effect of the choices, the drawing types would affect the form of their projects. In the case that section is the dominant design media, the vertical distribution of space would usually be more complicated than the horizontal; in contrast, project designed mainly through plan drawing usually shows more spatial complexity in the horizontal arrangement than in the vertical. For example, in 21st Century Museum of Contemporary Art designed by SANAA, the distinct character in the horizontal configuration of the project would indicate that the form was conceived mainly through a series of plan drawings.

Generally speaking, contemporary architectural design could be considered as operating in two distinct categories with different approaches of conceiving form. Based on drawing system, one is a problem of translation and transformation from 2D drawing to 3D object. And relying on the digital tool, the other could be described as a solely 3D form problem. Projects in the former category are the consequence of a series of drawings. Projects in the latter category are independent from any kind of 2D media. In the first category, drawings are still the primary generator of design, and therefore have to contain all the geometric information of 3D building. And because the mechanism of informational translation in architectural drawing system, either orthogonal drawing like plan or oblique drawing like axonometric, is based on parallel projection, the building form would be limited as Evans argued. As a result, when architects try to conceive non-Euclidean geometry, drawing would usually cost much more labors than other medias. So it would usually be abandoned in design phase.

However, despite this negative impact, drawing system still has some valuable features, which could be transformed and then utilized in contemporary architectural design. The geometrical projection from 2D drawing to 3D object involves a process of adding geometric information in the third dimension. So when architect conceives form through a 2D drawing, it usually opens up countless unpredictable possibilities for the 3D result. At the same time, because the way of working on a 2D media to generate 3D object stretches the design process longer just like what generative coding does, and architect does not have to deal with the 3D object directly, the requirement of imagination would be diminished.

Confronting the drawing's contemporary situation, the paper will try to transform the generative power of drawing into a form-finding instrument by combining the drawing's mechanism with new digital modeling technologies. And in order to accomplish the aim, the research will be subdivided into three parts. In the first part, by interpreting the drawing mechanism of Stereotomy as an analogical precedent, we will make a comparison analysis between the working mechanism of perspective and parallel projection, and then explicate the key features required for developing a new projection tool. In the second part of the research, we will try to construct a generative design instrument by adopting a particular drawing/projection system—spherical perspective, and then try to use this new tool to produce a series of non-Euclidean forms. Eventually, in the third part, we will conduct an experiment using the developed instrument to represent architecture interior space, and then discuss the tool's potential and limitation to become a professional design media for architectural practice.

2 Analogical Research

2.1 Notational System in Stereotomy

To some extent, architecture history could be interpreted as a history of mutual motivation between the development of design tool and the evolution of formal features. In the history, the drawing technique of Stereotomy was a highly advanced tool for craft man at that time to deal with the complicated geometrical problems, even non-Euclidean problems, of stone cutting. So by investigating the internal mechanism of Stereotomy, we might be able to locate some key requirements for setting up the new drawing system to generate non-Euclidean form.

During the period from Renaissance to Baroque, French architects invented a technique of correlating multiple drawing types and projection methods in a single 2D media in order to define the complicated geometry of stone vault of some projects in both design and construction process. This complex notational system for the cutting and assembly process of stone vault was named later as Stereotomy. At that time, Stereotomy was used to solve non-Euclidean geometric problems, which usually involved angular measurement and surface intersection. As José Calvo-López illustrated in his article "From Mediaeval Stonecutting to Projective Geometry",

'Such powerful graphical instruments were indispensable in Renaissance and Baroque ashlar construction, since the geometrical challenges posed by the

architecture of the period were quite complex. Archs opened in oblique or sloping walls or at the junction of two walls generate elliptical openings; lunette vaults and arches in round walls bring about cylinder intersections; windows opened in domes involve cylinder and sphere intersections…' [4]

2.2 Reinterpreting Stereotomy

In Stereotomy, using different types of projection lines to correlate multiple drawings in a single 2D media was a great improvement of geometrical control for architects. What made Stereotomy being capable of notating non-Euclidean geometry was that its drawing system contained both perspective projection and parallel projection at the same time. In the history of Stereotomy, the most famous example would be the tromp at Anet by Philibert Delorme. In this case, both plan and section drawing were unfolded into 2D, and correlated by the "invisible lines" of the projection system to describe the complicated geometry of each component of the vault (Fig. 2). If we fold these drawings back in three-dimensional digital space, we would find out clearly that the capability of Stereotomy in notating the complicated form derived from the perspective projection in its system [5] (Fig. 3, 4). The Fig. 3 on the left shows the situation, in which only parallel projection lines correlate the plan and section of the vault. And coinciding with Robin Evans' argument, the projective result in Fig. 3 tends to be more orthogonal. In contrast, the system presented by Fig. 4 on the right follows perspective projection lines to extrude the section drawing of the vault into 3D space. And as a result, the result in Fig. 4 shows more freedom in terms of the formal condition.

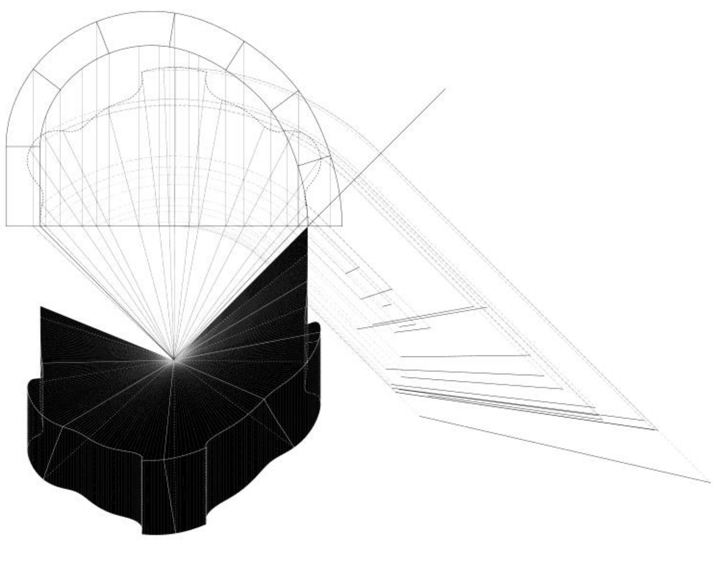

Fig. 2. Philibert Delorme, the tromp at Anet, geometrical construction. Redrawn by the author

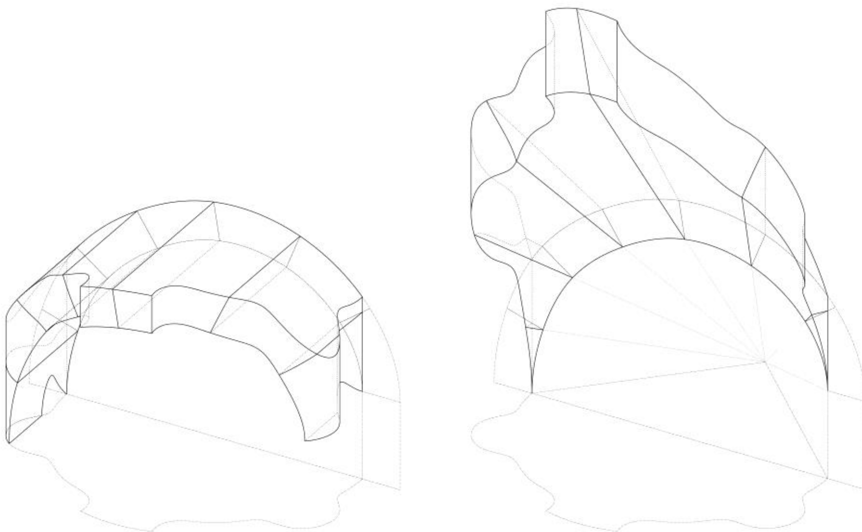

Fig. 3 and Fig. 4. Philibert Delorme, the tromp at Anet, three-dimensional presentation of the geometrical construction process. Drawing by the author.

Although parallel projection can provide precise information for geometrical construction in both virtual and physical process without any distortion, [6] it also confines the formal result into a more orthogonal condition. In another word, the projective geometry tends to be exactly the parallel extrusion of the 2D drawing. Perspective projection, on the contrary, offers architect more freedom in geometrical manipulation because of the changeable relative positions of viewpoint, object and projection plane. Meanwhile, even the geometrical distortion in perspective projection process could be utilized to produce non-orthogonal features in design result. In contemporary architecture, we can also find the examples of using perspective projection in geometrical construction. The works of Preston Scott Cohen could be interpreted as the transformation of Stereotomy. Cohen developed a generative design process in which the distortion of perspective image was utilized to conceive non-orthogonal 3D geometries from 2D media [7]. Therefore, perspective projection has more potential to become a design tool to notate non-Euclidean geometry.

3 Methodology

3.1 Spherical Perspective

According to the research on Stereotomy, the distortion caused by the projection lines in perspective could be utilized to provide more freedom and generative power for architect to produce non-Euclidean form.

So at the beginning of the exploration, a particular type of perspective, spherical perspective, was chosen and then analyzed with the focus on its working mechanism. Spherical perspective as a technique has been highly developed in global mapping or panorama drawing process. And it contains some important features, which could ensure both precision and freedom in the process of notating geometry.

First, spherical perspective could be considered as a particular type of perspective projection. There is a single viewpoint located at the center of the spherical system. And all the projection lines are emitted from the center toward the sphere. In contrast with parallel projection, perspective contains geometrical distortion, which is determined by the relative positions of viewpoint, object and projection plane. However, as object and sphere (projection plane) should be always concentric in a spherical perspective, and as the viewpoint should be always at the shared geometrical center, the distortion in spherical perspective would be actually fixed within the system, and could be utilized as a constant variable to manipulate form.

Second, spherical perspective involves the process of geometrical translation between drawing and object as other projection interfaces do. Therefore, it provides a possibility of using drawing to either notate an existing 3D geometry or generate a new one. And in either way, spherical perspective is more capable of dealing with non-Euclidean form than parallel projection, because of their different working mechanism. Parallel projection transmits the geometric information in certain amount of discrete directions, such as orthogonal projection system only containing three axes. In contrast, projection lines emitted from the central viewpoint of spherical perspective would be capable of covering the object's geometric information from all the directions in a continuous way, so it would have more freedom and capability in notating the forms that contain continuous variation features such as double curvature condition (Fig. 5).

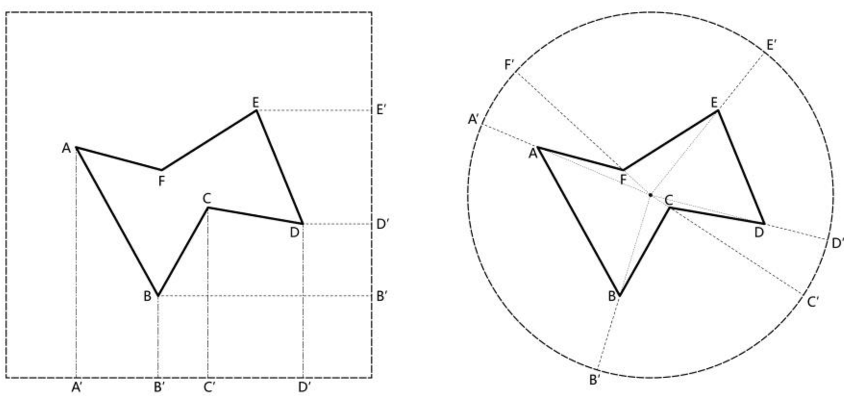

Fig. 5. Diagram: comparison of working mechanism between orthogonal and spherical projection system. Drawing by the author.

Besides the difference between the two systems, there's another observation from Fig.5. In order to define the position of a point in 3D space based on projection system, usually at least two drawings containing the point's information have to be provided. For example, in the left drawing of Fig.5, parallel projection system would not be able to define the position of point C in space unless an extra drawing containing the point's information is provided. However, in spherical perspective, there is only one drawing, which is the sphere. The way of using intersection result between projection lines from different drawings to generate 3D form would not be suitable with spherical perspective. So a new working parameter, besides the 2D configuration of drawing, has to be provided.

3.2 "Distance" as Geometrical Parameter

In the Stereotomy drawing by Philibert Delorme, the vertical distance from each vertex of vault stone to the ground surface was utilized to transmit geometric information from section to side view elevation. And as Tomás García- Salgado also discussed distance as a measurable relationship in his article "distance to the perspective plane",

'When quattrocento artists sought a sensitive representation of the object seen—not its measurement as a visual or practical problem—they introduced the concept of distance as a measurable relationship between object, pictorial plane, and observer. This is the first geometric foundation upon which the theory of perspective is built.'[8]

So in both parallel and perspective projection, the "distance" between object and projection plane could be considered as a measurable parametric variable, which is able to store useful geometric information. As we know, in the imaginary cube of "architectural working space" (orthogonal projection system), the geometric information of 3D object requires at least two drawings, which are perpendicular to each other, to be determined. For example, a plan drawing on the ground surface describes the 2D configuration of the object in horizontal, and then an elevation or a section drawing provides the object's geometric information in the vertical direction. However, if there is a working mechanism, in which the distance between object and drawing could be utilized as a parameter to provide the geometric information in the vertical direction as elevation or section drawing does, only one drawing would be adequate for notating the fully 3D geometric information of an object (Fig. 6).

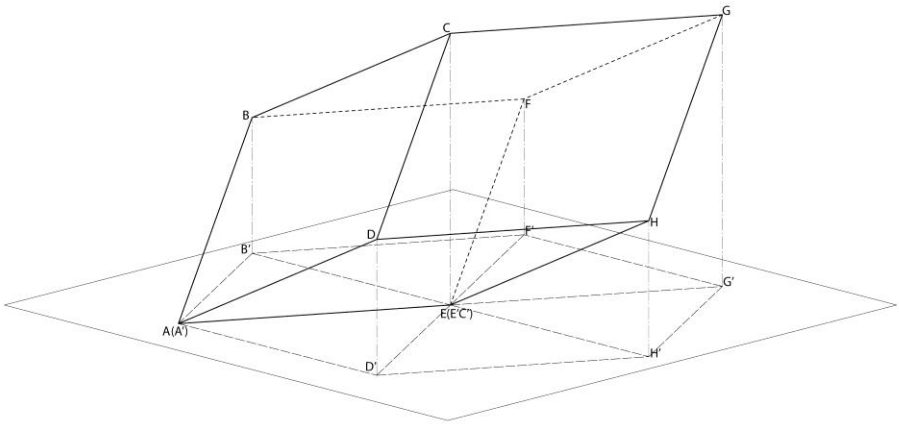

Fig. 6. Distance as a variable cooperating with a single drawing to provide the geometric information for a three-dimensional form. Drawing by the author.

In the parallel projection system of Fig. 6, we established a particular projection tool by using parametric modeling technique. When an 3D object is projected onto a flat surface and become a 2D drawing through the new projection tool, the distance between the drawing and the object would be calculated and stored. So the drawing contains both visible configuration and invisible "distance" parameters. For example, in Fig. 6, the plan drawing on the ground, which is generated by the parametric projection tool, contains full geometric information of the 3D object in space. In the system, each vertex X (X presenting all the capital letters in Fig.6) on the object has a corresponding point X' in the drawing. Point X' in the plan drawing is capable of determining the position of point X on the ground, and then the distance XX' is utilized as a parameter to store the "height" of point X in space. When the plan drawing is projected back to space, the distance XX' will control how long point X' should be "moved away" from the ground along the projection line to become point X. And following this operation, after all the points are projected out from the plan drawing and precisely located in space, the 3D object will be generated automatically.

3.3 Developing a Generative Tool based on Spherical Perspective

Based on the parametric projection tool described above, the way of correlating one drawing and the parameter "distance" to store geometric information provides a possibility of notating 3D object in spherical perspective system. And with this drawing-distance mechanism, we developed a generative design tool, which is able to translate any geometrical object from orthogonal projection system to spherical perspective system, to produce non-Euclidean effects. The tool contains two projection systems, orthogonal projection and spherical perspective (Fig.7). As Fig. 7 shows, the orthogonal projection system is presented as a plane on the left, and the spherical perspective system is presented as a sphere on the right. At the beginning of the generative process, a primitive geometry is placed on top of the plane in the orthogonal projection system. Meanwhile, the tool will automatically create the same geometry and place it at the center of the spherical perspective system. (The second geometry is invisible in Fig.7, for the clarity.) Then the tool will project these two geometries onto the plane and sphere surfaces based on the different projection mechanisms of the two systems respectively. So in Fig.7, the plan drawing in the left system and the spherical drawing in the right are produced from the same primitive geometry. The plan drawing presents the object's configuration in horizontal, and the spherical drawing presents the object's configuration in a panorama condition.

After the two drawings being produced, the "distance" between each point in the plan drawing and its corresponding point on the primitive geometry in the orthogonal system will be calculated and stored as a parameter. Then by reversing the projection, the spherical drawing on the right side will be projected back to 3D space to translate the geometric information from the spherical drawing into a new 3D geometry. And in the reversing projection process, the calculated distance parameters in the left system will determine how long the points of the spherical drawing will be projected back into 3D space. In another word, the distance parameter works as an interface to keep the same drawing-object distance in both projection systems. For example, in Fig. 8, the distance between the object's vertex Ds and the drawing's corresponding point Ds' is the same with the distance DD' in the orthogonal system presented by Fig. 6.

Finally, a new 3D object will be generated in the spherical perspective system. And because of the continuity of spherical projection, the new object shows certain degree of non-Euclidean formal effect.

3.4 Tool Development 01: Introducing Double Curvature

Any 3D object could be interpreted as existing in two different realities, a "rigid" one and a "soft" one. In the former, the object follows a rigorous geometrical hierarchy of point, line and surface. And it's usually the vertexes and edges that define the object's geometric information. In the latter, the object would be directly composed by countless pixels. Comparing to the first reality, the second one has more freedom to transform an object into double curvature condition. Therefore, the spherical perspective based generative tool is developed further to be able to work with a large amount of points (pixels) on the object. With the computational tool, the two drawings will be divided into thousands of points, and the distance parameters will be calculated one by one. Then each point on the spherical drawing will follow the reversing projection process under the control of the distance parameters to generate double curvature geometry. The projection process and the projective result are presented in Fig. 9 and Fig. 10.

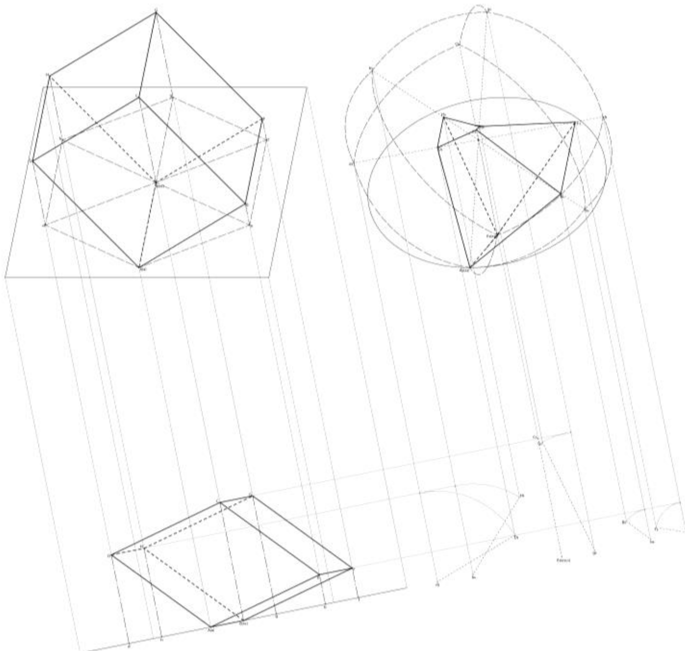

Fig. 7. Orthogonal projection system and spherical projection system producing different formal results based on the same drawing-object distance. Drawing by the author.

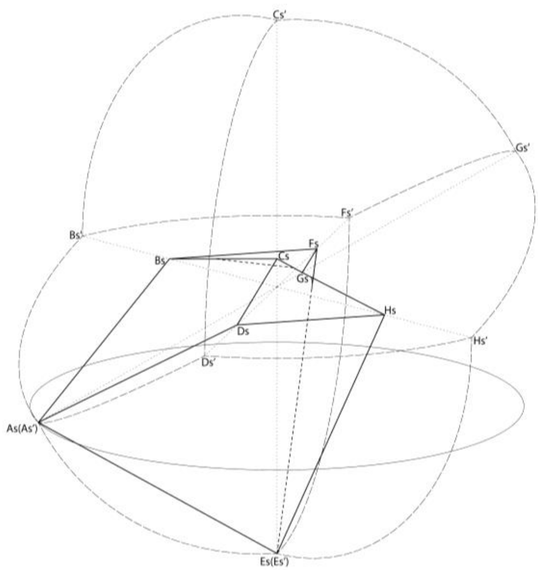

Fig. 8. Spherical projection system as “architectural working space” to generate fully three-dimensional geometry. Drawing by the author.

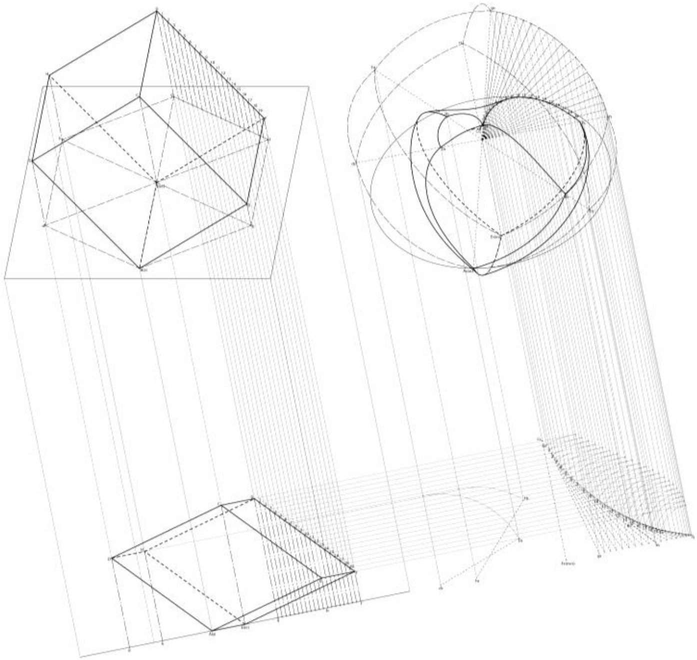

Fig. 9. Thee-dimensional objects being generated in both orthogonal projection and spherical projection, with the “meshwork interpretation” of geometry. Drawing by the author.

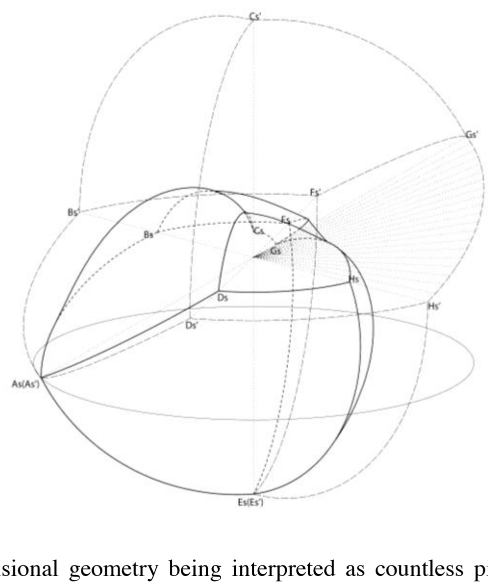

Fig. 10. Three-dimensional geometry being interpreted as countless pixels in the process of spherical projection. Drawing by the author.

3.5 Tool Development 02: Altering Projection Type

As orthogonal projection system notates 3D object through plan, oblique projection system produces 3D object through axonometric (Fig. 11). The primary difference between the two systems is whether the projection lines are perpendicular to the drawing. The further development of the generative tool tests its working process with an "oblique version" of spherical drawing. As Fig. 11 and Fig. 12 show, corresponding to the oblique projection lines in the axonometric system in Fig.11, each projection line of the spherical perspective in Fig.12 is rotated in 45 degree with the same geometrical logic. In consequence, by reversing the projection process, a complete new object is generated from the oblique drawing of the tool. This experiment shows the great variability of the generative system to work with different types of drawing.

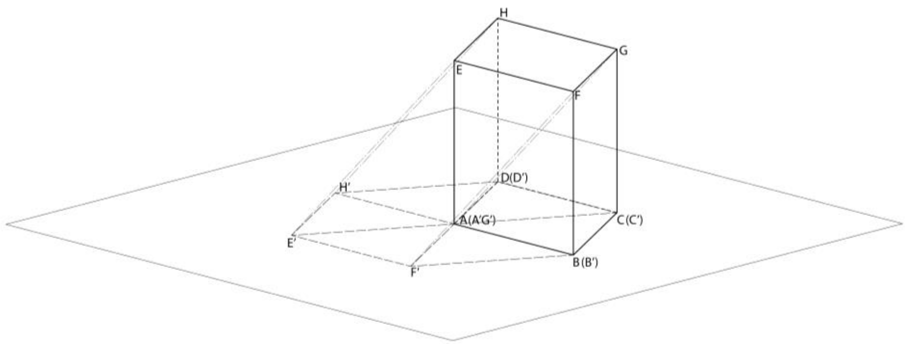

Fig. 11. Oblique projection being used in the imaginary cube to generate three-dimensional formal result. Drawing by the author

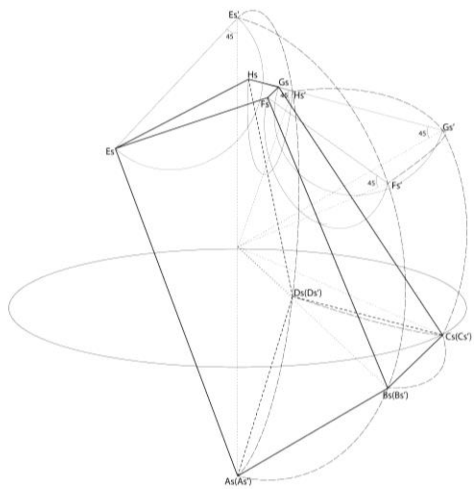

Fig. 12. Projection lines of spherical perspective being rotated into oblique for the geometrical construction. Drawing by the author.

4 Result and Discussion

4.1 Exploring a new Design Media

The generative design tool, which is based on spherical perspective, generated a series of non-Euclidean objects as the research results (Fig. 13). On one hand, these objects contain the features like double curvature and non-orthogonal posture, which could usually be found in the result of coding process or freeform modeling. On the other hand, these objects are highly geometrical constructed, so the location of each point on the objects could be precisely traced back to 2D drawing. The research provides us an opportunity to rethink the problem of the post-rationalization of the generated form in building construction. Instead of treating form generation and rationalization with different geometrical logic, we could now use one single drawing mechanism to define form in both design and fabrication process.

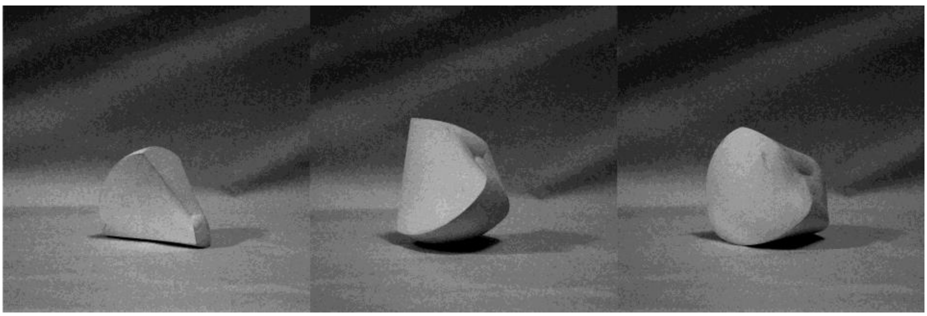

Fig. 13. Variable results from the developed generative design tool, photos of physical model

However, to allow the further development of this generative tool and to make it available to architecture practice, there are still some difficulties that need to be overcome. One difficulty is that the projection mechanism of spherical perspective is very unusual in the traditional design process. Sometimes the spherical drawing of space would be too strange or complicated to be perceived in a normal way. Confronting this situation, contemporary virtual reality technology might bring new solutions to the problem. Because of the working mechanism of human eyeballs, the spherical perspective could be actually more closed to our real visual experience than planar perspective.

Other difficulties would be how to unfold a spherical drawing into 2D media and how to extract useful geometric information from the unfolded result. Although right now the problem cannot be resolved easily, we still conducted a series of experiments to test the potential of this tool in producing 2D geometrical drawings. Derived from map making techniques for the globe, we created an approximation of spherical projection by developing a mechanism to translate the geometric information from a sphere to another geometrical type, which could be unfolded into flat sheet, for example a cylinder or a polyhedral (Fig. 14, 15). The former, also named as Mercator projection, was a mapping technique developed by Gerardus Mercator in 1569 and commonly used for navigation [9]. And the most famous example of the latter would be Buckminster Fuller's "Dymaxion map", in which the globe is projected into an icosahedron [10]. Regarding to the "Dymaxion map", John Parr Snyder also indicated in his article "An Equal-Area Map Projection For Polyhedral Globes",

'Folded polyhedral globes are easier to assemble without special techniques than spherical globes and serve as instructional tools, but they are bulky and small-scale. Like globes. Unfolded and flattened polyhedral globes form world maps on projections, which can have less distortion than other interrupted projections…' [11]

Then if we have a working mechanism to define the geometric information in these unfolded cylinder or polyhedral drawings, we would be able to reverse the process and to conceive 3D architecture space. In another word, architects would be able to design on a flat drawing, and then to fold it into a sphere to generate 3D building (Fig. 16).

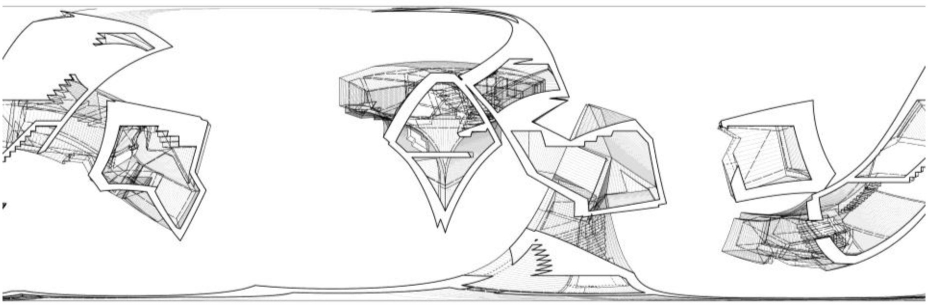

Fig. 14. Cylinder, as an approximation of the spherical drawing, being unfolded into two-dimensional surface. Drawing by the author.

5 Conclusion

In these studies above, with the transformation of the drawing/projection mechanism from parallel to spherical, original rectangular geometries were also transformed into objects with non-orthogonal and double curvature features. The studies show that spherical perspective, as an alternative system for architectural projection, could have great potentials to conceive and represent non-Euclidean geometry. Meanwhile, the research also reveals that the internal working mechanism of spherical perspective could provide us a fresh view to explore new techniques in generative design. And then by using the new tool for geometrical construction, we would be able to reactivate the role of drawing in contemporary digital scenario. And this new spherical drawing, being more closely related to our visual experience, could relink human creativity to the reality of our spatial perception.

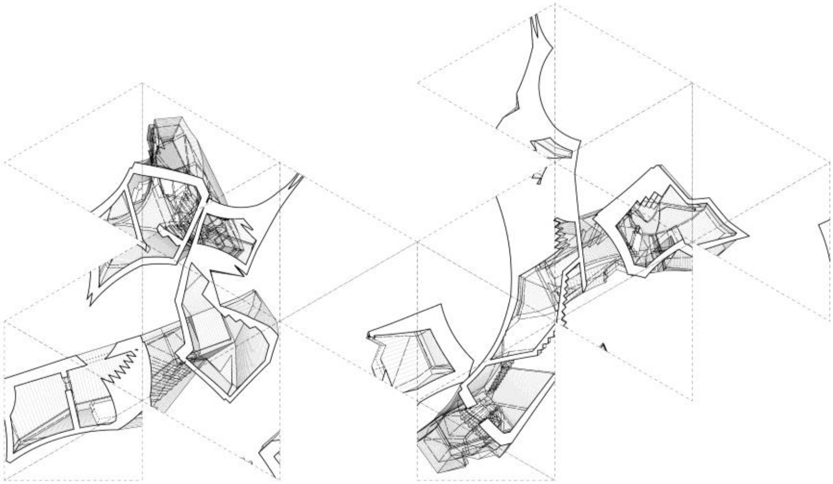

Fig. 15. Polyhedral, as an approximation of the spherical drawing, being unfolded into two-dimensional surface. Drawing by the author.

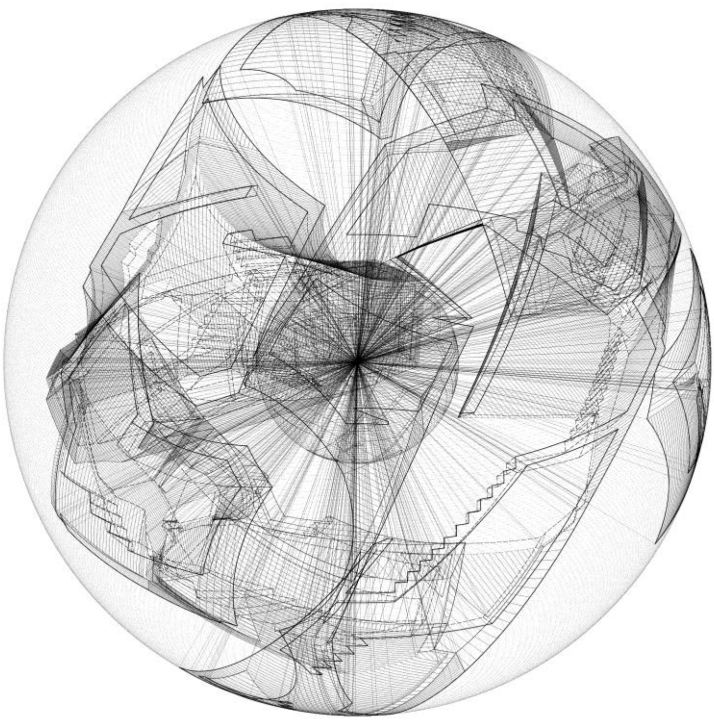

Fig. 16. Spherical projection as a way of representing architectural space. Drawing by the author.

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Kerfing with Generalized 2D Meander-Patterns

Conversion of Planar Rigid Panels into Locally-Flexible Panels with Stiffness Control

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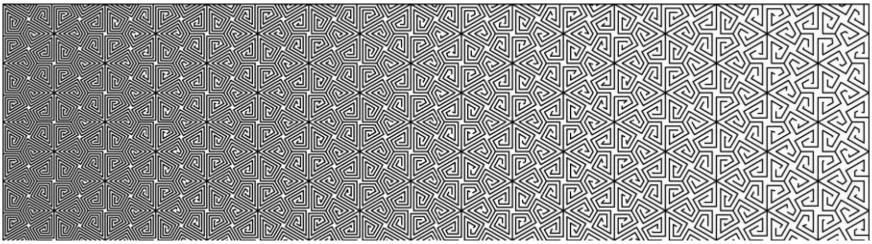
Abstract. In this paper, we present a kerfing (relief-cutting) method to turn rigid planar surfaces into flexible ones. Our kerfing method is based on a generalization of the 2D meander-pattern recently invented by Dujam Ivanišević. We have developed algorithms to obtain a large subset of all possible 2D meander-patterns with a simple remeshing process. Our algorithm can be applied to any polygonal mesh to produce 2D meander-patterns. The algorithm, when applied to regular (4,4) tiling pattern, in which every face is 4-sided and every vertex is 4-valence, provides the original 2D meander-pattern of Ivanišević. Moreover, since these meander-patterns are obtained by a remeshing algorithm, by changing parameters, we can control local properties of the pattern with intensity of images to obtain desired stiffness in any given region (See Fig.1). This approach provides a simple interface to construct desired patterns.

Keywords: Kerfing, Flexible Panels, Relief Cuts

1 Introduction

Relief cutting is a technique for turning rigid planar panels into flexible ones. In architectural practice, the process of relief cutting is called kerfing. There exist many relief cutting patterns that are recently invented by designers. Among them 2D meander patterns invented by Dujam Ivanišević [18] seems to be one of the most promising patterns to obtain very flexible panels that can provide double-curvature.

In this paper, we present an approach for kerfing rigid materials using 2D meander-patterns to convert planar rigid panels into locally-flexible ones with stiffness control. Fig. 1 and Fig. 2 show two examples of rigid panels with varying local flexibility. In our approach, the local properties of generalized meander patterns are manipulated by any 2D function that is given as an image. We chose to use images to simplify the interface for describing functions. One can simply draw an image to manipulate local properties of 2D meander-pattern to control local stiffness. Any B&W image can be used as shown in Fig. 3.



1. *A pattern whose density decreases based on the distance from line.*

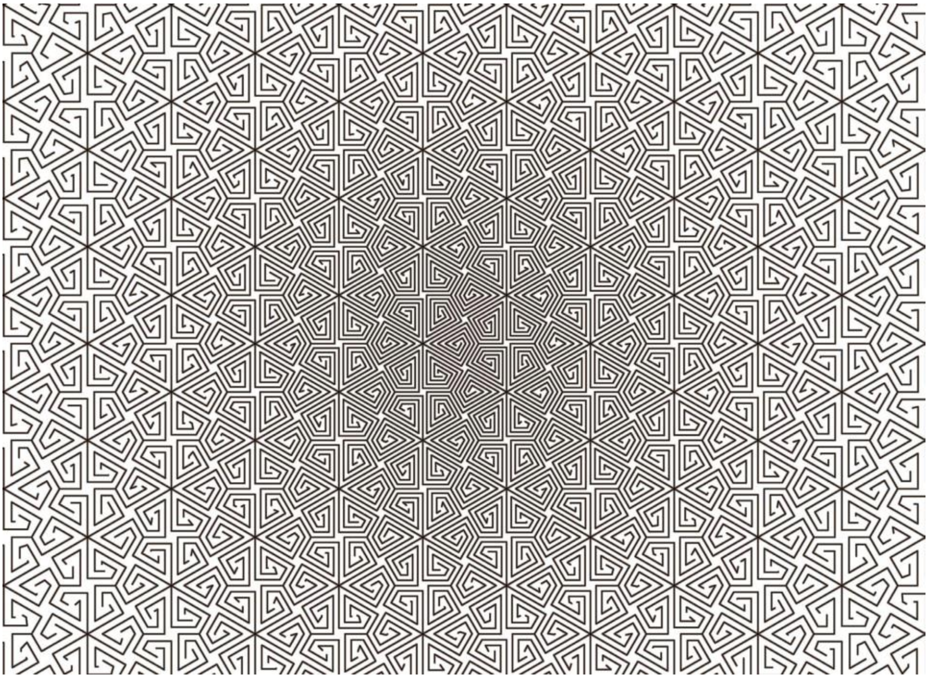
2. *When the pattern in Fig.1a is used for kerfing a planar wood panel, it turns a rigid wood panel into a gradually flexible rectangular panel which is rigid in one side and flexible in another.*

Fig. 1. An example of locally-flexible panels with varying stiffness obtained by kerfing using generalized 2D meander patterns

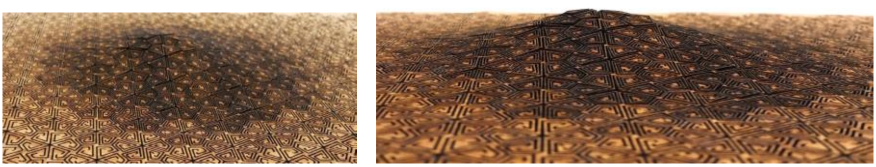
1.1 Motivation

Designing curved geometries is becoming easier as a result of the advancements in computer aided geometric design. Although we can design wide variety of shapes virtually, it is still hard to physically construct those shapes. One of the main challenges comes from the limitation of construction materials that are often produced in standard shape, size and rigidity in an industrialized mass production process. In the construction process, these mass-produced materials should be converted into flexible shapes with desired properties that meet designers' objectives. There is, therefore, a need for the development of methods to convert rigid materials into materials with desired flexibility properties.

The deformation of planar rigid panels results in strong forces in some regions. The panels cannot tolerate these forces in those regions and start to break starting from those regions. If we remove materials in those highly stressed regions of the original planar surface, it is expected to change the behavior of the material. The terms kerfing or relief-cutting is introduced to explain this phenomena of obtaining flexibility by cutting or, in other words, by removing materials. Many designers, in fact, have experimented with a wide variety of cut patterns and demonstrated that some specific cut patterns, such as spirals, generate significant amount of flexibility.

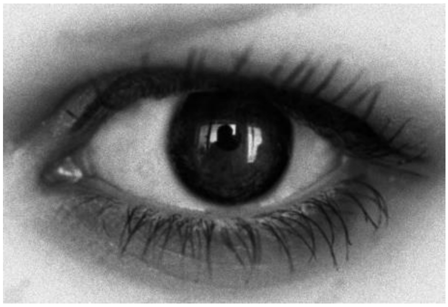


(a) A pattern whose density decreases based on the distance from a center point.

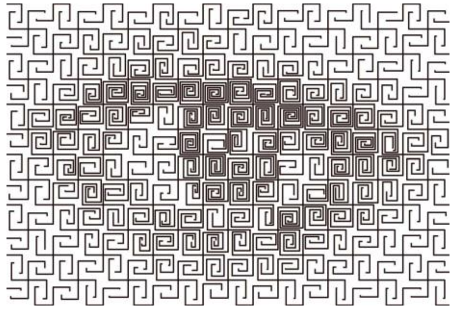


(b) When the pattern in Fig. 2a is used for kerfing a planar wood panel (also called relief cut), it makes the center of the wood panel flexible by allowing to turn it into a conical dome structure.

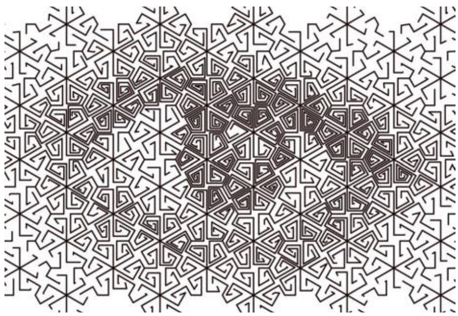
Fig. 2. Another example of locally-flexible panels with varying stiffness obtained by kerfing using generalized 2D meander patterns. In this case, we obtain double-curvature around a center point by changing the density of the pattern based on the distance from a center point.



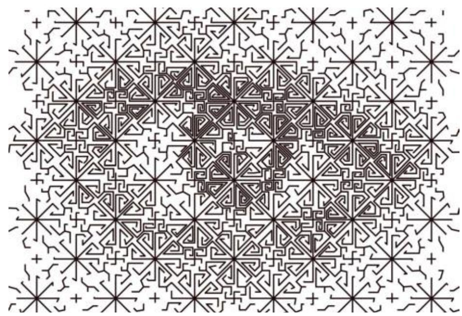
(a) Control Image.



(b) Resulting Pattern by applying our algorithm to a rectangular grid pattern.



(c) Resulting Pattern by applying our algorithm to a hexagonal grid pattern.



d) Resulting Pattern by applying our algorithm to a 4.8.4 semi-regular tiling pattern.

Fig. 3. An example that demonstrate the efficiency of our method to manipulate local flexibility using a control image. In this case, although the frequency of tiling patterns cannot be above Nyquist frequency [26] and it is hard avoid aliasing in resulting patterns [32], we are able to lessen the aliasing effects using a version of jittering technique introduced by Cook et al. [8]. Despite we use very low resolution patterns eye is still visible and no additional aliasing pattern is visible.

(a) An example of 1D symmetric periodic meander patterns from Etruscan amphora from 470 B.C. [30].

(b) 2D symmetric periodic meander Pattern designed by Dujam Ivanišević.

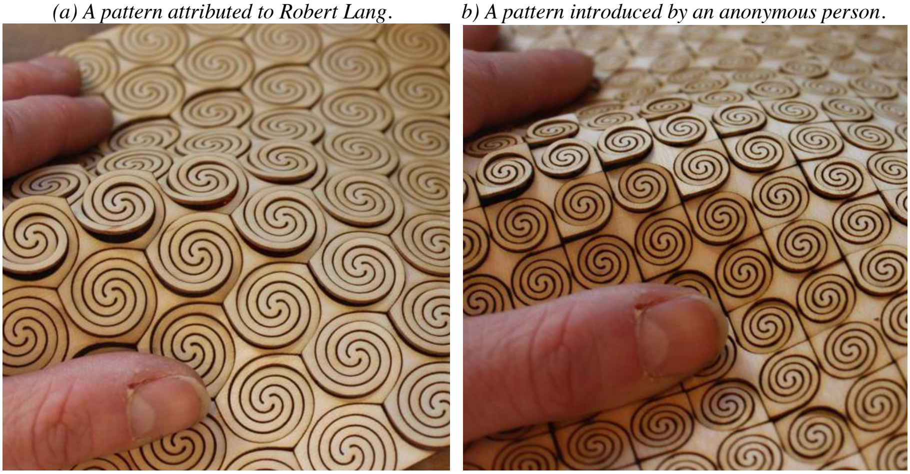
(c)We created these models using our generalized algorithm to demonstrate that our algorithm can produce the original 2D-meander-pattern and its flexibility.

Fig. 4. 1D and 2D meander patters. Super flexible plywood obtained by relief cutting by 2D meander pattern invented by Dujam Ivanišević in 2014 [18].

One of the problems with existing patterns the architects experiment with is that the cut patterns are regular structures. Since the flexibility of the surface is largely dictated by the cut lines, using predefined cut pattern do not necessarily produce a geometry that can morph to a desired shape and provide an anisotropic flexibility. To obtain such anisotropic behavior there is a need for the development of methods to obtain non-regular cut patters that can provide desired flexibility. In this work, therefore, we developed a method to obtain non-regular versions of one of the most popular cut patters: 2D meander-patterns (See Fig. 4).

(a) A pattern attributed to Robert Lang.

b) A pattern introduced by an anonymous person.



c) Extended of the original pattern to circular patters and hexagonal grid by M. S. Raynolds [29].

Fig. 5. Other Symmetric Meander Patterns motivated by Dujam Ivaniˇsevi´c’s work.

Meander-patterns are repeated labyrinth-like motifs that are commonly used in Hellenistic art to decorate borders or artworks [20]. Edwin Reissman recently classified a few of meander patterns in Hellenistic art [30] [1]. The Fig. 4 shows one of the most common meander-patterns that consists of S-shaped patterns that are interlocked together. Examples known from Hellenistic period are almost always one-dimensional repeated patterns as shown in this figure. In 2014, Dujam Ivanišević discovered a new 2D wallpaper meander pattern to be used as relief cuts to turn rigid materials into flexible panels [18].

[1] The name “meander” comes from the twisting and turning paths of the two “Menderes” Rivers in Asia Minor.

This particular pattern was so successful for kerfing that designers and architects use it to obtain flexible panels from wood and shared their experiences in blogs and youtube such as [34] after Ivanišević shared his discovery in 2015 in instructables website [19] (See Fig. 4c). In 2016, a few new 2D meander-patterns are presented in architectural blogs [19, 29] (See Fig. 5). However, the resulting kerfing from these patterns do not become as flexible as the original pattern as visually demonstrated by Ivanišević [19].

One problem with these 2D meandering patterns is that they are wallpaper patterns that can only be generated using basic symmetry operations such as rotation and translation [31, 3]. Using symmetry operations, we can only create exact copies of original pattern and it is hard to generalize these motifs in general tilings to study for finding more variety of patterns. Another problem with the wallpaper approach, it is hard to change local properties of the panels. In other words, we cannot make one regions more rigid and another region more flexible. All local regions always have exactly the same flexibility. There is, therefore, a need for a practical approach to provide most possible versions of these motifs with a local control.

1.2 Contributions

In this paper, we present an algorithmic approach to obtain a large subset of all possible 2D meander-patterns with a simple remeshing method. Our algorithm is conceptually based on subdivision methods in computer graphics that can allow to obtain any semi-regular mesh [6]. Similar to subdivision algorithms, our algorithm can be applied to any polygonal mesh such as regular or semi-regular polyhedra and allow to create consistent meander patterns on any 2-manifold surface. In planar surfaces starting from regular (4,4) grid pattern; it provides the original 2D meander-pattern invented by Dujam Ivanišević. Moreover, since we obtain the pattern with a remeshing algorithm, by changing parameters we can manipulate local motifs to control local stiffness of the surface. This method is also useful to create artworks drawn using the meandering motifs. As a conclusion our contributions can be listed as follow:

- We have developed a remeshing algorithm to generalize the 2D meandering pattern into general setting.
- By applying this algorithm to polygonal meshes, we can cover any 2-manifold surface with this meandering pattern.
- We have developed a method to manipulate local properties of the original meandering patter. Using this method, we can obtain different stiffness in every point. In addition, we can obtain artworks made from this meander-pattern.

2 Related Work

Auxatic materials that demonstrate elastic property with a negative Poisson's ratio is one of the recent interest in materials science research [35, 17]. It has recently been observed that Auxatic behavior can be obtained by relief cuts [17]. In fact, most of the existing architectural relief-cutting methods to obtain flexible panels comes from obtaining auxetic behavivor by using rotating polygons obtained by the cuts [16, 22]. Dukta is another type of architectural relief-cutting process that is introduced in 2007 by Serge and Pablo Lunin for turning rigid materials into flexible [23]. Formal analysis of folding and twisting by ducta process is recently provided [27]. In this work, we are working on a third type of relief-cuting process that are produced by meander-patterns [18].

Meander-patterns can be classified as spiral forms, which are one of the most common shapes found in nature, mathematics, and art [1, 11, 9]. Spiral shapes can be seen in many natural objects including snail shells, seashells and rams' horns, cochlea in our inner ear, galaxies [33]. Spiral forms also exist in almost all cultures as artistic and mystical symbols. Celtic crosses have whorls. Spirals can be found in Greek votive art and Tribal tattoos [21]. This widespread usage of the spiral form suggests that humans innately find them aesthetically pleasing and interesting.

Spirals are also popular in mathematics. They are among the most studied curves since ancient Greek times. Although spirals are usually represented by parametric equations, there are a wide variety of methods that can be used to construct and represent spirals. There are also many named spirals such as the Archimedean spiral, the Fermat spiral, the Logarithmic spiral, Fibonacci spiral, Euler and Cornu spirals [11]. Spirals even appear when we zoom in on the Mandelbrot and Julia sets [24]. Spiral forms are also used by Charles Perry [28, 14, 15] in his mathematically inspired sculptures.

A particularly interesting use of spirals that is related to meander-patterns is to cover surfaces with spiral patterns with interlocking N-branched spiral trees. Such spiral tree structures are used to construct Daniel Erdely's Spidrons [12, 13] and Ergun Akleman's Twirling Sculptures [1]. To develop an algorithm for creating generalized meander-patterns that consists N-branched spiral trees, there exist two possible approaches:

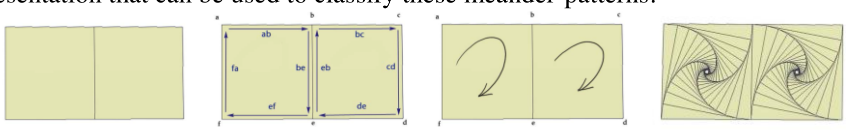
1. **Analog approach:** In this case, we can design differential equations from gradient fields that are produced from an implicit function. These differential equations can be used to create spiral vector fields [5], which can later to be used to construct N-branched spiral trees.
2. **Discrete approach:** In this case, we produce desired patterns by remeshing 2D polygonal meshes such as the ones that are used in creation of subdivision surfaces [6]. The remeshing algorithms of Spidrons [12, 13] or Twirling Sculptures [1] already produce spiral patterns that are similar to 2D meanderpatterns. We observe that those algorithms can be reformulate to obtain meander-patterns.

A particular set of implicit functions that can be used in the implementation of the analog approach is distance functions that are defined as distance to a set of points or lines. Such distance functions describe Voronoi structures as equi-distance from original points and lines. Resulting vector fields provide spirals emanating from original points and lines [5]. One advantage of this approach is that we can directly control the number of branches of the spiral trees. However, we observe that there exist two problems with this approach: (1) It is hard to control the shapes of the spirals and (2) It is hard to control distance between spiral arms. We, therefore, choose to use a discrete approach to produce N-branched spiral trees and initial algorithm for creating twirling sculptures provides a base for our algorithm (See Fig. 6). In the next section we present twirling algorithm and its shortcoming to obtain meander patterns.

3 Twirling Algorithm

The twirling sculpture algorithm starts with an initial 2-manifold polygonal mesh that is represented with the combinatorial structure of a graph and an associated ”rotation system” [10, 2]. Fig. 6a shows a portion of a 2-manifold mesh that consists of two quadrilaterals. In a 2-manifold mesh every edge can be represented by two half-edges pointing in opposite directions [25]. The boundary of every face in a 2-manifold mesh can always be described with a cyclically ordered sequence of half-edges, which can be considered as n vectors going around the face in consistent order (all clockwise or all counter-clockwise) (See Fig. 6b). This consistent order is the key to creating spiral branches using rotation order shown in Fig. 6c.

Our initial intuition was that a straightforward use of this twirling sculpture algorithm - with some minor adjustments - would be sufficient to obtain a generalized version 2D meander-patterns. However, this intuition turned out to be wrong. We obtained flexible sheets, however, our sheets did not seem as flexible as original meander-pattern. To identify differences between patterns, we first need a formal representation that can be used to classify these meander-patterns.



(a) Initial Mesh *(b) Half-Edges.* *(c) Rotation directions.* *(d) Interlocking Spirals.*

Fig. 6. The main algorithm for twirling sculptures creates interlocking spirals [1] (Images courtesy to Ergun Akleman).

4 Formalization of Meander Patterns

In 2D Meander-patterns invented by Dujam Ivanišević, each cut always consists of four spiral branches and each spiral branch of any 4-branched spiral tree is interlocked with another spiral branch of another 4-branched spiral tree. The pattern in Fig. 5b is different in the sense that each spiral tree consists of 6 branches and each spiral branch of any 6-branched spiral block is also interlocked with another spiral branch of another 6-branched spiral tree. The first meander-pattern shown in Fig. 5c is different from the other two in the sense that (1) each spiral tree is 3-branched and (2) each spiral branch of any 4-branched spiral tree is interlocked with two spiral branches of two other 3-branched spiral trees.

In conclusion, these meander-patterns can be uniquely classified by two numbers as [*N,K*]: where N denotes the number of spiral branches in a given spiral tree and K denotes the number of interlocking spirals. In this case, we use square bracket to differentiate from the regular mesh patterns. As a result, [4,2] refers the original meander pattern discovered by Dujam Ivanišević; [6,2] refers the meander pattern in Fig. 5b; and [3,3] refers the meander-pattern in Fig. 5c. On the other hand, the algorithm of twirling sculptures turns a n-valence vertex into an N-branched spiral tree and m-sided face gives m-number of interlocked spiral branches. Therefore, (1) a regular rectangular grid turns into a [4,4] meander-pattern; (2) a regular triangular grid (3,6), in which every face is regular and 3-sided, i.e. regula triangle and every vertex is 6-valence, turns into a [6,3] meander pattern; (3) a regular hexagonal grid, in which every face is regular and 6-sided, i.e, regular hexagon, and every vertex is 3-valence, turns into a [3,6] pattern. In other words, the straightforward application of twirling sculpture algorithm can obtain neither of [4,2] and [6,2]; nor [3,3].

5 Our 2D Meander-Pattern Algorithm

A careful examination of the differences between the patterns shows that [4,2], [6,2] and [3,3] are obtained by methodical "pruning" some of the branches that remove some of the trees. For instance, in [4,2] is obtained by removing every other 4-branched tree in a (4,4) grid sequence, [3,3] is obtained by removing every other 3-branched tree in a (6,3) sequence. [6,2] comes from a 6.3.6.3 semi-regular mesh [6] and obtained by removing 3-armed trees. Our initial FEA analysis also confirmed that the tree removal helps to make patterns more flexible.

Since spiral trees stems from vertices if the vertices of the initial mesh is 2-colorable, we can simply create every other tree. This corresponds to removing every other tree. In other words, if the mesh is vertex 2-colorable, we can always remove every other tree.

Although, a general mesh is not necessarily vertex 2-colorable, there exists remeshing algorithms that can turn any polygonal mesh into meshes whose vertices are 2-colorable. In this paper, we chose vertex insertion [4], which is the remeshing algorithm of popular Catmull-Clark subdivision scheme [7], to obtain vertex 2-colorable meshes.

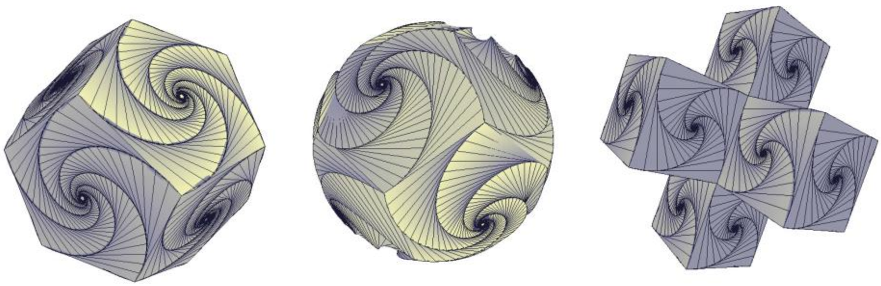


Fig.7. Interlocked Spirals on surfaces that is used to construct twirling sculptures (Images courtesy to Ergun Akleman).

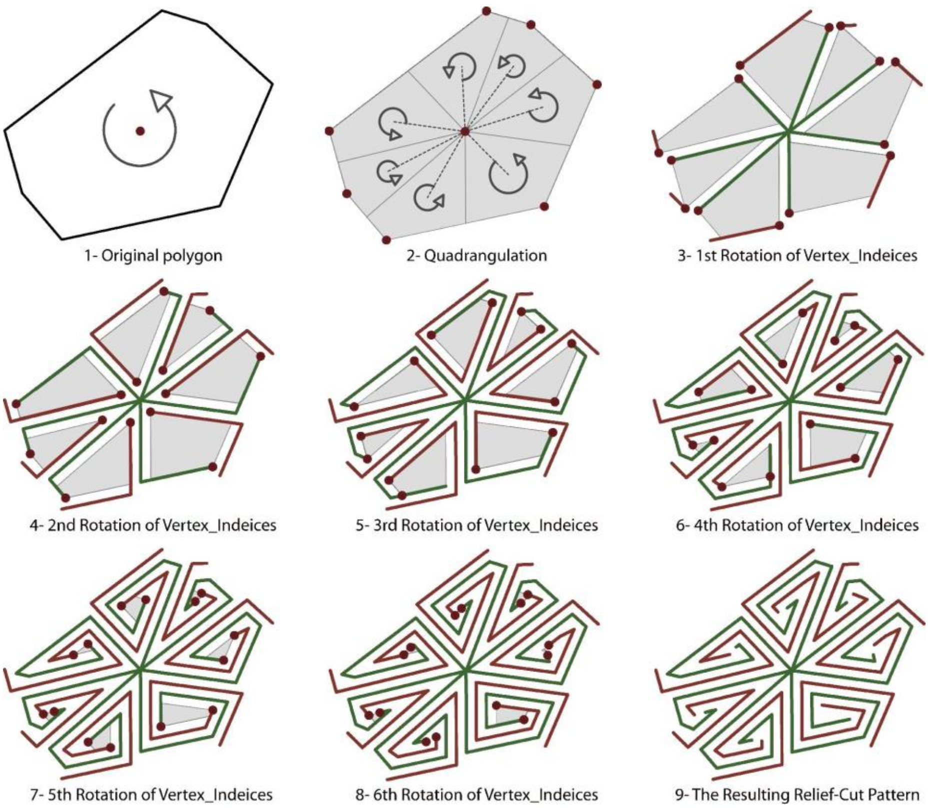


Fig. 8. The steps of basic algorithm.

5.1 Vertex Insertion Remeshing for 2D Meander-Patterns

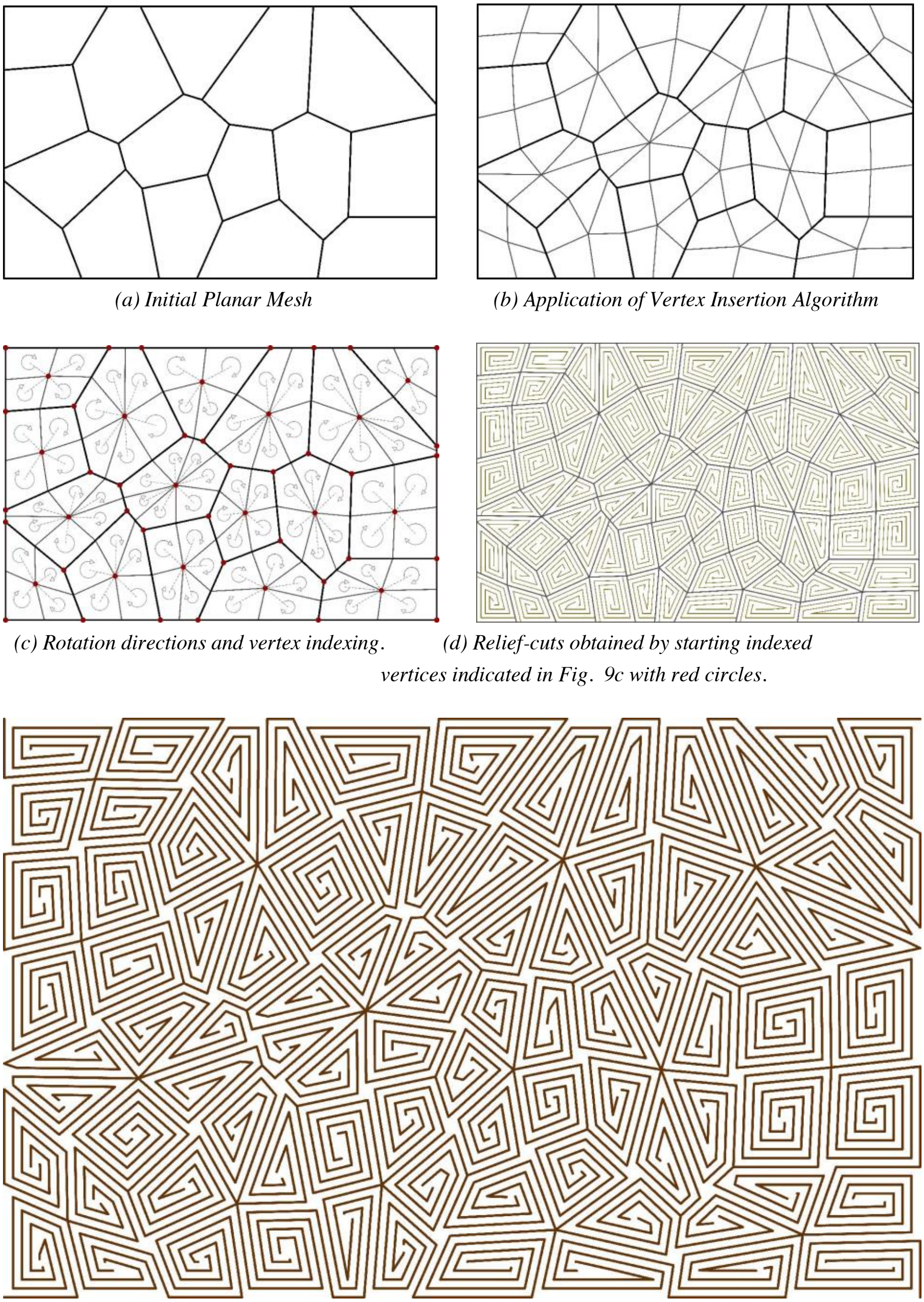
Vertex insertion is one of the simplest remeshing algorithms. It is obtained by first inserting a vertex in the center of each face and each edge. Then, each face-vertex (the vertices inserted to center of each each face) is connected with its edge-vertices (the vertices inserted to centers of boundary edges of the original face). This process turns each m-sided original face into m quadrilaterals (See Fig. 8.2). The vertices of the resulting mesh is always 2-colorable since we can always paint edge-vertices in one color and the rest (original vertices and face-vertices) in another color. The operation also creates a 2-manifold mesh, therefore, rotation orders are still consistent as shown Fig. 8.2.

We then apply a spiral creating algorithm starting from original and face-vertices. Since each spiral is created inside of a quadrilateral, this algorithm is relatively simple as shown in Fig. 8. Let the original vertex and face-vertex, i.e. two vertices that are selected as starting points of the two interlocked spiral-trees in every quadrilateral, are indexed to be labeled as selected as shown as red circles in Fig. 8.3. Then the two half-edges starting from these two selected-vertices. we draw two lines that are parallel to the two half-edges. Note that using this approach we can directly control exact distances between the lines.

An important property of our algorithm is that since we do not use edge-vertices to create spirals, the spiral associated with them are simply eliminated. This process turns any m-sided polygon into an mbranched spiral trees and each spiral branch of any spiral tree is interlocked with a spiral branch of another spiral tree. Therefore, the algorithm produces locally [m,2] structures where m can be any integer defined by number of sides of the initial faces of the initial mesh.

Fig. 10 shows two semi-regular meander pattern obtained by applying our algorithm to regular and semi-regular tilings. The meander-pattern shown in Fig. 10b turned out to be very flexible.

Based on this algorithm, the local control of flexibility is straightforward. For every step of line drawing, we obtain a integer value that comes from an underlying image. Based on this integer value, we simply control the distance between neighboring lines. To avoid aliasing we apply some randomization based on anti-aliasing approach introduced by Cook at al. [8]. As it can be seen in Fig. 3, the method allows to control local structure based on a given image. Two more examples are shown in Fig. 11.



(a) Initial Planar Mesh

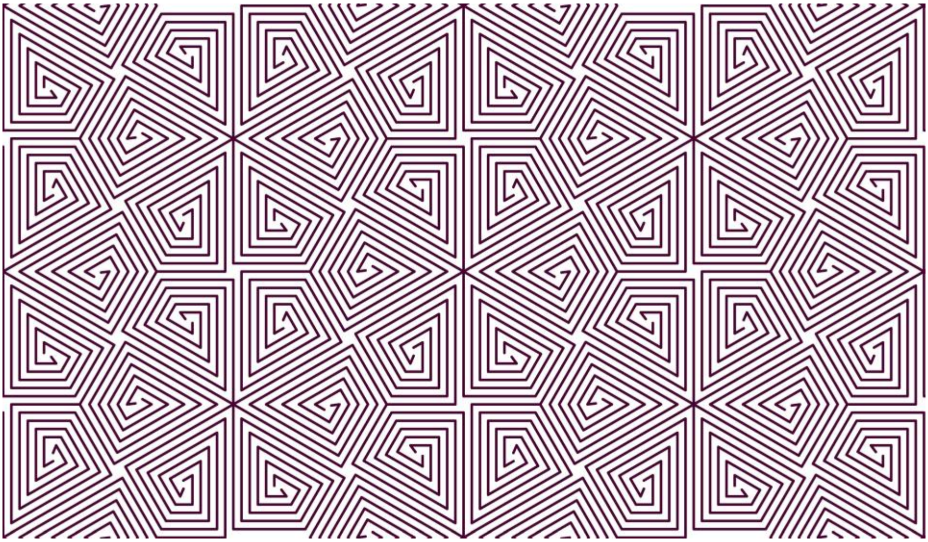
(b) Application of Vertex Insertion Algorithm

(c) Rotation directions and vertex indexing.

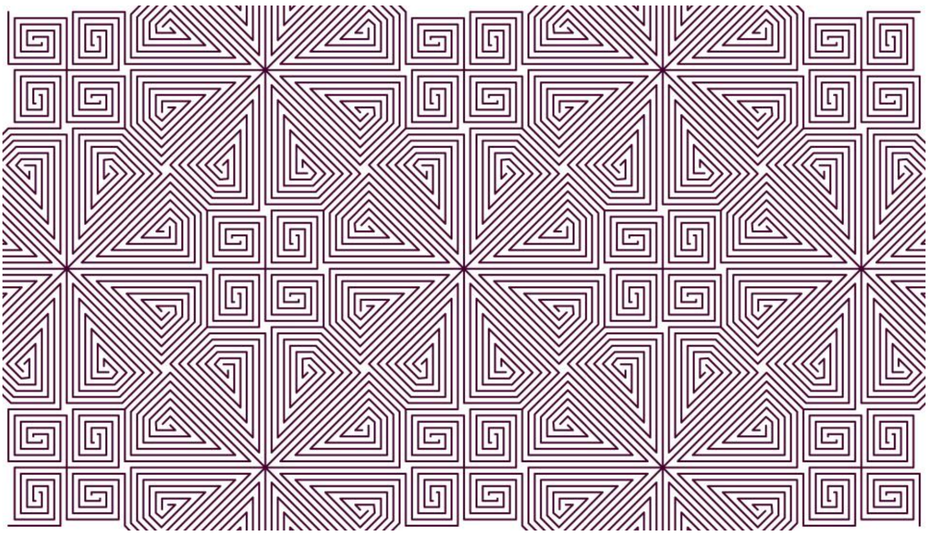
(d) Relief-cuts obtained by starting indexed vertices indicated in Fig. 9c with red circles.

(e) Final Relief-Cuts obtained by removing original mesh and quads.

Fig. 9. An example of overall algorithm working on a general mesh.

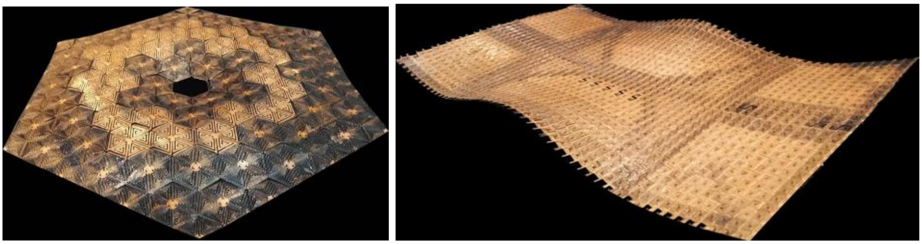


(a) 2D Meander-Patter obtained from Regular Hexagonal Tiling.



(b) 2D Meander-Patter obtained from Semi-regular 8.8.4 Tiling.

Fig. 10. Two examples of new 2D meander patterns obtained from regular and semi-regular tilings.



(a) A flexible shape with Negative and Positive curvature regions. *(b) Another flexible shape with Negative and Positive curvature regions.*

Fig. 11. Examples of panels obtained by our method.

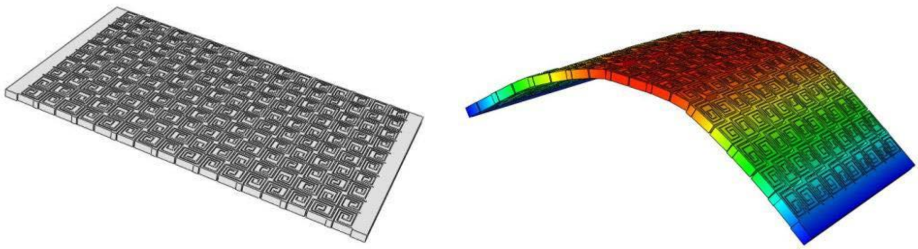
6 Finite Element Analysis

One way to optimally design the cuts pattern on the initial blank to achieve the desired shape of final product is to apply numerically analysis on how the material response to applied forces. Although by changing the cuts pattern parameters such as the pattern shape, density of cuts one may be able to deform the blank to desired shape but it is also important to keep the rigidity of wood. So cuts patterns may be chosen by trial and error but the easier and costly effective way is to use finite element analysis to predict the bank behavior under applied forces for different cuts parameters and then choose the optimal one for construction.

Fig. 12 shows Finite Element Analysis (FEA) result for modeling the flexible plywood under bending forces. As it can be seen from this example the deformation and displacement patterns of flexible plywood can be successfully captured by applying FEA and it can be possible to analyze the stress and strain patterns on the deformed plywood for optimally design the cuts parameters to achieve the pre-specified criteria. Using FEA analysis, we also observed that semiregular 8.8.4 tiling shown in Fig. 10b provides better flexibility than regular and hexagonal patters. For a complete analysis, more patterns need to be analyzed in a systematic way.

7 Conclusion and Future Work

In this paper, we have introduced a remeshing algorithm to obtain generalized 2D meander-patterns they are locally in the form of [n,2]. This method cannot create the [3,3] and [6,2] patterns shown in Fig. 5. We have recently observe that it is possible to obtain [6,2] pattern with a variation of this algorithm by replacing vertex insertion with another remeshing algorithm. We will report that in the near future. On the other hand, we are not sure if it is possible to generalize [3,3] pattern since we currently do not know any remeshing algorithm that can guarantee to produce 3-valent meshes with two-colorable vertices. [3,3] could possibly be a one of a kind pattern that can only be produced from hexagonal grid.



(a) Original 2D Meander-Pattern. *(b) Applying Forces*

Fig. 12. Flexible plywood under bending forces at two ends and displacement pattern on deformed plywood under bending.

The method is general and it can be applied to any polygon mesh. It will guarantee to produce meanderpatterns on any surface that is given by a polygonal mesh. Fig. 13 shows a few examples of covering arbitrary meshes with meander-patterns. We do not now an immediate architectural application of this; however, it can be helpful to produce flexible 3D shapes directly using 3D printer. Our local control algorithm works as desired avoiding antialising. There is now a need to develop methods to produce images based on desired flexibility levels.

(a) A cube covered with meander-pattern. *(b) A soccer-ball covered with meander-pattern.* *(c) Stanford Bunny covered with meander-pattern.*

Fig. 13. Examples of arbitrary shapes covered with meander-patterns.

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Building Information Modelling

A Comprehensive Application of BIM Modelling for Semi-underground Public Architecture

A Study for Tiantian Square Complex, Wuhan, China

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Abstract. The paper presents research on how Building Information Modelling (BIM) can be applied comprehensively throughout the design of an architectural project. A practical method based on BIM models that help to deal with multidisciplinary issues by integrating the design information from different sources, collaborators and project stages is formulated by adopting existing available tools. The 'Tiantian Square' building project in Wuhan, China combines a subway station with a commercial hug. According to the project's size and complexity, our study focuses on the multiple cooperation of professionals from different backgrounds, including the departments of architectural design, structure (civil engineering), HVAC (Heating, Ventilation and Air Conditioning), water supply and drainage, and electrics and sustainable design. Our paper presents how the BIM model bridges between various simulation platforms through our technical system and management, including steps of transformation, simplification, analysis, reaction and improvement. Our research has helped to improve the overall efficiency and quality of the project. We generated a successful analysis-design approach for the initial design stages, which does not require in-depth analysis. It is a practical method to immediately evaluate the performance for each design alternative and provide guidelines for design modification. Finally, we discuss how the coordination of different department becomes a crucial factor as we look forward to a more open, communicative and inter-relational design and development process.

Keywords: BIM, Subway Complex, Simulation, Semi-Underground Architecture

1 Introduction

BIM is widely used for accomplishing various design related tasks in an efficient manner [1]. The information within the building information of the BIM model can be shared and reused by different professionals to analyse for optimisation.

The 'Tiantian Square' project is an actual life project that includes complicated functions of commerce and transport transfers. It is an important subway station being the junction of Line 8 and 10 of Wuhan Subway System. Due to its high complexity, the project requires multiple cooperations of professionals from different fields. Therefore, building information modelling is even applied from the early stage in the design process.

The project is located at the junction of the Fazhan Road and Wuhan Road in Jiangan District. Above it is the Zhuyeshan Overpass. Under the complex lies the Huangxiaohe Tunnel. The project covers an area of 3.3 hm^2, with an architectural area of 28,062m^2, including the commercial part of 15,769m^2, the parking area of 10,303m^2, and the equipment area of 851m^2. The area of the buildings above ground is 1,139m^2. The landscape covers an area of 31,108m^2. The main architecture is a 3-storeys underground building.

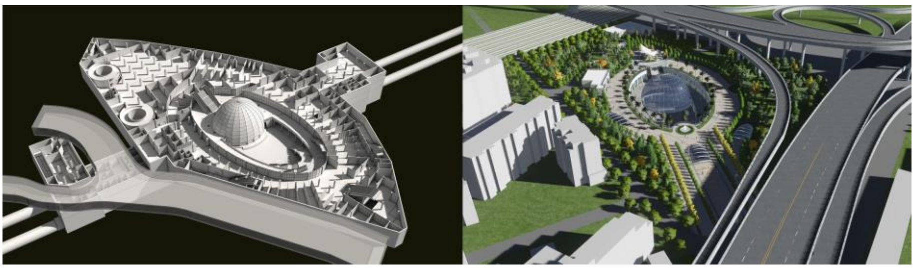

Fig. 1. The 3D model based on BIM of the project of Tiantian Square Complex

The challenges of this project lie in its complexity and design requirements and the limitation of the site. The architecture has been designed as a semi-underground type for providing more public green space and avoiding influence to surrounding buildings. The achievement of complex functions needs multidisciplinary cooperation. Therefore, a practical method based on BIM models that help to deal with multidisciplinary issues by integrating the design information from different sources, collaborators and project stages is formulated by adopting existing mature and reliable tools.

Our target is to make the project design process comprehensive enough that it considers all the aspects including the sustainable design for architecture, the structure design, civil engineering, and equipment arrangement. Collaborative design is needed to enhance design communication and improve the design efficiency [2]. The aim, firstly, is preventing the generation of errors at an early stage by strengthening the design information sharing. Secondly, as this is a complex project and design time is limited, we intend to promote the efficiency to shorten the design time. Thirdly, analysis and optimisation are needed to maintain or even improve the design quality compared to the previous projects.

2 Design Strategy

According to the aims discussed, the design prototypes have to be simulated on different software platforms. The calculation results can be the reference for the design. The transition from the paper-based exchange of design models to processes based on the use of digital models represents an important shift in the design and construction industry. Using digital models opens the possibility of automating a number of the analyses done during design, with significant consequences for the speed and efficiency of the design process, and for the quality of the resultant designs [3]. In an industry so heavily dependent on collaboration, challenges of interoperability must be addressed to maximise these benefits.

2.1 Project management

The BIM leading group and design team are founded to guide the departments of architecture, structure, water supply and drainage, HVAC (Heating, Ventilation and Air Conditioning), electric and sustainability [4]. 3D collaborate design mode has been set up by creating the centre model and working set. Models from different departments contribute to the centre model. Its information can be shared and modified in real time. Then, the information from BIM models is used for further analysis.

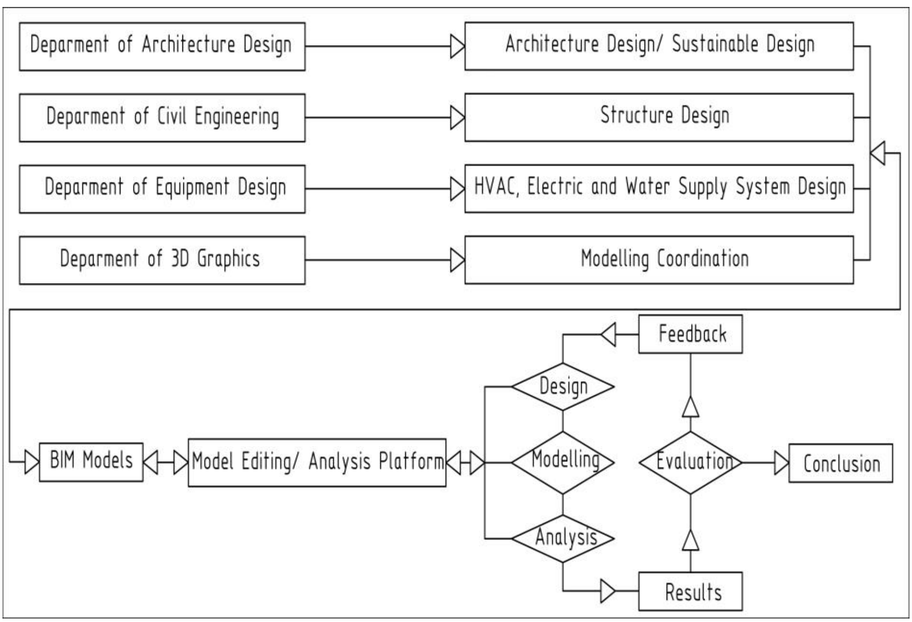

Fig. 2. The graph shows the project design workflow based on BIM

2.2 Analysis and Optimisation Methodology

For sustainable design, architectural performance such as daylighting, wind environment are studied. Previous sustainability analyses may require the establishment of new models because of the software environments. The simulation times are usually long, and models are hard to modify in some platforms. Therefore, this can be complicated and time-consuming, which affects the efficiency of architecture design process. In our study, we propose an alternative iterative approach to explore the issue by using a parametric performance analysis based on graphic and associated models. As the models are generated by a parametric method, they can be easily modified by changing their parameters. This modelling-to-analysis process can be repeated to compare the performance of models with different parameters. From this comparison and circulation, feedback can be generated. Accordingly, optimised design can be concluded. In this process, BIM models are sometimes transferred to different formats depending on the simulation platforms for analysis (Fig. 2). To be specific, for architectural design, as there are more analysis tool resources for *Rhinoceros 3D* (Rhino) software and *Grasshopper3D* (*GH*), and early-stage design is usually done in the environment, BIM models are sometimes imported to *Rhino* for further simulation. Moreover, the optimisation result will be reflected in the BIM models eventually.

Table 1. The table presents the adopted software tools, their users and functions

Users	Software	Functions
Architectural Designers	Revit (Architecture)	BIM models setting up
	Rhino/ Grasshopper	Parametric Modelling for Early-Stage design
	DIVA for Rhino	Daylighting and Illuminance Analysis
	Vasari	Wind Environment Study
	Ecotect	Daylighting Analysis; Sound Performance Analysis
	Tianzheng	Design Drawing
	Flow Simulation	Wind Environment Study
Structure Engineers	Explorer	Structure Analysis in Revit
	PKPM	Structure Design
	Revit (Structure)	BIM models setting up
	AutoCAD	2D Drawing
Equipment Engineers	Revit (Equipment)	BIM models setting up; Installation Simulation
	AutoCAD	Design Drawing

Furthermore, for civil engineering, the structure is analysed; for HVAC, electric, water supply and drainage, equipment installation can be simulated, cables and pipelines collisions can be detected. According to analysis feedback, optimisation can be implemented by editing the models in every aspect from different departments. Because of the parallelism of improvement, this increases the efficiency of the architecture design process.

3 The Modelling Process

For the modelling process which includes the main body of the architecture and its detailed parts, we employed *Autodesk Revit*, *Rhino* and *GH*. In the case of a complex application such as sustainable analysis, conversion processes are often involved in the modelling.

For this project, the major part of the modelling has been done in Revit. The model is divided into several child models which are connected to the main model. Several parts of the design are developed by different departments of the architectural firm. Then the parts are all assembled into a complete 3D model.

The sustainable design is mainly done in the other software environments such as *Rhino* and its plug-ins. So we convert the BIM models to the format that can be edited by *Rhino*. Before import, the models are simplified to reduce the computing needs of the software. The models are modified further in *Rhino* to fit the analysis environment. The reasons for doing so are: first, this can improve the analysis efficiency; second, in this case of sustainable analysis, physical and graphical information are the major part needed from the BIM models.

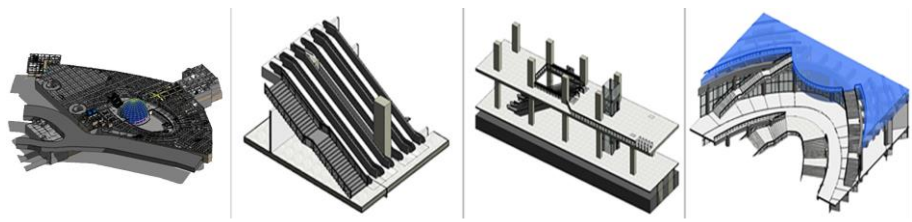

Fig. 3. Models of architectural components set up in BIM system. From left to right, they are the complex's main body, the escalator, the railway platform, and the atrium respectively

The modelling of specific detailed parts can be done in the environment of *Rhino* and *GH* [5]. For the generation of the reproducible works, using the parametric method is efficient and suitable for comparative research. Our novel approach is to generate the single components first, and then assemble them together. For the specific modelling such as the facade, the main strategy is to create the arrangement of points to locate the positions of its components. Then the shape of the components can be defined by using certain algorithms before attaching them to the location. For example, we can use the array algorithm in the *GH* to create a group of points. The horizontal and vertical number of the points can be defined by the inputs related to integer parameters. Then we use the move command to duplicate the components by attaching them to the array of location points. The generation process at this stage is not complicated, but it has the advantage in adjustments of the components arrangement, which is suitable for iteration simulations and analysis.

Moreover, this method can provide the significant potentials that allow us to create complex models and analyse them further by modifying the algorithms adopting different modules.

4 Sustainable Design based on BIM

For this project, we use BIM and parametric modelling methodologies paired with a simplified performance calculation method to assist our design. It is the first time we make use of this methodology in an architectural project. From our experience, this methodology not only offers benefits during the design phase but also further down the track during construction and management [6]. From the beginning, aspects of sustainability have been taken into consideration. Information about local climate, the existing circumstance of the site and architectural standards especially the *Green Building Standard* are included in the initial analysis. In communication with clients, requirements, specific functions and expected performance are determined to guide the initial design phase. During this, several analysis models have been generated.

4.1 Daylighting Analysis

The daylighting analysis strategy is to analyse the objects from large scale to small scale, from overall study to detailed study. The daylighting performance of the architecture has been investigated from the site to the façade, from the outdoor to the indoor environment [6]. The overall situation of the project including the site has been simulated first. The aim is to find out the time when the outdoor environment is covered by direct sunlight on specific days such as the winter solstice. It can be done in the Revit using its daylighting analysis function. The sun orbit of the whole year can be shown. Then the caused shadow can be simulated to find out the architectures which obscure each other. To study it further, we used a plug-in called *Daylighting Calculation* in '*Tianzheng Architecture*', which is a widely-used CAD software platform developed by a Chinese company. In its environment, the graphic information such as height and shape can be taken into consideration in the analysis process. The software tool can calculate the solar irradiance time of every area of outdoor space at any height on any day of the whole year.
Then detailed analysis has been implemented. In this session, we would like to study the indoor illuminance performance of the architecture, especially the design strategies that mean to allow more daylight into the indoor environment. First, the graphic information of the BIM models has been selected, exported and modified for the analysis system. The model has to be simplified or rebuilt according to the tools we selected. As introduced above, an atrium has been designed to let natural light can reach the sub-basement; the glass dome set in the middle of the atrium is aimed to allow more daylight into the architecture; increase the area of the windows on the façade properly. Our analysis has proved the effectiveness of these design steps. After

the simulation, we improved the design of the façade, the atrium, the dome through minor modification. The analysis tool of *Ecotect* has been used first (Fig. 4.). As its calculation is based on the daylight factors, and to make our simulation more accurate, the software of '*DIVA*' which is an optimised daylighting and energy modelling plug-in for *Rhino*, has been introduced to repeat the analysis [5]. According to the result, we can confirm that our design can surely improve the indoor illuminance. Exploring this possibility another analysis tool of '*PKPM*' has been used to calculate the daylighting and especially the glare performance. The analysis is necessary, as the architectural design is required to meet certain standards. It is part of the evaluation of the whole project that a report has been generated for the authorities.

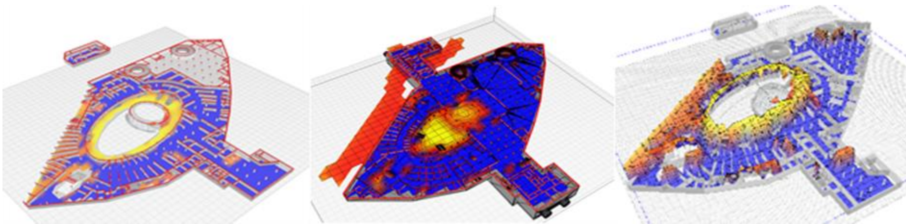

Fig. 4. On the left, the image is the illuminance analysis of Basement Level 1. In the middle, the image shows the analysis of Basement Level 2; on the right, the image shows the 3D display of the illuminance value of the Basement Level 1

4.2 Wind Environment Analysis

The designed atrium cannot only allow more natural light into the architecture but can also provide better natural ventilation performance. As we know, isolated by the soil cover, underground architectures have the difficulty of exchanging the indoor and outdoor air without artificial ventilation instruments. The atrium has provided a bridge to connect the indoor and outdoor space.

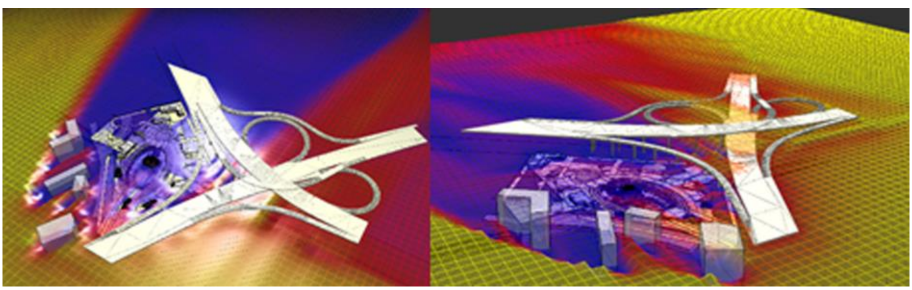

Fig. 5. The images illustrate the wind environment analysis based on BIM

To prove the design effectiveness, the software tool of *Autodesk Vasari* has been applied to analyse the wind environment (Fig. 5). *Vasari* used to be an instrument to assist sustainable design, which can analyse the daylighting, energy and wind environment. However, it is not supported anymore. The advantages of *Vasari* include its simple way of operation and the rapid analysis speed. It can reduce the analysis time remarkably and efficiently give a response to designers and engineers. Another advantage of *Vasari* has been its friendly environment to BIM models built up from *Revit*. The models do not need much modification before being imported to the software. In this case, the model of the complex is mainly simplified before analysis. With the consideration of the local climate, parameters such as wind speed and its direction have been set to certain values. Different situations according to various seasons have been simulated. There are mainly two study objects: (1) the interaction between the complex project and the site; (2) whether the design of atrium can introduce more airflow to the space and the façade. In the site, there are not many buildings in the surrounding area. However, there are several viaducts beside the complex. To find out whether the viaducts will affect the complex, their influence has been studied. The results have shown the influence is relatively rare not only from the viaducts to the complex but also from the complex to the viaducts and other architectures. It is believed the semi-underground form of the project would hardly impede the natural ventilation in the district.

As *Vasari* is inaccurate in its calculations, we undertook further studies to cross check *Vasari*'s results. Some tools like *Fluent*, *Phonics*, or *Flow Simulation*, which are plug-ins for *SolidWorks*, can be applied to verify the results. Moreover, we were able to ensure the effectiveness of our design.

4.3 Acoustic Performance Analysis

Though an acoustic study is not required by the client or any authorities and standards, in this case, we still take it into consideration as a test of one part of the workflow. It not only tests our system but also improves the acoustic performance of the architecture and accumulate research experience in this field. For architectural acoustics, two factors have been mainly considered (Fig. 6.): one is the noise control; another one is the reverberation time in the architecture, which includes space in the atrium and the glass dome.

For the noise control research, we mainly study the influence from surrounding environment and how it affects the complex. After a preliminary inspection, the main noise source comes from the vehicles on the viaducts. A parametric method has been applied to calculate the closest distance within the viaducts and the complex. Then the noise source point has been set in the model analysed by *Ecotect*. After this, the simulation of the noise attenuation can be done, from where we find out the noise intensity has been remarkably reduced to a certain degree before they reach the architecture. So the study can confirm that the noise would not affect the architecture. Moreover, as it is a semi-underground building, the influence will be weakened further.

As mentioned, the complex is a semi-underground architecture with the atrium and the dome in the middle. The space in the atrium surrounded by the façade is semi-isolated. This kind of form can cause an echo in the space. To the buildings like theatres or concert hall, the generation of echo has to be controlled; the reverberation coefficient is designed to be restricted in a certain extent. In this case, as the complex is a public architecture that includes the functions of commerce, subway station, such sound performance is not required. Still, the reverberation coefficients in the atrium and glass dome have been calculated spiritedly.

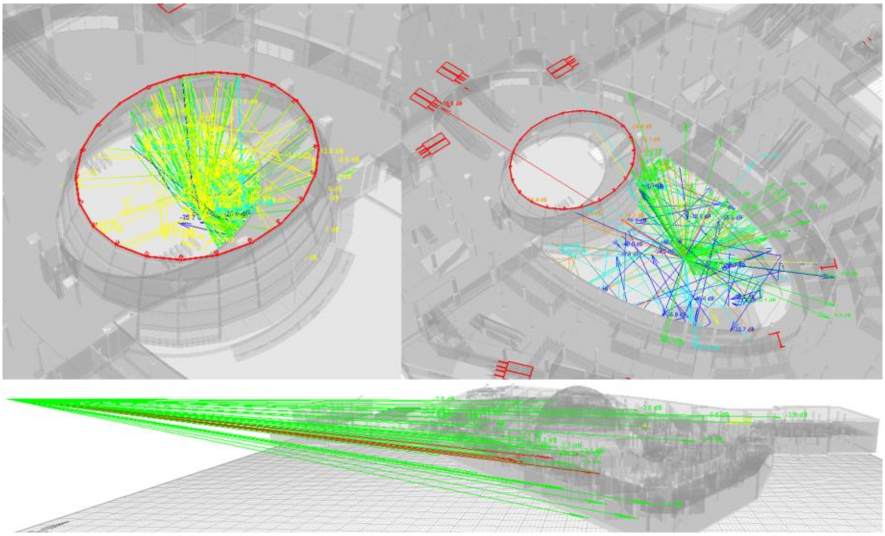

Fig. 6. The models illustrate the acoustic performance analysis: Top-left shows the reverberation simulation in the glass dome; top-right shows the reverberation simulation in the atrium, and the bottom figure shows the noise analysis

5 Civil Engineering and Equipment Installation

The department of civil engineering has taken charge of the structure design. For electronics and water supply, designs are by the equipment design department. After the preliminary architectural design has been proposed, the design information can be shared through the BIM system. The architectural department can communicate with the civil engineering department and the equipment design department using the BIM models. These two departments can start their own design tasks efficiently.

For the structure design, the civil engineering department has completed their design applying the structure function in Revit (Fig. 7.). At the same time, they have analysed the design using a new plug-in in the same environment, called *Explorer* invented by a Chinese company. Then, the BIM models have been exported to PKPM, which is a normal software for structure calculation in this field. In there, the model is simulated further.

For the electronics and water supply, the equipment design department will usually face problems of installation of the instrument, cables and water pipes. In the design stage, for example, the position of a certain cable may be blocked by another water pipe without noticing that the system is too complicated. Finding and correcting such conflicts usually, take a long time. In this project, BIM models have changed the situation as the software is capable of checking every installation. The influence of the structure and architecture design will also be considered so that the problem such as a water pipe being struck by a beam can be avoided from the beginning.

Besides the application in the structure and equipment design, the technology also helps in the fabrication process. As the glass entrance of the subway station and glass dome are manufactured in the factory, our parametric modelling based on BIM can assist to decide the sizes of the components and locate the positions of them accurately.

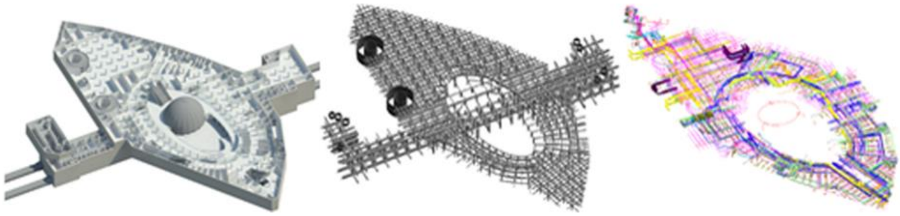

Fig. 7. The figure on the left shows the model from architecture department; the figure in the middle shows the structure design; the figure on the right shows the models of pipes, cables and instrument developed by the equipment design department

6 Design Result

For the semi-underground architecture, our study has helped in architectural design, sustainable design, structure design, equipment design and even the fabrication process. The outcome from the sustainable design such as daylighting analysis and wind environment study has proved that the architecture can meet certain standards. Moreover, the further analysis and optimisation have made the design exceeded the requirement. It will surely let the project get a higher score in the green building assessment in China. Now, the design has passed through the evaluation from certain authorities. Moreover, the complex is already under construction.

Also, our study has helped to improve the design efficiency and quality of the project. It has suggested an alternative analysis approach in the early design stages and put it into practice. By setting up the link of the graph-based system and associative system, we try to take the best advantage of the BIM models for multiple applications, which let us have developed a more advanced BIM-based methodology for practical architecture design projects in the future.

7 Discussion and Conclusion

This study has proposed a novel methodology and workflow to evaluate and analyse the performance in multiple aspects of the semi-underground architectures. A practical method based on BIM models that help to deal with multidisciplinary issues by integrating the design information from different sources, collaborators and project stages is formulated by adopting existing available tools. Though the technologies adopted may not be cutting-edge ones, they are efficient enough to solve problems. It is believed that, because of its generality, it can be universally applied in other architectural design. The simulation we have done is not common in-depth one, but a practical method to immediately evaluate the performance for each design alternative and provide guidelines for modification on the early design stage. The simulation approach is based on both the associative and graph-based models. In sum, the contribution can be summarised as follows.

First, based on our research outcomes, the design strategy we proposed for the semi-underground architecture at the beginning can get certified and improved. We can give our design guidelines to the following similar projects such as subway station complexes. As the models are developed on parametric computational platforms can seamlessly be employed to construction and maintenance stages.

Second, the study has attempted to explore a parametric design-analysis workflow to determine the advantages of parametric design in studying real-time changes in building design. Compared to conventional workflow, it is more easily possible to design a performative-responsive façade using parametric design. It allows for efficient editing the model in any stage of the design process. With the established relationships between parameters in parametric design, architects have better dominance on the project.

Third, our study has developed an alternative approach to accomplish the architecture design, sustainable design, structure design, and equipment design by using a parametric performance analysis. This modelling-to-analysis process can be repeated efficiently to compare the performance of models with different parameters. Based on comparison and circulation, optimised design can be concluded according to the feedback. By setting up the link of the graph-based system and associative system, we have been able to take the best advantage of the BIM models for multiple uses.

Acknowledgements. The research project has been supported by the Changjiang Survey Planning Design & Research Co., Ltd (No. CX2015Z08). The project of The Tiantian Square Complex has won The 3rd Class Prize of the 2nd BIM Design Competition of Exploration & Design Association of Hubei Province (EDAHB), China, in December 2014.

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Plug-ins State of Art in BIM Software

Repositories Assessment and Professional Use Perspective

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Abstract. The increased need for optimization in design processes has led BIM software users to customize their projects by the use of programming and external applications. This paper presents the state of art of Revit plug-ins by means of an explorative, quantitative study of current repositories and the proposition of a categorization system to identify to which purposes the tools are being developed. Then, through a questionnaire to AEC professionals, assessment on the use and necessity of the tools is made by comparing the user experience with the proposed state of art categories.

Keywords: BIM, Revit, Plug-ins, Programming, Survey

1 Introduction

With the uprising of different modeling necessities and unique uses of BIM software, the users' community started to develop and upload a great amount of tools to assist the project practice, among the different aspects of BIM technology is the use of applications external to the main platforms, tools known as plug-ins, add-ins or apps, which use the programming already established by the BIM software to manipulate different features of the design environment, possessing defined purposes such as adding versatility to the existing functionalities.

BIM professionals can use the plug-ins to achieve particular goals of design processes, as well as to increase their productivity, letting the applications execute repetitive tasks, perform calculations or run commands in sequence through programming routines, among other uses.

The process of developing plug-ins is currently given by the community of BIM technology users, who look for specific solutions for a variety of project situations. One of the prominent communities is Autodesk App Store, composed of members who use the authoring tool Autodesk Revit, which through its Application Programming Interface (API) allows them to interact with the tool's functionalities, enabling the production of content for the repository [1].

The potential of tailoring an existing software to specific project needs lies in the increased range of possibilities and to overcome platform limits, even though customizing a software to specific user needs is a new practice in architecture, it has already been widely implemented in mechanical engineering and design [2].

Among the added possibilities of using external tools to complement design processes, also stands out the project integration and information sharing provided by plug-ins along BIM platforms, which subsidizes project management by facilitating BIM model interaction, providing support to existing management features and encouraging holistic project development [3].

Plug-ins can also be used to facilitate cost, scheduling and sustainability analysis for construction projects, while these tasks are usually complicated by the several constructive system alternatives, along with the ever-changeable design processes and decision making, an external tool can, for example, help increase synchronization and automate processes by interrelating the model's existing information with another external software or servers that contain data relevant to the task at hand, allowing for agile decision making and a larger pool of solution possibilities [4].

Even though the importance of sustainable design has been growing in the construction industry, energy and performance analysis still does not have the required integration to BIM design processes, with these steps usually being fulfilled only after the architectural design is completed [5]. In such environment, plug-ins and programming can increase the viability of assessing different technological solutions at the project's initial stages [6], allowing designers to focus on achieving less negative impacts on building life cycle and energy efficient design [7].

The current state of BIM-based software has a gap in the field of solutions optimization, with performance feedback being necessary to enable decision making support and designers' creativity. Thus, the use of external and multidisciplinary programs, integrated with the main BIM platform, can enhance the parametric approach of authoring software as Autodesk Revit, improving project performance [8].

This paper focuses on assessing the current state of the art of Autodesk Revit plug-ins, with the objective of analyzing the development of recent external extensions, by exploring the current add-ins, tools and applications, reviewing the present repositories and elaborating a comprehensive category system. This enables the inspection of needs and implications on different areas by means of a user perspective study, conducted through a questionnaire to AEC professionals, to elucidate how plug-ins are implemented in their design processes, as well as if the tools meet expectations of use.

2 Methodology

The methodology of this paper is composed in a two-part study: first, a quantitative search of existing plug-in repositories for the authoring tool Autodesk Revit is done, so they can be separated in categories and the state of art of these applications can be shown. Then, by means of an interview with Brazil's AEC professionals, a qualitative questionnaire is carried out, allowing discussion about the use and necessity of programming and external applications in BIM software.

The choice of Autodesk Revit as the software of interpretation derives from particular reasons: firstly, because its API's – Application Programming Interface – functionalities and possibilities, which serves as Revit's main development tool, allow users to manipulate, organize and research different ways to interact with existing functions, therefore enabling creation of a variety of plug-ins [9]. Secondly, due to the initiative of established community, which develops the programming practice, uploading and discussing produced content through the Revit API Forum and Autodesk App Store [10].

2.1 Revit Plug-in Repositories Assessment

The Revit plug-in state of art searching is done through exploratory analysis of existing repositories, taking Autodesk App Store as the main content source, which, as of the date of this study, possesses 583 Revit plug-ins available for purchase or download, divided in 15 default categories. The search is then complemented by secondary repositories, which are characterized in this paper as websites that contain at least 3 Revit plug-ins available for purchase or download.

However, albeit a solid starting point for beginners, the categories proposed by Autodesk App Store have very varied concepts, specific information on apps is given through category filters which are defined by the peer who submitted the application, who can have a different understanding of the category meaning and may select multiple categories for a single plug-in, consequently enabling irregular concepts about its categorization. The process of classification is further complicated by the fact that the filters do not subtract each other, in other words, applying two or more filters will show results in an additive way, not enabling a search through intersection of filters.

A new categorization is proposed, in a way so that the quantitative plug-in amount searched in the repositories can be grouped in classifications defined by keyword-based criteria. The initial category definition is done by analyzing the Autodesk categories through an iterative and exploratory process: a sampling of up to 20 plug-ins from each of the 15 Autodesk categories is set, and through a text analyzer tool of Microsoft Excel, the most frequently used words of the group sample are revealed. Words that are inserted in compatible contexts with each other, form a new category, this process continues until at least 15 relevant keywords (Table 1) are enough to explicit and separate a general concept as well as to match the proposed category description, as follows:

Structural: tools related to structural design, calculation, dimensioning, detailing and analysis, presenting materials like concrete, steel and timber in situations where they act as structural elements: beams, columns, slabs, roofs, bracing, trusses, foundation, among others.
MEP – Mechanical, Electrical, Plumbing: tools associated with complementary building projects such as mechanical, electrical and hydraulic installations and facilities, or to serve as subsidy for flow, pressure, circuits or ventilation system calculations.
Performance: tools focused on performance, building life cycle assessment, energetic efficiency, thermal, acoustic and light comfort, water consumption, sustainable materials and emission control, plug-ins related to building environmental sustainability.
Productivity: tools connected to schedules and workflows, used to generate reports, quantity take-off and help in performing repetitive tasks in design processes, used to streamline designers' activities or to automate actions.
Conversion: tools with the sole purpose of converting files, being able to import and export a variety of formats with the objective of enabling interoperability between software or the generation of documentation.
Component: tools related to parametric design of walls, windows, doors and other family components, as well as product detailing and graphic representation improvement, annotation tools and rendering related applications.

Table 1. Proposed categories and keywords

Structural	MEP	Performance	Productivity	Conversion	Component
structur	duct	environm	table	ifc	wall
steel	mep	performance	sheet	pdf	window
bridge	pipe	impact	schedule	convert	paramet
frame	pip	cycle	quanti	export	dimension
beam	circuit	assess	takeoff	dwg	room
collumn	pressure	energy	take-off	link to	family
concrete	water	heat	automatic	impot	product
wood	flow	efficien	quick	share	detail
reinforce	fixture	thermal	annotat	extract	curtain
brace	cable	consumption	filter	enhance	component
timber	ceiling	daylight	workflow	external	factory
slab	ventilation	eco	estimat	document	seek
truss	conduit	rain	productivity	dxf	families
l analysis	electric	certificat	purge	server	section
robot	hanger	illumin	provide	excel	render

Then, each of the main and secondary repositories' plug-ins is filtered by a Plug-in Detection Device, a tool created in Microsoft Excel which counts the number of times the keywords appear in the text of the plug-in being analyzed, presenting in a radar graph the most dominant category, allowing identification and storage of information with context awareness and increased accuracy by using the same method on each of the plug-ins.

The text in the name, presentation, features and characteristics of the plug-in are analyzed, the keywords are counted and the category which possesses the higher number of compatible keywords classifies the plug-in in it, in the case of a draw or if the Plug-in Detection Device does not elucidate a category sufficiently, a re-reading of the text of the plug-in description is made and the category context that most closely resemble the proposed features' description qualifies the plug-in.

2.2 Professional Plug-in Use Diagnosis

The second part of the study consists of a qualitative questionnaire composed of three sections, created from Google Forms, with the objective of diagnosing the design practices of Brazil's AEC professionals in the field of BIM tool usage, seeking to understand how plug-ins are implemented in design processes, which are the most used types of applications and if they are effective in achieving their purposes.

The questionnaire is composed of three types of responses: characterization responses, free narrative responses and Likert scale responses. Characterization responses are presented solely for displaying the professional profile of the respondents, with questions of single or multiple alternative selection. Likert scale responses are composed by questions where the respondents must express their opinion about statements with five possible positions (1 for Totally Disagree, 5 for Totally Agree).

In free narrative responses, professionals answer questions by text boxes in the questionnaire, the most notorious answers are selected, while similar answers are concatenated, this is made to further highlight characterization and generate discussions based on the professionals' perceptions about design processes.

The questionnaire is sent by email to several recipients in an exploratory manner, with selection criteria defined as: AEC professionals in Brazil, that work in offices, institutions or construction companies, that utilize BIM technology in their design processes.

Firstly, a declaration of consent is presented highlighting the questionnaire's academic purpose, then in Section 2, data on general respondent information is collected for sample characterization: educational background, location, project experience time and BIM technology experience time.

Plug-in and extension concepts are then presented in the questionnaire through Section 3, where respondents answer questions about productivity, utility and usage of programming in design processes, which plug-ins are used in their design processes, as well as if they have developed plug-ins. Lastly, respondents may demonstrate their need for solutions in a specific area, by suggesting and describing a plug-in they would like to be developed.

2.3 Comparative Studies

Through presentation of Revit plug-ins state of art and diagnosis of plug-in use by professionals, it is possible to compare the availability of plug-in categories in repositories with the plug-ins used and suggested by the professionals. This is done by intersection between questionnaire informed data and the proposed plug-in categorization.

The questionnaire is then used to validate the categories proposed in the state of art, as well as to add plug-ins used by the professionals that were undiscovered or that were not covered in the methodologic procedures to the state of art database, therefore serving as means of feedback to the proposed categories.

The narrative responses where the respondents explicit the plug-ins they utilize and suggest are interpreted by similarity of category description and then used for comparison with the state of art presented, to assess if what is developed in the repositories reflects the use and needs of the questioned professionals.

3 Results and Discussion

3.1 Revit Plug-ins State of Art

Quantitative result on repository research enables the identification of which plug-ins are the most commonly produced by the community, as well as what paths this segment of BIM technology development is heading on.

By exploratory analysis of current repositories, it was possible to collect 583 Autodesk Revit plug-ins from Autodesk App Store and 214 plug-ins from secondary repositories, for a total of 797 applications found (Table 2), within which 16 were added from professionals' suggestion, a stage of this study that will be detailed later.

Table 2. Plug-in Repositories

Autodesk App Store [10]	583	RevitWorks [17]	5
Tools4revit [11]	23	David Pinto Consultoria [18]	3
AGACAD [12]	33	CGS Plus [19]	9
AEC-APPS [13]	54	IdeateSoftware [20]	4
CASE Apps [14]	44	RTVTOOLS [21]	7
Kiwicodes [15]	12	Professional's Suggestion	16
BIM Interoperability Tools [16]	4	**TOTAL:**	**797**

All plug-ins passed through the Plug-in Detection Device, to perform keyword occurrence analysis in the plug-ins' description texts, in order to determinate its dominant category in a graphical manner (example in Fig. 1), then by exhaustive analysis of repository content and separation of plug-ins in their matching dominant categories, the state of art of plug-ins developed for Revit as of the date of this study can be shown (Fig. 2).

Analyzing the results, it becomes possible to verify a considerable quantity of external applications being developed with various file conversion purposes, as well as tools with the objective of manipulating and detailing components, however the most prominent category is Productivity, which represents that 36.17% of the plug-ins analyzed are developed to automate repetitive tasks, manipulate schedules and workflows, among other uses related to this category. In contrast, only 3.38% (27 plug-ins) were classified as Performance, even though it's a category that aims to cover multiple concepts such as energy efficiency, environmental impact and comfort.

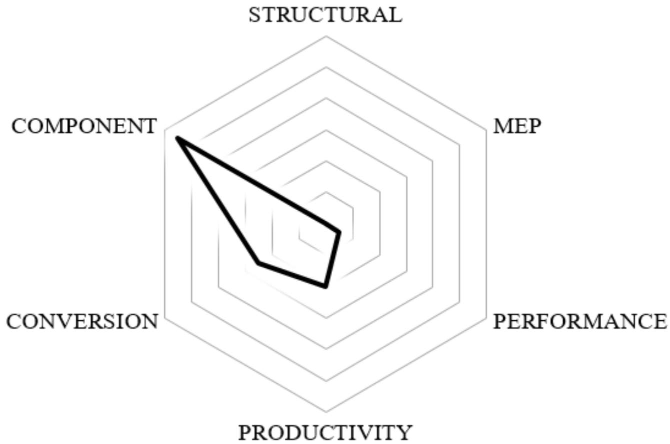

Fig. 1. Plug-in Detection Device classifies a plug-in as Component-based

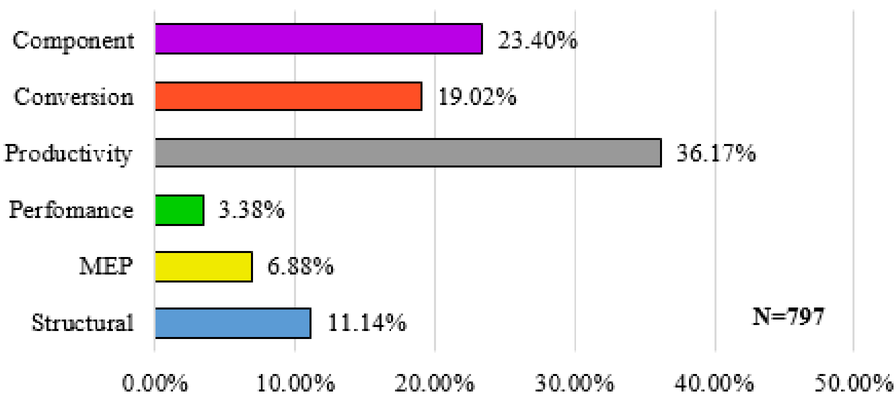

Fig. 2. Revit Plug-ins State of Art

3.2 Professional Use Characterization

The questionnaire was sent by e-mail to the recipients following methodology criteria and as result covered 29 professionals. According to characterization steps, the questionnaire is composed with professionals graduated in schools of Architecture (62.07%), Civil Engineering (34.48%) and Business (3.45%), moreover, some respondents stated they also graduated in areas such as Electrical Engineering, Design and Building Technician Course. The respondents work in offices, institutions or companies in Brazil, located predominantly in the states of Rio Grande do Sul (10 respondents) and São Paulo (8 respondents), other locations are Rio de Janeiro, Paraná, Paraíba, Mato Grosso (2 respondents each), Goiás, Distrito Federal and Bahia (1 respondent each).

The working time with projects was declared to be 6 to 10 years in 27.6% of responses, and more than 10 years in 48.3%, demonstrating that the profile of the respondents is that of professionals potentially experienced in project practice. Working time with projects specifically using BIM technology was declared as less than 2 years in 10.3% of responses, 2 to 4 years in 31%, 4 to 6 years in 17.2%, 6 to 10 years in 13.8% and more than 10 years in 27.6% of responses, which allows to observe a variability in the adoption of BIM technology throughout the years by different companies in various locations in Brazil.

Among the respondents, 58.6% declared using plug-ins or extensions related to BIM authoring tools in their design processes. The professionals then were presented to some statements, and by Likert scale responses, could express their opinion in values from 1 (Totally Disagrees) to 5 (Totally Agrees) in relation to plug-in, extension and programming use for diverse purposes. Table 3 shows mean and standard deviation values from the statements' responses.

Table 3. Plug-in and programming statements and professional agreement

Statement	N	Mean	Std. Dev.
1- The use of plug-ins and/or extensions can improve productivity.	25	4.60	1.31
2- The use of plug-ins and/or extensions optimizes decision making steps.	24	4.42	1.07
3- The use of plug-ins and/or extensions simplifies repetitive design processes.	25	4.60	1.24
4- Project area professionals can use programming to reach new levels of excellence in design.	27	4.59	1.34
5- Project area professionals can use programming to reach new levels of excellence in performance.	28	4.61	1.36

Based on this question, it is possible to affirm that there is agreement between the professionals, which demonstrates that the respondents believe in the potential of programming as a way to increment their design processes. This conclusion becomes clearer when professionals answer the following: "How can programming help in improving design processes?" Following narrative question methodology, among the main responses are: (i) productivity improvements: enabling automation of repetitive tasks, checking and validation of standards and methods, performing manual tasks such as family editing with agility, reducing operational tasks, (ii) accuracy improvements: reducing the margin of error in complex modeling processes, identifying conflicts and consequently minimizing rework, (iii) design improvements: increased productivity provides more dedicated time for solution development and compatibilization, enabling the design of more complex forms with more details and annotations, as well as generative design, (iv) interoperability improvements: facilitating interchange between BIM applications, freeing models of some restrictions between platforms, (v) management improvements: facilitating coordination and communication among team members, offering solutions directed to specific company flows, reducing wastes from mistakes and making it possible to increase company profits.

When questioned whether they develop plug-ins, 5 professionals (17.2%) declared yes. Some functionalities raised for the developed plug-ins were: numbering and creation of structural elements, topographical surface finishing, automatic creation of wall coating, synchronization of schedules with budget and cost composition data lists, design and documentation of partition walls, information management at the construction site, creation of parametric components and communication management among company professionals.

When asked to quote through text field, names of plug-ins they use in their design processes, a total of 43 plug-ins names were raised, of these, 27 were already included in the quantitative research of plug-in repositories, the 16 remaining were searched for their functionalities and then used to increment the database of secondary repositories, providing feedback to the state of art.

Through Plug-in Detection Device, it became possible to research the use of plug-ins by the professionals, following the same categorization methodology, enabling assessment of main purposes of the tools used (Fig. 3).

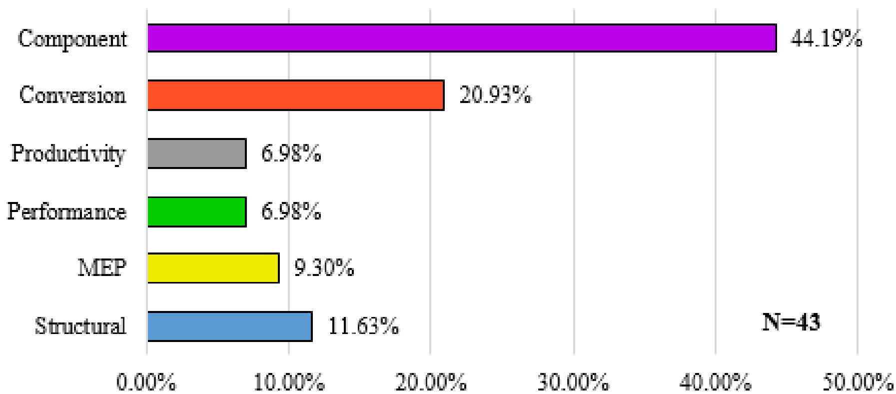

Fig. 3. Revit plug-ins by professional use

From Figure 3, it is possible to notice the predominance of Component based plug-ins (44.19%), which reflects a possible relation with the current state of BIM technology implementation of the respondents, most of which are graduated in Architecture, who can use plug-ins of this nature for purposes of modeling families, designing and rendering buildings and interiors.

The predominantly cited Conversion plug-ins (20.93%) are related to increased cross-platform collaboration and information maintenance, enabling additional ways to integrate information modeling between different software, sometimes to complement the interoperability of IFC format, which, as presented previously, has different levels of agreement in relation to its utility in design process by the respondents.

Productivity plug-ins, albeit being the most frequently developed in repository communities (36.17% of state of art), were among the least utilized, with only 6.98% of use by the respondents. Such result makes it possible to infer that the plug-ins available in this category sometimes do not meet the specific needs of the professionals.

Performance plug-in category, although also little used by the professionals (6.98%) is available in much smaller quantities in repositories (3.38% of state of art), their uses by the respondents are related to sustainable building design, energy efficiency, accessibility and landscapes.

In MEP and Structural categories, similar percentages show approximation of use by professionals (9.30% and 11.63%, respectively) and available in repositories (6.88% and 11.14%, respectively).

Next, an analysis of respondents' plug-in needs was made. This time, the professionals could suggest by text field, a plug-in which they would like to be developed or that would be useful in their design processes. The suggestion text was interpreted through the described data and then, a matching category was proposed, based on the context of responses and following methodology. A total of 26 possible plug-ins were described. With this information, it was possible to compare the suggested plug-ins with state of art categories (Fig. 4).

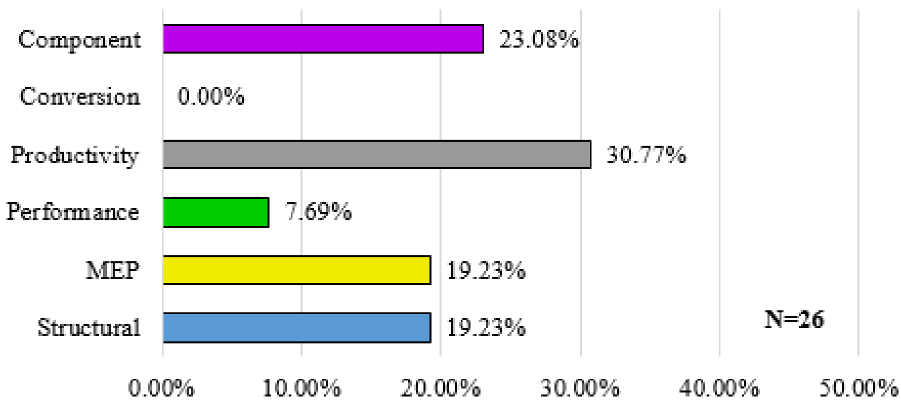

Fig. 4. Revit plug-ins by professional suggestion

The results of this interaction reveal that, although important to manipulate different file formats and to facilitate information interoperability, Conversion plug-ins weren't described in the suggestions. Instead, the respondents highlighted the necessity for applications in Component (23.08%), MEP and Structural (both at 19.23%) areas, presenting suggestions such as plug-ins for parametric furniture design, modular containers and generative design routines, as well as plug-ins that facilitate calculation related to electric projects, roof framing, reinforced concrete rebar and structural standard appropriate design.

The interest for new Productivity plug-ins (30.77%) when related with previous results of this category, indicate that plug-ins used by professionals (6.98% of use) possibly do not meet specific productivity demands of respondents, this information is further understood when a large number of plug-ins in this category are available in repositories (36.17% of state of art).

Performance plug-ins described (7.69%) were connected mostly to design focused on accessibility, not directly referring to life cycle analysis, sustainable design, energy efficiency or environmental impacts.

4 Conclusion

The contribution of this paper is the review and assessment of the current state of the art of Revit plug-in development, a quantitative research about plug-ins developed in repositories, which presents a classification of external applications in six distinct categories, making possible the discussion of trends and challenges for the industry with the arrival of new technologies.

Additionally, user perspective context was introduced through a questionnaire to AEC professionals: Brazilian architects and engineers, users of BIM technology and relatively experienced in design processes. It was possible to evaluate the proposed state of art of Autodesk Revit platform plug-ins, by means of interrogation about use and necessity of these tools in the respondents' context, allowing for comparison between plug-in development and user experience.

This paper may subsidize argument for the use of programming in BIM software, as well as the study of BIM in conjunction with plug-ins in AEC companies, helping in the development of this technological field of BIM and seeking to point out solutions for project optimization through the use of external tools and software customization.

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AS&BIM – A Unified Model of Agent Swarm and BIM to Manage the Complexity of the Building Process

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Abstract. Analyzing the success rate of the building process, it emerges that it is an industrial sector that lacks efficiency. Nevertheless, during decades the trend was to compare and bring into contact manufacturing management procedures vis-à-vis the building industry. But, whilst a manufacturing product is essentially a standard object produced in a controlled environment, a building is a prototype in itself. To bridge this gap research on Artificial Intelligence was conducted, so as to move from the traditional trial-and-error process to the simulation approach, defining in a virtual environment results of design and management choices before the real application, thus mitigating risks. To attain these results, a prototype was developed based on the Hybrid Actor Agent approach. The Agents, governed by their rules, behaviors and goals, define actions while Actors manage communication among them. The Network intertwined among these Agent/Actor systems is capable of stratifying knowledge based on the success rate of the choices made. The result of these concurrent computations is an optimized building process flow-chart

Keywords: Artificial Intelligence, Project Management, Building Information Modeling

1 Introduction

Workers using conventional Codes and rules of thumb, as expressed in this design process is a complex activity that involves an increasing number of professionals having different roles and skills. Practically, they challenge the planning process from different and often conflicting points of view. Therefore, on the building scale, the complexity is the outcome of aesthetic motivations, technical issues, economic aspects and different users' habits.

Merely by referring to contemporary architectural shapes, the complexity is given by their morphogenesis as governed by parametric design; likewise, the complexity of technical issues has multiple facets: also in small buildings, innovative materials and construction techniques are used. These procedures are actually more similar to tailor-made works than to industrial ones.

This ever-growing complexity is less manageable when the building is related to users, especially when workers and users are present at the same time, for instance during intervention to preserve service continuity.

Moreover, it is difficult to foresee the unpredictable behavior of users and handbooks as in the 19th century: now, with the progressive spread of the Engineering approach and advances in Computer Science, it is necessary to envision innovative workflows to deal with the ‘complexity’.

Therefore, bridging the initial maturity gap, important contributions to the correct understanding of phenomena were generated by appropriate ICT technologies, that help to define their own choices in a multi-disciplinary model and consequently reduce mistakes and misunderstandings.

Nowadays, the challenge is extended beyond the model by means of dimension representations, material properties or, side by side with project managers, simple representation of geometries and resources related to them.

The paper thus outlines the panorama and the possible outcomes of Artificial Intelligence techniques in the building construction process.

The first results are thus reported concerning a Hybrid Agent-based system now under development that is implemented by means of an Artificial Neural Network. This system has the goal of automatically establishing the correct sequence of activities in a defined construction site area, calculating the time and resources required to accomplish a task for the purpose of properly managing risks referred to the construction activity (cost increases, safety concerns, viability of solutions adopted …) by means of a *lean construction* approach [1].

2 State of the Art

Operators regularly use tools to program and check construction activities in order to quickly identify problems and evaluate process optimization opportunities. The planning is performed by means of a periodic time schedule definition, number and type of resources used, and estimations and assessments, mainly based on the experience of the actors [2].

Planning is defined using an activity breakdown into progressively simpler sub-activities and defining the Work Breakdown Structure – WBS. The Work schedule related to the project WBS is usually handled by software tools derived from techniques based on Program Evaluation Review Technique – PERT – and Critical Path Method – CPM [3]. This approach was conceived in the assembly-line era, when processes were mostly serial. In the building industry, stakeholders often prefer to use simpler techniques, such as the Gantt chart, which is useful for providing a general view of the overall process, but is not completely effective for managing a huge quantity of similar tasks performed by the same specialized worker-teams allocated to different spaces [4]

Innovative developments in technology or avant-garde architecture are often characterized by construction difficulties that appear only late in the planning, especially in the construction phase, and have their origin in lack of experience coupled with the inherent challenges of assembly.

Furthermore, traditional planning methods lack automation and 'insights' that depend mainly on the implicit knowledge of the experts involved; moreover, this also denotes difficulties in visualizing and sharing embedded knowledge among different actors, which favors the propagation of errors.

This methodology, when applied to building construction, produces over-production, time wasting, misallocation of resources, inappropriate timing of deliveries and operational conflicts, which can cause a highly negative impact on process efficacy and efficiency.

An improvement of this methodology is afforded by studies on the use of parameters that are statistically defined through interviews targeting building process actors, and applied to the construction site, but '*even* [*if*] *the constructability score does not give any absolute real value for constructability, because it is not sufficiently empirically tested, it gives valuable pieces of information about the emerging constructability issues*' [5].

To provide project managers with tools capable of providing them with support in the decision-making process, a line of the research review is being developed based on linking the Artificial Intelligence – AI – techniques to common models used to manage the building process.

Starting from the implementation of databases and BIM models aimed at automatically attaining near-optimum project scheduling [6], it is extended as far as advanced methodologies based on sophisticated techniques of simulation like Agent Modelling [7] or the machine learning approach by the use of Artificial Neural Network techniques [8].

The tendency is shifting from reactive behavior models to prediction behavior models in order to avoid risks by an early identification of them.

Evidently, by simulating the most likely situation that could occur during the building process activity, it is possible to come up with a set of possible choices, in order to mitigate risks that could affect the final product, or damage the resources committed in the construction process.

3 Dealing with Complex Construction Sites: BIM and Project Management Tools

Nowadays BIM have shown great design potential, contributing to the support of designers (architects, urban planners, engineers, etc.) in managing the complexity of large quantities of information, also allowing the automatic identification of conflicts [9], in particular the geometrical ones. At the same time, they have not shown any clear-cut capabilities in associating a building entity and its assigned resources with its construction methods, required materials, execution time and interferences to be solved.

The support that these tools provide in architectural design, and the need to move toward the simplification of the project construction model, starts from the initial stages of design and must continue during the whole life cycle of the building, optimizing required construction time and mitigating risks.

It is currently possible to use BIM and project management integrated tools based on PERT and CPM techniques as a stated approach. Conversely, the ‘complexity’ demands an explicit representation of management and assessment for:

a) working-team behaviors in the construction site related to the context,

b) necessary space for the execution of the work to be carried out, and

c) number and the type of the resources involved.

For these reasons, techniques based on *Location-Based Structures* – LBS – [10] are more suitable for developing a different approach.

4 A Step Forward: Associating Artificial Intelligence (AI) Techniques with BIM Environment

“*Simulation is the imitation of the operation of a real-world process*”[11] and the step forward made by planning science is to prevent process failure through the evaluation of data obtained from virtual experiences before testing related consequences in real life.

To predict the outcome of a process we need to model the behavior of the process components, which consist of the relevant materials and manpower. All these components are modelled as an Agent with established goals and reasoning rules: the output of agent interactions thus goes to make up the knowledge base for the construction process.

However, this is not a very reliable system because every building process is, by definition, a prototype. The current need is to apply a methodology capable of adapting the agent’s behavior to the real dynamic conditions of the context that, in the building process, correspond to a working area that is also the final product.

For this reason, in the past few decades the Artificial Neural Network – ANN – has been extensively applied in forecasting models [12], also in the construction industry [13]. Researchers have applied this technique to many aspects of construction management in order to benefit from its advantages and to profit from the capability it affords to automatically gain experience from simulation feedback.

On the other hand, the BIM focuses as much as possible on defining building components and construction phases in advance in order to achieve process behavior simulations: in this way, it is not very simple to identify and solve conflicts from the outset where components are not well defined.

The adoption of these techniques, together with the LBS ones, paves the way to build up a system that can dynamically define the LBS in terms of progressive and dynamic updating. Finally, designers can become aware of time scheduling and the wasted time associated with the design and construction strategy choices.

The proposed unified model, called *Agent Swarm and Building Information Modeling* – AS&BIM – is intended to interact with a BIM, defining the corresponding LBS chart on the fly.

AS&BIM consists of two closely linked layers: The *Knowledge Wrap* – KW, that 'wraps' the knowledge together, in a progressive stabilization and evolution thanks to ANN continuous learning, and agents associated with BIM objects, in addition to methods needed to define the LBS and Work-Teams feature. These agents act on the KW by reacting to events generated by the modifications of BIM data (the topology of the system) resulting from the design choices made and subsequently by daemons and hidden computational procedures. This system consists of an implementation in .Net environment using the C# language of the existing project management tools, which lack automatic decision-supporting systems.

Some KW agents correspond to the BIM families and instances that act as a Cache Memory, providing access to the BIM World.

When access to BIM data is required, these are duplicated in the KW agents and when an actor modifies the BIM data, the system refreshes data contained in the KW in order to avoid inconsistencies. The KW/BIM interaction is guaranteed by the *Advanced Programming Interface* – API - embedded in most BIM-based software.

This interaction varies according to the type of specific interaction required: any request made via a BIM interface is forwarded to the KW, and the BIM system awaits the completion of the task. Otherwise, a KW request must interact with a BIM, possibly defining a new topology.

5 Methodology

5.1 Actor Paradigm

In the Actor paradigm [14] an Actor is the fundamental element of a concurrent computation model, used in order to develop a parallel and distributed system. Object Oriented, Actor and Agent paradigms share several aspects but, depending the application in which they are involved, they have three different approaches.

The Object Oriented – OO – paradigm is very popular today. Objects are software entities that encapsulate a certain state. The Objects perform actions and methods pertaining to their own internal state. The OO paradigm implements encapsulation, composition, inheritance, delegation and message passing. Objects remain 'passive' and become 'active' only when message processing is needed. The existence of an object in the system is irrelevant unless some messages reach it. Thus, to communicate with an Object by sending it a message you must know that the Object exists.

The Actors paradigm instead is quite similar to OO. Actors implement the same concepts but have control over their own internal state. Actors, like Objects, communicate with each other by exchanging messages. In order to send a message to an Actor it is not necessary to know whether the Actor exists since messages can be broadcasted. Once an actor receives a message it may send other messages, create new actors and modify its own local state. Actors process messages taken from a mailbox sequentially. To complete a task, an actor can store information locally while waiting for other messages in order to complete information needed to complete the task.

Object Oriented systems differ from Actors and Agent systems mainly in the autonomy level of the object themselves. In an OO system, indeed, an object displays methods and attributes of other objects, but it is always the Object that decides whether to invoke the method exposed. On the other hand, in Agent-Actor systems, the object decides autonomously whether to activate procedures and methods on the basis of the messages received.

Actors and Agents approaches in any case differ in some respects. Actor modelling is basically a programming approach, whereas the Agent-based approach is modelling dependent. In any case, the Actor Model is one way of implementing a Hybrid Actor-Agent Model.

5.2 Actor BIM World Interaction

The correct communication between the two systems represents a fundamental aspect of the prototype proposed because it is necessary to provide designers with a BIM system capable of updating its features on the basis of settings computed by Agents that act concurrently on the model itself.

This possibility is normally not available to applications that interact with BIM systems because it could easily determine 'Race Condition Conflicts' between requests made by the project team members and the updates required by the external management system.

In order to avoid these conflict situations, the communication between BIM and Actor take place via the BIM Event Manager – BEM. The BEM subscribes some events that the BIM system creates every time a modification occurs in the parametric model as when an object is created, eliminated or modified. Indeed, events and their subscription are typical mechanisms of the .net framework in which the entire system is developed.

Among the events generated by the BIM System, *Idling* plays a major role. The Idling event occurs between user interactions when the BIM system is in a state in which an external system could successfully access the model.

The BEM forwards events to the Actor system via a special Actor called Master Actor – MA – which then broadcasts the message or sends it to a specific Actor according to the relevance of the message.

Information requests or modifications activated by the actor system are intercepted by the MA which records them in a FIFO (First In, First Out) queue.

Successively, every time that a BIM system signals an Idling state (usually after a stated time), BEM provides modifications in order to apply or search for the necessary information: these are sent directly to the requesting actor by the BEM, without any additional passage from the MA.

The time needed for the communication between BIM system and the Actor System is evidently reduced: this is possible because when the BIM system is not used by the designer, the information provided by the agent system takes place in parallel, in an asynchronous way.

5.3 Actors Coordination

In a Multi-Agents system, coordination has a fundamental role, because '*the coordination rate measures how much an agent's system behavior is like a unity*' [15]. For this reason, '*managing inter-dependencies between the activities of agents'* becomes necessary [16].

Incidentally, several strategies are defined for the agent's coordination. In the proposed framework, a technique is adopted which is inspired by '*Distributed Constraint Optimization*' – DCOP [17].

Actors must coordinate their choices in order to optimize a modelled objective function. Each agent is aware of the constraints affecting it and operates asynchronously. The problem requires that the global objective function is modelled as a set of valued constraints returning a range of values [18].

5.4 Multi-Agent Paradigm and Simulation

An Agent Based Simulation Model is made up of a set of Agents that interact with each other. In this approach, the simulation of a complex system does not require the knowledge or correct formalization of the entire system but requires only an exact definition of the Agents' behavior.

An agent is normally equipped with a set of possible actions that can be undertaken as a function of certain conditions of activation.

The primary aim of an agent is to achieve the goals defined, even though agents operate in the interests of a given user. The behavior of the system derives from the behavior and interaction of the community agents (Agency).

Despite the growing interest in agent-based simulation systems, there is no universally accepted definition of the term Agent and, even today, a heated debate rages on this issue though the characteristics that an agent must have are sufficiently widely shared.

The term agent is normally used to refer to an abstraction, an idea or a concept that can represent any element whatever of a clearly identifiable complex system [16].

Agents are capable of autonomous behavior (Autonomous Action) in a given context and choose for themselves the appropriate action to achieve the objectives for which they were designed. Agents have the ability to cooperate with other agents in order to achieve their goals.

An agent does not however have full control over the environment in which it is situated, but can influence it. The same action activated twice in apparently identical conditions can produce completely different results or even fail. Agent-based systems must therefore allow that failure can be a possibility [19].

For this purpose, the Agent is equipped with a repertoire of possible actions and with a utility function that allows the performance of the actions taken to be assessed with respect to a goal. The utility function establishes '*how good a state is'* [19].

Agent behavior may be purely Reactive in the sense that the reaction to stimuli from the environment takes place without any particular reasoning, or else purely Deliberative when the reaction is the result of a complex reasoning process.

Hybrid Agents designed to produce behavior intermediate between the two extremes today represent one of the most promising architectures. Hybrid Agents are based on *Subsumption Architecture* [20] which comprises several levels (Fig. 1).

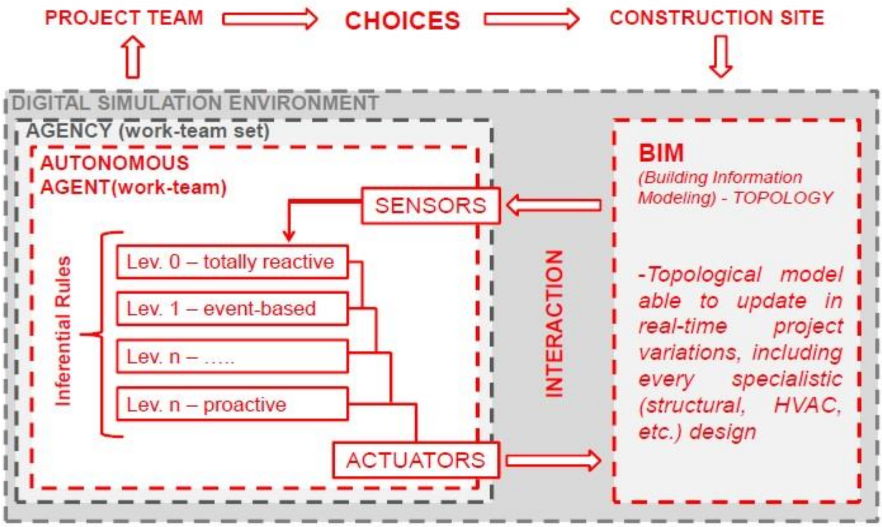

Fig. 1. Conceptual Framework of the Agent Swarm BIM – AS&BIM - prototype, based on *subsumption* architecture.

The lower levels are purely "reactive" and react automatically to input from the exterior while higher levels, which are more "proactive" with increasing hierarchical level, can inhibit the lower.

Subsumption Architecture assumes that intelligent behavior does not necessarily require an explicit symbolic representation of the context and abstract reasoning but emerges from the system itself [20].

In the proposed framework, implemented using an Actor system, Agents are used to simulate Elementary Activities - EA - in the building construction process.

Elementary Activities, in the meaning of the term used in this context, represent a project breakdown structure as defined using prescribed WBS criteria. Elementary activities are defined as univocally identifiable and logically distinct Work Elements which do not need to be further broken down. Elementary activities may thus comprise both simple work operations and complex preassembled or prefabricated elements considered as single units for work programming and management.

Elementary Activities are identified using the well-known 100% rule: the WBS must cover 100% of the programmed work. The 100% rule applies to all hierarchical levels. It is also necessary to ensure that the sum of the work of the lower levels always corresponds to 100% of the upper level work.

A dynamic correspondence will be established between BIM parametric objects present in the "BIM World" and the system agents by means of the *UniqueID*. Some activities will be represented by a single Elementary Activity- EA, while others will be constituted by sub-activities and BIM parametric objects.

Further stratification levels or new components not previously represented in the BIM World will be hierarchically edited by BIM coordinator, actors and software Developers of Knowledge Bases – DKB.

For each EA, a Construction Operating Plan – COP – will be defined. A COP is defined as the structured set of indications and prescriptions for elementary procedures for building elements in site construction and/or assembly, expressed in terms of integration and consistency with the functional, spatial and technological design of the building construction, in compliance with the safety requirements laid down by law. To each COP corresponds an Agent of the System:

$$COP \rightarrow Agent$$

The Operational Design – OD – is in turn made up of Construction Operating Plans and therefore constitutes an Agency

$$OD \rightarrow Agency$$

COPs are organized into homogeneous classes.

To enable the system to handle the information referring to the project it is necessary to organize it into homogeneous classes in order to construct a simplified semantics by means of which the various components of the system (BIM, DKB and ABMS) can interact and exchange information. To this end a simplified semantics will be adopted based on WKB prototypes.

Each of the COPs present in the DKB belongs to two distinct classes. The first class is the set of processes which contribute to defining a given building object. Each object in the BIM world will be connected to the COPs that contribute to its construction and are defined using the information in the BIM system supplemented by the information present in the WKB.

The second class is defined by the prototype that determines the structure and characteristics of the COP. The elementary activities can be represented in a knowledge base through prototypes which identify a class of processes having the same characteristics and which can be considered as “instances” of the COP prototype itself. The COP prototypes can then be ordered in time and thus form a partially ordered set.

The geometry of the BIM World represents the Topology of the AS&BIM Model in which the agents interact. Topology has a fundamental role in the definition of an AS&BIM model comparable to the individual agents’ behavior. The placement of the agents in a space plays a fundamental role in reducing the number of agents that interact with each other, limiting them to those belonging to a particular neighborhood of each agent.

The agents will be situated in the “BIM World” made up of the geometry as represented by the BIM Model.

The *BIM World* has the typical features of a typology suitable for multi-agent system development. It is Deterministic in the sense that any change caused by the agents has a well-defined result. It is Dynamic in that it changes over time at a speed that allows the agents to detect any changes that occur and react accordingly.

The characteristics of the *BIM World* are “visible” to the agents through the API provided by the BIM and, furthermore, again using the API, the agents may act on the context.

5.5 Progressive Artificial Neural Networks

The agent-based systems and relative messages among them could be interpreted as an Artificial Neural Network in which every agent represents a Neuron and messages that Agents exchange with each other could be modelled like the synapsis (Fig. 2).

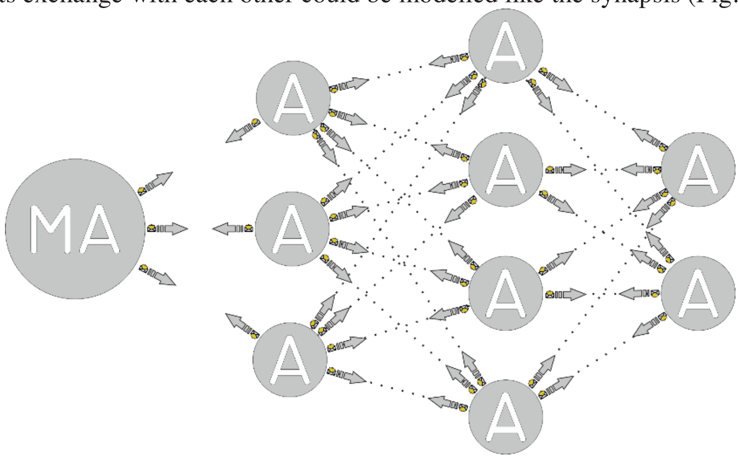

Fig. 2. The Master-Agents that manage the input/output of the internal network. The network represents the flow of messages exchanged among agents.

The frequency of messages and the statistical factor of choices embedded in the ‘neural-actor’ describe the ‘experience’ acquired by the network. In effect, when a correct choice is validated by the designer, the MA catalogues the choice in the library.

When a refinement is requested by the designer or by the BIM environment, the network associates the path and the statistical rate of the neuron to the consequent decision and, thus, catalogues the choice as wrong: the result is that when a situation *probably near* to the past wrong decision happens, the network will alert the designer.

6 Conclusions and Future Development

The methodology described allows project stakeholders to take the opportunity provided by current computational capability to simplify the complex work of building design and construction using a system able to support process actors in deciding *where, when and what to do with awareness* of coded risks and the results of simulations performed.

This will be made possible by the capability of intelligent agents equipped with machine-learning capability of ANN to dynamically determine the effective construction sequence needed to improve the quality process rate via the reliable prediction of type and number of work-teams to involve, achieving effective resource allocations. Moreover, a useful outcome would be to link this system prototype with Augmented Reality – AR – capabilities, to train workers prior to the actual construction activities, and to display the real construction progress to clients.

7 Conclusions

AS&BIM was conceived of as a proactive design support system that can dynamically determine a construction plan consistent with the choices made by the designer in the initial phases of the design process in order to reduce wasted time and to promote the sustainability of the construction process.

The proposed prototype will allow the LBS to be defined as the result of the interaction of a system of agents able to dynamically determine the most suitable construction sequence, in order to accomplish the tasks according to defined and reliable scheduling.

During the design work AS&BIM, in cooperation with the designer, will be able to evaluate the consequences of choices adopted in terms of type and number of Work Teams needed as a function of the construction timing while ensuring the continuity of the teams' work and an appropriate allocation of the resources needed.

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Why Do We Need Building Information Modeling (BIM) in Conceptual Design Phase?

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Abstract. Many researchers point out that, in conceptual design, many significant decisions are taken to directly affect functional qualities, the performance of the building, aesthetics, and the relationship of the building with the natural environment and climate, even if there is no certain and valid information to create and obtain satisfactory design solution. The focus of the study is to observe and explore how BIM can be used in conceptual design phase and also to investigate how and how effectively BIM can help architects during the process. To develop an understanding to these aims, a case study implementation within sketching and BIM environments which consists of three stages was carried out in an educational setting by three participants who are undergraduate degree students of Faculty of Architecture. Qualitative research methods were used as research methodology and the findings of the implementation were discussed with prominent related literature in the same context.

Keywords: BIM · Building Information Modeling · Conceptual Design Phase · Conceptual Design Analysis · Energy Modeling.

Decision Support Systems and Human Computer Interactions

Interactive Projection Mapping in Heritage

The Anglo Case

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Abstract. This work is the outcome of a multidisciplinary collaboration in the context of the VidiaLab (Laboratorio de Visualización Digital Avanzada). It proposes an application of interactive video mapping techniques as a form of experiencing the Fray Bentos industrial landscape, declared as a World Heritage Site by UNESCO in 2015. An immersive environment was created by enriching a physical scale model of the site with projected digital images and information, providing new and attractive ways of interaction with the cultural heritage. Proposals for future work and educational applications of the developed tools are also discussed.

Keywords: Video Mapping, New Media Art, Heritage, Museum, Human-Computer Interaction

1 Introduction

This papers presents work as part of the research project "The smart city; A Digital Palimpsest" which is currently being developed by VidiaLab, which is part of the Design Applied Information Technologies Department of the Universidad de la República. This project has as its central theme the recent designation of the "Paisaje Industrial Fray Bentos" as a World Heritage Site by UNESCO in 2015. (Delgrosso, 2015).

The Fray Bentos Industrial Landscape is located in the Department of Río Negro (Uruguay) and covers 275 hectares, including the Liebig's-Anglo slaughterhouse, its industrial facilities, the docks on the Uruguay River, areas dedicated to grazing, the residences of chiefs and workers and their places of leisure. Its value lies in that the place allows "(...) to apprehend the whole process of meat production that had world importance" (Damino, 2006) in the XX century.

The three-dimensional digital model referred to in this work was obtained through a mixed technique of scanning and reconstruction using photographs (terrestrial and using drones) with digital modeling from plans and historical documents. This model was materialized in a scale model 1/400 by processes of digital manufacture and 3D printing in white PVC and paperboard respectively, by the VidiaLab.

This paper presents the work processes adopted to integrate this model into an open *in situ* exhibition environment in an innovative way by incorporating interaction with *video mapping* techniques. By means of an installation placed at the exhibition, the visitors are provided with an attractive access point to explore the landscape and information on the historical heritage of Anglo by using interactive digital multimedia.

Video mapping is considered, in the context of this project, as a form of augmented reality -according to the conceptualization of Azuma (1997) which makes it possible to integrate a digital dimension to the tangible one. Which, as stated by Prendes (2016) allows for a more experimental learning process and facilitates knowledge acquisition. Video mapping as a projected augmented reality can, therefore, have a promising future in education given its potential for the presentation of information in ways that increase the possibilities for conceptual assimilation by facilitating inference processes and contributing to the transformation of the object (scale model) into knowledge in the sense that authors such as Prendes (2016) highlight.

1.1 Video Mapping and Model as a Metaphor for a Digital Palimpsest

The research project "The smart city; a digital palimpsest" proposes the incorporation of digital contents for architectural-urban space in heritage contexts. Within these contents are applications that seek the interaction user-reality by physical-digital information. These devices should provide an intuitive interface while minimizing the complexity of the interaction with the applied technologies.

In the work referenced in this paper the physical reality is the scale model (intervened with video mapping), which becomes the support on top of where different layers of information overlap, giving form to the “digital palimpsest”: a mix of strata containing fragments of texts, images, sounds and other discursive forms from different times, disciplines and perspectives that provides a departure platform for intellectual exploration without having to leave the model / palimpsest / territory. (Corboz, 2004).

1.2 Interaction with Heritage in the Digital Age

Information technologies, as Castells (1996) highlights, constitute not only a new form of production and economy but also intervene in the relationship with the environment through the production of meaning. The mediation that these technologies generate both interrupts and enrich the experimentation of reality.

By their ubiquitous nature, digital communications provide new access paths to the material heritage of a society, fostering its knowledge and appropriation.

Cultural industries, traditionally responsible for safeguarding and disseminating heritage, have opened up new spaces by means of the incorporation of new technologies, generating exchanges with new creative industries and actors in diverse academic fields. The case analyzed in this work is an example of such productive interaction.

Nowadays, institutions and heritage dissemination strategies demand for novel ways to attract users for who rely on digital technologies in most aspects of their lives; in particular as means to select and access information. This requirement calls for the collaborative contribution of actors with different backgrounds and expertise, as is the case in the present study, where design and digital architecture has a determining role.

Fig. 1. Projection on the model

2 Methodological Procedures

Through the observation and analysis of ethnographic qualitative data, the description and identification of the main methodologies, strategies and relevant elements that are carried out in the planning and implementation of this project are intended. The chosen methodology was considered appropriate for a first exploration.

The project was divided into two layers in order to facilitate observation and description. The first layer refers to the production / management and editing of digital contents to be projected on the physical model. The second layer describes software and hardware used for implementation of the interaction component of the project.

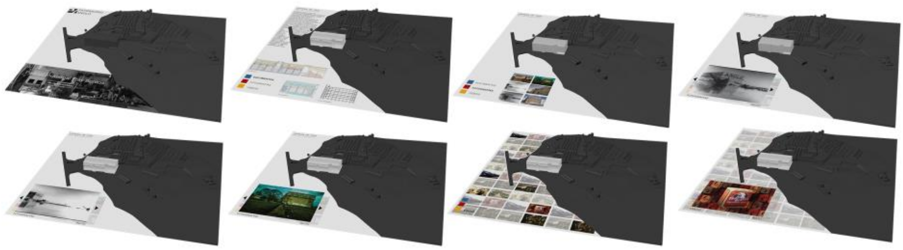

Fig. 2. Information displayed on the model

2.1 Delimiting This Project. Layer 1: Managing Digital Content

For the analysis and development stage of the digital content management component of the project we followed the guidelines of second level interactive digital objects[1] as educational objects[2], and in particular, in relation to their use in the context of managing and accessing architectural heritage information.

A contribution of this project is the exploration of new methods and practices to manage digital educational objects taking into account aspects such as the modularity, interactivity, usability and reusability required for their integration into the proposed interactive components of the project, including the video mappings.

Limitations of this association were also identified. For instance, not all the guidelines had application in this case[3] given that it was not sought to strictly develop an EDO (Educational Digital Object)[4], but to use the criteria of these to improve the proposal.

The adopted strategy for the management of digital content to be used in the projection is based on three elements observed during the process:

- The scale of the model was rather small and made difficult the performance of a strictly visual animation, as well as the display of information directly on its elements. For this reason the informational contents were given more prominence.
- The understanding that a digital content management that integrates an educational perspective will allow the production of structured and organized

[1] According to the norm UNE-EN 71361.

[2] According to the LOM standard of the IEEE *Learning Technology Standards Committee* (2002) in which any entity, digital or not, is used for learning activities.

[3] For example, it does not apply the rule of integrating some form of evaluation or self-evaluation to verify that a specific educational objective was fulfilled in the context of this model, because of its performance character, However, it can be assessed in a high school or school context within the teachers or professors interests.

[4] It is understood that it is not a proper EDO, as it is not momentarily disposed as a hypertext document in html accessible by web. Nevertheless, we are facing an object of learning as it is proposed to teach some themes studied in secondary / primary school on the Anglo heritage.

layers of information that includes the historical and social complexity of object of this installation.

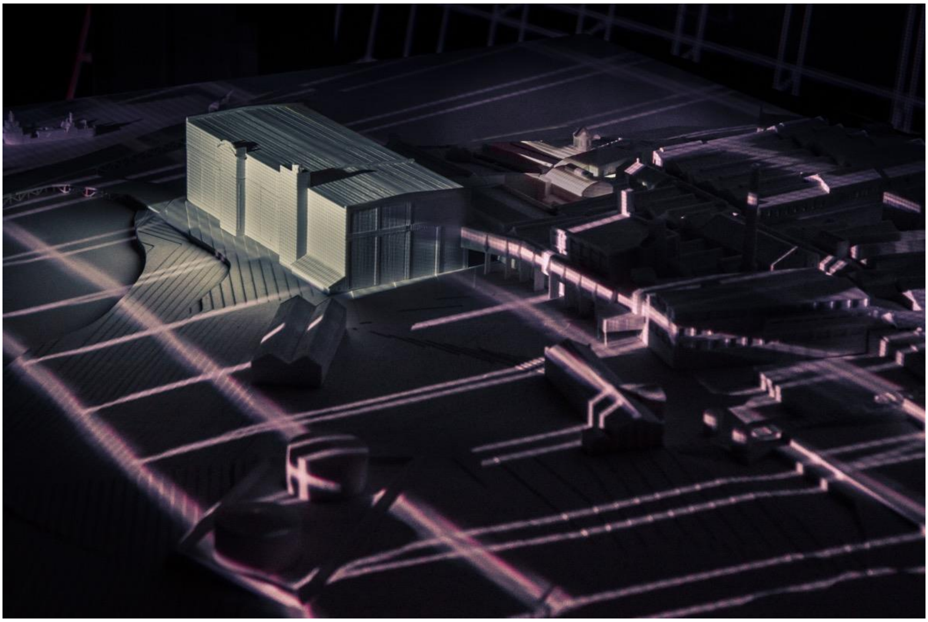

Fig. 3. Projection on the model

Based on these factors, it was proposed to prioritize the digital content on performance, referring the following elements:

- The integration of some of the contents used in the primary and secondary program units that deals with Anglo's complex and its historical context.
- The theme of the complex was approached in relation to the first and second world war, so that interactive menus containing textual information of them, photographic material and audiovisual under public domain license, as well as audiovisual animations and remixes containing images captured by drones, connected with photographic and audio-visual records of both wars.
- Digital objects are grouped together according to a modular structure, allowing their relocation in other modules or content proposals.
- Associativity is present from the use of buildings and structures represented in the scale model as an element of access to themes that are associated with these historical facts.
- Reuse of digital objects handled in the scale model through a digital repository.

Regarding the steps followed in this layer, the upcoming instances can be distinguished:

Documentary research and selection of digitized documents of historical value. Relationship with associated institutions of the context where the installation would be located was fundamental because it contained the memory and associated documentation. Specifically the Museum of Revolution and its archive, as well as those works of compilation and investigation carried out by referents of the theme Anglo complex.

Structuring and production of digital content. At this stage the presentation of information, the main projection script and the digital design are discussed. Strategies (activities in context, presentation of the project in community, etc.) and methodologies (interviews, conversations) were developed to integrate the perspective of the Industrial Revolution Museum, a fundamental actor, as well as other actors of the environment such as teachers and Design professionals linked to Anglo. Scholars were also consulted on the contents and the program that is handled to address the Anglo theme in the classroom.

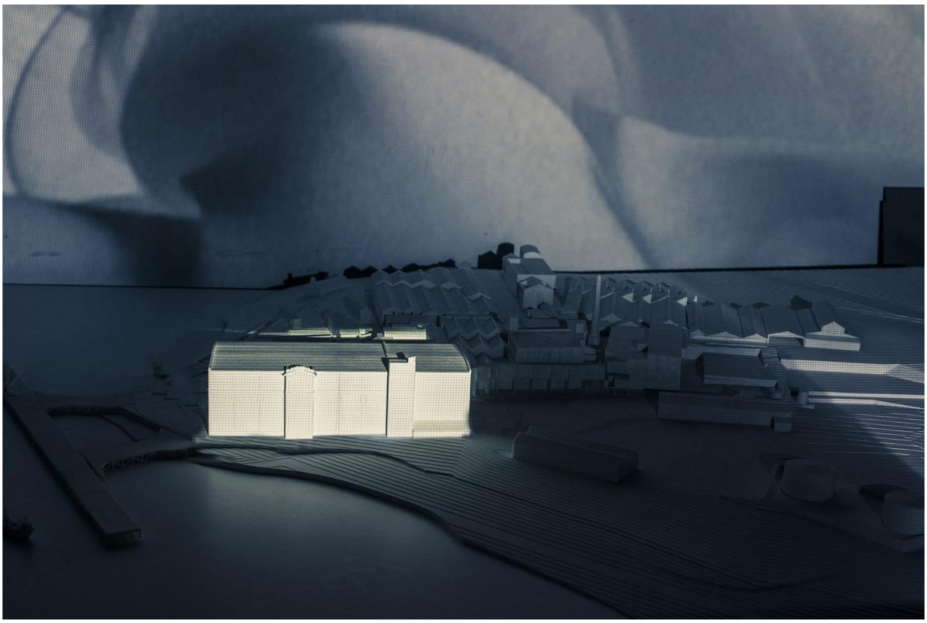

Fig. 4. Projection on the model

As Zapata (2012) highlights, "the production of digital content demands complex production steps, since convergence includes multiple supports and requires an information organization thought about the interaction and usability towards the user."

There are three levels of contents: the first –and most important one- is the one that references and designates the main features of each physical area represented in the model, for which was consulted the School of Architecture's History Institute pre-Inventory, as part of a university extension work.

This level provides information about the characteristics, functions and historical evolution of each area represented in the scale model from which are grouped photographs, videos and related animations. In summary, the digital model was intervened generating layers with information associated with each part of the model. For the development of a second level of structured content, the contribution of the museum's guides as well as teachers of secondary education was fundamental. This level was developed as a pilot on a thematic axis in which to deepen, on one hand the touristic route (that covers almost all the production process that was developed in the Anglo complex) and on the other hand the topic of the first and second war to contextualize the heritage involved.

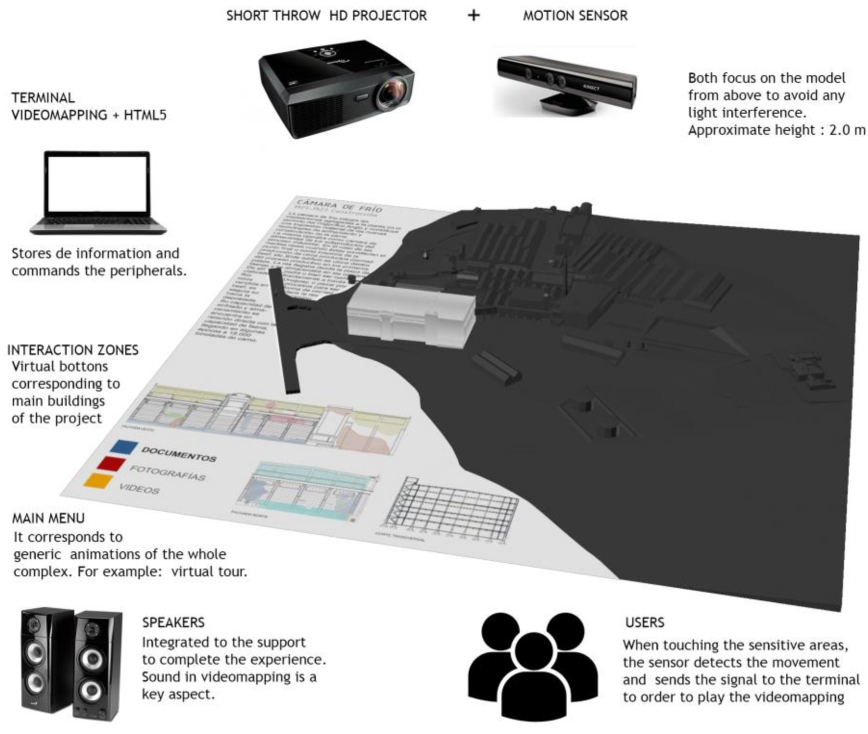

Fig. 5. Work scheme. Devices

In the third level of content the interaction is left aside and the contents are structured in order to create an automatic video mapping (in loop). From a script that emulates the typical site tour, it was gathered documentary and current photographs, historical audiovisuals and current aerial views in video editing software combined with the video mapping software. This part allows the installation to be configured as a passive show, but preserving a visual and sound impact force as a real time video mapping.

Table 1. Scheme of processes and workflows

PROCESSES	SOFTWARE	HARDWARE	DESCRIPTION	RESULTS
Obtaining the digital model of the site.	Autodesk 360 3ds max	Gopro 4 camera Drone Dji Phantom 4 Reflex Photo Camera	It was obtained through aerial photography with drones and ground level photography. These photographs were loaded on Autodesk 360 platform to get the first approximation of the digital model. Then we loaded it on 3ds max to make it accurate.	Digital model of the site with digital fabrication technologies and 3D printing.
Production and edition of contents. Model manipulation	3Ds MAX Adobe Premiere Pro Adobe After Effects Adobe Photoshop			Video clips and sound. Digital remix. Visual representation based on informational layers. Projection mapping setting up.
Projection mapping installation. Image display and sound testing.	Resolume Arena	Projectors of 3000 lum Multi-screen graphics card - Matrox	Model projection testing. Adjustments and calibration of projectors.	Projection mapping installation.
Interaction testing	Ubi software	Kinect - sensor Projector	Combination of a motion sensor (Kinect camera) and software that makes any surface interactive by creating nodes of recognition. We load the information previously produced on the software.	Interactive projection mapping setting up.

Reuse and dissemination of digital contents used in the projection on the model. For this purpose, the implementation and development of a digital repository using the Omeka digital object management software were done simultaneously. Omeka uses the OAI-PMH protocol (protocol for content transmission open access), which allows metadata to be harvested by other services generating greater international visibility, allowing interoperability, information exchange and integration to the networks of national cultural information and international sources. Through a wide variety of plugins available for this software it is possible to provide access to the contents used and produced for the model for later reuse by any interested party. It also provides concrete tools to generate digital exhibits with the curated content facilitating its integration in the development of learning objects in educational settings.

Fig. 4. Model interaction through hands

2.2 Delimiting This Project. Layer 2: Hardware and Software Required

In this layer there are two fairly defined methodological divisions. On one hand, the design and implementation of video mapping in the model, and on the other one, the possibilities of interaction by users with it.

The first step in integrating the digital content referred to in the previous section into the scaled model was the digital three-dimensional model. Starting from here, video clips are generated when editing it in 3D design software such as 3ds max. In this software the development of complexity animations of the digital three-dimensional model takes place, which are subsequently rendered from a point of view coincident with the location of the projector in relation to the actual physical model. In this way the visual deformations are absorbed so that the projection can perfectly match the volumetry of the scale model. In the case studied, having two projectors, two video renderings must be made, each corresponding to each projector. At the time of testing the same model, perfect fusion or blending of both animations must be achieved with a multi-output graphics card (Matrox) and the projection software that results in definitive calibration. With the calibration the connection line is adjusted as well as the colorimetry or color temperature of the projectors so that they coincide.

In parallel, images and videos that compile the contents selected from the previous stage are generated and edited. In this instance, raster editing software such as Photoshop is used as well as video editing software such as Adobe Premiere Pro and After Effects to treat audio-visuals also produced in the content production and editing stage. In the case of these animations, projection software to deal with visual deformations becomes more prominent.

In the actual installation two projectors of 3000 lumens each are used, being realized in the interior of a building, and allowing a control of light and darkness without demanding too much luminosity of the projector.

Both projects are connected through the Matrox device, and related hardware and software. A graphics card for multiple screens or graphic expansion modules allows managing and connecting more than one projector to the same projection control terminal to cover the surface with sufficient light intensity. The projectors are placed at a distance of 3 meters horizontally and at a height of 2 meters, arranged so as to generate a projection on the model and another on the back wall. It should be noted that in order to position the different pieces, it was necessary to design the corresponding supports to cover the surface / volume of the model. Along with these devices, the sound is integrated through the use of speakers to cover the entire area of the room where the installation will be arranged.

In terms of interaction, a systems engineer was incorporated to the team because of the inherent complexity of the project. This work consisted in the combination of several factors: on the one hand a motion sensor (Kinect camera) with a projector, and on the other one the projection software with the interaction software that determined the degree of interactivity with the users. This interaction was organized in a series of layers of visual, sound and textual content that are arranged according to the movements of the people detected by the sensor.

3 Results

It can be observed directly and indirectly throughout the project that this exploration (video mapping or projection mapping), if realized with some concepts in mind, allows to generate learning objects effectively adapted both for educational and dissemination purposes. While this implies some complexity in its realization, the results obtained so far validate this possibility.

Regarding the layer of hardware and software involved in the project, we highlight the importance of the integration and conjugation of design and editing software, which constituted the greatest degree of difficulty when implementing the project. In this sense, the observations made by some authors such as Manovich (2001) on this quality of hybridization that characterizes these new practices come to light.

On the other hand, a lesson learned is that the scale of the model was determinant in the execution of the project and has to be taken into account in the planning stage, as it poses limitations to the development of richer and more detailed animations as well as to information conveyed by the models itself, such as textures at a level of detail that can be appreciated directly by the museum's visitors.

The project is currently in its final phase. It was already deployed *in situ* and open to visitors. However, not many definitive conclusions can be assumed yet. Visitors are responding in a positive way, taking advantage of interaction capabilities and getting involved with all contents provided regarding Heritage. Also, several surveys are being made among them with the purpose of evaluate the project. After this survey process ends, relevant data will be collected and some important conclusions could be taken regarding the level of integration, utility and general acceptation for the whole object. This final phase will determinate the future of this installation, in reference to adaptation, focus and upcoming growing.

4 Discussion

The opportunities offered by digitalization technologies, advanced visualization and new associated trends in digital and material world interaction can be striking, attractive and motivating; but it is also important that they generate significance and significant processes. This means: processes of learning and development of knowledge. In the case study, it is hoped that the citizens acquire a leading role through knowledge about the Anglo heritage complex and its historical relevance in the national and international context. Also, it represents a relevant opportunity for our Lab and our School of Architecture to get involved with Heritage and to include the society in our research, which is an essential part of the University purposes.

This case study is both an example and a catalyst for actions for the implementation of theoretical-practical conversational spaces that integrate digital design, architecture, education, engineering and other fields of study.

It is considered of great relevance to make the observations and lessons acquired by this type of projects available to different actors both in academia and in the society at large, in order to contribute to trigger a debate on the issues involved in the access to information on heritage goods. We aim at fostering, in this way the empowerment of citizens by having access to knowledge that conveys meaning and relevance to our heritage and its preservation as an essential component of culture.

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Rule-based Security Planning System for Practical Application

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Abstract. Security planning is a vital part of the operation and management phase in a building's life cycle. Ideally, this will be addressed during the building design phase. However, reality often differs from this ideal. In the real world, information such as floor plans tend to insufficiently describe or imperfectly match physical buildings, and must be surveyed and re-worked during security planning. Because of this, security companies require two kinds of staff: those in the security business and those in charge of planning, including floor plan verification. This research focused on creating an efficient way to help staff in this work environment develop a system of security planning for buildings and facilities using a rule-based approach in a tailor-made CAD system. In this research, we developed a new 3D CAD system for desktops and mobile devices, which specializes in security planning using a game-engine. To avoid errors during security planning, a rule-based check system was developed and integrated into the CAD system. The rule-set of this rule base was built from the security planning manual, including guidelines on equipment layout and wiring in various situations, which could then be used in the development of an automated check. This research describes the method of system development and final results.

Keywords: Security Planning, Operation and Management, Rule Base, BIM, CAD

1 Introduction

The Computer Aided Architectural Design (CAAD) research domain has focused on catering to well-trained and educated users in industries such as architecture, engineering, and construction (A/E/C) since these studies started. Situational applications of Computer Aided Design (CAD) have therefore been well adapted to, and widely adopted in, the design and construction fields; however, operation and management areas are quite different during early steps in the building life cycle, as workers in these areas do not receive any formal A/E/C-related training or education. In summary, employees in these fields complain of the inconveniences and difficulties of using CAD due to complexities and excessive functions not used in their work. The security planning area in particular presents a more serious situation than other operation and management domains because of their work and business environment. By common convention, security planning is part of the building operation and management phase of the building life cycle. Ideally, security planning is done concurrently with the building design stage; however, reality is consistently different from the ideal. In practice, security planning is frequently started later in a project, sometimes not even until after the operation and management phase has begun. Because of this, security companies are required to employ two kinds of workforce: those performing security functions and those laying out security planning. The difficulty for security employees tasked with planning is that they don't have architectural expertise, such as drawing up and interpreting building floor plans. Furthermore, expertise is required to avoid errors when using floor plans for some aspects of security planning such as the layout of alarm equipment and wiring. Security companies have developed a security planning manual, giving their staff a solution to these problems in the format of a book. Unfortunately, this manual has proven insufficient for resolving the problem.

Given the ongoing nature of the problem, this research focuses on developing a rule-based system to assist in security planning for buildings and facilities using a tailor-made CAD system developed during research. The proposed security planning system was developed to overcome common security problems by converting the security planning manual into a rule base for an automation planning system and game engine. This development opens use of the tailor made CAD system to nonprofessionals who lack training or expertise in using architectural floor plans and layouts for alarm placement.

2 Related Research

2.1 Rule-Based Solution for CAD, BIM, and Security Planning

A bright vision of future applications for engineering knowledge, specifically to CAD environments, has been set forth by Gero [1], and past results have shown the value of CAD related knowledge in adapting and evaluating building design [2]. A rule-based system can store this type of knowledge and experience to make practical judgments in real-world situations.

Since a rule-based system was introduced by Hayes-Roth [3], many studies have been conducted using a rule-based system in CAD research. Recently, these have focused on adapting from 2D CAD to Building Information Modeling (BIM) [4, 5]. Since the BIM concept was introduced, it has been shown a rule-based system can successfully be applied to BIM. A prototype rule-based system, called Green Building Design Assistant (GBDA), has been developed for automatically checking green building design [6]. The system integrates BIM, rule-based reasoning, and virtual reality to help designers by automatically checking green building design codes and presenting real-time visual feedback from this checking. Additional research using rule-based systems has been performed to solve safety issues in design and construction. Zhang [7] demonstrates an automated checking system using rule-based applies the Solibri Model Checker (SMC) as a rule-based engine for safety planning and simulation uses. This system can be described an automated, table-based safety rule translation prototype based on Occupational Safety and Health Administration (OSHA) standards and construction safety best practices.

All the researchers mentioned above focused on design applications. Conversely, research conducted by SECOM Intelligent system laboratory (a Japanese security company) is investigating security planning using rule-based systems. Their research presents an expert system dedicated to security planning called ESSPL, which generates security plans for alarm systems using the rule-based system. The system consists of several subsystems including data management, zone planning, sensor planning, and control equipment planning [8]. SECOM argues that in order to provide a high-quality alarm system, it is crucial to optimize the remote sensors and equipment layout in a building. The results of their research aim to satisfy the requirements. One obstacle they have faced during research and field tests was obtaining building plan data for their models. Because of this, 95% of time during field testing was allocated for designing an accurate building plan model.

2.2 Tailor-Made CAD for System Integration

In this research, “tailor-made CAD system” refers to a drawing and modeling system specialized for a particular field in the building design life cycles such as operation and management (O&M) or facility and asset management (FM&AM). These are typically performed by laymen without training or expertise in the commercial CAD systems used by architectural designers and construction engineers. The space management system in place at the Incheon International Airport is one existing example of an in-house, tailor-made CAD system formatted as an intuitive 3D model viewer, which was developed using a game engine. However, this tailor-made CAD system still encounters usability issues between the complex 3D viewer interface and end user. Because of this, the airport has decided only few authorized users who have taken a special training program are allowed to run the program [9]. There are several additional reasons to further the development of tailor-made CAD systems: commercial BIM tools are exceptionally complex for end-users, lack sufficient Software Development Kit (SDK) support for developing specialized requirement functions [10], and have prohibitively high licensing costs. Further contributing to the complexity issues of commercial BIM software, most organizations require only the CAD system for their work, not the additional functions included in the license.

3 Rule-based Security Planning System

3.1 Background of the System

The company, which ordered this system, was the first company to provide on-line security service, dominating market shares in Korea. The company has established an Information Technology (IT) infrastructure for successful and efficient business. This IT infrastructure has been applied new technologies such as 2D CAD, a mobile viewer for field workers, and enterprise resource planning (ERP). New technologies introduced in the field are quick to adopt the IT infrastructure.

The company has recognized that 3D mobile CAD may be combined with engineering knowledge such as rule-based system development and adapted for their business. These technologies, now mature and stable, are ready for business applications. Hence, they have decided to upgrade their current system using this technology. This research is on the process of adapting such technology to security planning. The requirements and expectations were defined prior to starting the project using current system parameters and feedback from a field employee in the targeted field. The requirements and expectations were separated into five categories: easy to draw, estimation, customer relationship, security planning rule, and efficiently of operation. The detail is described in Table 1.

3.2 System Configuration with IT Infrastructure

The Rule-based security planning system (the new CAD remains under a codename in the company at this time) is a part of IT infrastructure in the aforementioned company. This infrastructure serves enterprise data from ERP to the system, and the system serves visual data to the central control and operation management systems. Here, the visual data is a 3D spatial model including property data for the surveilled space. Each system is connected through intranet as well as the internet. The Rule-based planning system consists of two CAD programs working on both a PC and a mobile platform (Android based Tablet). Although the CAD programs function on different platforms, the user interface is unchanged to avoid confusion in non-expert end users. The system configuration is illustrated in Fig. 1.

3.3 Tailor-Made CAD for Security Planning

CAD serves multiple required functions in the system, including provision of a precise and simple drawing method, 2D and 3D view support, and multiple platform support (desktop and mobile). However, CAD requirements are often prohibitive for users without professional architectural or engineering knowledge. It was decided a game engine would be used to meet these requirements in this research. The game engine Unity 3D was chosen because it supports multiple platforms, including Windows and Android, using the same source code. As the source code remains the same, the time and cost of multiple platform development is reduced. Thus, the proposed tailor-made CAD, supported simultaneously in 2D and 3D on desktop and mobile platforms, was developed in limited time.

Table 1. Company requirements and expectations for the system

	Requirements	Expectations
Easy to draw	• No system specific preexisting knowledge required for drawing • Precise and simplified drawing	• Increased production in drawing work • Eliminate the possibility of transcription errors • Create potential to unify communication based on precise drawings
Estimation	• Support automated and manual estimation • Support partially automated, partially manual estimation in variable situations • Support recording precise elevation of device installation	• Reduce estimation errors • Eliminate gaps between design and construction estimations
Customer relations	• Enable customers in the field to create drawings using mobile CAD. • Help customers understand proposals with 3D views.	• Reduce lead time • Easily convey use to customers with 3D dynamic viewer
Security Planning rules	• Automated installation when control units and sensors are drawn • Reflect interrelation among equipment, checking installation regulations for numbers and equipment	• Prevent human errors using automated installation • Enable security planning: final confirmation of missing equipment done by automated regulation check of Security planning possible
Efficiency of operation	• Propose company recommend equipment • Enable a stock check for equipment availability • Automatically verify risk elements	• Simplify inventory management for company supply policies • Enable checks in the instance of uncertain handling procedures or equipment availability

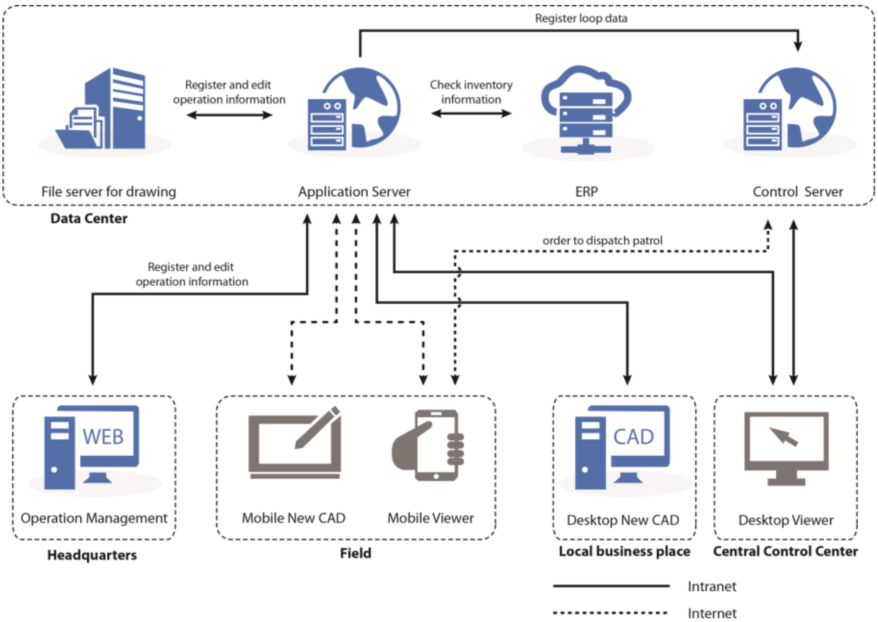

Fig. 1. System configuration including IT infrastructure from the company

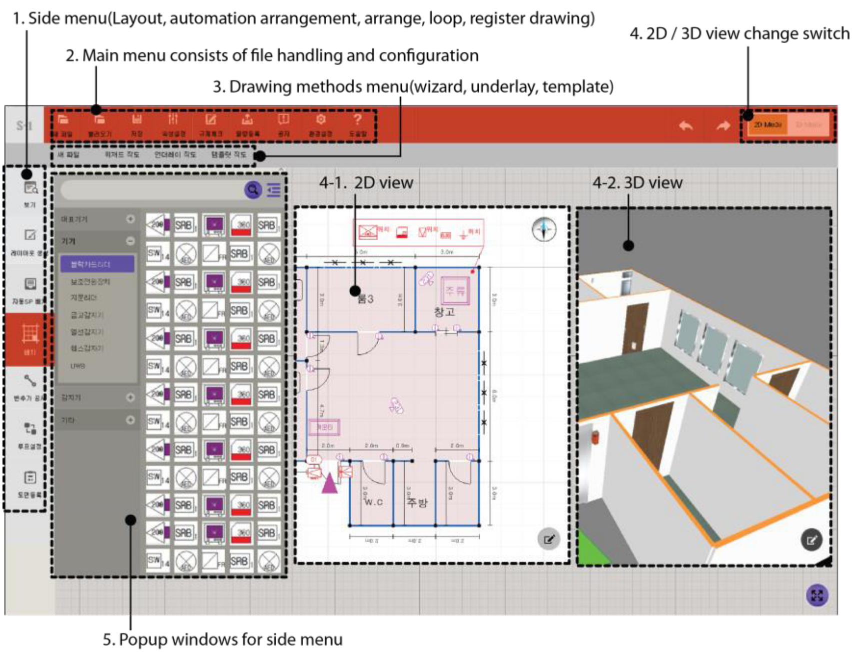

Fig. 2. User interface of the tailor-made CAD

The user interface is also considered to be a crucial element in achieving the required user-friendliness of this CAD. Many ready-to-use CAD systems on the market have complex user interfaces with too many buttons, causing delays in learning and mastering the CAD system, which naturally lead to user frustration and complaints. The proposed CAD uses the design philosophy that the simpler things are, the better. Fig. 2 shows the final product of these ideas. The number of buttons is minimized, and the design remains the same between desktop and the mobile platforms.

The ability to use CAD in a mobile environment was one of the core requirements for this project, due to the nature of security service and planning. A businessperson in the company's employ must visit the site upon customer request. Using the current system, they must survey the building for accuracy to the current drawing, return to the office to correct discrepancies and create a final drawing, and then again the site and meet customer for a second time. This is a time-consuming task, and the businessperson surveyed requested a way streamline the process, surveying the building and drawing a floor plan simultaneously in the field. Further improvements to the process were requested in the form of real-time estimations and equipment stock checks.

Developing a mobile CAD interface is not easy task. The integrated space management system of Incheon International Airport is one of good example of a successful implementation [9]. When the airport developed their CAD system, the 3D viewer worked properly and satisfied their requirements; however, the mobile CAD was different in this case because their mobile platform is still a Windows based mobile computer (using the same operating system and computing power as desktop computer). For the proposed system, the tailor-made CAD and 3D viewer will be used in two different development environments: a Windows based program and the previously described game engine.

In this research, the development environment was unified to the game engine with satisfactory results. Under this solution, the mobile CAD works on both Android-based tablets and pads. Fig. 3 shows a demonstration of the mobile CAD interface.

3.4 Rule Base for the System

The Rule-based system consists of the user interface, model controller, space model, rule engine, and rule database. This architecture is illustrated in Fig. 4. The architecture has two core parts: the model controller (shown in 2) and rule engine (shown in 4). The model controller handles space models using the model checker and layout system. The model checker analyzes features of the model against the rule engine to display information and adapt the features to applicable rules. The layout system automatically installs security devices such as sensors as directed by the rule engine. The inventory check system, a part of the model controller, verifies equipment stocks using ERP data. The rule engine handles the rule database and controls the model controller via the query interface and rule-set manager. The user interface activates the rule engine with queries and returns results and actions. Results are displayed as missing items and/or a violations list, giving users a chance to check and resolve mistakes.

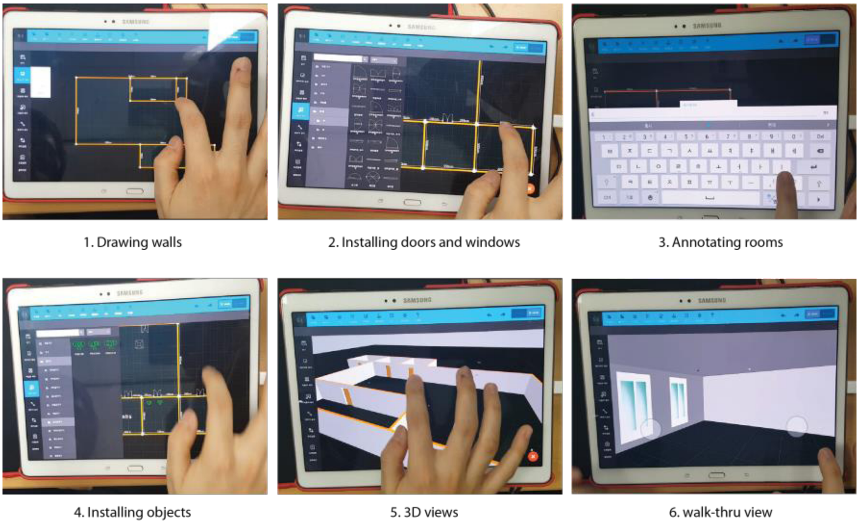

Fig. 3. Demonstrating the tailor-made mobile CAD

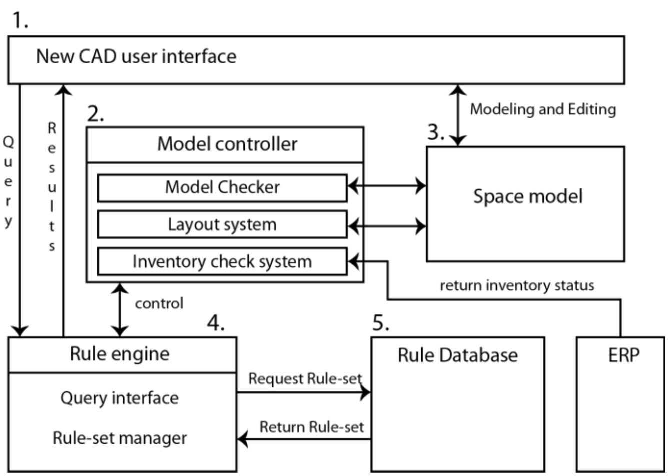

Fig. 4. Architecture of a rule-based system

The documentation-based security planning manual is converted into the database as a set of rules, and the rule database stores this as the official rule-set. The security planning rule set consists of types of business categorized by the level of security or risk, the type of space, the type of property in the space, the type of windows and doors, the type of security equipment, and the method of arrangement applied to security equipment.

The first information that runs through a rule-based system is the type of business. The rule-set used defines four types are defined as follows: 12–business common, 9–high risk common, 11–high risk business, and 10–significant business. An example of rule-set application can be shown through the process of checking whether or not a wall vibration sensor is required. First, the system checks whether or not the business type is defined as high risk. If the business type is high risk, such as a jewelry shop, the system checks if the shop has lightweight wall. In this case, a lightweight wall would be a built-in environmental risk to the jewelry shop and the system would instruct the user to install a vibration sensor on the wall. The rule can be represented in prolog style as shown below:

```
required_vibration_sensor(X):-
    business_type1(X, high_risk),
    space_type(X, jewelry_shop),
    wall_type(X, lightweight).
```

The rule application process in the system has several steps. First, the building or space model is prepared either by constructing a tailor-made CAD from scratch or converting an existing 2D CAD drawing using the converting tool. When the model is ready, the system requires the user to enter information on the model, such as the type of business and type of space. The system analyzes the model and information using the model controller and rule engine. During this analysis phase, the system checks the size of the space or room and what type of doors, windows, walls, and properties are installed. After analyzing the space, the system selects the required equipment as determined by the rules-set under the given analysis results. The system then checks the ERP information relating to the selected equipment to determine if it is in stock. Finally, the system designs a layout of the required controller and sensors in their correct positions in the model.

The system provides further regulation of the company's designed security by checking relationships between the central control device and sensors, and then reporting any missing equipment or violations. Any problems, which the system finds, must be solved, by one of the two methods provided by the system. The first method is to accept the problem, at which time an automation solution will be provided for use. In some cases, however, the system is unable to check all aspects of the situation, and the user will need to ignore the violation. To ensure maximum security and avoid errors, a single user cannot override a violation even if the situation calls for a given rule to be disregarded. For this, users must receive confirmation from the operation center to avoid critical problems. Hence, the second method is the service to request solution from the operation center. Both methods in this process are illustrated in Fig. 5.

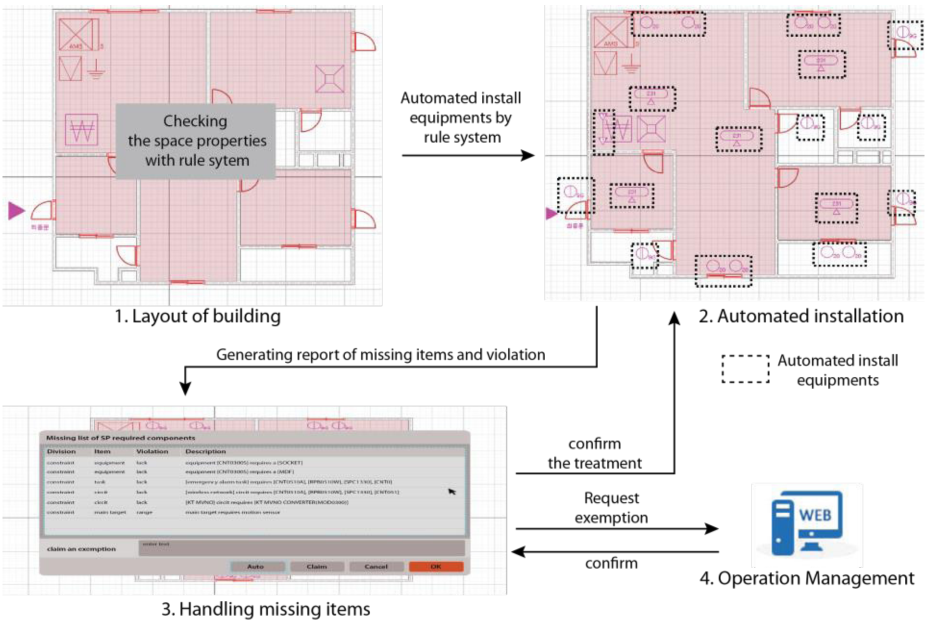

Fig. 5. Rule application process in the system

4 Conclusion

The primary aim of this research was to increase the utility of a CAD system in security planning during the operation and management phase of a building's life cycle. In the security planning phase, a 2D CAD system typically used for sales and security purposes, as businesspeople in these roles tend not to have the extensive engineering or architectural knowledge required for CAD system use. This situation may be resolved with a 3D CAD system, which is easy to use, automatically corrects errors, provides intuitive visual information, and functions on a mobile platform. The requirements are a result of the unique working environment in which salespeople must respond to clients' requirements promptly in a mobile environment. This research designed a CAD system development strategy to satisfy the field requirements. The first issue was how to develop a 3D CAD system for desktop and mobile platforms with an intuitive viewer and user interface in limited time. To do this, the Unity 3D game engine was used, chosen because it is supported across platforms including Windows for desktop and Android for mobile devices. Additionally, the game engine easily implements an intuitive user interface and 3D viewer. The second issue was how to avoid errors during security planning, such as regulatory violations regarding equipment installation and wiring. For this requirement, the security planning guidebook was converted into the rule-set for the rule-base.

The rule-base was integrated into the CAD system developed in this research so that the user can automatically check their work for errors. Furthermore, whenever a security planning rule is changed, the alteration is spread to all of staff members effectively in real-time and effectively because the system works in the company's existing IT infrastructure. As a result of this feature, issues have arisen with rule version control and change management. Regulation changes are difficult and often delayed, resulting in confusion in the field.

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BIM-based Interdisciplinary Collaborations in a Student Project Competition

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Abstract. Architecture is a profession that requires collaboration among professionals from various fields. Despite the important nature of these interdisciplinary collaborations, architecture students rarely obtain the opportunity to learn about the work areas of other stakeholders and the practice of working together. In all sectors there is a growing need for professionals who possess in-depth knowledge in their own disciplines and also develop an understanding about other related disciplines. In a setting of a student project competition, this article examines how students from various AEC fields collaborate using BIM as a common data environment and emphasizes several considerations for implementing interdisciplinary collaborations in curriculums of architecture schools in students' perspective.

Keywords: Interdisciplinary Collaborations, Architectural Design Studio, BIM, Building Information Modeling

1 Introduction

Due to the introduction of sophisticated free building forms, new materials and construction methods, the number of stakeholders involved in building design and construction has steadily grown. Architects serve as a member of a large team consisting of many stakeholders (Kirk and Spreckelmeyer, 1988). The exchange of information between these stakeholders is critical and carried out electronically in most cases.

Until very recently building professionals often worked together by exchanging CAD files during building design and construction. CAD-based collaborations frequently bring about translation errors between different applications, coordination problems in project documentations and production of redundant information, hence time and labor losses that cause financial burdens for building firms (Gallaher and O'Connor, 2004).

BIM (Building Information Modeling) is a relatively new collaboration platform that is highly promoted for building professionals as a common data environment

(EUPPD, 2014) and supported by collaboration protocols that enable professionals to work together (BS 1192, 2007; Penn State, 2011).

Interoperability is one of the strengths of BIM-based collaborations. In a team-based approach architects, engineers and other allied stakeholders develop and work with a common data model from early to final stages of a building project (Fig. 1). The ability of utilizing an interoperable model by different stakeholders (a) enhances the production of consistent project representations, (b) facilitates the project revisions, (c) reduces replications in projects and (d) improves the coordination between project documents (Ofluoğlu, 2014).

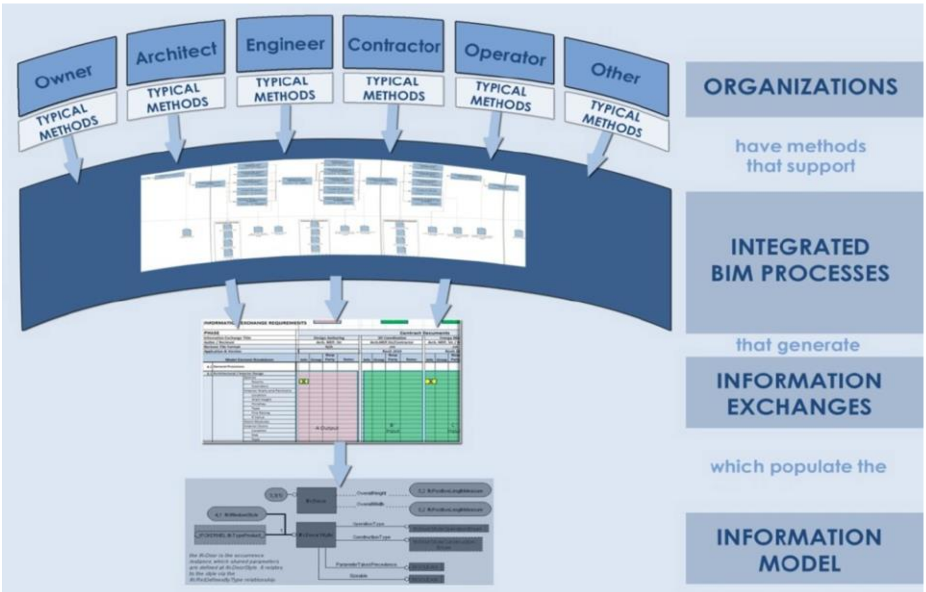

Fig. 1. Process of building information model with stakeholders (Penn State, 2011)

Interoperability is also significant for Integrated Project Delivery (IPD), a prevailing project delivery method that encourages project stakeholders to work together, to exchange information and to share risks and rewards, as part of the same team from the early stages of the project. Utilization of a plan or systematics in designating the roles/responsibilities of project stakeholders, specifying project phase(s) in which participants will involve and the content and format of the information they will excange is critical for the success of IPD.

BIM serves as an enabling technology for Integrated Project Delivery. Collaboration and data management is an aspect of BIM project processes (Fig. 2). Collaboration protocols that allow different stakeholders to work together are supported in BIM (BS 1192, 2007, Penn State, 2011). Stakeholders can work in parallel on the same project with defined a team hierarchy, a discipline-based project organization, user authorizations, common data formats and server-based collaboration opportunities.

Third-party software environments are also built on this collaboration through the interface of BIM software.

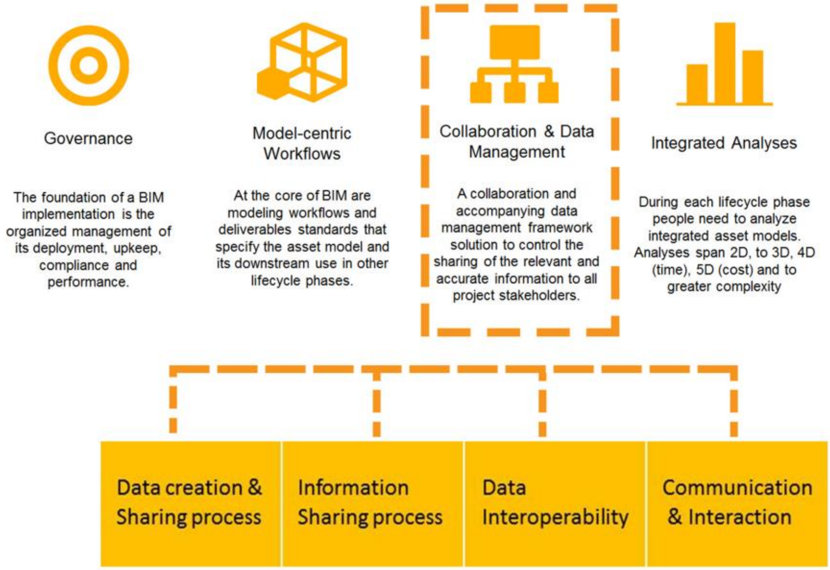

Fig. 2. Collaboration and Data Management in BIM Project Processes (Koppula, 2012)

2 Use of BIM in Interdisciplinary Collaborative Learning Environments

In education, BIM also constitutes a platform that helps developing important operative skills and understanding through simulations and virtually built projects. Due to its semantic data structure, a BIM building model can be subjected to various simulations, since it possesses all the qualities of a physical building. For instance, in order to predict performance and sustainability of their designs, students can examine their models' climatic behavior and energy use with environmental simulations. With the availability of 4D/5D BIM simulations, that integrate time and/or cost parameters, it is possible to determine the potential problems with construction sequences, timing and cost before the actual construction. It is also possible to detect possible conflicts between BIM models of different disciplines and view them both graphically and in reports in order to correct them. There are various research studies that examine the integration of BIM into design education (Guidera, 2006; Ambrose and Fry, 2012; Kocaturk and Kiviniemi 2013).

The Integrated Project Delivery settings described above also have implementations in educational environments (Ilal et al., 2009; Boeykens, et al., 2013; Tomasowa, 2015). Students experience the collaborative nature of IPD beginning from early phases of design and learn the priorities, interests and views of students from allied disciplines as if they work in a professional project environment.

One of the earliest examples of these collaborative environments is the interdisciplinary BIM studio held at the Pennsylvania State University in the USA. This BIM-based studio environment has been carried out since 2009 with the participation of students from architecture, landscape architecture, civil engineering, mechanical engineering and project management departments. It is an elective course that is planned to be transformed into an alternative design studio. Students collaborate in a BIM environment and have an experience working with students from other disciplines (Fig. 3). The feedback received from students reveals that due to collaborative group activities they learn more about the process for coordinating with members from other disciplines and understand their concerns (Holland et al., 2010).
Similar multidisciplinary design studios are also organized at University of Illinois, University of Florida, University of Maryland, Kent State University in the USA, Salford University in the UK University of Leuven in Belgium, and Sydney University in Australia.

Fig. 3. Interdisciplinary BIM Studio at Penn State University (Holland et al., 2010)

3 The "Design Together" Competition and Survey Research

The "Design Together" competition is one of first efforts creating a similar interdisciplinary work environment to the studios mentioned above in Turkey. It is aimed at promoting collaboration among AEC students and creating an awareness of BIM in universities. The competition was organized by the Istanbul Technical

University Engineering Preparatory club and sponsored by several Turkish software and construction companies in 2016.

In this interdisciplinary working environment students of three disciplines (Architecture, Civil Engineering and Mechanical Engineering) were allowed to participate as teams. 24 teams consisting of 112 students from 12 Turkish universities enrolled in the competition. Members of participating teams were given a short training on BIM software and the culture of collaboration in School of Civil Engineering at the Istanbul Technical University (ITU) (Fig. 4).

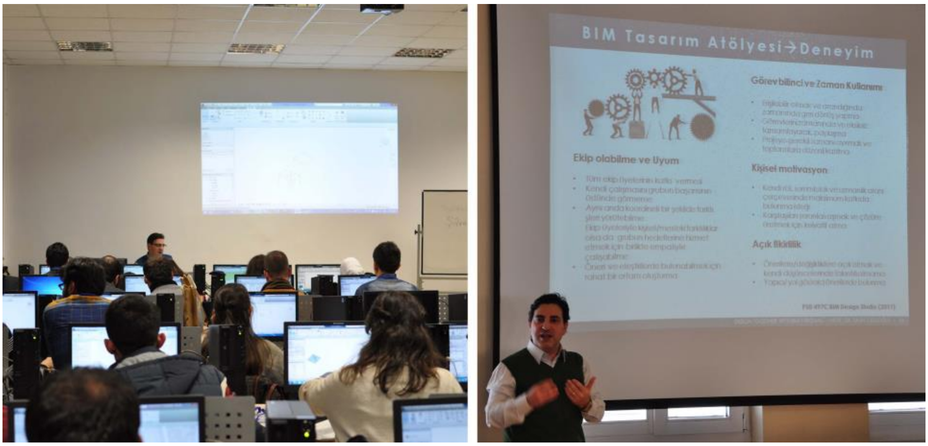

Fig. 4. "BIM Sustainability Analyses" and "Culture of Collaboration" trainings

The project involves designing a 2000 m^2 student activity center at the ITU main campus. The building contains different social-cultural spaces that enrich the campus life of students and needs to incorporate high-performance and sustainable design strategies utilizing energy efficiency and renewable energies. In this context, BIM is considered to be the key working method in achieving a high performance building in a collaborative setting.

The teams were asked to prepare architectural, structural and mechanical BIM project models, to conduct sustainability analyses and to produce clash detection reports between models along with a 4D model that illustrates the sequence of construction processes and cost. Most modeling operations and analyses were executed with software products of Autodesk, the main sponsor of the competition. Six teams submitted their final projects and three of which received awards for their achievement (Fig. 5).

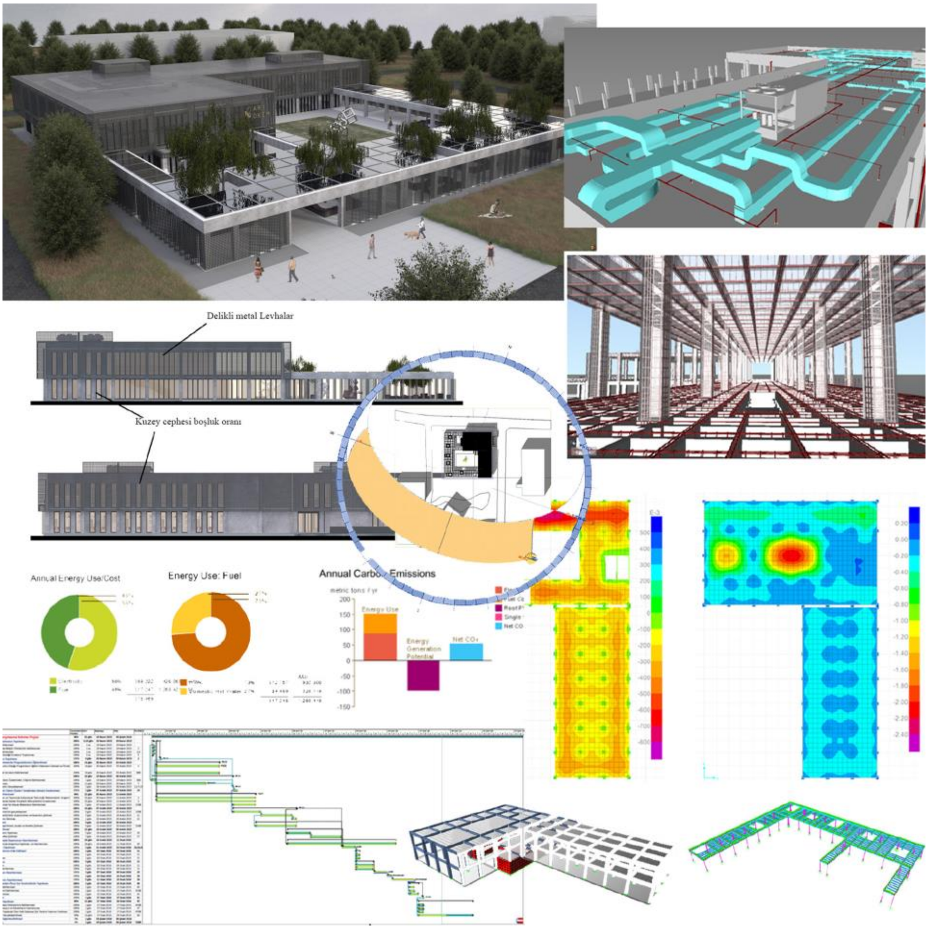

Fig. 5. The project of "KTU-Together", the winning team

Two surveys were conducted with members of participating teams. Both surveys included questions related to interdisciplinary collaboration processes, the role of BIM as a common data environment and the implementation ideas for interdisciplinary collaborations in educational curriculums in architecture and engineering schools.

The first survey was completed before the initiation of the project when teams came to Istanbul for the training. 56 participants that comprised of 20 architecture, 20 civil engineering and 16 mechanical engineering students participated in this survey. The objective of the first survey was geared towards understanding the students' expectations of working together with others and learning if they considered any systematics or implementation plans for project tasks.

The second survey was conducted only with members of six teams who submitted their final project. It contained 16 participants consisting of 4 architecture 11 civil engineering and 1 mechanical engineering students. This survey was conducted at the end of the competition and particularly aimed at understanding the extent to which the initial expectations of collaborative working are met and assessing the potential uses of interdisciplinary collaborations with BIM in educational curriculums.

All the survey data were processed and interpreted. One of noteworthy findings of the survey was that most teams had some type of a work plan to organize collaborative processes and information exchanges similar to BIM implementation plans utilized in AEC firms. According to the survey results BIM also appeared as an enabling collaborative environment that helped the progression of interdisciplinary work, and collaborative interdisciplinary environments are found to be beneficial for architecture and engineering school curriculums.

The following are the results of the questionnaire survey in three main categories. In each category both quantitative analyses and direct quotes of survey participants were presented.

3.1 Experience of Working Together with Other Disciplines

Collaboration among AEC stakeholders is a common practice. However, students generally do not have the opportunity to work with others from different disciplines during their education, with the exception of short internships, student club activities and competitions.

The "Design Together" competition offered students an experience similar to the Integrated Project Delivery environment in the real world. A very large proportion of the students found this experience positive (90%). Students also stated that working together is primarily useful for (a) sharing expertise decisions and responsibilities in a holistic project (91%), (b) understanding the roles and needs of stakeholders from different disciplines (95%), and (c) anticipating potential problems during construction (86%). Two students said that:

"*After architectural design is completed and its constructability becomes the issue. At various phases it is necessary to work with other disciplines and decide together. This competition is much like a pre-vocational training that enables us to fulfill our capabilities in the real business environment…*"
"*Architectural projects can be refined with the civil engineering and electrical-mechanical departments, producing more realistic results.*"

Although working together with other disciplines is found beneficial as stated above, it was also found to be challenging. 60% of members of the six teams who submitted their final project claimed that the interdependence of team members in the process led to occasional blockage in the information flow. This, in turn, caused delays in project delivery process. Another difficulty stated by students was that allocating common physical meeting times was difficult due to busy working schedules. This was confirmed by more than half of the team members filling in the second survey. In order to overcome this difficulty, applications such as WhatsApp and Skype were used.

Engineering students particularly emphasized the importance of utilizing a work plan to ensure smooth information flow and to coordinate processes. In the real world, too, it is critical, especially for integrated project delivery applications, to use an implementation plan to specify collaborators' roles, project processes and phases of information exchange. In this competition, 70% of the members of the teams who submitted the projects stated that they worked according to a plan. One participant stated that:

"*Certain phases of the project can be completed effectively in a specified period by setting out a plan, which determines the deadline for submission of the competition project.*"

Having a common team vision (83%) and respecting others' ideas (64%) were considered very important for working together by survey participants. One participant described this attitude as follows:

"*As a team we worked in collaboration by exchanging information and respecting each other's ideas and insights. Together we did brain storming and corrected our mistakes. Thus, we have combined different views. At the same time, this cooperation has enhanced our workforce.*"

Despite such value attributed to teamwork, in the second survey conducted after the project submission, more than half (56%) of the students said that they did not work with the same vision and understanding. The fact that only 6 of the 24 teams in the competition delivered their project might support this finding and suggest that there may be a lack of co-operative culture in various teams. Difficulties in working together might arise from different interdisciplinary priorities and views. One student claimed that:

"*... my teammates who are engineers have more rational approaches. I am convinced that they will make fun of my aesthetic worries by saying "a typical architect's attitude" A tough process is waiting for me. They consider architecture as making a house from cardboard.*"

3.2 Utilization of BIM Tools in Interdisciplinary Collaborative Projects

One of the most important challenges for the teams was that they were required to develop their project in BIM environments, which they had never used before. More than 75% of the students who participated in the competition did not use any BIM software previously. Nine of the architectural students and four of the civil engineering students used BIM software; none of the mechanical engineering students had any BIM experience. In real professional practice in Turkey, engineers' BIM software usage rates are lower than that of architects as well.

Of the survey respondents %77 stated that there was not any BIM related courses in their schools. They also mentioned that their school faculty do not have much information about BIM software and do not encourage its use. Some used the following phrases for the situations they encountered:

"They want a hand-made model (instead of a BIM model), they are prejudiced."

"They generally think that we should not use it and say that they (BIM software) are the worst among all three dimensional software."

"So far no one said anything positive about BIM; they even tried to convince me to use other applications."

Three questions were asked to students about their attitudes towards BIM. In the first question, they were asked to choose their five most important reasons for using BIM software. Students appeared to choose the tasks with which they might be familiar from geometric modeling software instead of marking BIM-specific features only.

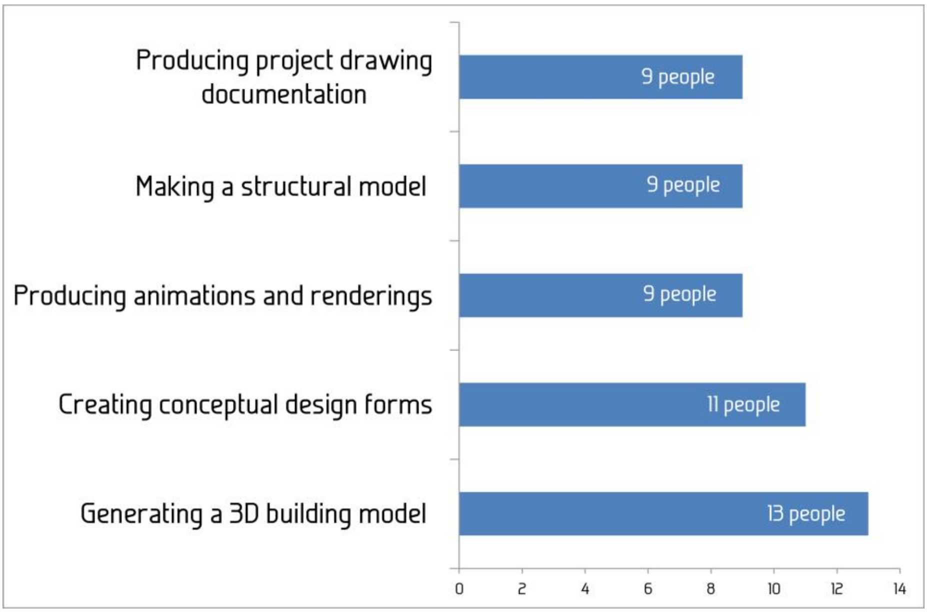

Fig. 6. Five important reasons for using BIM for survey participants

In the second question, students were expected to mark three of the most important capabilities of BIM software. The resulting ranking reveals that more general features of the technology is preferred over task specific operations such as sustainability analyses, clash detections and 4D simulations.

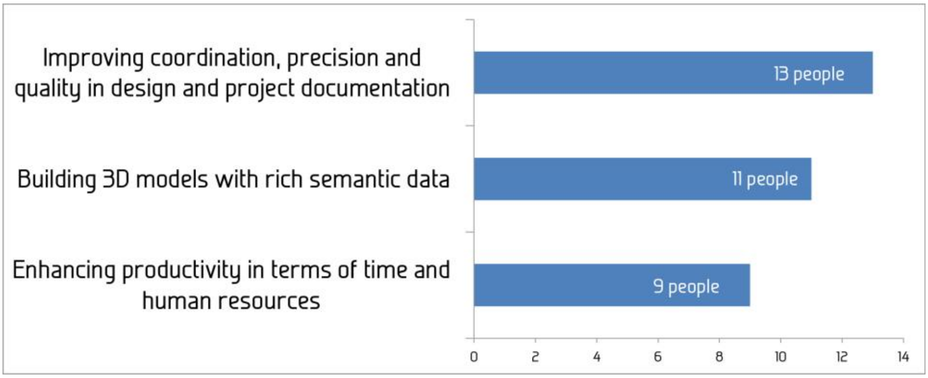

Fig. 7. The most important capabilities of BIM according to survey participants

The third question was about which areas BIM software can contribute to team working and collaborative projects. The three areas that are most preferred by participants are:

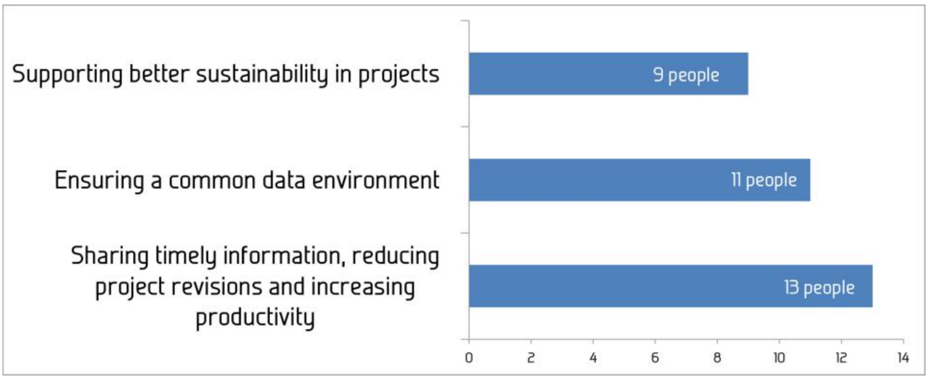

Fig. 8. The most preferred features of BIM according to survey participants

3.3 Interdisciplinary Collaboration Opportunities in Academic Programs

Another area examined in the survey study was the possibility of integrating interdisciplinary collaboration environments into undergraduate and postgraduate programs in AEC disciplines. In the second questionnaire, students were asked whether such collaborative settings could exist in an educational program and how it could be achieved.

All the students (16 people) from the teams that delivered their project stated that it would be beneficial to have a project course based on interdisciplinary collaborations like this one in the curriculum. They think that such a course should be offered in the later years of the curriculum, specifically in the third year (6 people) or the 4th year (10 people). Some students also believe that this course must be compulsory (10 people). Students emphasized that the important asset of this course would be to create an environment that is similar to the working culture in the real world (16 people) and to allow people from different disciplines to get to know each other (10 people). Two participants said that:

"*Through this course, students will have the opportunity to see the real life problems....*"

"*It is absolutely crucial to have such a course that brings all the disciplines together... In this type of a course, students may encounter real business world problems. This course can provide students with solutions to these problems.* "

Some students suggested that this collaborative project course can be organized as a construction project studio, a diploma project studio or a workshop outside the curriculum. They also implied that there must be good coordination between departments and faculty members, and the buildings/campuses of participating disciplines should be in close proximity to each other. Several students recommended the following educational scenarios:

"*Existing project studios can be revised (to accommodate other disciplines).*"

"*... departments can offer joint projects, especially in diploma projects of the final year.*"

A significant number of the students (63%) feel that the use of BIM software as a common data environment should be compulsory and knowledge of BIM should the prerequisite for interdisciplinary courses that require collaboration.

In the first survey that involved more participants, some students also expressed reservations regarding the integration of interdisciplinary collaborative environments into their educational curriculums. They pointed out that it would be difficult to implement this new teaching methodology in already rigid and intensive course curriculum. They also had doubts about the existence of visionary teaching staff who would implement this new method. They mentioned that:

"*The teaching staffs have their own instruction methods and behaviors. I do not think they will be open to different ideas*"

"*Our school program is already busy, so it is difficult to implement it. BIM requires intense work and it is hard to do that in addition to our existing studies.*"

"*Schools' administrates should be visionary (to implement it).*"

"*The students in different departments are stuck with time because of different campuses, different curricula, different exam calendars ... it is very unlikely that common courses and curriculum will be organized*"

One student also stated that instead of creating such interdisciplinary work environments in an existing curriculum, long-term internship opportunities could be considered:

"I think that every discipline must first gain competence in itself. I think that the encounter of these different disciplines should be in a pre-professional business environment, not in school. This pre-professional environment should prepare students for the real world. I think that our existing internships should be extended for a longer period of time."

4 Collaboration Opportunities in Educational Programs in Architecture

The survey results highlight the significance of interdisciplinary collaborative working environments and possible implementation options for AEC schools. Architectural programs in many schools appear not to adequately address the practice of working together with people from other allied disciplines in their curricula (Macdonald and Mills, 2011). However, in architecture and other sectors there is an increasing need for professionals who are already experts in their own field and also have a working knowledge about the fields with whose members they collaborate (Hansen and Oetinger, 2001; Buxton, Bill 2009). Some classify these people as T-shaped professionals (Kelley, 2005). There are many institutions and universities that support the type of education these professionals need and encourage interdisciplinary approaches (Bardecki, 2015; Oskam, 2009; Karjalainen and Salimaki, 2009; Holley, 2009).

There may be several ways to offer such interdisciplinary environments in architectural curriculums. Specialized design studios, elective courses or workshops outside the curriculum can be appropriate venues to offer needed collaborative skills for architectural students and to allow them to interact with students and faculties of other departments. The survey results incorporate several considerations that might influence the implementation of interdisciplinary collaborative environments in universities.

1. **Supportive BIM and digital media courses:** The prior knowledge of BIM, as indicated by survey participants, would be an asset in collaborative design studios. Availability of BIM and other digital media courses offered in earlier semesters can allow students to allocate more time for design and project documentation in design studios. Introduction of online software training materials can also offer active learning opportunities for students outside the classroom.
2. **Availability of technology-savvy staff:** One of the complaints of the students taking part in the Design Together competition was the lack of knowledgeable instructors in the utilization of BIM. In recent years, instructors of architectural design studios are expected to possess professional knowledge in architecture and to be competent in digital media. These instructors convey their knowledge of design and presentation skills using digital tools. In a collaborative context, every

discipline should be represented with one or more instructors, and one of which can be assigned as a coordinator to organize the events. In addition a teaching assistant who can help students with their day to day BIM and CAD related tasks would be an asset.

3. **Implementation plans for managing sources and actors:** It can sometimes be challenging to bring together people with different professional qualifications, priorities and working styles on a project. This can become even more difficult in educational settings where the roles and responsibilities and work schedules are not clear. The importance of implementation plans was also emphasized by students taking part in the Design Together survey. It is therefore important that project stakeholders prepare an implementation plan that will guide them to work together, facilitating, project workflow, data exchange and assignments of roles.
4. **Coordination among departments:** The course schedule of the faculty and students of the collaborating departments, the availability of classrooms and departments' physical proximity to each other can make the arrangement of physical meeting time difficult. Necessary efforts should be made to create common times and flexible schedules for all collaborating parties. This issue was also highlighted by several survey participants in this study. Utilizing electronic communication media would also be an option to meet outside working hours in case of necessity.

Overall, this study reveals that students find BIM-supported collaboration experience beneficial and would also like to see its implementations in educational settings. This research only reflects students' perspectives. This view should be complemented with further research that would examine the opinions of other participants such as teaching and research staff that take part in such collaborative environments and integrate pedagogical outcomes of this approach.

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Designing as a Team by Utilizing Analogue Media versus a Computational Tool for Parametric Modeling Lessons Learnt from a Study in an Educational Setting

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Abstract. In this paper, we report on the conceptual design processes of two teams of graduate students that emerged in an educational setting as the teams worked on two different but scope-wise similar problems by utilizing analogue tools and a computational tool for parametric modelling respectively. We describe the similarities and differences that we observed within each of the teams' respective design processes and the nature of the solutions they generated for the respective problems as well as the similarities and differences that we discerned across the teams' design processes. We discuss the implications of our findings for integration of digital technologies in architectural curriculum and development of digital technologies for supporting collaborative conceptual design processes in architecture.

Keywords: Design Behaviour, Teamwork, Collaborative Design, Parametric Design

1 Introduction

Reflecting the changes within the architectural design industry and the substantial demand for graduates to be digitally well-educated, the significance of developing digital design skills and knowledge in employing the digital tools in the conceptual design phase is gradually acknowledged. As technology continuously advancing, the question of how and what to teach to the new generation of students in this digital era becomes more challenging that would 'require the consideration of new pedagogical approaches employing emerging design medium' [1, p.203]. With these ideas in mind, we delivered a digital design studio for the graduate students in Istanbul Technical University, providing a comparative environment for students who were exposed to the analogue to cutting edge parametric tools for the conceptual phase of their design process. We reported the course structure, outcomes and our observations during the digital studio, discussing the findings and possible benefits of the digital design studio.

One of the key aspects of the course was to provide an environment for the students to experience digital design tools, such as parametric design tools in collaborative design settings. Architects use parametric models that 'are in essence created by a set of constraints specified using parameters and their relations' [2]. Ostwald [3, p.9] suggests that a parametric model must have four of the following guiding principles: the first one is that parametric objects should be the combination of ‘dimensional, innate and rule-based parameters’. The second one is that the models should keep ‘connotative rules; this means that any change in parameter will have an impact on any others within the project’. The third one is that the model should not encumber ‘established rules or they will signal to the designer if they are forced to breach the rules or requirements of the system’. The final one is that models should be able to ‘output various forms of data’. With the developments of the digital design technologies such as ArchiCAD, Revit, and Rhinoceros 3D, the parametric modeling would be able to occur in the digital realm.

Previous literature has investigated parametric design from various perspectives with differing methodologies. Yu et al. [4] studied the design behavior that is exhibited while designing in a parametric design environment. The studies concerned with understanding the design processes conducted via parametric techniques have mostly been conducted in individual design context [5] and in educational contexts such as courses [6-9] or in workshops with students working on a design problem individually [10]. Similar to those studies, we also focused on one of the simulative packages that is Rhinoceros 3D in our design teaching, but differing with the addition of teamwork in design teaching.

Working in teams in the field of design is based largely around the determination to explore what the digital realm can achieve and provide to the collaborators in both practice and education. Collaborative projects are often rendered complex and challenging to carry out by establishing a common goal, and a common working culture and understanding, reconciling multiple concerns and ideas. Most research on co-located conceptual design processes in architecture as conducted via analogue tools has been studied with teams comprising expert architects [11]. Among the studies that looked into collaborative design processes of students, most have either focused on distance collaboration as realized with collaborative design environments such as virtual design environments [12] tools that support collaborative sketching or sketch based modeling or via tools of building information modeling [13,14] or focused on co-located collaboration that takes place as the teams co-generate digital sketches via sketch boards, tables or tables.

As digitally mediated collaborative and parametric tools appeared through popularization in design studios, the strategy of testing the new pedagogy would account for the opportunities it presents. In this paper, we discussed our findings from a course examining design behaviors of teams of students that would exhibit while working with two different mediums, analogue media and a computational tool for parametric modelling.

2 Methodology

The ‘Digital Architectural Design Studio’ (DADS) is a compulsory 3 credit course for the graduate students of the architectural design computing program in Istanbul Technical University. Every semester, the course is delivered by a different lecturer with a certain theme relating to the intersection between digital technologies and architectural design.

In Spring 2016, the course was announced to be carried by the second author with the theme of ‘design collaboration in the computer mediated design environments; its objectives were (1) to introduce students to concepts of team work mainly over synchronous communication, (2) to introduce students to varied design environments from analogue to object based and parametric, (3) to develop skill of managing and monitoring a team work in a computer-mediated environment, (4) to gain an understanding of the changes in the architectural design practice through the employment of different design medium.

In the course, the students would be required to generate conceptual designs for three different design problems by working in teams and utilizing three different media respectively. First, they would be designing additional workshop and exhibition spaces for the faculty of architecture at the area located behind the faculty building via utilizing analogue media (this is called- AT in this paper). In the second design problem, they would be generating an initial design of a high-rise tower at a virtual island within a 3D virtual world, Second Life, which supports object based modelling and scripting. In the third, they would be designing a pavilion at the University's main campus with a parametric design approach by adapting a tool that supports parametric modelling, Rhinoceros with Grasshopper plug-in (this is called PMT in this paper).

This course attracted nineteen graduate students from the architectural design computing program with eighteen holding a bachelor degree in architecture and one holding a bachelor degree in interior architecture. At the first day of the course, the students were randomly formed into 5 groups. They were introduced to the content and structure of the course and were required to establish a team-blog until the second class in order to keep logs about the experiences they had, the schemes they worked in, and the activities they carried out on a weekly basis. During the term, the students worked on design with AT for two weeks (at weeks 2 and 3), worked on their design within virtual world for 4 weeks (at weeks 6 to 9) and worked on design with PMT for four weeks (at weeks 10 to 13). They were introduced to the design environments at the first week of their designs within virtual world and with PMT and presented their designs to the jury following the completion of each of these projects, including weeks 5, 9 and 14 respectively. After the exercises were carried out, students were asked to write a reflective report about their design processes with an emphasis on how they collaborated throughout the process. The students were also required to fill in a questionnaire about their design with AT, and their past experiences of designing with analogue tools.

During the term, students worked in two different classroom settings: in a classic studio setting in first design exercise and in a computer lab during the second and third design exercises. The study was conducted via the first authors' participating in all the classes during the term as an observer by informing the students about the motivation of her participation and collecting various forms of data from the four teams that gave consent for participating in this study in addition to those collected via direct observation. These involve video recording the processes of the teams, images of the drawings or sketches that the members generated, any written material that teams have generated, such as notes they had taken during the class and off the class hours if any and personal accounts collected via unstructured interviews and informal conversations with team members on the issues that came to attention during the study.

Since the end of the term of the class, we have been reviewing and transcribing the video-records of the groups' design processes, presentations and the members' reflective reports in order to investigate the issues that we set forth in the context of larger research agenda. In this paper, we mainly discuss the partial findings that we reached at in this larger study regarding the processes of two teams as they design with AT and PMT, where we are in the process of reviewing and transcribing 80 hours of video footage collected during the course of the whole semester.

2.1 Overview Of The Design Outcomes

Group A- Design with AT. Group A's proposal for the first project, welt-beat (Fig. 1), involves a series of prismatic demountable units connected to a wheelchair friendly walkway, a walkway that starts from the back door of the main building, continues straight to the service road at the back yard in alignment with the main axis of the main building. The walkway is composed of set of stairs with different widths and a ramp composed of parts (sloped and un-sloped) running in oblique direction in between the stairs. The pavement of the stairs composing the walkway are also used at the courtyard of the main building in the same proportion with that used in stairs, as if the stairs are continuing inside the building.

Fig. 1. Representations of Group A's design proposal for the first project

Group A- Design with PMT. Group A 's proposal for the third project, the 'ex-quilt' (Fig. 2) is located at greenery in front of classroom building in the campus area, a space which is commonly used by the students for leisure purpose during the class breaks at the dry and warm weathers. The proposal involves a shelter designed to cover semi open and enclosed spaces defined for the required facilities. The shelter involves a free form surface that curves multiple times in both directions, is supported by tree-like columns, a surface which is located at the minimally used area on the greenery, and whose form is defined based on the paths pedestrians were likely to take while roaming at the greenery, the relative densities of movement on these paths, the spacing between grid underlying the organization of the classroom building's façade.

Fig. 2. Group A's proposal for the third project

Group B- Design with AT. Group B's design proposal for the first project, 'the axis'(Fig. 3) mainly involves a building with two intersecting prismatic masses with one slightly higher than the other. The project is called axis, mainly because the two intersecting masses mainly emerged upon groups' conceptualizing the referent axes. One of these masses lies on the entrance-exit axis of the main building and houses the main entrance area and the workshop area. The other mass lies on an imaginary axis that is parallel to the contours of the terrain and houses the exhibition area, the service areas like kitchenette, offices, and the service entrance. It should be noted that the physical model of the project also involves an undulated shelter over the entrance, which the group included into their proposal symbolically at the time, with the vision that they could work on its design when working with PMT.

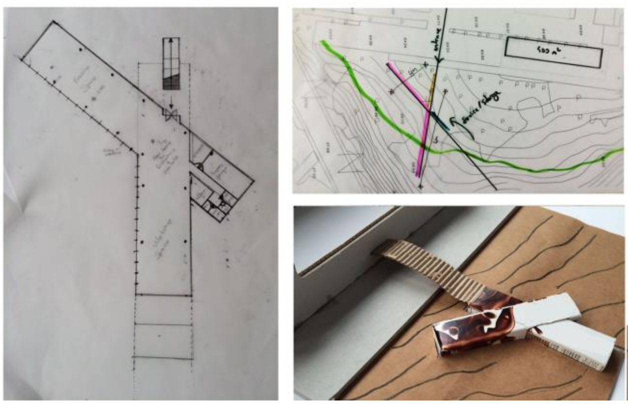

Fig. 3. Group B's design proposal for the first project

Group B- design with PMT. Group B proposed their design 'the amphitheatre' (Fig. 4) as to be located at the as they call 'lake area', at a spot which can be accessed from the road, and where the terrain slopes down towards the lake. The design mainly involved a shelter covering service areas, an area for seating and a stage for performance. The shelter is composed of a free-form shell surface that descends down in the direction of the slope towards the lake 'as if welcoming people and leading down to the stage area' as the team says. The shell sits on the ground at 5 points, 4 at the corners and 1 in the middle. The seating area rests directly on the terrain, with the terrain being carved and prepared to generate the seating area and the stage is a floating stage above the lake and is connected to the land via walkways.

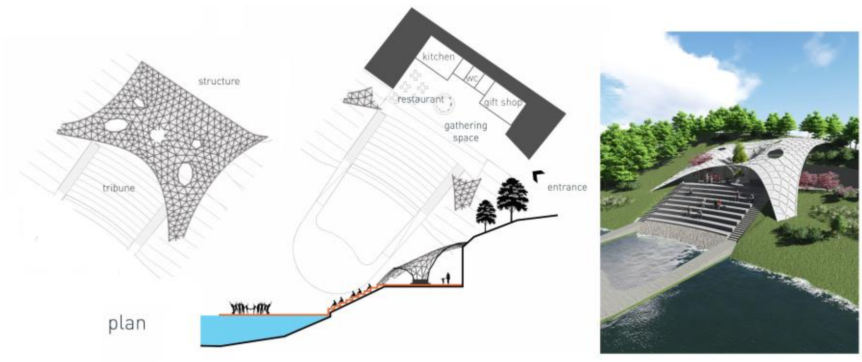

Fig. 4. Group B's design proposal for the third project

Next, we first outline the similarities and differences that we observed across the different team's design processes while working with the same media and give a brief overview of the groups' design processes with regard to the aspects that we discerned to be similar and different across the groups. We first focus on the processes conducted with AT and then those conducted by utilizing DPT.

3 Observations

Although differing in pattern of their occurrences and intensities, the groups undertook a similar set of design activities in a cyclic fashion while designing with the same media and carry out some further activities in their processes with PMT. In both processes, the teams carried out a series of activities for defining and framing the problem, generating ideas for possible solutions, modelling and evaluating these ideas. The additional activities observed in processes with PMT, mainly involved those that relate to parametric thinking/modelling, such as establishing the relationships between parameters or constraints and those that relate to realization/making of the design ideas such as evaluating/manipulating alternative solutions by considering whether they can be realized with the form generation capabilities of the tool or with their tool knowledge; or whether they can be fabricated with the fabrication technologies available to the groups' use at the time.

The members of each group interchangeably worked in at least two different modes of collaboration throughout their design processes. These were much like what Kvan [15] defines as close-coupled and loose-coupled modes, where "the participants work intensely with one another, observing and understanding each other's moves, the reasoning behind them and the intentions" and where "the participants work separately on the agreed-upon parts and then they put them together" respectively. Here we use the term 'at least' because there were various instances where some members of a group worked in a close coupled mode while other(s) work independently in a loose coupled mode.

We further observed that the members of the same group worked in the same collaboration mode when dealing with similar issues and/ or carrying out the similar activities across their processes with different tools, in other words we observed members to somehow establish their own collaborative design styles. For instance, in both of their processes members of group A generated their design ideas by working in a close-coupled mode, and often worked on visualizing/detailing alternative ideas in a loosely coupled model; members of group B carried out both of these activities in a closely coupled mode across different processes. In addition, we found members of both groups, to work almost at all times together in close-coupled mode, at the times they work on defining the constraints and goals, exploring possible ideas for solution and deciding on the idea to pursue with, while working with both media.

Like their carrying out similar activities by working in the same collaboration mode, each of the teams exhibited similar approaches in their design processes, as though they have developed their own ways of designing. In both tasks, group A, first worked on defining the problem by collecting a large amount information and identifying as many of the constraints and requirements as they can and explored various alternative ideas for solving the problem that is being specified in parallel. They then narrowed down their solution space by evaluating their various ideas against the emerging set of goals/criteria/requirement, and worked on one or a couple of more ideas in detail, to elect and develop it into a full solution. On the contrary, in both tasks, group B focused on identifying a possible solution or partial solution, or a means to derive at the solution as early as they can with a concern for its applicability for the problem at hand, or the problem that they redefined in the light of the potential of the identified solution. Once they justified the solution at hand, they immediately proceeded with developing it further or modifying it in accordance with the current definition of the problem at hand.

In their both design processes, the participants heavily relied on sketches, along with verbal utterances that describe the entities they were sketching at the moment, for expressing and communicating their design intent. In cases where they cannot sketch, for instance due to lack of a drawing sheet or an easily accessible surface for sketching on, they turned to co-speech gestures for depicting the visuospatial aspects of the design ideas that they are referring to in speech at the moment. They also tended to produce gestures at the times they are talking about a further visuospatial aspect of an element (as in Fig. 7 and 8) that they have depicted in their sketches or are currently inspecting the computer screen, such as the relationship of a building bock with the sloppy terrain, or the 3D form of a roof depicted in plan or section view.

Both groups heavily relied on sketches for - expressing and exploring their ideas both when designing with AT and PMT; they did not generate any physical model for exploring design in their processes with AT; they only generated one for presentation purpose. Indeed, they made use of the PMT in different ways while designing with PMT. As will be described later, one of the teams did not use the parametric component in their design processes at all. They rather used the geometric modelling component for the purposes of generation and optimization of form. On the contrary, the other group used the parametric modelling component along with a suite of different applications such as those supporting swarm intelligence.

As can be observed in Fig. 1 to 4, nature of the designs that groups generated while working with different mediums were quite different from each other. In their design with AT both groups generated forms with prismatic geometries whereas while designing with PMT both groups generated forms with free-form surfaces.

3.1 Groups' Design Approach While Working with Analogue Tools

Group A. Upon coming from the site visit, members of group A first studied the characteristics of the site individually with reference to their observations on site and by looking into their copies of the site plan and tracing sketching certain/derived features of the site on the sketch paper laid over the site plan (Fig. 5- left). This session was followed by a collaborative session (Fig. 5- right) where members worked in a close-coupled manner; expressed visuospatial aspects of their ideas mostly via sketching and/or gesturing; explored their ideas via spontaneously and collaboratively sketching often on a shared surface, (on the surface of a tracing paper laid over the site plan), and by interpreting, adding to, modifying and reinterpreting the developing sketches.

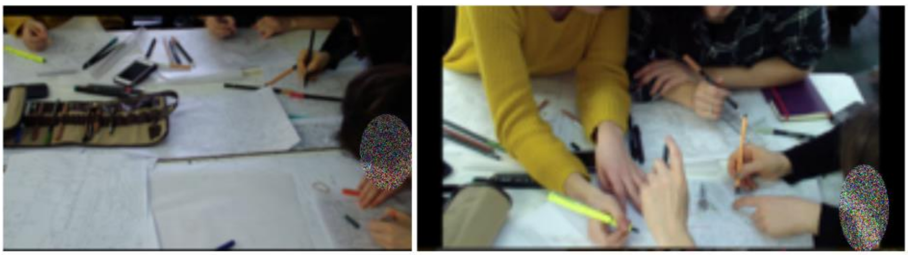

Fig. 5. On the left: members of group A are studying project site in a loose-coupled mode; On the Right- members are exploring ideas for a solution in a close-coupled mode via sketching on a shared surface

In this session, the group examined the potentials of the site; identified constraints and requirements imposed by the site/ building the program; set up their goals and concepts for the project; began to explore possible ideas for solution mainly by focusing on issues of circulation, access and possible schemes of layout for masses /functions on the site. In developing the proposal, group was mainly concerned about developing a path for, 'affording access' as they say, between the back yard and the main building, a path walking through which one can, 'become a part of' as they say, visit/view exhibitions or come across/join workshops. The path should be aligned with the main axis of the main building and should be accessible for the wheelchairs so it had to involve a ramp. The enclosed exhibition and workshop spaces should connect to the path by creating courtyard like spaces. These functions should be housed in demountable units that have minimal contact with the ground and would have a minimal impact on the terrain in the case they are to be removed.

After coming up with a set of initial ideas for the design solution, the group members continued to work in a loose and close coupled fashion in a cyclic manner; close coupled at all the times they work on generating alternative ideas and making decisions, and loose coupled often at the times they work on developing/visualizing versions of the same idea or exploring an aspect of an idea e.g. calculating the relative levels at which the building masses should sit on the ground in relation to the slope of or different aspects of a core design idea, and studying cases and/or collecting information about an issue the group is dealing with at the moment.

Group B. Design process of group B started with some of the members' studying the site plan and reading the brief for a brief episode by occasionally asking questions to each other. It then continued with the members' discussing the characteristics of the site in close coupled mode and occasionally drawing some of the aspects/features/reference lines that see in/ identify at the site on the sketch papers that they each placed over their site plans (Fig. 6- left). The design took its course around the 10th minute of the discussion, when the members considered to use the entrance-exit axis of the main building as an axis in their design and the line one of the members drew in intersection with this axis, and in parallel to the contour lines of the terrain as a second axis in their design and then decided to house two primary functions by generating masses that lie along these two axes.

Fig. 6. On the left: members of group B are studying project site and reading the brief in a loose-coupled mode; On the Right- members are exploring ideas for a solution in a close-coupled mode via sketching on a shared surface.

From this moment to the time that the team (have thought to) have taken all the decisions for specifying their conceptual design, the team intensively worked on developing the idea of designing the building by using axis, in a close-coupled manner (Fig. 6- right), and with members often expressing their ideas via sketches, by referring to the sketches or gesturing about them, and generally one member generating the sketches for capturing/expressing the ideas under discussion. In this session, the team mainly explored the physical characteristics of their masses, the layout of the functions in relation with each other and with the constraints/ opportunities/ goals that they identify based on the characteristics of the terrain, physical conditions of the site and the existing uses /buildings at the site. Following this session, the members of the team concluded their design process by working on the details of their design and generating its drawings in a loose-coupled mode.

3.2 Groups' Design Approach While Working with Parametric Modelling Tools

Group A. At the beginning of the process, members of group, alternatively carried out two primary activities sometimes by working individually, sometimes in subgroups and sometimes all together. First of these activities was the examination of precedents in pavilion design, particularly those designed via a parametric design. The other was searching for the possible sites and the kinds of analyses that can be conducted for identifying potential sites on the Campus for the project. While carrying out these activities, the members spent considerable amount of time in discussing the constraints for their design, ranging from fabrication techniques available to their use to the modelling capabilities of the tool; thinking about possible schemes or sources for deriving parameters ranging from via conducting chemical experiments with materials to examining patterns on leaves; and methodologies they can adapt for defining the site and generating their form.

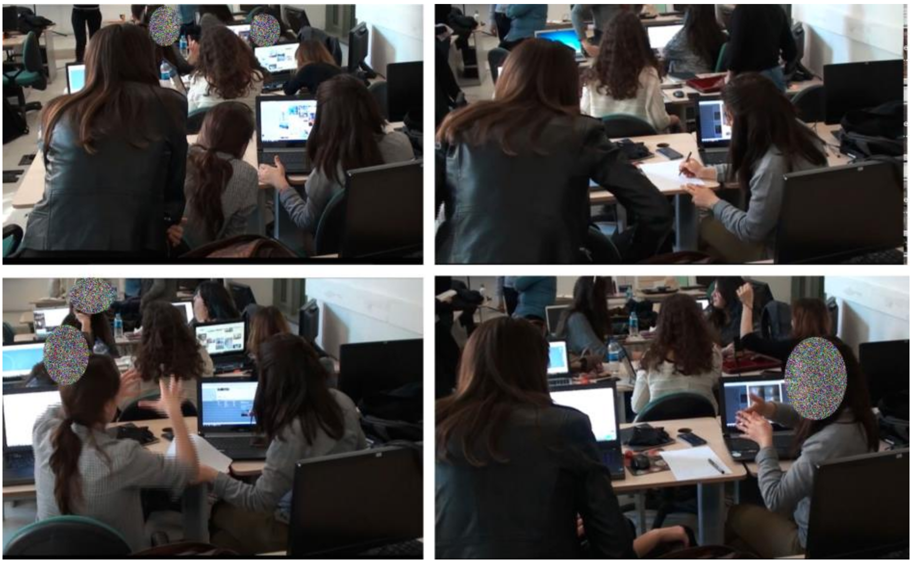

Fig. 7. Image above left- members of group A are discussing about a precedent design; Above right- one of the members is sketching an idea, Below left- one of the members is expressing and modeling the form she imagines in her gesture space, Below right- one of the members is expressing her idea**.**

Following this initial process, the group identified trajectories of movement by simulating swarm behaviour, and use these trajectories for developing the 3D geometry of the pavilion. The groups' process unfolded with this decision. From this moment forward, working in a close coupled mode, they expressed and explored their ideas via sketches, thought iteratively about: how they would identify exact spot for the pavilion based on the outputs of the simulation e.g. least dense area, mostly passed by area; how they would use the trajectories of swarms in deriving form e.g. whether they would use them for fragmenting the surface, or as trajectories of strings that would then become intertwined to define surfaces; what other site-driven data they could use for generating their forms such as the patterns to be driven from the leaves of the trees on the site, the grids on the building surface; the methods of modelling they could use to and whether they could generate the forms that they envision within the environment of the current PMT and by which digital fabrication technology or how those forms could be fabricated.

During this process, the members relied heavily on sketching to express and explore their ideas, particularly to envision the layout of the form on the site, and the nature of the building form to be derived based on the selected variables. They often used gestures to communicate their ideas about form and procedures to derive form particularly at the times they are trying to express free forms; and even simulated the transformations the tool would apply on the trajectories by drawing them and then simulating to be stretching them to the third dimension in certain forms via their gestures. Having identified their methods, and envisioned and visualized the possible geometry of their form by working in a close coupled mode, the members started to work on activities for realization and making of the form in a loose-coupled mode by allocating the work based on their interests and expertise, such as a participant working on acquiring data from simulations of swarm intelligence, other processing that data for it to be used in the PMT, another working on generation of the model within the tool's environment.

The issues that concerned the members most were mainly related to finding generating, or fine-tuning the form of a design, based on parameters that might or might not be related to the design problem at hand, rather than the functional and behavioural aspects.

Group B. The group started the process by identifying a site for the project which is not specified in the brief, with the consideration that getting to know/analysing the project area first can make their design task easier as it did in the analogue design session. Studying the site plan of the campus, the group considered lake area as a potential site for the project; the lake area houses dorms that are far from facilities at the campus area and has a sloppy site where the land descends towards the lake. If they selected their project site from the lake area, they could focus on providing students, living at the dormitories there, a place to eat during the weekends and the people at the campus a place to eat and/or spend some leisurely time by looking over the lake.

As the group was examining topographic characteristics of the lake area, and trying to figure out further reasons or motivations for selecting the site, one of the members suddenly recalled his friend at the university's drama club mentioning about the club's being in need of a performance area and suggested that with such a slope they could design an amphitheatre. The other said they could put the stage on the lake, and seating towards it; he knows a case where the stage was on the water. This moment was much like the moment at which the group's design process with AT had taken its course by members seeing the two imaginary axes as the axes of the masses in their design. Following this moment, they conducted a search for relevant cases, previous designs relating to performance areas and their shelters and stages on lakes as cases to learn from or transfer certain features.

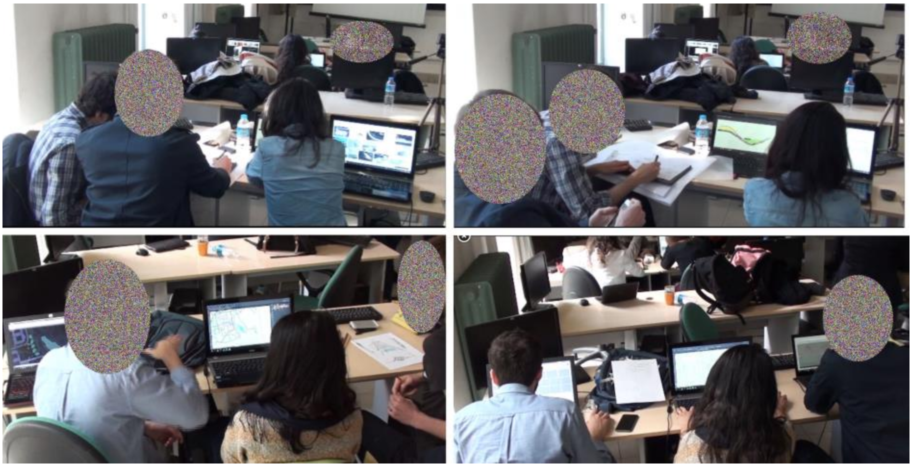

Fig. 8. Image above left- members of group A are discussing on an idea with one of the members sketching at the time, Above right- one of the members is sketching his idea; Below left- one of the members is expressing and modeling the form he imagines in his gesture space; Below right- members are carrying activities relating to realization and making, in a loose- coupled mode.

From this moment to the moment that they believed they had an idea that they could go further with, the group carried out various activities and focused on various issues at a time in a cyclic manner such as identifying requirements'/constraints based on the precedents and site characteristics, setting up goals, determining the exact project area with the consideration of the requirements and their goals, generating ideas about the form of the shelter, arrangement of the seating area, the form of the stage and their relations and etc. This process was quite similar to that they carried out while working with AT with the only difference being in team's considering the modelling and fabrication issues while thinking about the form of the shelter such as in what ways the idea they generated can be modelled with the tool, whether they can model it with one of these methods and what implications these methods might bring about in fabrication of the model. As in designing with AT, during this process, group members expressed and explored their ideas by sketching and occasionally gestured to represent their ideas about the geometry of the form, indeed more than that they did in designing with AT. They began to use PMT in service of their design (not for learning) during the process only after they had a conception about the form of the shelter and the layout of the shelter, the seats and the stage on the site (as in Fig. 8). They mainly used the geometric modelling module of the PMT together with an add on for optimizing the geometry of their form.

Throughout their overall design process, team members worked on the design by alternating between closely coupled and loosely coupled modes. They worked in close coupled mode particularly in discussing about and identifying potential areas for the project, defining the constraints, requirements and goals towards framing the problem and generating ideas for solution, and loosely coupled mode particularly while conducting case studies to deepen their understanding about seating arrangements in performance spaces, parametrically designed shelters, and searching for methods to model the generated form in the PMT, and modelling and fabricating their design proposals.

As can be inferred from the members' conversations, the group's conception of parametric design was that it involves generating/fine tuning design based on parameters- where parameters have to be driven from the site, function, etc. Although thinking so, the group did not incorporate any parameters in their generation of design.

4 Discussions and Concluding Remarks

In our study, we observed the teams to carry out similar set of design activities while working with both media with the only exception of their processes with PMT to involve activities relating to the realization and making of the form. We also observed the teams to exhibit different approaches while designing with both media but each team to exhibit similar strategies while designing with different media. Among these outcomes, groups in a sense developing their own ways of designing, approach to design, was an intriguing outcome for us given those that the members of these groups had never worked together and some even did not know each other prior to the class, and they were working with different media. We need to carry out further studies to investigate occurrence of such a phenomenon as group way of designing and its exhibiting itself in different design situations.

In our study, we observed that members of each group interchangeably worked in lose coupled and close coupled modes throughout their design processes, and exhibited similar collaboration behaviours while carrying out similar activities across their different processes, a phenomenon that we refer to as collaborative work style in this paper. We further observed that the groups' members worked in close-coupled mode at all the times they were working on defining the constraints and goals, generating and evaluating ideas for potential solutions while working with both media. Kwan proposes that collaborative design is cyclic and often co-operative in nature and collaboration occurs at the times of negotiation and evaluation [15] our findings here tells us that collaboration in design can take both forms alternatively and there could be a relationship between the nature of the activities and the collaboration to occur; groups might work in close coupled mode while carrying out activities other than those relating to negotiation and evaluation. They further suggest that different teams might exhibit different patterns of collaboration, and due to each establishing its own collaborative work style and they might have different needs and expectations from collaborative work environments.

In this study, we observed group members to use sketches both for communicating their design intents and thinking about their design ideas as a group, and turn to gestures for communicating visuospatial aspects of their ideas in cases where they can access to a drawing surface. When we asked the groups about their sketching, they said sketches are indispensable for them, if they were to work again as a group, they would utilize sketches as their main medium for sharing and exploring their ideas together, regardless of how experienced they would become in using digital tools. Whether this is just a feeling or a necessity for group design processes for expressing their design ideas, needs to be explored by further studies. Here, gestures deserve attention as a medium of communicating the design intent and as a means to quickly complement information that is not expressed in referent sketches.

As reported by previous studies [4], members of the two teams employed different methods and approaches for defining and deriving the parameters and thereby generating their designs. In the groups design processes with PMT, the most intriguing observation for us was that the students have different conceptions about how to design parametrically and what parametric design is mainly about. One of the groups seemed to consider that in parametric design constraints and variables can be driven from various sources, which might or might not be critical, related to the needs of the design. This group after exploring variety of sources ranging from form finding experiments with chemical experiments to patterns on leaves at the trees on the site, derived their geometries by generating values based on analyses of swarm behaviour conducted at the site and the grids of the columns of the building on the site. The other group, after stating the need for defining parameters based on site variables, did not carried out a parametric design process and only used the geometric modelling component of the tool for generating a digital representation of their design intent and an add on for form optimization.

Given that some of the students in course had previous experiences with parametric design processes, such as having completed a project in education/practice, we do not know what led to such a conception. This raised the question of how we should teach parametric design and realisation/fabrication processes. We believe that students first should be introduced to concept of parametric design as a methodology in analogue medium so that they apply this knowledge while designing with any digital tool. As such any conceptions of parametric design that might originate from the capabilities and the limitations of the tool can be avoided.

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Flat Form:

A Software Design for Capturing the Contribution of Personality and Ordinary Activities in the Design Process

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Abstract. Flat form is an ongoing research that introduces a workflow that aims to enhance the contribution of the user during the design process. At first, implicit as well as explicit data, about both space as a living place and the user as a personality, will be captured. Then, the data will be analyzed in order to build an ontology that will eventually be visualized in human readable format. After that, an external application will evaluate the resulting data structure, pointing out any potential conflict between the spatial arrangement and the user's desires. The outcome will be visualized in a form of a topological diagram that will constitute a new augmented "active" memory for the architect.

Keywords: Participatory Design, Ontology, Topological Representation, Human-Computer Interaction

1 Introduction

What is a design process? A brief answer could be that a design process is a reaction to a design problem. Usually, such a reaction is considered as a cognitive process that receives, manages and infers information in order to recall or create units of knowledge in the context of a problem-solving method (Definition: Symbolic Order, 2016, Hamel, 1995, Norman, 2013). The information or the unit of knowledge is either stored to or extracted from memory. According to Hamel, memory is divided into three sections, "Long Term Memory", "Short Term Memory" and "Working Memory" (Hamel, 1995). Each part refers to nonactive, active, and instantly activated information respectively each time a problem solving process occurs.

Normally, humans break down the whole, maybe yet unknown, problem into clear parts using their "active" memory. At the same time they retrieve further information from both "working" and "long term" memory in order to eventually find a solution. Especially for design problems some extra data is required deriving from additional external sources such as visualizations (Hamel, 1995, Alexander, 1965), interviews or live data monitoring.

The limited capacity of the "active" memory (Hamel, 1995), the intense need for different data sources, and the inability of the human mind to access too complex data structures "in a single mental act" (Alexander, 1965) are the key motivating challenges for this research.

2 Defining Design Process

How is the design process generally applied? The immediate response to a problem usually drives to an intuitive and likely rough solution. Most of the time, the initial satisfaction is temporary, the need for improvements emerges and thus an optimized version is achieved. This step is repeated until the optimal solution is found. Through this trial and error method, all the potential aspects of the design problem that may emerge are integrated into the solution over time (Lawson, 1997). This "craft-based" method, that is mostly common in vernacular design problems, created a one-to-one relationship of master and apprentice. The most common workspace in which this relationship was developed was the house of the craftsmen. As a result, in the pre-industrial era work space and domestic space were identical. This mix also had a high impact on the way of life (Forty, 1995).

On the other hand, in the post-industrial society, the notion of the house was totally different obtaining its own substance distinct from the workplace (Forty, 1995). As a result of the removal of the working place from the houses, the model of everyday life changed completely. The house "acquired a new and distinctive character, which was vividly represented in its decoration and the design of its contents" (Forty, 1995). The desire of having a place that people could relax away from the "oppressive conditions" of the working environment, transformed the house to a "mirror of self" (Marcus, 1995).

Since the nineteenth century, the house was already identical to the personality of the owner. Although it was supposed to reveal especially aspects of the housewife's character, this assumption was superficial and strictly related to her femininity (Forty, 1995, p. 105). During the twentieth century, though, as psychoanalysis was gaining ground, the relationship between the house and the habitat started to become more substantive. In a deeper analysis of human nature, George Herbert Mead mentions the contribution of physical objects to the form of self-identity. Although still mostly driven by external sources like magazines and books, the unconscious selection of furniture for a house describes aspects of our character (Marcus, 1995).

In this social context, Richard Neutra developed his own design method which was a primary form of participatory design. Although Neutra was an important figure of modernism, he brought the user in the centre of the design process, objecting to a mass housing approach. Many years before psychoanalysis become widely accepted as an official therapeutic method, Neutra was engaged with the impact of "empathy" on architectural space. Because of his close relationship with Freud he soon developed an increasing interest in psychology and the ways it could affect space. He was always curious about "the unconscious and all kinds of irrational motivations that swirl around the production and reception of architecture" (Lavin, 2004). Highly influenced by Freud's text 'The psychopathology of everyday life', he focused on "the most unconscious and habitual minor details of domestic life" (Lavin, 2004). Considering also Wundt's theory about the relationship of the sensory apparatus with consciousness, he developed his own design process trying to objectify "the body and its perception" in the notion of home while the contemporary architecture was trying to rationalize the program and the structure of a house building (Lavin, 2004). His overall goal was to embody "mood" in the space. He truly believed that this could happen through the close relationship he was creating with his clients through extended interviews, continuous correspondence and detailed questionnaires. Using this intense communicative method to extract data, he believed that he could transform the house to an affective emotional environment (Lavin, 2004).

In the contemporary era, within a totally different context from that of the architectural practice, a pioneering research group of MIT develops contemporary user - centered architectural design strategies integrating various digital processes. The academic research is highly focused on the study of the interrelations between the user, the technology and the house in a complex network of living ("House_n Introduction," 2016). In order to collect the "live" data required, the laboratory established real scale "living labs". The research methods aim to study human behaviors, to identify interaction patterns and to reveal implicit needs and desires through the live monitoring of everyday life. The space used for current projects is called "PlaceLab" and is fully equipped with different kind of sensors and monitoring devices so as to capture any potential data for both the user and the activities that are being held. Potential users can voluntarily participate in the project for various durations ("House'n The PlaceLab," 2016).

The above mentioned examples constitute two leading approaches of architect-client interaction in the context of user-oriented design methods. The former refers to a preparatory stage of the participatory design in terms of user's desires' extraction through intensive communicative processes. The later presents an academic research which uses cutting edge technology to capture live data about the everyday life and bring user's participation on a more active level. Although the two processes presented are completely different regarding the social context, the user's approach and technology available, the perennial goal is still to capture as many implicit data relevant to the user as possible. In between an unspecified number of studies have been carried out addressing similar challenges (e.g. Graham, 2015, Cemons, 2004, Torabi, 2012).

3 Looking for a Knowledge-Based Data Structure

The main challenge a designer has to confront is the nature of implicit data. Describing attributes and relationships among entities, it is neither quantitative nor visually perceptible. In mathematical terms, objects that share the same attributes regardless of the way they are represented are considered as topologically equivalent ("Topology – from Wolfram MathWorld," 2016). Thus, in this research the data required are considered as topological data. In order to collect, organize and eventually use this data, a particular structure is necessary. The most important aspect of the qualitative data is that it has to be inherently enriched with knowledge in order to be significant. As a result, a knowledge-based data model is required. Such a conceptual model is called a semantic model. Since a semantic model represents a set of relationships, and includes entities describing the way these concepts are informed by each other. The occurring concepts should correspond to a part of the real world, and the overall structure should be capable of answering real problems. Semantic models are widely used in research to capture topological information regarding either the geometry of space (e.g. Tamke, 2014, Langenhan, 2011) or space as emerged through user's needs and actions (e.g. Meagher, 2016). An advanced version of semantic model constitutes an ontology ("What's a semantic model and why should we care?" 2007). In the contemporary world various projects are based on ontology-based applications. However, this method of data manipulation is not widely used in the design process yet (Meagher, 2016). Most design applications that use ontologies aim to the creation of a data warehouse as a meaningful case library of topological characteristics of the building, in terms of geometry, to be used in BIM or other applications (e.g. Lin, 2013).

4 Methodology

The aim of this project is to create a hybrid design method integrating computational operations as an extension of the mental process. The mixed strategies help the designer to visualize all the aspects of the architectural problem enhancing the "active" memory of the architect. The variety of the research methods that have been chosen proves that the different stages of the process are neither clearly distinguishable nor linear. Aiming for an alternative representation of the everyday life of the user, as well as the identification of the "kind of personality" the research methods comprise data collection, software development and information visualisation.

Data collection is the most common step in research. During this stage the researcher identifies the most appropriate questions that address the subject and starts gathering information about the respective variables. This process "enables one to answer stated research questions, test hypotheses, and evaluate outcomes" ("DataCollection," 2016). The data collection could be either an active or a passive process. Active processes involve human interaction whereas passive methods are focused on mere observation. The methods employed for this project stem from both types and are summarized in an architectural drawing, a personality test, a sketch and an interview (Fig. 1).

The architectural drawing can be either provided by the user or designed by the architect on a previous visit to the place during the first meetings of the stakeholders. The data captured form the measured drawing consists of the dimensions of the space in order for the relative size of each room to be identified based on its area, the spatial characteristics of the space like surfaces and columns as well as the adjutancy of the rooms.

Trying to decompose and understand the human personality scientists conducted series of statistical analyses regarding the words people usually use to describe themselves as well as other people. As a result the Five Factor Model (the Big Five) was created ("Personality and Social Dynamics Lab | Sanjay Srivastava," 2016).

Extraversion, agreeableness, consciousness, neuroticism and openness to experience are the five factors of personality traits emerged. Depending on the objectives of the research a further level of distinction may be useful. For that reason different kinds of inventories have been created. For the purpose of this study the IPIP-NEO (International Personality Item Pool Representation of the NEO PI-R™) by Dr. John A. Johnson is used. Some of the advantages of this particular inventory are that it is free when accessed online for educational purposes, it is based on the International Personality Item Pool - A Scientific Collaboratory for the Development of Advanced Measures of Personality and Other Individual Differences (IPIP) by Dr. Lewis R. Goldberg and it provides instant online and quite descriptive response. However, because its primary purpose is to educate people and because only the shorter version is available without cost it may impose some limitations on the accuracy of the results ("IPIP NEO-PI, Introductory Information," 2016).

An additional way to extract more implicit data for the personality of the user is to use art therapy. This approach uses “art-based assessments to evaluate emotional, cognitive, and developmental conditions” ("Art therapy," 2016). House - Tree – Person (HTP) is one of the tests that employs visual expression. The patient has to produce detailed drawings of a house, a tree and a person. These drawings are then analyzed by the therapist based on both qualitative and quantitative criteria. Focusing on the house’s analysis some of the important aspects are the overall size of the drawing, the stroke of the lines and the scale of spatial elements (windows, doors) in comparison with the whole house. For example, a considerably small size of drawing could be interpreted as rejection of the family life and weak lines on the walls could imply weakness in the ego ("House Tree Person Drawings," 2016). Although there is a detailed manual in order for the examiner to score appropriately the outcome, the test remains to a large extent subjective. For that reason, the person who evaluates the test should be trained in the method in order to extract as accurate results as possible ("House-tree-person test," 2016). Following the principles of the HTP a sketch drawing method is employed. The importance of the sketch lies in its use as self-expression. The user is free to draw his home as perceived on a piece of paper. The only restriction is that at the end he should use trace paper to superimpose on the top of the sketch a colour-coding of spaces according to activities. This annotation is useful because the range of space used for each activity can be instantly visualized. The analysis of the sketch according to HTP is followed by a set of questions which can either be selected from the manual or be created by the examiner. In the case of this project the questions are created by the researcher and they are integrated in the follow-up interview.

The last input needed for the system to start analyzing the data is a semi-structured interview. The architect initiates the process asking the user to describe verbally the sketch of the dwelling. After that questions about the everyday life of the user follow. The sequence of ordinary activities and the domestic habits as well as their correlation with the space and the spatial qualities (lighting, ventilation, transparency) it is quite important to be mentioned during the interview. The last area of interest is about the potentials and the obstacles of the house to become the user’s home, the desires and the dissatisfactions (Forty, 1995).

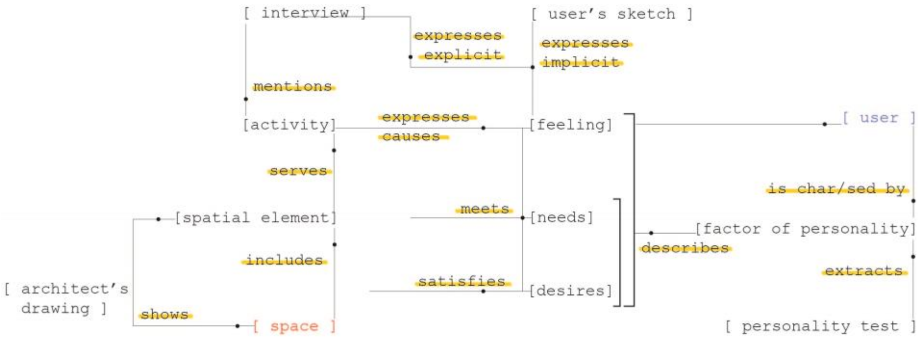

Fig. 1. Diagram representing the entity of home as well as the contribution of input data to the overall process

5 Developing Software

In order to capture the information desired as described above both manual and automated processes are applied either on an analog or on a digital mode. The data from the interview and the sketch are extracted manually by the architect. The direct interaction of the two people helps to enhance their relationship as well as to capture the overall abstract perception a user has about his dwelling (Cemons, 2004). Thus in this stage an automated process would be responsible for potential loss of information. However, the automation is useful in terms of time saving, so it can be used to extract quantitative data from the personality test and the architectural drawing. The personality test using a Likert scale ranking is already analyzed by Dr. Johnson. On the other hand, the analysis of the architectural drawing does not include any automated operation yet. In the future work of this research though it will be analysed based on an image-analysis algorithm which will provide data about the area of spaces, the spatial characteristics and the accessibility of the room.

Depending on the methods of data collection the information has already a specific structure. One of the project's objectives is to integrate all these different structures in a single knowledge-based data model. A software development is thus employed. Among various knowledge-based models, ontology is the most appropriate for the purpose of this research. Ontology "consists of a network of concepts and the relationships between those concepts" ("What's a semanticmodel and why should we care?" 2007). A descriptive vocabulary is established and the knowledge captured becomes instantly explicit. The information is available to be analyzed, shared and reused ("What is an ontology and why we need it," 2016). In order for that knowledge to be represented and both human and computationally interpretable, a semantic programming language is required. To enhance the interoperability of the software a Web Ontology Language (OWL) is employed. OWL is built on the XML and RDF formats. XML (Extensible Markup Language) is a passive programming language unable to carry out any function unless an application is executed. The main advantage is that the stored information can be transferred wrapped in tags. Thus, the author is able to create his own vocabulary using customized tags and build a self-descriptive data structure. The format used to store the data is plain text which makes the document readable by both humans and electronic devices. The use of text also improves interoperability between different applications and operating systems. Although these attributes make the data quite flexible in terms of usability they do not provide any kind of semantics. This gap can be covered by RDF (Resource Description Framework) standards. RDF is a computer readable framework which combines the data, building the interrelationships. The relationship built is called statement or “triplet” and consists of a “subject”, a “predicate” and an “object”. Thus, data obtains properties and property values ("XML RDF," 2016). Based on these principles OWL uses more semantics structuring the data model accordingly. In order to facilitate the process of building an ontology, Protégé ontology editor is used.

Once the ontology is structured, an external application is needed to evaluate it and mention any potential conflicts identified. As already mentioned some of the automated process are not digitally applied yet, so at this step the evaluation of the ontology is conducted manually by the author. Each activity according to the vocabulary of the ontology triggers a personal trait and occupies a certain space. The first step is to set the conflicts between the personal traits which are self-evident. After that the opposing activities are inferred from the ontology or defined manually by the user. Some of the relationships emerged between the ontology’s entities are architecturally contradictory while some others are considered by the user as such. All these inconsistencies constitute the evaluating application’s rules. The ability of constructing customized rules makes the application flexible and efficient. Thus, Flat Form creates five conditions to evaluate the whole structure.

#rule 1
If activity’s experience is rated as negative by the user
#rule 2
If two contradictory activities occupy the same room
#rule 3
If two related activities which trigger conflicting traits occupy the same room
#rule 4
If an activity affects more rooms than the one it occupies
#rule 5
If an activity occupies rooms which are not adjacent

then conflict is identified

6 Visualizing Information

The most effective way to communicate complex information is to use a visual sign-system. Using the processes of human cognition and the “schemata” developed, the visual perception is able to capture instantly multiple data in a non linear order, evaluate it and create inferences. In this workflow there are various levels of visualization. Although ontology creates a human readable data structure preserving the inherent complexity of the data collected, it is still too difficult to understand it because of the text format. A topological diagram which describes objects and their emerging relationships is therefore the most appropriate graph for this research (Meagher, 2016, p.4). Topological graph consists of a network graph, which communicate the knowledge carried by the data structure ignoring any morphological aspect of the data described. Consequently, a vocabulary of logos is established by the author in order to depict the knowledge acquired (Fig. 2).

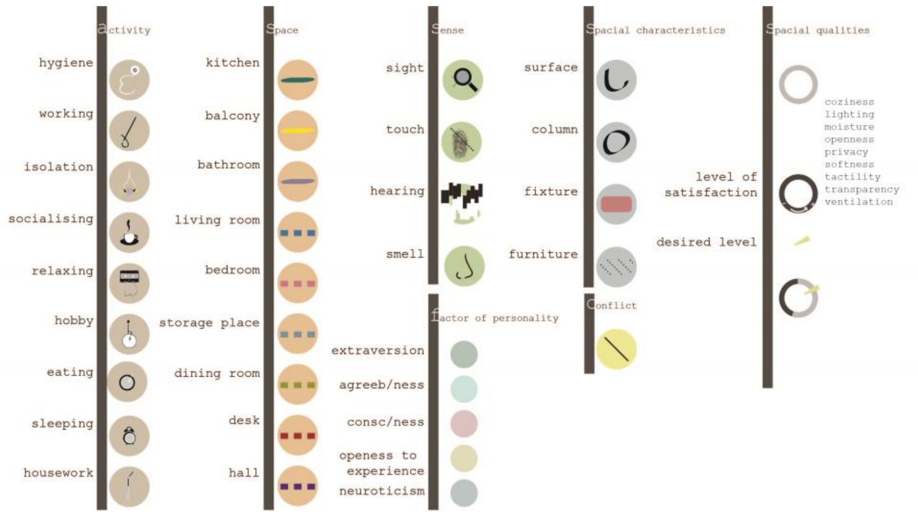

Fig. 2. Legend of topological diagram created by the author.

The final step before user's feedback is for the architect to use the above mentioned graph and translate the data captured into space. The ability of visual perception to capture data in all three dimensions is now necessary to be triggered in order for the spatial information to be communicated. As the term of visualization is continuously updated, Virtual Reality (VR) is now considered as a contemporary interactive technique of visualizing information (Fuller, 2008). The immersion helps the user to envision the changes implied by the space on his everyday life regarding activities and feelings rather than a lifeless space. Using this method the feedback the user provides at the end is as close to the reality as possible.

6.1. Case Studies

In order to test the initial hypothesis that the user's personality and ordinary activities could inform the design process through software development two case studies are implemented. In the context of this research a comprehensive outline of the whole workflow is designed as a proof of concept. This paper constitutes a part of an ongoing research so it is focused more on the operations during the early design stages. The processes which are supposed to be automated are manually conducted in order to save time from troubleshooting. Thus, selected operations are presented. As case studies a studio and an one-bedroom flat are selected to limit the complexity of multiple users (Graham, 2015). Following the research methods as presented, the data required are collected, an ontology is developed and the rules of the evaluating application are implemented to identify any potential conflicts.

The first step in order to facilitate the overall process for the user is to create a friendly and familiar "environment" which will ensure a gradual and pleasant interaction with both the physical and computational agents. To collect the data required for the following analysis a first layer of a completely digital interaction is activated. The goal of the first contact with the system is to use the interface provided to upload the data required without precaution due to any potential involvement of the architect. The initial welcome screen functions as an interactive guide which will help the user to navigate through the platform. Three main buttons are instantly available. "User" and "architect" buttons provide the necessary instructions for the data to be uploaded while "about" button gives a brief description of the application. Once the user is selected the next screen shows a menu which guides him to a step by step process to import all the data about himself as well as his dwelling. Two additional buttons for the"personality test" and the "sketch" become available (Fig. 3).

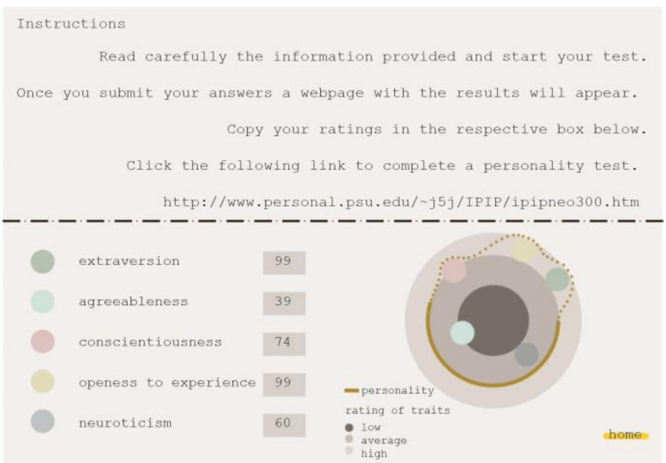

Fig. 3. User's interface - Screen of personality test

After the completion of these steps the "home" button should be pressed in order for the architect to get involved to the process by clicking the respective option of the initial screen. The first interaction between the two persons is an extended interview which includes open questions about the domestic life of the user and a further discussion about the sketch created. The last upload needed is an architectural drawing of the house including all the measurements.

At this point the aforementioned data is categorized in classes and attributes introducing the vocabulary needed for the knowledge-based model. Based on this vocabulary a semantic model is eventually structured. OntoGraph plugin is used by the architect to navigate in the ontology editor in order to access the whole data-model (Fig. 4). Subsequently, the evaluation of the data structure takes place in order to visualize potential conflicts regarding activities.

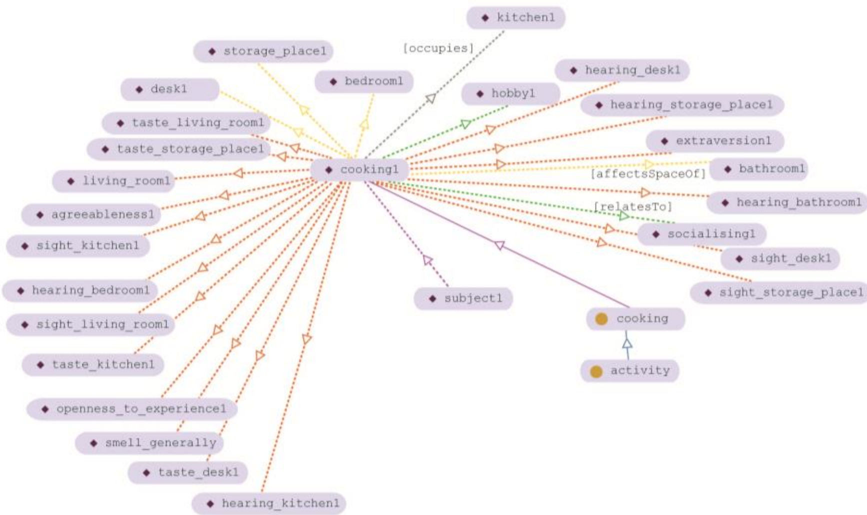

Fig. 4. Part of ontology visualization using OntoGraph plugin – indication of object and data properties related to "cooking" concept

Afterwards, the architect considering the outcome of the evaluating application is able to translate the topological diagram into VR space. The scenarios suggested rearrange the space in order to eliminate the difficulties encountered during the respective activities as well as to enhance the overall home experience.

A studio of 25m^2 constitutes the first case study. The design of the apartment does not predicate any change to properly accommodate different activities in the same room. So, the coexistence of a fixed private space with a potentially shared one makes the place inadequate to host guests. However, the most salient traits of user A were extraversion and openness to experience. Thus, based on rules 1, 2 and 3 a conflict regarding "socializing" and "sleeping" activities has been identified.

Analyzing case study B the activity of cooking was identified as problematic because of the rules 4 and 5 (Fig. 5). Expanding the concept of "cooking" in the ontology, two object properties are firstly activated. The information acquired is that user B usually cooks with friends because the two activities (cooking and socializing) are interrelated and "cooking" is considered as hobby as well. In a further expansion some spatial relationships are revealed. Although "cooking" occupies the kitchen, in this case kitchen is "split" in two non adjacent rooms. In addition, the main space used for the activity is quite small to accommodate more than one person. Consequently, spatial conditions are against the desired experience.

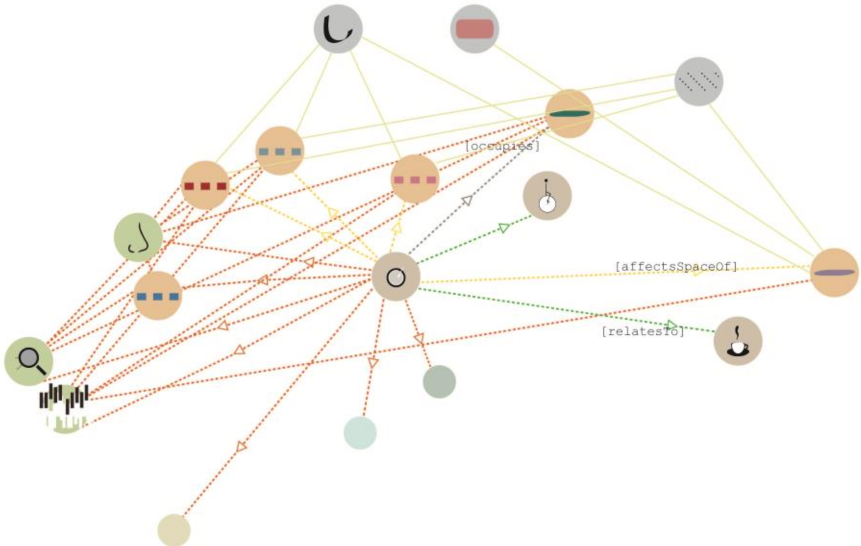

Fig. 5. Part of the topological diagram presenting the conflict identified regarding the activity of "cooking", according to rules 4 and 5

7 Discussion

Sometimes even if the user is able to recognize the difficulties of everyday life it is not possible for him to identify the source of these problems. Quite often the problems start from or even are reflected to the personal space which thus becomes a crucial factor in the equation. The implicit nature of those problems constitutes one of the main concerns of this project. The research conducted explores the contribution of software development in a participatory design process. However, the workflow is a combination of both analogue and digital operations in order to reinforce the direct relationship between the architect and the user (i.e. interview, sketch) while taking advantage of time-consuming procedural tasks (i.e. computational data analysis, ontology) and evaluating the initial hypothesis (i.e. visualisation). As this paper is apart of ongoing research there are still areas for continued development. In future work, some of the limitations of the research will be further investigated such as the status and the number of users involved in order for the design process suggested to be used in various contexts. Additionally, the digital operations required, such as image analysis, are going to be automated, so as to be able to save time and maintain a concise structure of all data used. Finally, the link of the ontology to the 3d immersive environments will be further explored in order to enhance the "active" memory as mentioned in the final steps of design process as well.

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Juxtaposed Designs Models:

A Method for Parallel Exploration in Parametric CAD

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Abstract. Computational tools mainly support authoring single-state models, which fall short in enabling designers to work with multiple solutions side-by-side. This is a natural design behaviour commonly observed when designers use other media or improvise digital tools to explore alternatives. In this paper we attempt to formalize a method that aims to help designers to create multiple design alternatives derived from a base parametric model and its controllers. The goal is to change alternative designs such that each alternative can respond to changes as their internal structures allow. We present five assumptions on the tools that this can be achieved and also a parametric design pattern to be used in similar situations. Despite the complexity of the models, we can demonstrate the possibility of working with multiple solutions in architectural design.

1 Introduction

The creative task of developing a design solution demands experimenting with alternative 'what-if' scenarios and reflecting on each solution generated. However, most tools today allow designers to interact with a single-state model hence provide little direct support for working with multiple solutions simultaneously. On one hand design research reveals the significance of working with alternative designs for informed exploration and better comparison; on the other hand, the tools available to support these activities fall short in meeting designers' needs. To work with design alternatives, designers adopt ad-hoc techniques, such as opening two files side-by-side, layering for superimposed comparison; copy-pasting parts of the solutions into a new file; or saving versions of design files. None of these improvised techniques provide global operators for linking multiple design alternatives to work with them simultaneously without losing design states.

We aimed to develop a method for parametric modeling that can enable parallel editing of multiple design variations. The method we propose assumes that a design model can be replicated through a deep-copy function [1]. This is the case in most CAD models particularly using propagation-based representations using graphs [2]. By the deep-copy, we mean that the model elements in the graph can be partially or entirely replicated within the same design file. One way of achieving this is using conventional copy-paste followed by renaming parameters. Although we observe improvised techniques by CAD modelers who duplicate models and edit them through ad-hoc solutions, each modeler's technique differs, and there is no shared and common approach across different designs. To our knowledge, we believe that the method proposed in this paper is the first attempt towards a formalization and possibly can influence the software structure and functionality of the future CAD systems.

In this paper, we formalize how multiple subjunctive designs can be set together to respond the changes in parametric variations. Building our previous research on parametric modeling such as ViSA [1] and graphed-based editing [2], we propose using modular controllers that can be associated with local and global parameters and changes the respective models simultaneously. We used *GenerativeComponents* (GC) [3] as our test platform because of its capability of using multiple model-views with some degree of decoupling in a single design model. That is, in the same file multiple designs can be created partially-independent. Among possible controller types, we present continuous linear controllers to change the size and number of design features; continuous curvilinear controllers to change the non-unified spread of features; and discrete controllers to change the visibility. At the end of the paper, we present a 'parametric design pattern' that structures the method to be used in design.

2 Motivation

This study is part of a research program on representing and interacting with alternatives in design. The larger goals are related with modeling simultaneous independent scenarios, comparing them, and manipulating them independently or collectively [4] [5] [6]. Lunzer and Hornbæk [7] call such interfaces *subjunctive*, which term we use here. Briefly, a subjunctive model is a derived model from another to execute 'what-if' scenarios. A subjunctive model inherits all properties (nodes and dependencies) from a prototype model; can override these properties, and add new properties; define parametrically or structurally different solutions; can compose properties from several prototypes.

Parametric CAD (pCAD) systems receive a single-state limitation from the CAD tools on which they are largely based. This approach limits exploration and comparison of variations. Although there are studies on exploring variations using representations resembling the intended result [8] [9] [10] [11], to the best of our knowledge, there is limited research on how interaction with them can be achieved.

Smith et al. [12] focus on CAD interfaces for generating and managing multiple ideas. They report a set of suggestions based on their empirical findings to improve existing systems: a) Make it easy to switch between ideas, b) Provide a way to view multiple ideas at once, c) Allow users to adapt the interface to their needs and preferences, d) Provide ways to label the ideas both pictorially and textually, e) Provide multiple ways to group and classify the ideas, f) Provide an explicit means for capturing the situation, and g) Support fluid composition and decomposition of ideas.

Combined with the qualities of creativity support tools, these give an overall direction for development of the next generation CAD tools to better support design [13].

3 Proposed Method

The method is built on two perspectives to design model creation: structural and functional. In structural perspective, we made the following five assumptions for a system to support parallel exploration:

Assumption 1: Any given parametric design model D_1 should be controllable by a tuple of arbitrary number of parameters $DP_1 \{p_1, p_2, p_3 ... p_n\}$.

Assumption 2: The model's structure can be deep-copied as described such that D_2 can be entirely or partially derived from D_1 ($D_2 \subseteq D_1$). The derived D_2 should have its own parameters DP_2 that are equivalent and subset of DP_1 ($DP_2 \subseteq DP_1$), i.e. DP_2 and DP_1 share the same semantics and exists independently from each other. The equivalency criterion allows changing parameter names without losing their function in the model. This and the first structural assumptions state that *n* number of partially or entirely identical design models ($D_1, D_2, D_3 ... D_n$) can co-exist in the same editing environment.

Assumption 3: All independent parameters ($DP_1, DP_2, DP_3 ... DP_n$) are accessible in the editing environment simultaneously such that they can be together or selectively changed, e.g., through a function call or command. The third assumption is crucial for *parallel editing* that multiple models can be changed together through shared controllers.

Assumption 4: During the changes the models should keep their integrity, i.e. their constraints are not violated. In case of constraint violation, visualization elements on the model should signal such situations, or the model's behavior must be obvious to deny such change.

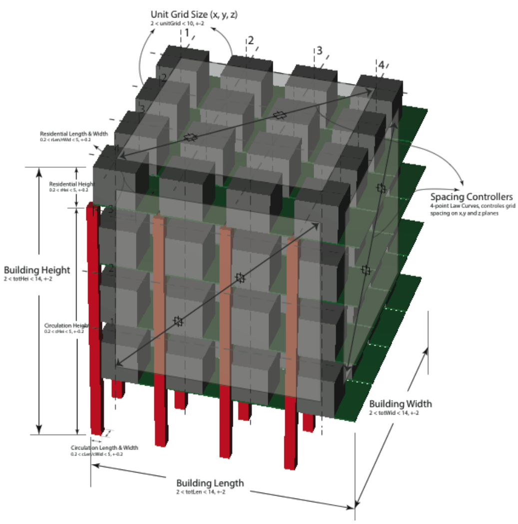
Assumption 5: Each model in the same environment should be amenable to receive new features, drop and modify existing features as design elements, controllers, or visualizations. This is needed to enable adding new features to a design model independent from the others to ensure that a design is not a mere parametric variation of the original one. However, it must be noted that the new features added to a model can also be shared with others if desired so, in this case the corresponding parameters and controllers are needed for parallel editing. Similarly, dropping a feature from a model would require to drop the corresponding parameters and controllers from the parallel editing view. Among the five assumptions, this is the most challenging and difficult one as the complexity of design increases, the models' structure may hinder this assumption.

The assumptions on structural perspective fundamentally guarantee modularity and decoupling the models, controller and views as in object-oriented and proto-type based software design. In our earlier work, we demonstrated that this can be possible in the current pCAD systems [1], and we formalized a method that can be followed to create modular parametric controllers and visualizations to *plug-in and –out* to a design model to meet the designer's specific decision-making needs.

The functional perspective of the method assumes that the modeler can view all derived models, controllers and visualizations simultaneously in the same editing environment. Also, the modeler must be able to turn on or off a model's response to changes in a parameter while other models respond the change. The required functional features are: (a) derive a model or part of model to create new variations, (b) activate a derived model to respond to changes globally or deactivate to take local changes only, (c) introduce new controllers and visualizations globally and locally, and (d) substitute controllers or visualizations with minimum effect on the integrity of the models. Below we briefly demonstrate how these can be manifested in a hypothetical design case.

4 Case Study: Conceptual Design of a Building

For demonstration purposes, we present a case study that demonstrates exploring conceptual designs of a residential building with three major spatial features: residential units, vertical circulation spaces, and terraces. Each of these features is modelled using parametrically defined boxes (Figure 1). The possible solutions that can be generated using this model can be highly diverse (Figure 2). Please note that, not all parametric combinations would result with a plausible design, but rather the goal here is to create a design space that can inspire *form finding*. We chose using this model in this case study for two reasons: the abstraction level of the model makes it open for interpretation and resembles mass modeling in the early phases of architectural design; and simplicity of the unit geometry (boxes) can reduce the complexity of the parametric model structure such that the method can be clearly described.



Parameter	Range	Step
Building Length (Max)	2 - 14	2.0
Building Width (Max)	2 - 14	2.0
Building Height (Max)	2 - 14	2.0
Cube-Grid (X, Y, Z)	2 - 10	2.0
Resident (Gray) (H, W, L)	0.2 - 5	0.2
Circulation (Red) (H, W, L)	0.2 - 5	0.2
Terraces (Green) (H, W, L)	0.2 - 5	0.2

Fig. 1. A building concept defined using 15 independent parameters. The size and position of each unit type can be parametrically adjusted based on the building size constraints

In an example scenario, the designers would be changing the unit dimensions and their spread in grid one unit type at a time. For example, if the designer wants to increase the size of the terraces, the corresponding parameters will be changed using the controllers associated with them. This is going to cause losing the previous design state and only working on the most current state. It is problematic as there is no mechanism that can enable designers to compare each state in a *juxtaposed* view, i.e. side-to-side. Also, in this scenario it is not possible to experiment with what-if scenarios with multiple states visible and editable independently at the same time.

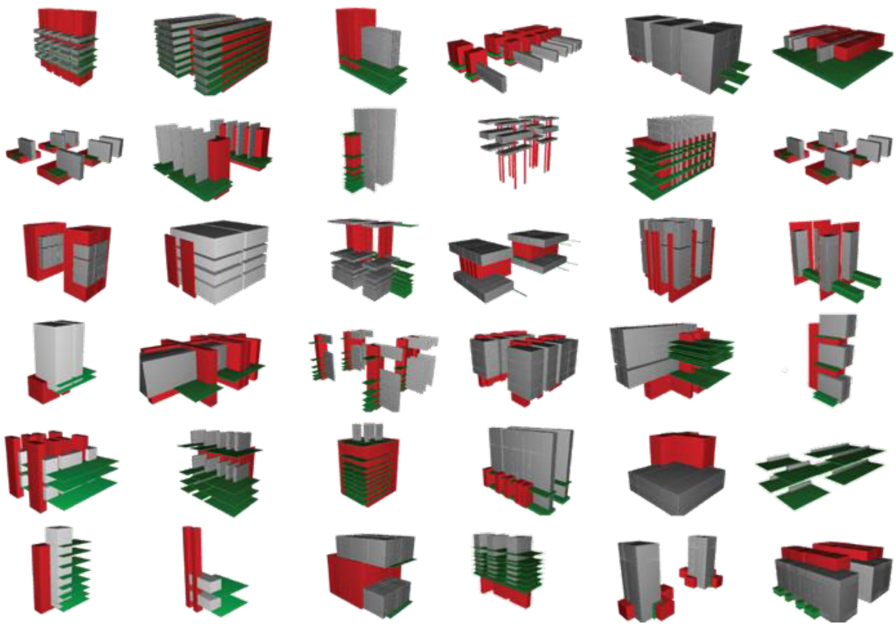


Fig. 2. A small sample possible design variations that can be created using the base model

5 Parametric Structure of the Base Model

The parametric base model is composed of three types of boxes corresponding three different architectural units: residences, vertical circulation, and open spaces. Instances of these units are placed in a 3D orthogonal 4x4x4 grid (Figure 3). The number of each unit type and their size along with their spread can be controlled parametrically using a continuous linear function. The distance between the same type of features in the model is defined using continuous flexible function to allow non-uniform spread of consecutive features. Hence, each unit type can be significantly of different proportions, location, and spread. The overall building size can also be parametrically defined, which the units fill the bounding box spanning the corresponding grid. This can be analogous to a bounding box of a complex geometry. The inclusion and appearance of select features are decided based on a proximity controller using a discrete function. The parametric structure we developed responds to these changes selectively or collectively, and is managed by the designer.

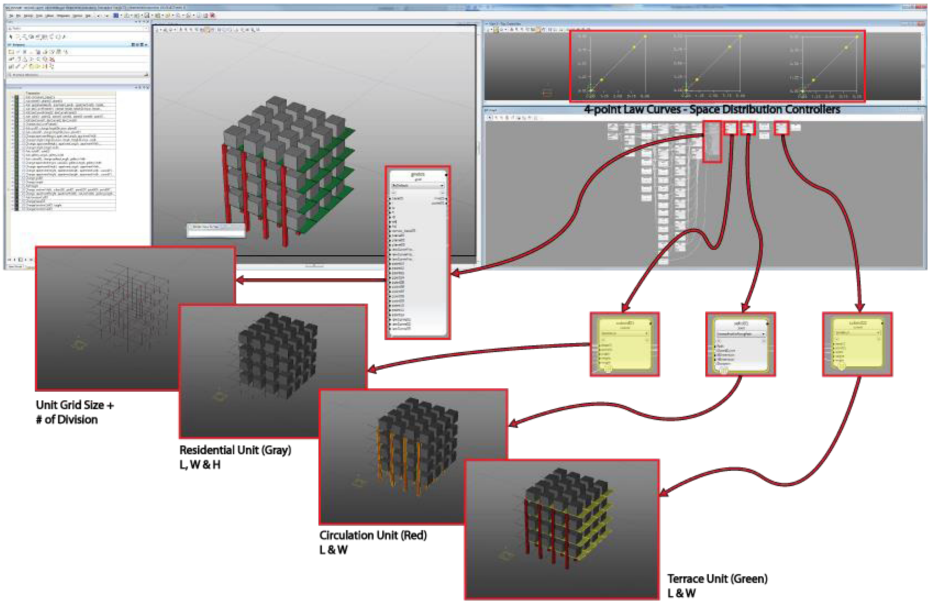


Fig. 3. Parametric structure of the base model

The independent parameters controlling the architectural features in the model are accessed through custom controllers we developed. The controllers are of three types: linear and flexible. The linear controllers change the parameter it is associated with by moving a point on a line, it has a fixed slope. The flexible controllers, on the other hand, are built using a spline curve with two control points, which the values assigned to a parameter can arbitrarily change in response to the curvature of the spline.

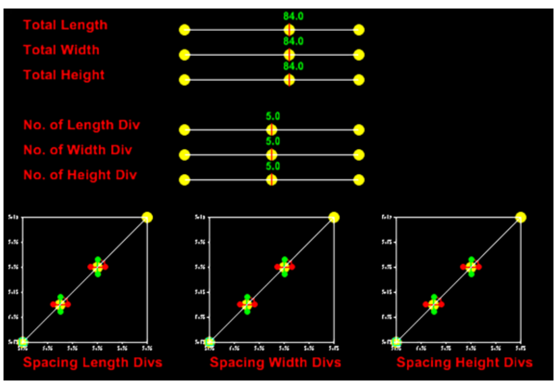


Fig. 4. Linear controllers (lines above), and flexible controllers as splines changed by two control points (boxes below)

6 Structure for Parallel Editing

The systems for editing a single model, by description, is not intended for creating multiple alternatives. For example, when working on a geometry on a vector graphics editor, the geometry is viewed only in its current state. Working on multiple states of the geometry, e.g. with different size properties, is not possible. The current pCAD tools are no exception to this. Therefore, the method we propose improvises the tool features of a parametric modeling system, namely GenerativeComponents from Bentley, to approximate to an environment that can edit multiple solutions parallel in juxtaposed views. This particular system enables creating up to eight *model-views,* each of which can contain a different model as part of a global model. The graph representation can be contained in one shared model-view. Each model-view can be named separately and represent an alternative for parallel editing.

Figure 5 shows the editing environment we configured for working with design alternatives in parallel. Due to the limitations in the number of model-views available in the parametric system we used, and rapidly increasing model complexity, we chose to work on three design alternatives. Each alternative used two model-views: one for the design model and another for placing controllers. One model-view is used to place controllers that can change the parametric values of the three alternative designs at the same time. However, this happens only if an additional global Boolean parameter to each alternative is switched to *true*, we discuss this below.

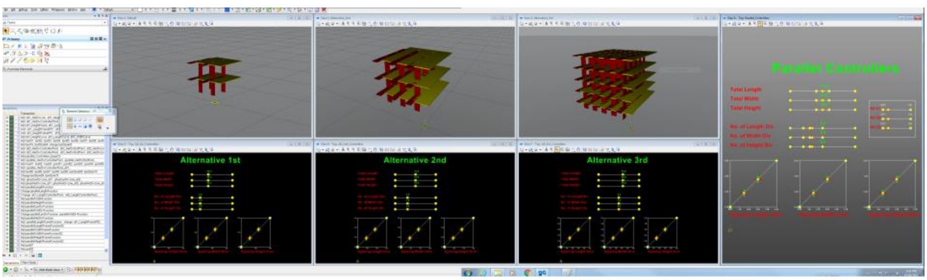


Fig. 5. Editing environment of alternatives in juxtaposed views

When creating the two alternative models from the base model, we applied the following process. First, we created a new base coordinate system in a new model view and copied the parametric model and pasted it into the graph. In the copied model, we replaced the base coordinate system with the coordinate system in the new model-view. Now that the new model can show on a separate view than the base model, we could rename all parameters it contained, e.g. from *Base_height* to *Alt_2_height*. These two moves are consistent with the second and third assumptions we stated earlier. We copied the original controllers and placed them into a separate model-view, similar to the deep-copy of a geometric model. We can do this as these controllers are threated same as any other parametric features as part of the internal data. Following renaming the controllers, we associated them their respective elements in the model by linking in the graph. In the same environment, we now have two solutions that are independently changeable. Following the same process, we created the set up for editing the third alternative. To the best of our knowledge, a formalized modeling method has not been documented before, although similar techniques are shown on particular design cases.

The most crucial part of the method is how to link all these models and have them response to changes together, if and when needed. For this, we introduced a 'global' Boolean parameter as part of each alternative design. The role of this parameter is to switch if the model should response to global edits intended for parallel editing. For example, if this switch is *on*, the model will ignore the local parameters and response to changes triggered in the parallel controllers (Figure 5). Up to know, the entire parametric model has already become more complex than we expected. Figure 6 shows this complexity on the graph. The method's applicability under the existing parametric software systems becomes highly difficult when the model's complexity increases. We believe that these systems should consider new functions to alleviate their bottlenecks.

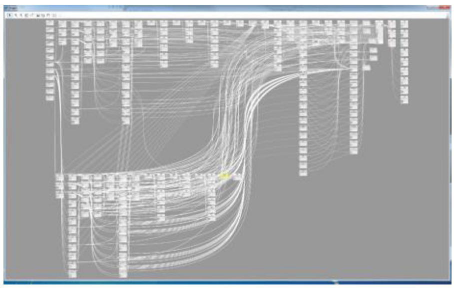


Fig. 6. Graph model generating three alternative design models and corresponding controllers as well as a model view for global controllers

Although the structural criteria of the models were complete after these parametric modeling moves, we have yet to control the models: this required implementing a functional schema using an available technique in the selected parametric system: functional features and scripting. However, this was not as complex as the structure of the model. The following pseudo code presents the logic behind the functions:

```
ON_CHANGE (Global.<P_name>)
     FOR EACH a in Model //a: alternative with distinct baseC
          IF a.updateGlobally is true
               a.< P_name >.value = Global.< P_name >.value
               UPDATE (a.controller(< P_name>))
               UPDATE (a)
          END IF
     END FOR
```

Please note, despite the simplicity in logic of this function, the implementation of this logic took more than 200 lines of code. We had to implement the following subroutine to cover 6 different conditions for each parameter (permutation of two states for each alternative to set response to the changes in the global controllers). Although it was a labor-intensive task, we only had to copy-paste the code and edit them. Once again, it is worth to note the difficulty of using the system features that are not designed for editing multiple solutions.

```
//parallel_LengthControllerPoint.Level = 1;
////////////////////////////////// FIRST ////////////////////////////////////////////////
    if (parallel_Toggle_alt1.T < 0.5 && parallel_Toggle_alt2.T  <0.5 && parallel_Toggle_alt3.T < 0.5) //off state
{

        double x = alt1_LengthControllerPoint.T;
        double y = alt2_LengthControllerPoint.T;
        double z = alt3_LengthControllerPoint.T;
        parallel_LengthControllerPoint.ByParameterAlongCurve(parallel_LengthLine, (x+y+z)/3);

        SetPropertyFree(alt1_LengthControllerPoint, "T", true);
        SetPropertyFree(alt2_LengthControllerPoint, "T", true);
        SetPropertyFree(alt3_LengthControllerPoint, "T", true);
        SetPropertyFree(parallel_LengthControllerPoint, "T", true);

        x = (Distance(parallel_LengthStartPoint, parallel_LengthControllerPoint)-Distance(alt1_LengthStartPoint, alt1_LengthControllerPoint))*(-1);
        y = (Distance(parallel_LengthStartPoint, parallel_LengthControllerPoint)-Distance(alt2_LengthStartPoint, alt2_LengthControllerPoint))*(-1);
        z = (Distance(parallel_LengthStartPoint, parallel_LengthControllerPoint)-Distance(alt3_LengthStartPoint, alt3_LengthControllerPoint))*(-1);

        ghostLengthLine_alt1.ByStartPointDirectionLength(parallel_LengthControllerPoint, parallel_Controllers_baseCS.XDirection, x);
        ghostLengthLine_alt2.ByStartPointDirectionLength(parallel_LengthControllerPoint, parallel_Controllers_baseCS.XDirection, y);
        ghostLengthLine_alt3.ByStartPointDirectionLength(parallel_LengthControllerPoint, parallel_Controllers_baseCS.XDirection, z);

        parallel_LengthControllerPoint_alt1.ByParameterAlongCurve(ghostLengthLine_alt1, 1);

        parallel_LengthControllerPoint_alt2.ByParameterAlongCurve(ghostLengthLine_alt2, 1);

        parallel_LengthControllerPoint_alt3.ByParameterAlongCurve(ghostLengthLine_alt3, 1);
```

Fig. 7. Snippet from the function that updates the corresponding parameter in each alternative following a change on a global parameter

7 Parallel Editor Pattern

Following the lessons learned when building the model for parallel editing, we decided to convert our experiences into a (parametric) design pattern that can be shared with other designers who wish to follow this method. A pattern—in our context—is essentially a generic solution to a recurring problem in a particular domain. For example, linking a geometric element to control its properties is a design pattern, which is commonly known as *Controller Pattern*. There are four salient features of a pattern [1413].

Explicitness: Explicitness aids reflection. Tools for advancing design skills. To write a pattern is to commit to a definite media for others to read in your absence.

Partiality: They are above nodes, below design. Properly written they are informal devices by which modules can be expressed in principle.

Problem focused: They state a problem with several clear solutions to it. They aid sketching by accelerating the creation of approximate models. They often combine geometrical, mathematical and algorithmic insights.

Abstract/Generic: Lastly they are abstract. To use them evidences mastery of the 'divide' part of divide and conquer.

Name: Parallel Editor

Related Patterns: This pattern can be implemented on top of all existing parametric patterns:

- Slider, Dial, Equalizer, Controller, Hyperboloid of one sheet, and Azimuth Altitude

Intend: Whenever there is a need to edit multiple models simultaneously to see the effects of a change side-by-side
Use When: Exploring alternative solutions through applying what-if scenarios
Why: Overcoming the challenges a single-state system poses when exploring design alternatives
How:

1. Build partial or complete base model enough to explore its variations
2. Deep copy the base model with its controllers that the new model will have its own base coordinates.
3. Rename the parameters and other model elements considering their unique place as an alternative solution
4. Add a unique global Boolean parameter to the alternative to indicate its state for following local or global edits
5. Do step 1-4 for each alternative
6. Deep copy the base controllers to set the global controllers
7. Implement a global update function that updates alternatives if their update switches are on
8. Link function to the global controllers.

Global Samples:

1. A controller with multi-handles that can change the length of the line, changes the t-value for each controller point, hence the geometrical model attached to each controller point simultaneously.
2. A controller with multi-handles plus a switch to turn updates on and off (two modes), such that all alternatives have an individual switch. When the switch is turned on, the models becomes active on parallel editing mode. Therefore, changing the length of the controller line, changes all models in parallel editing mode.
3. A controller with multi-handles, a switch, and a parameter for retaining last value (recorder). When it comes back from its parallel editing mode to individual editing mode, it retains its last parametric value.
4. Four-point law curve controller that can be used as flexible controller.

8 Conclusion

The method we introduce in this paper is in its infancy. The main challenges include the lack of build-in functions in pCAD tools that can support direct deep-copy and functional feature libraries that be used in any given CAD model. Although the latter one can be overcome through a design community using ‘compiled’ or ‘generative’ components, the prior needs a direct involvement of the CAD companies. In this research, while we aim to demonstrate the utility of working on multiple solutions in design exploration we also wish to discover the new functional and structural features of the future CAD tools. In our previous work, we presented some of such functions for graph-based editing [2]. In this method, we attempted to apply some of the ideas presented in an existing CAD tool.

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Association Rule Mining to Assess User-generated Content in Digital Heritage

Participatory Content Making in 'The Museum of Gamers'

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Abstract. Association rule mining is one of several approaches in game design for discovering correlations among user-generated content items. This paper aims to aid the digital heritage field by analysing user preferences in interactive environments designed for participatory cultural heritage making. Textual and diagrammatic explication of the feedback mechanism introduces the universalization of the knowledge gained in this research that is supported with the outcome of a workshop which offered two gamified interactive environments. Three key pleasures of cyberspace in digital heritage are extended from immersion to meaningful experience and to transformation. User-generated content engenders meaningful correlations that help improve and evaluate digital heritage applications. Qualitative findings explicate the relationship of 'The Museum of Gamers' with the authenticity issue. This paper is among the first to investigate the association rule finding methods in relation to indexical authenticity in digital heritage.

Keywords: Digital heritage · Game analytics · Association rule mining · User-generated content · The Museum of Gamers

Making Sense of Design Space

What Designers do with Large Numbers of Alternatives?

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Abstract. Today's generative design tools and large screen displays present opportunities for designers to explore large number of design alternatives. Besides numerous studies in design, the act of exploring design space is yet to be integrated in the design of new digital media. To understand how designer's search patterns will uncover when provided with a gallery of large numbers of design solutions, we conducted a lab experiment with nine designers. Particularly the study explored how designers used spatial structuring of their work environment to make informed design decisions. The results of the study present intuitions for development of next generation front-end gallery interfaces for managing a large set of design variations while enabling simultaneous editing of design parameters.

Keywords: Parametric design · Alternatives · Design space exploration · New interfaces · New media · Protocol analysis · User study

A Matter of Sequence

Investigating the Impact of the Order of Design Decisions in Multi-Stage Design Processes

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Abstract. The design as a process is not a new topic in architecture, yet some theories are widely unexplored, such as the multi-stage decision-making (MD) process. This design method provides multiple solutions for one design problem and is characterized by design stages. By adding new building components in every stage, multiple solutions are created for each design solution from the previous stage. If the MD process is to be applied in architectural practice, fundamental and theoretical knowledge about it becomes necessary. This paper investigates the impact of sequence of design stages on the design solutions in the MD process. A basic case study provides the necessary data for comparing different sequences and gaining fundamental knowledge of the MD process. The study contains a parametric model for building generation, a parametric Life Cycle Assessment tool and an optimization mechanism based on Evolutionary Algorithms.

Keywords: Multi-stage decision-making process · Design process · Life Cycle Performance · Design Automation

Fabrication and Materiality

Soft Computing in Design

Developing Automation Strategies from Material Indeterminacies

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Abstract. Integrating concepts of soft computation into advanced manufacturing and architecture means perceiving the element of chance not as a hindrance, but as an opportunity. The projects examined in this manuscript explore opportunities for integrating material indeterminacy into advanced manufacturing by pairing a certain degree material unpredictability with the rigid order of machine control. The three projects described investigate three common categories of automated tooling including additive processes, subtractive processes and molding / casting processes. Each project begins with the question, what opportunities might arise from the mediation between material volition and computational control? By embracing indeterminate material results and taking an optimistic stance on chance and uncertainty, which are usually treated as problems rather than values, the intent is to provide ways for automating unique material effects and explore the opportunities for integrating soft computing in design.

Keywords: Robotics, 3d Printing, Digital Fabrication, Automation, Indeterminacy

1 Introduction

Architecture's relationship with instrumental knowledge and indeterminate systems has a long history. From the drawing instruments of the 18th century, such as those exhibited in George Adams's *Geometrical and Graphical Essay,* to the advent of human computer interaction in design seen in with Nicholas Negroponte's foundation of the Architecture Machine Group, instrumental knowledge has played a pivotal role in mechanized and computationally based approaches to design [1]. While we see this history of machine epistemology arising early on in architecture, the capacity of architecture to engage in indeterminate systems finds its strength much later in the 1960's speculative projects, such as Cedric Price's *Fun Palace* and Yona Friedman's *Ville Spatiale* –both questioning the long accepted Vitruvian notion of *firmitas* and suggesting ideas of choice, freedom, and individualism though flexible soft systems [2].

Sanford Kwinter defines a soft system when he writes:
"The system, one might say, is driven by its very 'softness,' its capacity to move, to differentiate internally, to absorb, transform, and exchange information with its surrounding [...] A system is 'soft' when it is flexible, adaptable, and evolving, when it is complex and maintained by a dense network of active information or feedback loops, or put in a more general way, when a system is able to sustain a certain quotient of sensitive, quasi-random flow." [3]

In other words, a system is soft when it is driven by dynamics, responsive to change, and comfortable with chance and indeterminacy. As with the architectural projects of the 1960's, soft systems were under investigation in many disciplines at this time, including philosophy and the sciences, and represented a common thread of speculation. Importantly, multiple disciplines, which integrate the topic of chance, also deal with the soft systems. Chance has been an area of interest present in day-to-day life, a topic of many works of literature, a technique embedded in mathematics and statistics, and an open concept in the softer sciences. Chance because of its vastness has also been a major idea of interrogation in philosophy, including Aristotle's philosophical work *Physics,* which sought to examine the relationships and systems of nature [4]. While these references provide an overview of an ongoing interest in chance and soft systems relative to both phenomena and techniques, the research in this manuscript seeks to explore the opportunities, which lie in material and machine based approaches for appropriating soft systems in design.

2 Soft Computing in Architecture

Computational techniques in architecture today engage in a multiplicity of approaches, which often involves designers borrowing concepts from computer science and adapting them to specific design problems. Similarly, this manuscript examines a collection of on-going research projects, which borrow ideas from soft computation applied to design and architecture. Soft computing as defined in computer science is "a collection of methodologies and computational approaches which aim to exploit tolerance for imprecision, uncertainty and partial truth" [5]. In other words, soft computing often involves development of approximate or soft solutions to computational hard tasks often applied for the development of intelligent systems. Import subtopics of soft computing, which are applicable to this research include fuzzy logic (FL), which works within a range of values, and evolutionary computing (EC), which works based on trial and error [6]. These subtopics are further explored and applied to the research projects outlined in this manuscript through analogue and machine approaches to computation.

Negroponte's book, *Soft Architecture Machines,* was perhaps the first formal introduction of soft computing in architecture and proposed ideas of self-generating and adaptive architectures. Negroponte offers an alternative to the long-standing ideal of firmness, by exploring softness in design with methods ranging from movement and materials to intelligence and computers. More recently, John Beaumont explored this architectural dichotomy of hard and soft pointing out that even the materiality of architecture embraces firmness when "clay is fired into brick, wood is dried and compressed, and sand is melted and annealed into its solid form" [7]. This research investigates these moments of softness before the translation into hard. More specifically it investigates softness as a tool for innovation in computational design relative to advances in automation and robotics.

The vastness of softness in architecture is further outlined in *Bracket*: *Goes Soft* which articulates that soft "describes material qualities, evokes character traits, defines strategies of persuasion, models of systems thinking and problem-solving, and new approaches to design [2]. Similarly to Kwinter, this issue argues that softness is a way of addressing contemporary complexity in design, which requires room for flux and indeterminacy. Bhatia argues that historically "the role of the Architect has been to determine lines that ordered the world;" however, rapid changes and transformations have "sparked a disciplinary identity crisis characterized by a yearning for architecture's opposite, flexibility, dynamism, immateriality, and indeterminacy" [8].

Therefore, soft in the context of this research takes on a multiplicity of meanings, which relate more to material characteristics, reconfigurability, and as a model for systems thinking. This multiplicity of definition allows each of the subsequent research projects to not only engage in softness as a computational idea, but also investigate their potentials for material based approaches to appropriating technology in design.

3 Softness in Advanced Manufacturing

Returning to the topic of chance, it is important to note, uncertainty or imprecision is often avoided in manufacturing, and construction. Present day research looking at the advancement of manufacturing processes is often centered around material techniques [9]. The projects examined in this manuscript also take material investigation into account; however, they differ by examining soft computing methods relative to materials and machines. Each project pairs a certain degree material unpredictability with the rigid order of machine control. Currently the common categories of tools and manufacturing process include: Subtractive Processes or Material Removal; Molding, Deformation, and Casting; and Fabrication or Additive Processes [9]. The three projects described investigate each of these machine processes by integrating material indeterminacy.

Each project begins with the question, how might indeterminate processes be integrated into architectural design and construction and what design opportunities might arise from no longer being constrained by existing methods? What opportunities might arise from developing an automated system, which does not rely on direct translation, but instead operates and predicts outcomes within a range of potential results? How might designers work with automated processes, which mediate between material volition and machine control? Drawing upon these questions and the lessons from the histories of instrumental knowledge, indeterminacy, and softness, we find the context for the polemical suggestion for opportunity driven research relative to soft computation in design.

3.1 Additive Material Indeterminacy

This first research project, entitled Motion Capture, examines the potential for integrating soft computation in design by integrating material indeterminacy in an additive manufacturing process by seeking to capture opportune moments of material fluidity. Other additive based systems which integrate softness and precedent this work include Roxy Paine's automated sculpture makers (1996-2001) and Anish Kapoor's 3d printed concrete (2012). The project involves the development of a 3D printer, which uses gravity as the z-axis to freeze key fluid moments in a change of state material (illustrated in Fig.1-3). As seen in his iconic photograph *.30 Bullet Piercing an Apple* by Harold Edgerton, which strives to capture key moments of movement using multi-flash process, the Motion Capture project similarly tries to still moments of formal interest during the curing process. The project tries to find the equilibrium between the cure time and rate of deposition through material testing.

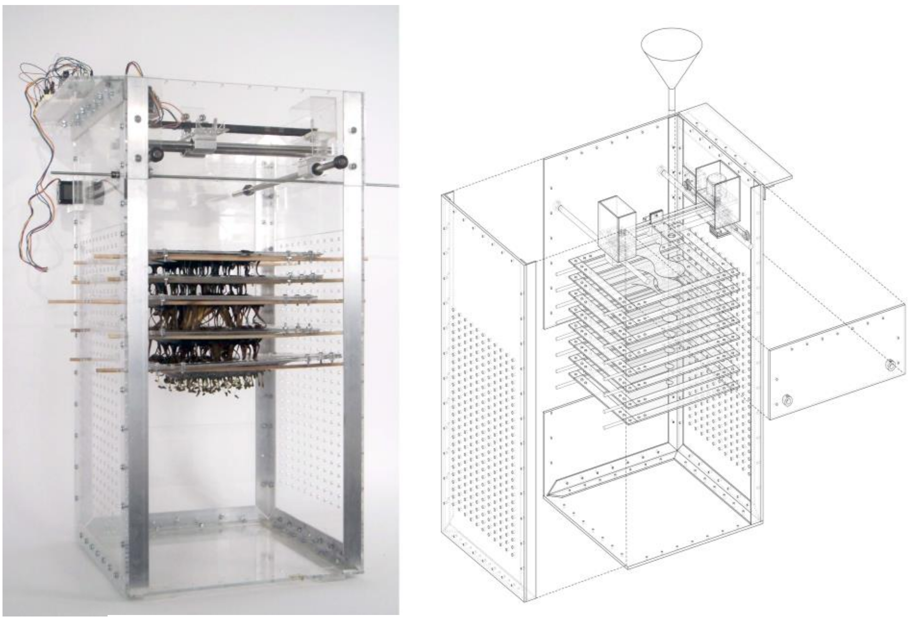

Fig.1. Motion Capture 3D Printer and Axonometric Drawing

The research method involved a two-part process of material testing and automation development. The material tests sought to find a balanced ratio of the ingredients: vinyl acetate copolymers, resin, wax, and sucrose. The evaluation criteria during the testing involved cure-time, toxicity, strength, elasticity, and fluidity appearance after flowing through extrusion armature and changing state from liquid to solid. Figure 4 catalogs the documentation of these tests relative to each of the criteria. Each test sought to arise to a challenge developed by the research team which involved asking, how might we develop a plastic composite with low toxicity levels when heated and which easily decomposes when discarded? Additionally we asked, how might the material stand and support itself once it was cured to capture material fluidity (Fig.5-

7)? How might the extrusion amateur dissolve or melt by building it out of a material such as ice, which would melt from the heated solution during the curing process?

Fig.2. Detail Images of Motion Capture Printer Output Prints

Once the team achieved the ideal material composition, the testing began for the additive automation strategy using a 3D printer built with Arduino, a programmable micro-controller, and controlled with Firefly, a plug-in for Grasshopper. The automation strategy integrated a controlled constant rate of deposition and a variable location in three axes. The variable location of deposition and speed of the printer would produce effects not entirely predictable except within a range of possibilities exemplified by sending identical prints and documenting the range of changes from each one. While this printer is only an initial study of how construction methods might integrate ideas of material indeterminacy, it provides designers with an imagined scenario where they could rethink existing methodologies—perhaps no longer working from intent to execution, but starting with material execution strategies and speculating on the range of possibilities from there.

Fig.3. Motion Capture 3D Printer Output Print

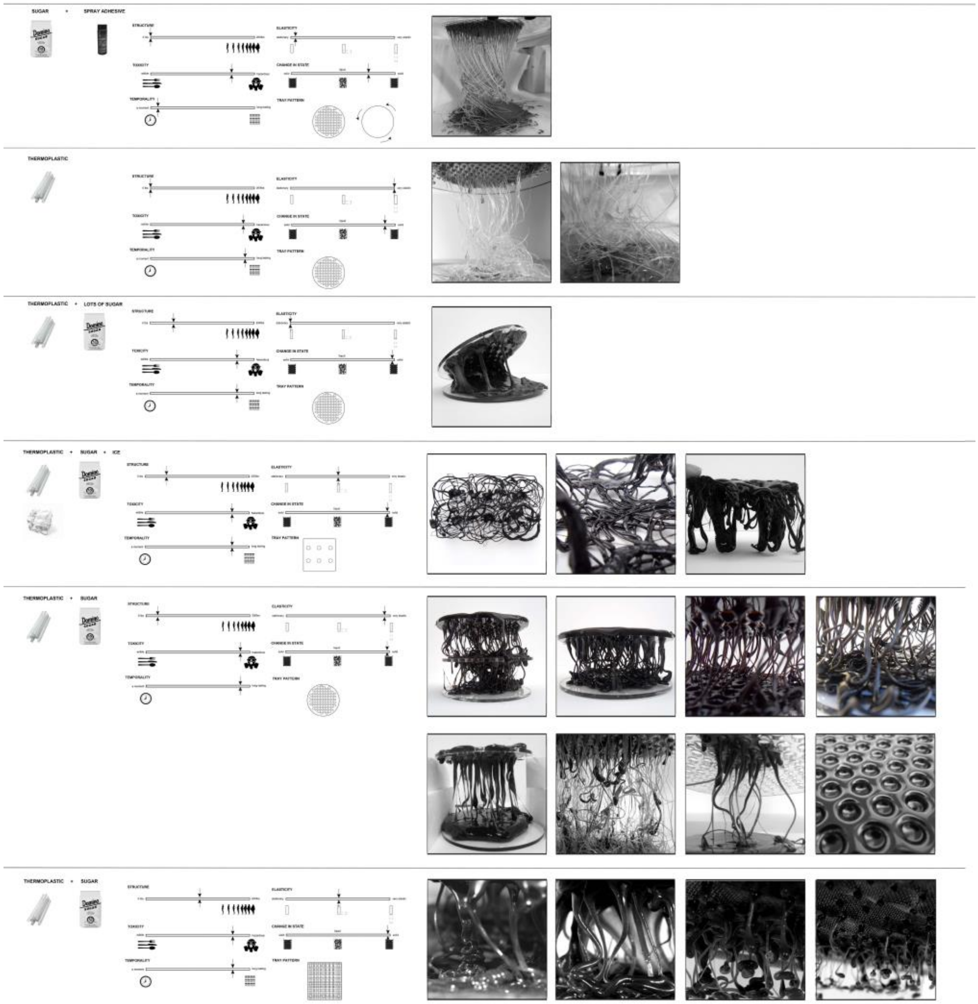

Fig.4. Taxonomy of material tests illustrating cure-time, toxicity, strength, elasticity, and fluidity appearance after changing state from liquid to solid

3.2 Subtractive Material Indeterminacy

The second project, entitled Objects of Rotation, strives to explore a subtractive process, which results in varied material effects by pairing the soft and malleable material, clay, with the automated control of robotic technology. It draws from the craft based process of throwing and interfaces traditional ceramic tools with the robotic arm to develop a subtractive tooling process which carves away while the ceramic wheel is rotating, similarly to how a lathe operates (Fig.5).

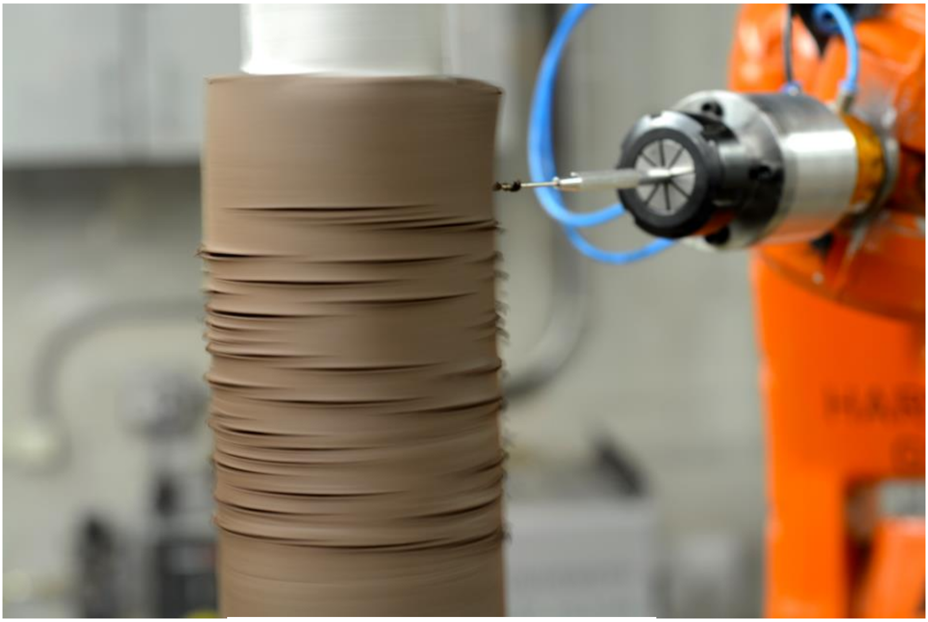

Fig.5. Objects of rotation research setup

The setup involved traditional ceramic carving tools integrated into a collet for robotic control of the toolpath. The tool then moves along an extruded clay cylinder while in rotation. This area of this research was an extension of an earlier project, which sought to explore automated tooling methods related to craft based processes [10]. This development specifically seeks to catalog the range of material variations from a consistent tooling process relative to understanding material indeterminacies. The research team ran each tool path multiple times in order to show the variations in the carving process from identical test runs.

By cataloging the material responses to the carving process certain target results were predictable; however, the exact replicability of each experiment was not possible nor desired; instead, the unique characteristics within the research and tooling development were celebrated. The research team describes materials, which produce these unique effects from an identical process as *materials with fingerprints*, meaning the materials which are embedded with unique identity such that the results, in repeated experiments, are distinct from one another, but recognizable as a *relative* because of similar characteristics.

3.3 Casting Material Indeterminacy

This last project examines the potential of material discrepancies caused during the casting process caused by elasticity of a fabric layer in between a robotically calibrated reconfigurable pin-mold. The overall setup for reconfiguring the pin mold involves the robotic arm with a steel push pin held in place by the spindle, a pin mold (made up of 121 pins, an aluminum plate, and a two inch rubber clutch layer), and a base scaffolding to elevate and position on the mold. Once the mold is set with the robot pushing pins in place, an enclosure box is place around the pins with a spandex lycra fabric layer on top to prepare for casting (Fig.6). While the pins are precisely placed and calibrated, the stretching of the fabric due to its placement and the weight of the plaster cause irregularities within the casts.

A parametric model allows for the development of the tool path for pushing the pins in place to calibrate the mold. The research team also used a physics engine to try and simulate the unique attributes of the casts such as the stretching and wrinkling in the fabric. By calibrating the mold in an identical pattern and producing multiple casts, the research team was able to document a range of possibilities as a result of the variations in stretching for each test (Fig.7).

The research team also decidedly chose this last method, not only to test indeterminacies in casting relative to machine control, but also had an interest in indeterminate conditions relative to human response and interaction since the resulting casts attempt to evoke a haptic response through their visual implications of softness. Overall, this project attempts to demonstrate the capacity of architecture to engage indeterminate processes in fabrication process and through experiential interaction. While this study of interaction is only a surface based approach, there lies a greater opportunity to explore ideas of interaction, which are fundamentally relevant to the soft computing discourse of artificial intelligence, which aim to develop systems capable of responding to change, imprecision, which are all fundamental characteristics to human behavior or response to environments.

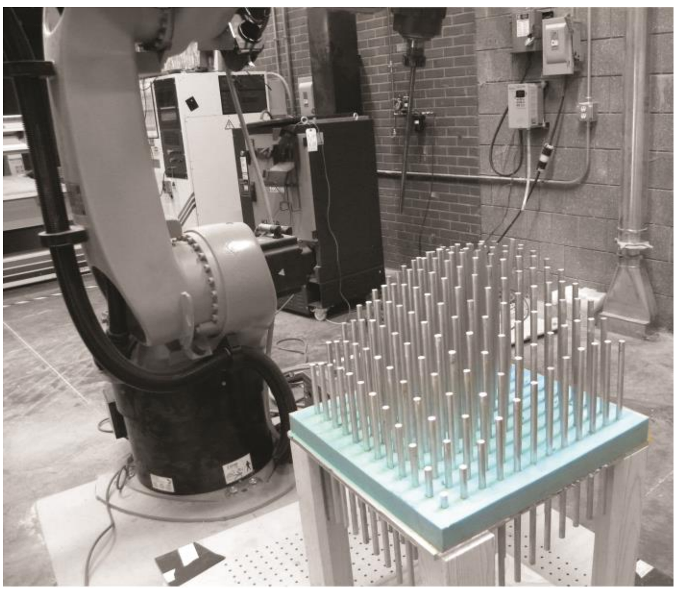

Fig.6. Reconfigurable pin-mold

Fig.7. Resulting casts

4 Conclusion

These experimental projects ultimately aim to address the question, how might we orchestrate a scenario which celebrates material indeterminacy as a design opportunity and integrate material effects into automated strategies for manufacturing and construction? By embracing indeterminate material results, it is import to note that these experiments also provide a framework for further exploring feedback in systems in stochastic processes for soft computing relative to interaction and intelligent systems.

Going back to Negroponte's interest in collaborative machines this study of material indeterminacies provides room for further research with self-influencing systems. For instance, with the scaling up of the Motion Capture device, the question arises regarding how feedback could allow the system to scan and recalibrate in order to provide sufficient structure or delineate and differentiate space. With this type of development, lies potential for integrating machine-learning processes as an additional method for appropriating soft computing techniques within the system.

With developments in large scale 3D printing at University Southern California, the appropriation of robots on construction sites at the University of Stuttgart, and the integration of drone technology in construction at ETH Zurich (*Eidgenössische Technische Hochschule Zürich)*, technological advancements are impacting the way buildings are both designed and built. Integration of feedback loops with 3D scanning and sensors are allowing for additional developments in decision-making machines; fabrication robots will one day be capable of learning from data in real time and make decisions about the next moves.

This continued research takes on two parts. First, it involves illuminating the possibilities of what can be, by looking at history as a way to see the world and as a predictor of what may happen. Second, it attempts to demonstrate the proof those possibilities through research projects, which actualize those ideas. Looking at history, we see ideas of indeterminate construction methods dating back to Ruskinian notions of savageness, a characteristic of the idiosyncrasies, mistakes, and imperfections in the construction of gothic cathedrals made by craftsmen, often due to harsh climates and conditions in which they built. Ruskin saw these rough details as beautiful attributes because they told a story of the workers and were markers of the act of construction [11]. Embracing the Ruskinian notion of savageness, this research leans against the tendency of technology to generate uniform results and embraces the idea that originality arises from imperfections, even material irregularities made by machines. In a future of buildings constructed in collaboration with intelligent robots, what Ruskinian markers or savage details will result? Will the buildings tell of extreme precision and control or will they deviate and embrace material indeterminacies? Will robots be capable of thinking creatively?

Antoine Picon, in his assessment of robots in architecture, points out, “Robotic fabrication may confront us for the first time directly with the need to cooperate with our technological auxiliaries rather than simply use them” [12]. Looking beyond material and tooling methods, Picon draws upon Negroponte’s ideas and opportunistically calls for the emancipation of the robot, no longer acting as a workforce, but as a contributor to discourse of design [12]. Similarly, Greg Lynn calls for alternative ways of thinking about robots in his introduction to the 2016 issue of *Log*, suggesting the ability to go beyond “robotic fabrication of primitive huts” [13]. Perhaps instead of an obsession with efficiency, predictability, and precision, we should start the quest for opportunistic alternatives for robotics in design, by finding ways to integrate responses to change, uncertainty, and imprecision.

This research outlined here focuses on indeterminacy centered around material and machine agency in architecture. Promoting such agency requires less rigidity in authorship, which promotes softness not only in terms materials and movements, but also relative to artificial intelligence, suggesting machines could have agency beyond merely using them to facilitate human agency. Such a softening of authorship requires room for chance and a willingness for collaboration with computer-controlled methods. In *Soft Architecture Machines*, Negroponte suggests such design faculties might allow machines “to develop their own design methods and methodologies perhaps better than our own” [14].

This is a call for continued advancements in these tools in tandem with conceptual approaches for looking forward. How might we collaborate with machines? How might our relationship with technology provide design opportunities? Finding ways to collaborate with machines becomes a pedagogical and scholarly endeavor in defining the types of knowledge necessary for design and the kinds of information essential for the creative process. Therefore, integrating concepts of soft computation into architecture provides a framework for discussing the qualitative, the subjective, and the immeasurable in a world of machines and data. This collection of experimental projects act as a call to consider our future trajectories and for us to find ways to integrate computation in architecture more *softly*.

Acknowledgements. The Motion Capture 3D printer (Additive Material Indeterminacy) was produced in collaboration with Olga Mesa and Ana García Puyol as part of Andrew Witt's Expanded Mechanisms Empirical Materialisms course at Harvard Graduate School of Design. Objects of Rotation (Subtractive Material Indetermiancy) was an extension of research started in collaboration with Jili Huang and Saurabh Mhatre. The casting material indeterminacy project was produced as part of the Design Innovation Fellowship at Ball State University.

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Constructive Design: Rule Discovery for 3D Printing Decomposed Large Objects

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Abstract. This paper presents a rule discovery process for designers that work with physically large 3D printed models. After a period of discovery, rules were formalized, then developed into operations and programmable functions used in a generative design system. Past examples of generative systems are built based on visual constraints leading to graphical outcomes. With the emergence of 3D printing, we introduce ideas for rule building based on physical constraints and outcomes. The decomposition rules are: curved surface slicing, freestanding attribute, interval patterning, edge mating, and pneumatic attribute. The freestanding attribute, the most novel rule, is based on Chilean anti-earthquake building techniques. This rule provides the greatest degree of structural stability to a model. We conclude with a discussion of results from the case study used to generate the set constructive rules. We believe this method of module generation, 3D Printing and assembles can support design prototyping and model manufacturing across scales.

Keywords: Decomposition, Large Objects, 3D Printing.

1 Introduction

We have experience many years of construction scale, additive manufacturing with success in machining development, however little advancement in computing [1]. Researchers have presented a variety of methods to 3D print buildings each mainly focused on print of large scale concrete structures. However, mass production of these machines is still far from becoming a reality and currently accessing a generic undersized 3D-printer is much easier. Therefore, the discovery process of rules for decomposing large scale complex objects is needed. It is our intent to explore which rules produce successful decomposing results. Decomposition rules enable 3D-printing of such objects by smaller pieces. Our research formalizes a set of rules for decomposing large objects for the 3D print manufacturing, exploiting current widely used machines. This advancements goal is to broaden the scope of 3D printed objects, as with novel techniques is would be possible to print cars, airplanes and buildings.

How to compute the decomposition of a large complex model into sub-pieces that fit in a generic 3D printing machine, preserving the model's structural and aesthetic soundness, is the question that leads this research. As an answer, we designed a complex form and subdivided it by pieces. This process allowed us to test different decomposition criteria, and to evaluate those criteria iteratively. We formalized such rules as a generative design system; in order to develop a generalizable method. We produced eight 3D-printed powder models that embody the evolution of the work.

Fig. 1. Assembly of final model

2 Related Work

Recent interest in creating large 3D printed objects in concrete by using digital fabrication can be found in Martin's work [7]. Garcia and Retsin have sought to increase the scale of printed objects by extruding plastic, printing large layers with the material. In both cases the printers do not have a bed, but rather work as independent devices, therefore the size does not depend of the device's size [4].

Past examples of large scale objects are the Larry Sass's exhibition at the Museum of Modern Art in New York, in 2008, 'Home Delivery, Fabricating the Modern Dwelling'. This house was produced by computing the subdivision of every constructive element in a board that could be assembled by interlocking.[1] Notwithstanding this example was built with lasercut plywood; the interlocking feature is highly well developed and constitutes an example for the presented system.

Prevost et al. have optimized internal mass of 3D printed objects by making those designs hollow in some areas and solid in others [8]. By these operations the researchers have tested the object's internal balance. In our research, as a secondary improvement, we follow the same idea and reinforce the structure by thickening specific zones. In other developments, using structural analysis, Telea and Jalba have developed a '*robust method for thin region detection based on distance'* [10]. This work revolves around the same idea that existent partitioning software use, as it will

[1] Museum of Modern Art | MoMA. (n.d.). Retrieved February 14, 2017, from https://www.moma.org/explore/multimedia/audios/80/450

be explained later. Umetani and Schmidt [10] have developed a framework for detecting weakness in 3D model for printing optimization, complementing Telea and Jalba's work. Zhou et al have analyzed the geometry of the objects to determine the worst case loads in the structure of the model [13]. This approach is of interest because it is focused on the object's geometry for determining the loads.

One example of an existent digital tool that can subdivide large complex models is Autodesk's 3DPrintTech Software (www.apps.autodesk.com: Nov 2015). This tool determines how to split an object into as few boxes as possible that can fit inside a generic 3D-printer machine. However, 3DPrintTech does not take into account fragile sections of the model; it makes straight cuts, and the modules do not interlock. Linjie Luo et al. present "Chopper" software that partitions using a search algorithm, developing such system one step further from 3DPrintTech [6]. The algorithm finds fragile areas of the model and starts splitting from there. This is a remarkable tool; yet, it slices the shapes with straight cuts only, producing disjointed rebuilt models. A newly paper published by Song et al. have presented the development of an algorithm that subdivides 3D models in cubes, as a voxelization, and afterwards the algorithm interleaves the blocks [9]. We had access to this paper after the development of the research presented in this paper. Song et al. research project makes a wonderful progress in developing the interlocking system based in the "Chopper" idea. Unlike these projects that work with full filled volume models, our approach works with shallow shapes because this method uses significantly less material. The “Choper” cannot successfully subdivide the geometry presented in this paper. Our research project is also based on the work of Linjie Luo et al. and takes one step forward their development by finding a method to increase the stability of the structure [6].

In addition, the “embodied problems” that 3D printing produces, have been scarcely addressed in previous research. By these problems we refer to the factors that emerge when assembling the object from which the sub-pieces were computed from. Often, the assembly process is obstructed because is not possible to operate with our hands over the model, to hold de pieces together or to scaffold a side of the object. For our research process we considered these issues and addressed them with design.

Fig. 2. In this image is possible to observe which pieces present the freestanding attribute that will be described in detail in the following section

3 Overview

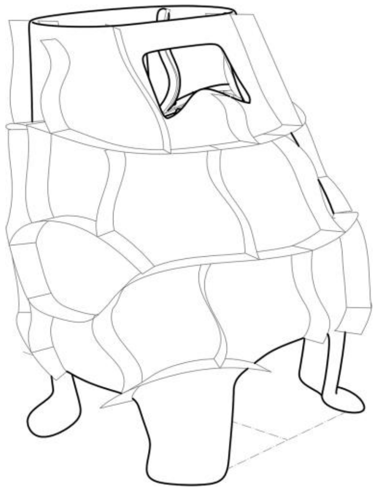

Fig. 3. Final model shape and planar outline of decomposition pattern

Our main research question consists of: How can one compute the subdivision of a large complex model into parts or modules that fit in a generic 3D-printing machine, preserving the model's structural strength and improving its aesthetic soundness? When computing the subdivision, the following question emerges: How to start subdividing the model? As previous work have demonstrated, salient and special parts of the model are required to be whole pieces and therefore such zones stand as a starting point for splitting. What shape should the modules have in order to achieve a more stable assembly? How can gravity be used, addressing compression stress to favor the structure, and minimizing shear stress in the connection zones?

This research project uses a hollow shape, emulating a chair at a fourth of its scale, constituting the "chair volume." The chair volume conserves the finishing elements of a common chair such as the legs and a handle. The hypothesis tested is: parts with curved edges, freestanding attributes, and interlocking assembly are structurally and aesthetically sound. As was stated before, the aim of the research is to find a system, a method, to compute the decomposition of large complex objects into pieces, modules that fit in a generic 3D printer, enabling the 3D-printing of such objects. Current 3D-printers are underexploited, limited to producing only small objects. Current methods to subdivide large objects are a valuable advance; however, these methods are often based in graphical results.

Powder 3D-printing machines can produce elaborated shapes. Consequently, the module's geometry is designed exploiting the machine's capability to handle complexity when depositing layers of powder. We, as designers, decide and evaluate every step of the iterative process, by finding the required rules and then applying them recursively. Our approach and selected tools focus on the geometrical shape, in order to control structural behavior and formal expression first, and generate decomposition criteria that is generalizable.

In another line of inquiry, related to Continuous Designing, in terms of open source design / production system, if this and other methods promote and make accessible the printing of large functional objects by pieces, perhaps 3D-printing will become massive, enabling many people to produce objects by their own means. If numerous people gain these skills, reaching a reality in which many people are makers, these types of enterprises could contribute to creating a 'distributed mode of actions and responses' [12]. Consequently, the following question arises: How is it possible to make this method accessible and simple to apply? Our system relates to open source/production system by enabling designers to understand how to decompose complex geometries to be 3D printed by pieces. Instead of generating a tool that would limit the variety of models that could be subdivided, we focused on designing principles that can be adapted by a designer to almost any geometry. Generic 3D modeling software can be used to produce this decomposition. Our ambition is that this method can be done using any 3D-modeling software, including free and open source software; therefore making it accessible for a large public.

Generative design approach guides this research project: understanding design as a process capable of being interpreted in a system of rules that can be used to produce new designs. An open iterative process leads to the final result, going back and forth when applying the proposed features and avoiding the constraints of a sequential process. Visual expression and tactile information acquire predominance for making decisions. The stance of our research is to focus on visual, structural and material information for the discovery of constructive rules.

4 Rule Discovery

4.1 Process

Our goal is the discovery of *constructive rules* for a generative design system to be used for decomposing a shape into smaller elements/modules ready for 3D Printing and manual assembly. Unlike traditional decomposition systems that work with visually based rules, constructive rule generation is governed by laws based on structure, resistance, and how we think-manufacture objects with our hands. We present our method of rule discovery through geometric modeling and 3D printing in five-steps. The ultimate goal is shape preservation after the components have been assembled. Here, our constructive rules were discovered through iterative modeling, 3D printing as a way of observing assembly behavior and redesign to manage errors. Any variation in the physical model from the virtual model is defined as an error. A selection of five key models is shown in Fig. 3. The final model is an abstract hollow shape composed by light pieces. This model was an easy to assembly set of contoured sub-shapes with three dimensional freestanding properties.

Fig. 4. Sample of models used to discover modulation operations

4.2 Step 1: Curved surface slicing

A previous method to decompose a shape into smaller puzzle pieces, with joineries decomposed in large curved shapes [14]. In this case a tiling pattern was created by dividing the initial shape evenly horizontal and vertical (fig 3a). Our current approach uses spline curves for the initial decomposition of shapes into tiles as a way to assume fitting, reduce assembly errors, and reinforce the structure. (fig 3b). Spline curves create a unique connection between tiled elements, distributing some of the\structural loading across neighboring modules. As the shape is decomposed it is relevant to maintain its structural properties as a whole. Spline curves engage geometrically and structurally the total of the final shape. Unique parts aid in organizing the direction and sequence of the assembly. In this case, the model is assembled from bottom to top and therefore the modules must follow that sequence.

Fig. 5. Prior study, the decomposition of an initial shape using straight cuts. Current study using spline curves to decompose the initial shape.

4.3 Step 2: Freestanding Attribute

Adobe anti-earthquake construction techniques are the source of the most original application of our method for 3D-printing large objects by pieces; the freestanding attribute. Adobe walls must be designed to be freestanding, in order to resist earthquakes. In order to satisfy this condition, walls must be shaped as “L”, "X" or “T” figures in plan. These figures resist horizontal structural efforts in every direction. Fig. 10 is part of the book "Basic Construction Course" written by Prof. Euclides Guzman [5]. This book is used to teach architecture undergrads construction and structural resistance in Chile. Chile is one of the most seismic countries in the world, and adobe construction techniques have proven to be a successful measure to preserve these fragile buildings.

The model of the presented research project was decomposed checking that most of the modules have 3D-dimensionality. The pieces were defined using curved slicing for the edges and seeking to be spatially curved in more than one direction, similarly to adobe walls. This rule builds on previous rule. Thus, by incorporating the concept of decomposing a shape into pieces that have freestanding attribute, the final artifact gains a greater structural resistance.

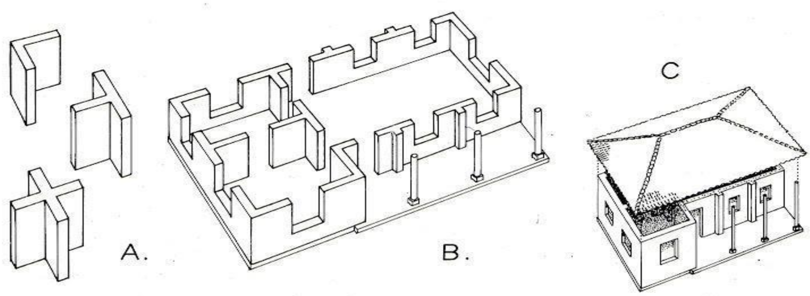

Fig. 6. Chilean adobe anti-earthquake construction techniques. Image from "Basic Construction Course" by Prof. Euclides Guzman [5]

4.4 Step 3: Interval Patterning

A third method is used to increase the strength of connections between modules is by staggering the link between rows, or the creation of a brick bonding patterning (fig 5). This is an obvious system of tile assembly (brick bonding), however the challenge is computing such a pattern in particular at the bottom and top of the shape. The brick pattern prevents the shape from vertical separation. The challenge in interval patterning is computing seam location, seam variation and alignment.

Fig. 7. Interval patterning

4.5 Step 4: Edge Mating

A fourth attempt at modeling, printing and assembly of modules resulted in parts that assembled out of plane. Applying convex and concave features at the edges of each module provided a seat and sustained assembly after many courses of modules. The challenge here was sorting of profile edges between modules. Spline curve edge of each module provided a starting point for profile generation (Fig 6). A convex, concave was a hard coded profile applied to spline curves *sP-X*.

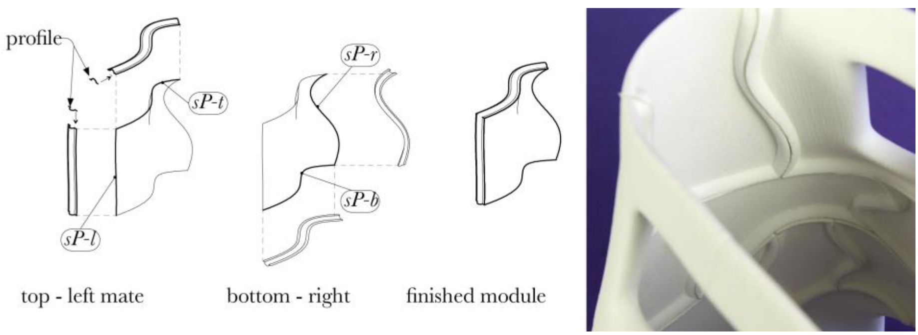

Fig. 8. Finished mating geometry and reduction in weight through pneumatic modeling

4.1 Step 5: Pneumatics

Finally, we developed a system to perforate each of the modules, making them lighter and generating an aesthetic effect. We were inspired by topological mass optimization, in which the surplus mass is removed, leaving the parts of the volume that respond to structural effort. We followed the principle of skeletal pneumatics, which in biological terms, refers to hollow bone structures found in birds. The perforations were made using 3D splines, and following grid geometry.

4.2 Assembly

The assembly strategy consisted of defining a series of rings, starting from the lower part of the model and ascending to its top. Each of the rings edges were defined by splines, in the same way that each of the models was in the curved slicing step. The spline curved edges facilitated the fit between neighboring rings. Models were assembled manually using a small amount of tacky white glue. The five operations used to form each element resulted in an easy to assemble artifact.

Fig. 9. Assembly process

5 Results

How to decompose large complex models into parts that can be printed with a generic 3D-printing machine is the question that leads the development of the discovery process and the produced models. In the presented research project we developed a method in an iterative process of discovery and formalization of rules that can be used to decompose a shape into modules. Overall, there was a significant structural stability increase in the final 3D-printed model. In parallel, there was the development of an aesthetics that reflects the process that was taken to produce the geometry of the model. In our opinion this weighted aesthetics produces attractive objects.

The implementation of the *curved surface slicing* rule proved to provide increased efficacy for the assembly process. It was possible to observe that the pieces were more solidly joined together. The discovery process derived significant insight about how to decompose a complex geometry into pieces. At the final stage we used a model with straight cuts as a control model for the *curved surface slicing* feature. The comparison between these models allowed us to observe the improvements achieved by our method. In further steps the structural resistance of the decomposed and not decomposed models can be compared in order to test their structural resistance. Nevertheless, it is possible to observe in the physical model that both present similar conditions.

The *freestanding attribute* rule provided structural autonomy to the model, fostering the production of self-supporting objects. The freestanding attribute increased model strength against gravity. The *interval patterning* made the assembly process more efficient. As a result of the implementation of this feature, we were able to easily assemble pieces in weak places, such as on the legs of the model. *Edge mating* rule increased the contact surface between pieces. Correspondingly, the mass projections form a secondary structural network composed by nerves inside the models, which could also be manipulated in further research. Finally the *pneumatics* feature reduced the weight of the pieces and improved aesthetics final object. This step also improved the assembly process in an unexpected way; the previous model to the final one, did not have perforations and because of the weight of the modules the pieces did not join accurately. After the pneumatics rule was performed, the link between neighboring modules improved significantly. Further, the discovered rules present an interesting and particular aesthetics that express the criteria and process behind the design.

Fig. 10. Detail of the structural nerves network inside the models

The validity of our proposal lies in the fact that we generated a sufficiently complex first model to be subdivided and rebuilt. Decomposing the geometry of the model into valid modules presented a difficult challenge. In addition, powder 3D-printing is one of the most fragile 3D-printing technologies, and therefore our process faced the difficulty of providing structural soundness through the design. The reliability of the process lies in the extensive series of models that we produced to test and iterate our ideas. The final model was decomposed applying the discovered rules, and with this process we increased its strength, stability and aesthetics. The model that we produced to test our process is sufficiently complex to validate the idea that the discovered rules are applicable to other designs.

6 Discussion

From the rule discovery process we identified and formalized rules and produced a generative design system for decomposing a complex shape into modules for 3D Printing and manual assembly. The formalization of these rules implies that the hidden potential of currently under used 3D printers can be exploited for 3D-printing large objects by pieces. Consequently, our project contributes to the enterprise of automating the production of large 3D pieces, as the rules can be used as parameters of a manufacturing sequence. In addition, our method is a generative design system that is generalizable to a wide range of objects. As stated in the overview, our goal is to present principles or steps to be adapted by designers for decomposing almost any complex geometry, in order to contribute to open-source design/ production systems.

Previous decomposition rule systems did not include the majority of the construction rules presented on this paper. In our prior experience we subdivided complex shapes with a continuous grid, without curved surface sliced edges, freestanding attribute or interval patterning. In those cases the joints between neighboring modules received a considerable load, producing a high level of shear stress. The new method solved those problems and introduced further advancements. The transfer of the *freestanding attribute* from adobe anti-earthquake construction techniques is to the extent of our knowledge, an idea without precedents. It is relevant to emphasize the importance of rescuing principles, derived from obsolete construction systems, to be used within the processes of digital manufacture.

One limitation of the proposed study is that we only explored five rules for the development of our generative design system, when in fact there might be several other techniques that are significant and useful. For example, it is possible to observe that the thickness and mass of the modules is an important factor to structure the 3D-printed model. Therefore, the mass of each piece can be designed with higher detail. Further, due to time constraints, we produced the presented eight models and determined that a real life model size will be part of following studies. Additive technologies present the challenge of structure and scale, addressed by this paper in a discovery process. Weak instances of the model were discarded by visual and tactile inspection, evaluating the two main factors of additive printing; structure and scale. Our models are a quarter of its real scale, allowing us to carry out these analyses. Nevertheless, we 3D printed pieces in one to one scale to evaluate their strength. Real scale pieces conserve strength characteristics. In further studies, structural and scale improvements will be measured with quantifiable methods.

Finally, in the future our proposed method can be used for 3D-printing buildings. Parts designed with the rules presented in this paper function as pre-fabricated construction elements to be assembled into an architectural object. In further research steps we intend to print real life scale model, and develop a script following the method. Different materials provide different constrains. It is of interest to test our generative design system with other materials such as concrete, ABS and PLA. Notwithstanding the impossibility knowing a priori, it is possible to speculate that concrete would behave similarly to powder, and that plastic would present a new elasticity component to be handled by the design. Nevertheless, working with the constraints of powder 3D-printing challenged our techniques even more, proving our rules useful and significant for digital fabrication practice in general.

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Igneous Tectonics
Turning disaster into resource through digital fabrication

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Abstract. This investigation aims to develop and establish digital fabrication and design techniques and protocols to process volcanic materials that have caused significant environmental and social damage, using them to reconstruct new and improved structures to replace those destroyed, palliating the negative effects of volcanic eruptions and contributing a new economic resource to affected communities. The study recovers underused material and explore its qualities, recovering lost stonemasonry skills though advanced CNC and robotic manufacturing.

Keywords: Robotic manufacturing, parametric design, digital fabrication, material research, CNC stonemasonry.

1 Introduction

As we have witnessed the progressively increasing frequency of natural disasters that devastate both natural landscapes and man-made urban territory, we have realized that volcanic eruptions are among the greatest threats. Chile is located on the Pacific Ring of Fire (PROF), which concentrates ninety percent of the seismic activity on the planet and eighty-one percent of the volcanic phenomena. In fact, the Chilean territory presents one of the highest concentrations of volcanic presence in the world, with over 160 registered volcanoes and around 90 estimated active volcanoes permanently monitored. We have experienced a number of eruptions in the past decade, often with devastating results, in terms of both human distress and suffering and material and territorial loss, as on average there is a volcanic event every 3.5 years in our territory. According to the Volcanic Threats Map of Chile [1] out of the 15 Regions of Chilean territory, only two of them are exempt from volcanic activity currently being monitored. These threats are scattered all over the territory along the Andean mountains (Fig.1), particularly concentrating in the 15th and 2nd Regions in the north, and in the Metropolitan through 10th Regions in the center-south. For the purpose of this study we have chosen the Villarrica Volcano due to its convenient accessibility, known and stable current status and personal on-site experience. Its proximity to populated areas and its active behavior in the past years makes it both a suitable case study and a fresh source of pyroclastic material. Located at the border that separates the 9th from the 14th Region, Villarrica Volcano has registered 50 eruptions (90 estimated but less documented) and has erupted in recent years (1984, 1985, 2015) [2], endangering surrounding populated areas and causing around one hundred casualties just in the 20th century. Damage, evacuation and relocation of settlements and smaller rural localities have also resulted from Villarica's eruptions. Beyond this particular case study though, the ultimate goal is to develop methods that could be adapted and deployed to specific conditions and locations on a national scale as required by volcanic events or social demand, since they are so widely spread over the territory.

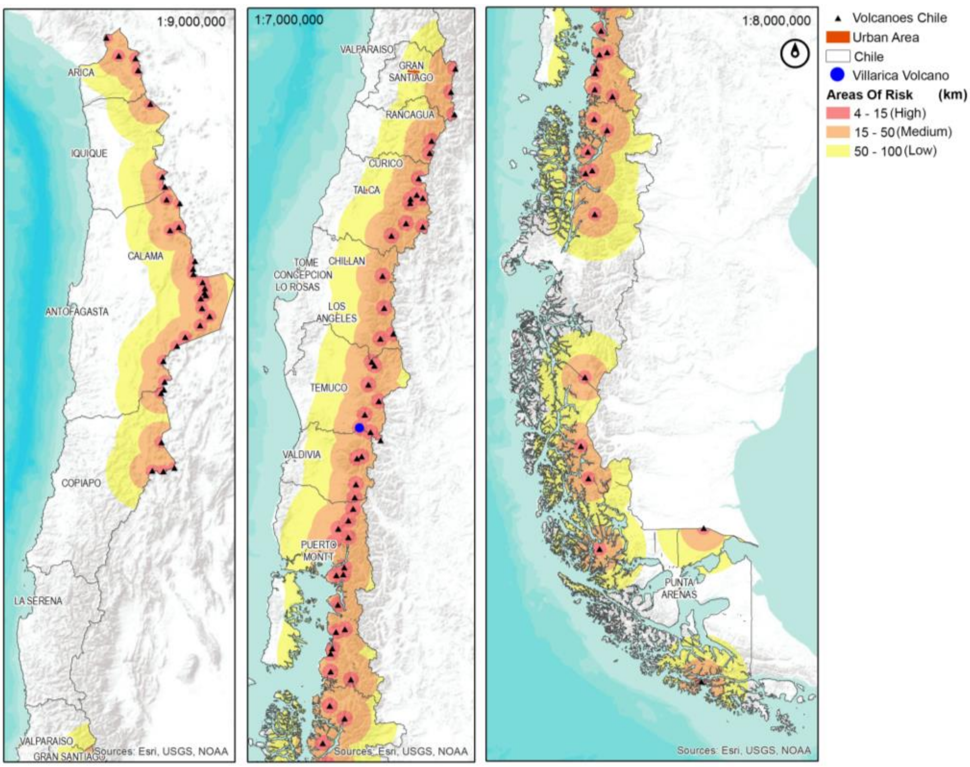

Fig.1. High risk volcanoes map. Source: SERNAGEOMIN

1.1 Objectives

This research focuses on the advantages of combining underused material with CNC and robotic technologies to produce a construction component and system; the design focus centers on creating sound components and assemblies that allow for connections between (preliminary at this stage of the research) perpendicular and/or coplanar structures. Taking into account the unpredictability of site locations and the critical and complex logistical variables within a post-disaster reconstruction process, and therefore the implementation of these methods in relation to disaster recovery strategies and reconstruction strategies, our three main objectives are:

- To assess developable capacities for working and/or handling the material in non-industrialized environments. Turning a detrimental and wasted material into a productive resource.
- To evaluate material properties and technical properties of assembly systems. Confirming mechanical quality of components and systems.
- To enhance structural and material qualities of reconstructed structures and dwellings in relation to pre-existing structures. Refinement of structural assemblies and improvement of material qualities through finishing. Adding value to raw material.

We understand and are fully aware that we have left out an important aspect of the architectonic strategy, at least to this point: Spatial and Formal explorations given the new materials and systems. We are focusing for now on setting the basic parameters and confirming the material properties of both components and basic assemblies. We intend to pursue different paths in terms of architectural expression and explorations at a later stage, once we have firmly established these initial foundations.

1.2 Historical Context

While volcanic rock was quarried in the past, particularly during 19^{th} and early 20^{th} centuries in areas close to PROF, and was used as walling and building material (Nathan, Hayward, 2013) [3], it was a time when labour was cheaper and stonemasonry was still a relevant building technology and trade. Stonemasonry is one of the oldest building techniques, but it is time and labor intensive and has limitations as a construction system due to the weight of the parts, low insulation capacity and spanning dimensions. The availability and inexpensiveness of timber eventually lead to a loss of skilled labor in relation to stonemasonry [4]. While vernacular construction often utilized volcanic rock as a construction material, with the emergence of industrialized and standardized materials in modern and contemporary markets, the use of stone, and in particular of volcanic rock, has moved to façade or veneering applications, or to ornate and decorative elements.
Off the Portuguese coast, in the Azores, traditional construction methods make use of volcanic materials as a means of adapting to local conditions. Located along the Terceira Rift (where the Eurasian and African plates meet), the nine islands making up the Azores are of volcanic origin. An important feature of the region is Pico Volcano, at 2351 meters high. Seismic and volcanic events occur frequently among the islands and have given rise to strategies that make use of volcanic rock as a construction material, whether for main, structural purposes or for complementary techniques. Under these conditions, construction criteria have been established using masonry with stones or with reinforced concrete for vertical components. Records from before the most recent earthquake that occurred in the middle of the island (affecting Faial, Pico and São Jorge) showed that more than 50% of

local buildings on Faial (vertical structures or load-bearing walls) were built of stone, while 30% were made of a combination of reinforced concrete and stone, both of which were complemented with roofs structures built of lighter materials such as wooden trusses. With the irregular shapes of the stones, whose width averages 60 to 70 cm, the strategy is to use volcanic debris bound with clay and mud to even out the differences (Fig. 2). A variety of clayey materials are also used to finish these structures, stucco-like, in thicknesses of no more than 2 cm [5].

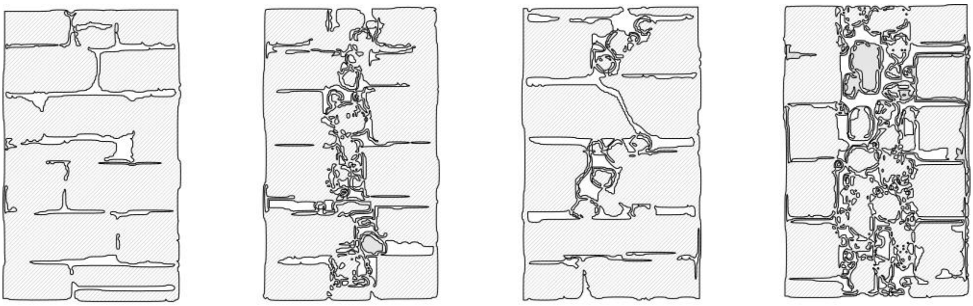

Fig. 2. Types of external stone masonry walls, Azores. Source: [5]

New robotic technologies and digital fabrication techniques allow for more efficient processing of the raw materials, development of parametric joints and assembly systems, automating manufacturing processes and in addition obtaining a finishing quality that greatly surpasses previous results adding value to solutions and new aesthetics possibilities to designers. Our focus on a particular type of volcanic rock, scoria, which is highly porous and therefore lightweight, reduces weight issues for transportation, processing, structural concerns and final assembly. It also increases the insulation properties of the built structures. Finally, by controlling the finishing of the pieces ranging from completely raw and abrasive appearance through coarse but planar finish all the way to a highly polished and reflective surface, a residual material can be turned into a performative and elegant structure.

2 Methods

This ongoing research proposes a novel approach that emerges as a reflection on the current state of disaster relief strategies, but that can potentially expand much further by focusing on material tactics that incorporate and use the solidified molten rock and pyroclastic flows that were majorly responsible for the damages caused to populations and settlements in the first place. A combination of robotic manufacturing algorithms and parametric design of modular systems transform highly abrasive volcanic rock into a smart, lightweight, insulating and structural system that can be used to reconstruct the housing units of those who lost everything under that same fluid volcanic material.
Volcanic rocks have widely different characteristics depending on their location, composition, type of volcanic event, and other factors. Among them, the depth at which

the original material is found and the way in which it is melted, expelled to the surface and formed will define the different properties this material will have. Basalt stones are made up of materials of high density and strength, depending on their level of open porosity. Alternatively, pyroclastic rocks are formed by fragments of materials with different characteristics, such as grain size and textures and with high levels of porosity and low densities. This paper studies a basaltic type of pyroclastic rock [6] because of its compressive strength and light weight due to its open porosity.

2.1 Tooling / Machining Setup

- Multicam Classic Series D 3 Axis CNC Router. Range of movement at X axis: 1 – 2440mm, Y axis: 0 – 1200mm, and Z axis: 0 – 110mm. Flat tip diamond drill bit Ø1/4" (6.35mm). Routine programmed in RhinoCAM v.2.0.
- Kuka KR 180 R2500 robotic arm. Maximum length 2500mm. On a linear axis 3860mm long. Bosch angle grinder with 4.5" flange-mounted diamond disc. Routine programmed in Rhinoceros v.5.0 / Grasshopper v.0.9.0076 / Kukalprc by Johannes Braumann.

2.2 Experimental Test Setup

To determine which tool is best adapted to working with the material and to compare the two, a cutting/grinding routine is performed to assess best work speeds and optimum finishing levels for each batch (Fig. 3). Once these parameters are established, the most appropriate combination of variables for the proposal is determined for each tool. The work (milling) area to be tested measures 10mm wide x 50mm long with a depth of 10mm. That is, we associate the work area with a socket component of the assembly system. A similar milling strategy is established for both diamond tools, which is to generate a set of lines that are parallel to each other and cover the work area. The distance between the lines varies according to the width or diameter of the tool, which is 6.35mm for the drill bit and 2mm for the disc.

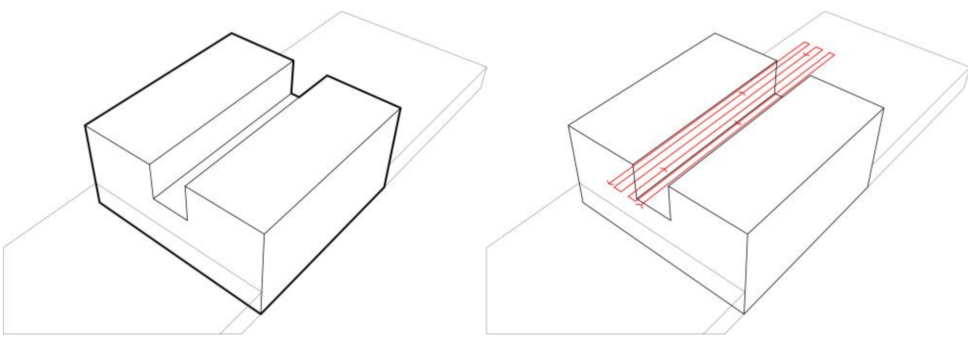

Fig. 3. Socket component test setup. Socket area to test + Routine path.

Although there are studies that have tested stone-based materials in cutting and milling routines [7-8] in order to establish certain characteristics of how the tool has interacted with the material in the past, determining progress speed, cutting depth, etc., it is difficult to validate previous results with the material being studied in this research due to its composition. That is, the average grain size or porosity may be determined but, due to the anisotropy of the material, it is impossible to anticipate how it might react, for example, to the amount of pressure the tool exerts on the material. From this criterion, and based on observations of the mechanical behavior of the material as the tool moves along its path, it has been determined that the diamond disc has a better time/definition ratio; that is, it is faster and has a better level of detail. Regardless of the fact that, given its diameter, the drill bit can cover a larger work area, the vibrations generated by the tool on the material require that both the speed and cut depth be reduced in order to generate less mechanical stress that could produce fissures and/or cracks in the block, or uneven disaggregation of the material, that is, the expulsion of particles (grains) of varying size that do not allow for well-defined joints.

Table 1. Average progress configuration

Tool	R.p.m	Cut Depth (mm)	Cut Speed
Flat tip diamond drill bit ø ¼”	1.000*	0.5	1% of 2000mm/m
Diamond disc 4.5”	11.000*	10	5% of 1m/s

*Minimum configuration **Default (and only) configuration

2.3 Processing Phases

The methods that we developed to produce the blocks that constitute the construction system, start by defining a digital design and fabrication strategy involving proportions, shapes of each recovered volcanic rock to be turned into brick components, kinds of tools to use, mechanical aspects of the material, and specific anisomorphisms on the material stock. After determining which tool is most appropriate for working with the volcanic material, processes must then be designed to transform the stone from a raw material, one that is irregular in both shape and porosity, into a construction component. To attain this goal, we have established three stages of material handling, starting with a process whose purpose is to obtain optimal sizes for future processing. This first phase involves laminating (Fig. 4) the basic shape to reduce the degree of intervention with the stone and standardize the process with the new shapes.

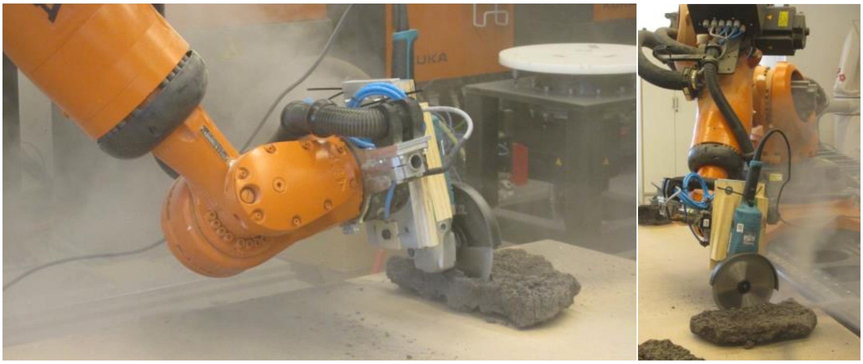

Fig. 4. First cutting test.

In the second stage, each brick to be used in construction is produced, focusing on how to streamline the steps in the milling process by using intelligent outlining that will then be followed by the tool to complete the work. Finally, the material is polished to give it a finish that enhances the texture of the stone, contrasting its raw, irregular face with a sophisticated, elegant surface. These phases are developed from an understanding of the form to be built, that is, the components of the vertical structure. The design varies depending on the role of each component (brick) in the structure and how they interact with each other. As a design exercise, a determination is made of what blocks and/or bricks are to be used to build coplanar and perpendicular structures using side and frontal joining. This parameterization in designing the wall determines the formal relationship among the different components while providing information for the subsequent manufacturing process. Finally, a simulation is done to determine what mistakes might be made by the robotic arm or to observe and correct outlines in the different cutting processes.

2.4 Digital Design and Fabrication Strategies

Given the constraints assumed in the objectives of this research, a digital strategy is developed using a design based on two variables: optimizing materials and generating simple geometries which will ease construction and assembly time.

2.4.1 Digitalization and Nesting

One of the factors to take into account when working with a material whose process, both in formation and in extraction, cannot be repeated and/or equaled, is the geometric consistent result of each of the samples prepared. That is, due to environmental (natural) variables that influence the formation of the material, or to the process used in extracting the material to transport it to the work space, it is very difficult to know ahead of time the base block format (size and/or proportions) that one will be working with. Therefore, a strategy is established to optimize or adapt the variables mentioned above and to make the most of the properties of the block extracted (Fig. 5). The first decision considers how to split a geometric form without an orthogonal perimeter; that is, the optimization strategy seeks a minimum loss of material, considering the initial geometry to be extracted from the base block.

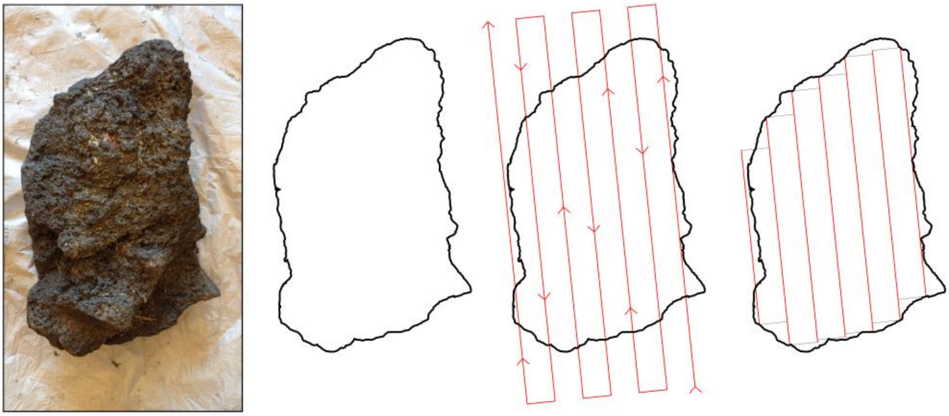

Fig. 5. Digitalization process.

Each block is photographed from above to obtain its vectored perimeter. The photographs were subsequently digitalized, enabling us to enter the shape of each base block into the computer. There, the information from the resulting digital outline will then be translated into cutting routines for the robotic arm.

The organization, or subdivision, of the base block must take on the shape of the brick that is ultimately sought and that will form part of the structure to be built. The reference for this first subdivision is the total height of the brick. A series of mutually parallel lines are then projected onto the area whose perimeter was obtained from the digitalization of the aerial images. This is done through digital iterations drawn in Rhinoceros 5.0 and Grasshopper 0.9.0076 which makes it possible, in real time, to rule out options with less material optimization and to identify those with reduced levels of loss.

2.4.2 Joints Design

Unlike the process described above, which performs a uniform pattern, cutting lines (axes) throughout the length/area of a certain irregular geometry, that is, unidirectional lines, the joints design is developed to work on surfaces and with multidirectional geometries (Fig.6). The latter constitute a challenging aspect for the join system protocol which, in a subsequent process, will have to be precision mechanized. There are formal aspects to keep in mind based on the knowledge of the tool to be used, such as what type of geometry can be obtained with a specific type of diamond coated aerated disc (regardless of its diameter), that is, a design based on the manufacturing process. This is used to determine the rules of design in order to optimize the process.

- Being a unidirectional work tool, the joint components must have orthogonal geometry.
- The geometries must consider the circular shape of the tool and avoid both interior orthogonal and concave outlines such as, for example, a socket component that does not extend the entire length of the brick.

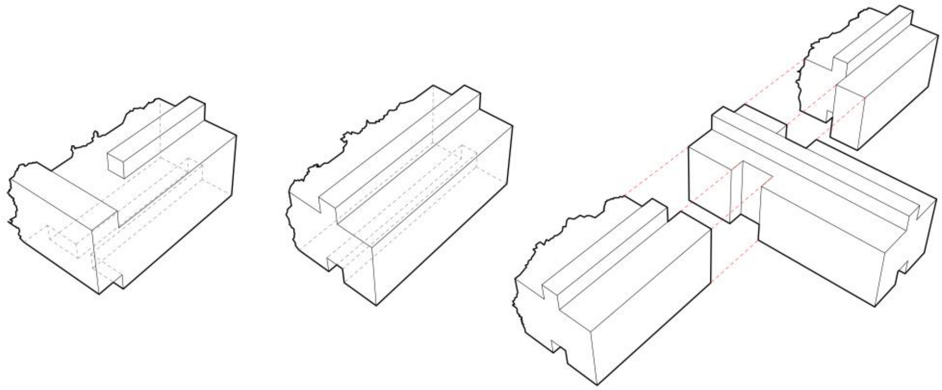

Fig. 6. Types of bricks. End wall. / Intermediate. / Perpendicular joint.

2.4.3 Digital Fabrication Strategies

A fabrication methodology is established based on the simple designs pursued. The methodology is organized in three scale levels, starting with working the rough block, with no previous handling and/or intervention other than the extraction process. This is followed by the interior machining of the bricks, that is, the joints that build the self-supporting structure and, finally, the finishing of the interior and exterior of each item.

2.4.4 Cutting Process

Given the formal characteristics of the stock to be worked with, that is, the lack of previous knowledge of the size and shape of the material, what is proposed, in this first stage of milling, is a sandbox/molding that can adapt to the rough block on a horizontal plane. Given the texture and/or roughness of the material, this avoids placing the block directly on the work table and thus avoids the rocking inherent in the block during the cutting routine due to the vertical pressure exerted by the disc.
Once the base block to be worked has been stabilized on the horizontal plane, cuts are made following the pattern of parallel lines drawn during the design phase, extracting layers of material. During this cutting process, it is important that the work tool, the diamond disc, have a radius larger than the thickness of the block to be cut due to the need to perform the cutting routine on only one side. This avoids having to turn the block since,

knowing its irregular format, it is highly improbable that a precise record can be generated that keeps the cutting axis the same on both sides.

2.4.5 Roughing Process

When the areas to be milled have been determined in the design phase, it is important to take into account factors that will subsequently have an effect on the self-supporting aspect of the structure. That is, despite the fact that the system can be complemented with a binder at a future stage, the outlining and/or path that the disc will follow must consider the tolerances among the joint system components and avoid excessive friction between the vertical planes that make up the dovetail system of each brick at the time of final mounting. Among the possible consequences are the fracture and/or cracking of the material, or an excessive tolerance between the parts making up for an unstable joint propagating this instability throughout the structure.

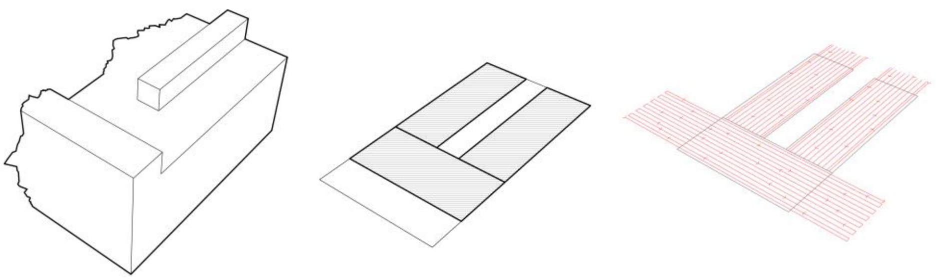

Fig. 7. From brick design to roughing path.

The area to be milled must be along a path formed by parallel lines whose distance apart is determined by the width of the tool. However, the separation between the segments making up the pattern to be followed must be less than the thickness of the disc, thus avoiding rough areas that exceed the work plane and do not allow the structure to work properly after the final mounting.

Fig. 8. Peg and socket joints first roughing test. Front / Back views.

2.4.5 Finishing (polishing) Process

We previously discussed the texture of the base material in terms of the problem of how to place an irregular shape on a horizontal plane for it to be worked. Once we have processed the material, milled the base block and machined its joint sections, the purpose of the finishing phase is to take advantage of its texture, or how the roughness and/or porosity enhance the final structure by contrasting the irregularities of the original material with the smooth areas. Exterior/interior conditions are established with a different surface treatment for each. The process starts with a manual phase in which porosities must be leveled out in order to create a smooth plane using a marble filler, a product used in the marble industry to finish blocks with fissures and/or cracks with which all of the pores disappear.

While the use of robotic arms in manufacturing (on a smaller or larger scale) has a comparative advantage over manual work, that is, less production time, greater capacity to automate processes, etc., manual processes have an advantage over automated ones in procedures that require a certain tactile sensitivity [12]. In its work routine up to the current state of the experiment, the machine cannot be programmed to provide a sensible solution or provide sensitivity criteria to determine whether the work was completed

properly, but can only follow instructions based on previously programmed codes. A feedback mechanism based on image capturing/processing might apply, but is ruled out for now and postponed for future work. With the manual process complete, the robotic arm is adapted to generate a smoothing routine to extract the excess material previously worked, using abrasive discs that, with increasingly fine grain, prepare the area for the upcoming polishing process.
Here, the only requirement is the co-planarity of the pores that have been filled and the surface of the rock that has been worked.
Depending on the final thickness of the filler, and once it is dry, depth criteria is determined so that each disc can come down and perform its routine.
Finally, polishing takes place along the same horizontal path used by the abrasive disc (milling). In this phase, a stone-polishing machine has been mounted onto the robot which, using a constant flow of water and a set of diamond discs used especially to perform this finishing work and whose grain size varies from 50 to 6000, works in such a way that the friction generates changes in the sharpness of the block, finishing the process with a brick that has one rough, untreated side, and another polished side (Fig. 9).

Fig. 9. Polishing setup. / First polishing results.

The final result is a brick that can vary from a rough, coarse, aggressive yet natural aesthetic, through a porous ceramic component all the way to a mirror-like, marble-type, highly refined and elegant architectural material. This is a process that, ironically, transforms detritus and waste to a structural luxury material within a disaster recovery housing context.

3 Discussion

Disaster recovery usually implies emergency policies of reconstruction, shipping prefab structures to site, adding cost, and neglecting structural and material quality of the housing solutions provided. Our proposal is to utilize material available on site at no cost (which, in fact would require removal for recovery or even for soil remediation) and to create structurally sound, energy efficient, and materially generous architectural solutions using a flexible modular system of interlocking stone blocks (Fig. 10). We have seen a number of studies emerging in the recent past using parametric design and computer controlled fabrication [7-11] applied to stone as a return to old techniques with new and innovative technologies. Here we aim to target an under-studied material, developing custom techniques to process it, while contributing to the expansion of digital fabrication knowledge to help serve a social cause.

Fig. 10. Vertical structure prototype. Front / Back views.

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Robot-Aided Fabrication of Interwoven Reinforced Concrete Structures

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Abstract. This paper focuses on the realization of three-dimensionally interwoven concrete structures and their design process. The output is part of an ongoing research in developing an innovative strategy for the use of robotics in construction. The robotic fabrication techniques described in this paper are coupled with the computational methods dealing with geometry rationalization and material constraints among others. By revisiting the traditional bar bending techniques, this research aims to develop a novel approach by the reduction of mechanical parts for retaining control over the desired geometrical output. This is achieved by devising a robotic tool-path, developed in KUKA|prc with Python scripting, where fundamental material properties, including tolerances and spring-back values, are integrated in the bending motion methods via a series of mathematical calculations in accord with physical tests. This research serves to demonstrate that robotic integration while efficient in manufacturing it also retains valid alignment with the architectural design sensibility.

Keywords: Robotic fabrication · Robotic bar bending · Concrete composite · Geometry optimization · Polypropylene formwork.

Computing Stitches and Crocheting Geometry

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Abstract. This paper presents a study that explores the computability of the craft of crochet. The study involves two consecutive stages: an analytical and systematic approach to crocheting three-dimensional objects to discover the underlying computational aspects, and a formal representation of the deducted computational logic in the form of a computer algorithm. The aim is to explore the computability of hands-on making processes where computation extends beyond the use of computers and digital tools to spatial reasoning in general.

Keywords: Computational making · Parametric design · Digital craft.

Parametric Tools and Models for Design

Practical Trajectories of Parametric Tools in Small and Medium Architectural Firms

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Abstract. Initially used as an extension of hand-drawing tools, digital design tools and moreover parametric ones are nowadays deeply modifying the architectural design process. Big offices with star-architects were able to adopt these tools but most architects working in a small office are still trying to cope with these parametric design tools. Several questions arise in this regard: what digital tools do architects usually use? Do they express interest for new technologies and software such as parametric ones? What is their understanding of the term "parametric architecture"? Why is this kind of tools still not largely adopted? Going through the results of an online survey, this paper first discusses the meaning of parametric design for architects. The contribution then analyzes the Belgian case regrouping mostly small and medium offices. It reflects particularly on the way architects do or do not implement these new digital tools in their workflows, and it sheds light on the fact that parametric tools also have the potential to free the creativity of SME's.

Keywords: Complexity of Digital Tools, Parametric Tools, Small Architectural Firms

1 Introduction

First introduced as a substitute for hand-drawing tools, digital design tools and particularly parametric ones are today challenging the entire architectural design process. Conventional Computer Aided Design (CAD) tools and packages are nowadays deeply rooted in most day-to-day architects' work. It took time, however, for them to be implemented in such a global way. Parametric tools are facing an even slower adoption rate, their integration to the design processes being still a challenge for most small and medium architectural firms. One of the reasons is that beyond enabling the integration of multiple parameters, these design tools are also partly responsible for the growing complexity of the design process itself.

Originally, parametric modeling was developed for design in aerospace and automotive areas [1]. "Star-architects", thanks to their large teams of software engineers and resources to train teams to a new workflow, were of course able to adopt, and adapt, these innovative tools. But when we consider the practice of most other architects, there is a very different reality – at least at the time being.

The paper first discusses the meaning of parametric design and analyzes theoretical contributions comparing different practices embedded in this concept. The contribution then describes and analyzes the situation of small and medium Belgian offices, reflecting particularly on the way architects implement and take advantage of digital and parametric tools when designing architecture.

2 A Theoretical Look Into Parametric Practice Through History of Architecture

On the theoretical side, we can define three different eras in architectural history from the viewpoint of design support tools' evolution. These three eras can be summarized as follows: 1. morphogenesis through experimentation; 2. first steps into the digital era and 3. digital architecture nowadays [2]. Parametric modeling is one of the digital modeling methods integrated in the current architectural design praxis.

The impacts traditional digital tools have on the main phases of design processes have been the subject of scientific attention since their adoption in the 80s. By now, many researchers have demonstrated the positive and negative influences of these tools and moreover report on the influence of parametric tools and their growing interest for architects given the new perspectives they open in terms of workflow and diversity of morphologies [3], [4]. Yet, these studies are generally performed within large offices whose parametric practices are recognized, this way setting aside the experimental applications of parametric tools inside Small and Medium Enterprises (SME's). Some of our previous research indeed sheds light on the fact that parametric tools are mainly used by large agencies while smaller offices still operate with more traditional CAD tools, more profitable to their day-to-day activities [5]. Therefore, we can confirm that the architects' community is split into two major groups such as described by Bourbonnais [6]: the ones easily adopting technologies and the so-called "technophobes", somehow reluctant to implement renewed ways of modeling on a day-to-day basis.

Within the communities of adopters, two main types of parametric tools are currently at use [1]. The first group of tools is more focused on *Building Information Modeling* (BIM), where parametric relationships encapsulate parametric descriptions of components of a building design, across multiple disciplines [7]. ArchiCAD© is an example of such a software. The second group of parametric design tools is based on *associative-geometry*, where parameterized mathematical descriptions and associations between points, curves, surfaces and solids are made possible. Parameters, in this context, can also characterize and control performance, structural, material, social, urban or environmental features. The tools belonging to this second group include Bentley Generative Components© and Rhino Grasshopper© for instance. Worth to underline is the fact that the evolutionary processes implemented through parametric tools totally contrast with the static behaviors of more traditional modeling methods, used to create one instantiated model. Theoretically, this evolutionary process is more effective than traditional numerical modeling [8]. A survey, described in the next section, helps us understand how both communities of adopters and technophobes interact with these different ways of practicing.

3 A Look Into Practices of Small and Medium Architectural Firms

Digital tools and parametric ones in particular are presently recognized for their potential to develop new kind of complex, "non-standard" architecture. But how do small architectural offices deal with those tools? Do they achieve such breakthrough as easily? This section will report findings from a survey sent to all Belgian architects and architectural engineers, and more specifically about the challenges they face in dealing with digital and parametric tools during the various steps of their design processes. Belgium is, in this regard, an interesting case study because it is known to be dotted with quite small offices.

3.1 Research Gap

Following up existing literature, we understand that a gap of knowledge exists when it comes to current parametric architectural practices in small offices. A significant amount of work has been done about large architectural firms using parametric tools, such as Shelden [4] focusing on Gehry's architecture. The only study paving the way on how small agencies deal with such design tools was carried out in Austria and England but could not be concluded due to lack of architect's participation [9]. More specifically in Belgium, the last study about the use of digital tools by architects was conducted in 2008 [10]. The goal of this research, mainly addressed to the North part of the country, was to assess the impact of different types of design support tools (DSTs) through the decision making process. This research was thus not specifically focusing on the role of digital tools in architectural practices. It rather classified six types of design tools according to the role they played all along the design process: knowledge–based tools, communication tools, modeling tools, presentation tools, structuring tools and evaluation & analysis tools.

Considering this current state of knowledge, and regarding results previously published elsewhere [2], this paper will therefore address three main research questions:

[-] How do architects use digital tools in general? Do they express interest for new technologies and software such as parametric ones?

[-] What is their understanding of the term "parametric architecture"? What fears/hopes/beliefs are driven by this term?

[-] Why are parametric tools still not largely adopted, at least by the Belgian practitioners?

3.2 Methodology

Regarding the large amount of people to reach (about 13.000 architects or architectural engineers), we used an online-based survey strategy in order to explore the previous research questions. The following sections aim at developing the methodology used to rigorously build and analyze this survey.

The questionnaire was built around three main sections. The first part began with collecting the participants' demographic data in order to contextualize each profile. Ten questions were formulated (1 open-ended question, 7 semi-open questions and 2 closed-ended questions) and mainly related to the participants' gender, age, background, expertise, main day-to-day tasks and size of firm. The second and most important section questioned designers' digital culture, the digital tools they use, their feelings about those digital tools and the impact those digital tools have on the architectural design process, from their point of view. This section contained 26 questions with 6 open-ended questions, 10 semi-open questions and 10 closed-ended questions. The results about the use of digital tools in general, the feelings about those digital tools and their impact on the architectural design process, have been published elsewhere [2]. The concluding section investigated parametric design and tools. It was structured around 9 questions (1 open-ended question, 1 semi-open question and 7 closed-ended questions). This section asked, for example, to rank the difficulties encountered when using parametric tools, according to the architect's priorities; it also investigated whether designers felt concerned by the arrival of new design tools called "parametric" or also in what time period they plan to train themselves to parametric tools use. The whole survey is available on demand (please contact authors).

The questionnaire was tested with a first round of a few participants, which enabled us to specify the meaning of some statements, to adapt some fixed-alternatives answers and to test the time needed to complete the questionnaire rigorously.

After this test-survey, we concluded that if a completed survey fulfilled one of the following criteria, it was considered unusable and therefore was not included in the next steps of our research:

[-] The survey was completed far too quickly and therefore could not have been taken seriously. The test-survey round demonstrated that the 15 minutes boundary was the right limit;

[-] Only the first section of the survey was completed (the other two completely ignored), and therefore offered no data about neither digital nor parametric design/tools. This means that some surveys, where only a few questions had been dismissed, were still considered as valuable (in that case, a "no answer" – NA appears in regard to the few dismissed questions);

[-] Regarding the size of the firm, we put aside participants working in structures of more than 100 people. These people, the "background" and "main tasks" sections reveal, are mostly architects working as academics only or included in larger, contractor structures.

The analyze of the data mostly concentrates on quantitative results basically treated in order to delineate general trends, and supported by qualitative data to more closely look at some of these trends.

3.3 Sample Description

For this study, over 700 responses were collected and 572 answers were eventually selected for analysis after cleaning data. This amount represents 4.1% of the architects registered to the three different regional Architects Associations. The female-male observed ratio is close to the one collected through a survey conducted in 2014 by the Architects' Council of Europe (73% male architects at that time, [11]). In our case, 72.9% of the surveys has been answered by men and 26.8% by women (while 2 people did prefer not to answer), indicating that the current sample is sufficiently representative of the Belgian population. Our survey displays 49.3% of the participants under 40 years old, confirming the relative youth of the population as already observed by the 2014 survey. In regard of expertise, 32.9% of the respondents are practicing their main occupation for less than 10 years, 27.3% are practicing it for 10 to 20 years and 38.3% for more than 20 years. Regarding their professional situation, 52.6% of the respondents are isolated, independent architects (working on their behalf), 22% are independent architects working for some collaborator, 5.5% are employees, while 3.9% are architectural engineers and 2.6% are teachers (other participants distribute among other occupations). Throughout this paper we will refer to the participants as "designers".

The 2014 survey moreover showed that the amount of medium-sized offices is continuously decreasing, in favor of smaller structures: at the time being, already 74% of European offices counted only 1 person [11]. Table 1 demonstrates the relevance of our Belgian case, since 42.7% of the respondents are indeed working in a firm of only one or two people. Furthermore, almost 80% of the participants are working in a structure smaller than 10 people. This trends also supports why the paper intensively focuses on understanding the daily routines of small and medium architectural offices, not deeply studied by researchers and yet making up the larger part of the professional practice.

Table 1. Size distribution of firms in Belgium, according to our survey.

Size of firms (number of people)	1 to 2	3 to 5	6 to 10	10 to 20	20 to 50	50 to 100	NA
Percentage	42.7%	22.6%	12.4%	11.9%	5.2%	3.7%	1.6%

3.4 Use of Digital Tools in Belgian Offices

Our results first show that 76.9% of the participants indeed use digital tools during the design phase. Fig. 1 moreover shows that designers using design tools just for 2D drawing mainly use AutoCAD© (56.2%), followed by Vectorworks© (19.6%) and ArchiCAD© (14.8%). ArchiCAD© is also used as a 3D support tool (22.8%) but Sketchup© remains the reference for 3D modeling in architectural design, at least for 52.3% of the users. Parametric software such as Grasshopper©, Generative Component©, Vasari© or Digital Project© as Fig. 1 demonstrates are either totally, or largely unknown by the Belgian sample.

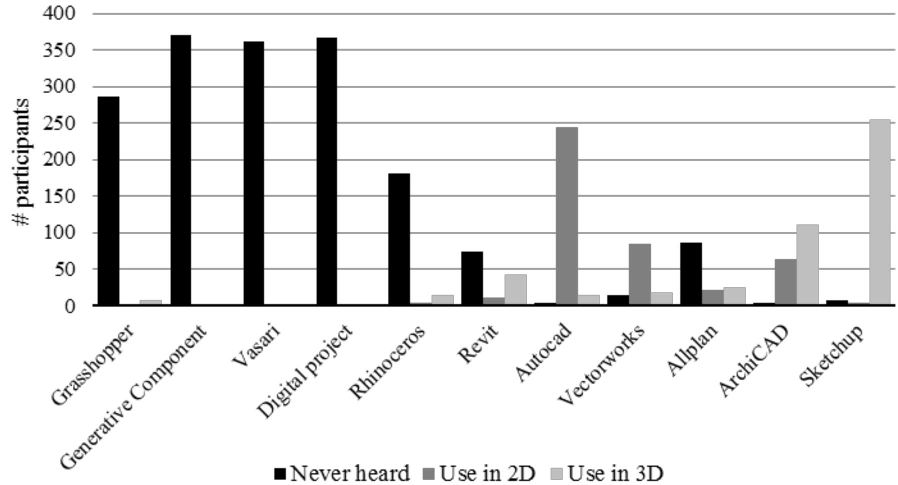

Fig. 1. Knowledge levels and use of digital tools in architecture.

The survey moreover asked the participants to evaluate how design tools impact several parameters of the architectural practice (Fig. 2). Most of them agree that digital tools have strongly increased the execution speed of projects, strongly facilitated exchanges with stakeholders and the implementation of projects, but they state digital tools have not promoted diversity of the shapes produced. Excerpts of free-field answers such as "*complex shapes are difficult to represent"* (e.g., curves) and "*non-standard element is complex"*, generating *"less creativity"* bring qualitative support to this result.

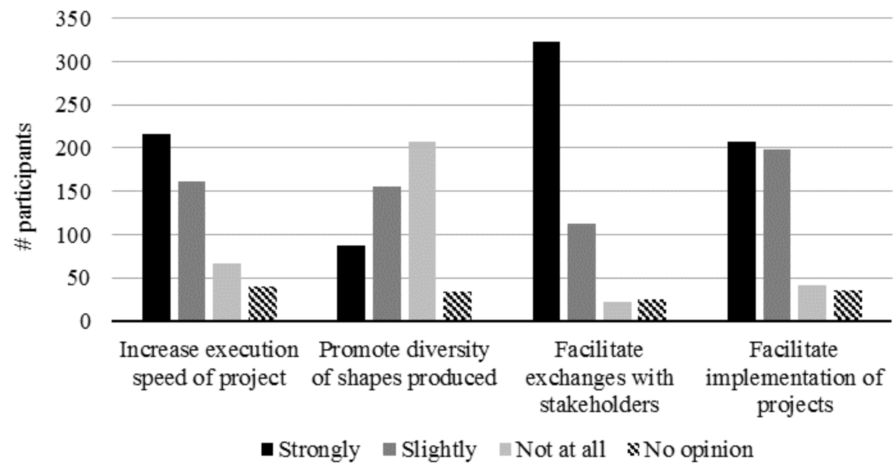

Fig. 2. Influence of digital tools on several parameters of architectural design.

A deeper analyze has been published by the authors [2] addressing the notion of complexity in the use of digital tools according to the designers' age or size of office for example. This previous paper also develops the factors and actors influencing the designed and produced shape, and eventually discusses the interdisciplinarity management inherent to such digital design task.

3.5 Use of Parametric Tools in Belgian Offices

In this section we will consider why parametric tools are still not largely adopted, at least by the Belgian practitioners; we will discuss the meaning of the "parametric" term and the perception and interest practitioners develop for this type of tools.

Interest and Understanding of Parametric Tools. First of all, our study shows that more than half of architects (51.5%) have never heard of the term "parametric modeling". X axis on Fig. 3 shows the increasing size of offices, while the Y axis presents the percent of participants that respectively (from top to bottom) didn't answer that question, "never heard" about parametric modeling or "already heard" of the term. We can observe that there is a slight growing tendency to know about parametric modeling with the office growing in size.

Our results moreover underline that only 14.4% of the respondents state "being concerned" about the arrival of these parametric tools on the market, leaving 38.6% of non-concerned participants and 47% who do not have an opinion. Fig. 4 additionally shows that the larger the size of the office, the higher the interest rate for parametric tools is. Small offices, at least at the time being, do not see any interest in those.

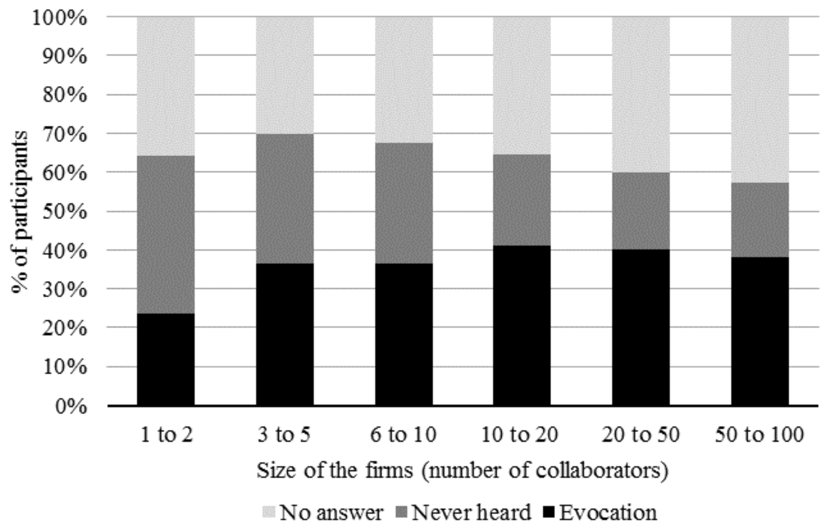

Fig. 3. Evocation of the term "parametric modeling" depending on the size of the offices.

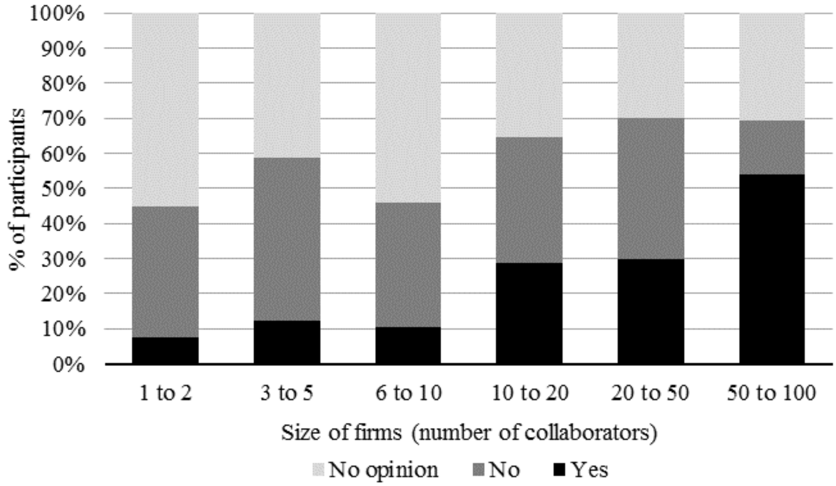

Fig. 4. Interest rate for parametric tools depending on the size of the offices.

Let's now focus on the perception of the term "parametric tool". Among the 87.5% of Belgian architects *not* using parametric tools, 34.5% refrain from giving a definition of parametric modeling, according to their point of view. 25.5% of these "non-users", on the other hand, try and give a definition. Out of this rough quarter, 18.8% associate it with BIM process and 53.6% incorrectly define it. Answers such as these ones are given by non-users: *"ability to output 3D, 2D and cuts generated by the model"*, *"complexity of shapes"*, *"whim of the 2000s"*. As for the remaining 27.6%, the definitions are not complete. Globally speaking, one can observe that designers are generally able to explain the methodology but do not grasp the added-value parametric tools could have for their own practice. Moreover, they associate to the term some strong mathematical notion generating an impression of complexity and fear of use (one of the respondent for instance quotes: *'A modeling of complex shapes using mathematical formulas.'*). Moreover, the parametric is obviously associated by some of the non-users with large projects: *'an advantage for large projects'*. The Belgian architects surveyed associate the term "parametric" to three well-known offices: Zaha Hadid, Frank Gehry and Foster and Partners. This misunderstanding of the term is also observed when looking at numbers: 82% of ArchiCAD© users indeed think that it is not a parametric software; yet this software can be consider like one of the BIM category with it library of parametric objects. Conversely 83% of those who have taken the plunge of the second type of parametric software (associative-geometry process) and who do use a plug-in such as Grasshopper© are aware of doing parametric design.

In that regard, 95% of the architects actively using parametric tools have given an explanation of what this term means to them. 3.3% of them provide what can be considered as a wrong answer with no regards to the real added value: *"image created on basis of points defined on the X and Y axis"*. 2.8% associate the parametric only to the BIM process and 93.9% of those who use parametric tools give a complete definition. We can refer to given definitions like this one:

'Design by using certain parameters (see i.e. Grasshopper). The term is mostly associated with the flamboyant forms of architects like Zaha Hadid or Frank Gehry but the technique could also be used for less extravagant designs, i.e. to design a façade system, vegetation scheme in a landscape plan…'
This means that the more parametric tools one uses, the more coherent the definition is.

Usefulness of Parametric Tools. Coming back to the current use of these tools in Belgian practice, 12.5% of the participants state they use parametric tools on a regular basis. Those who do engineering calculations are the most frequent users of so-called parametric software (Fig. 5), followed by those who practice 3D modeling (18.6%) and those who do designs of public buildings (17.8%), i.e. larger projects. The design of residential projects come in last (11.9%), whereas this type of project represents 37% of the tasks globally undertaken by Belgian architects. These numbers validate the fact that designers carrying out residential projects (generally corresponding to small to medium-sized buildings) do not feel concerned by the arrival of the new generation of digital tools, leaving those tools to larger, more complex projects.

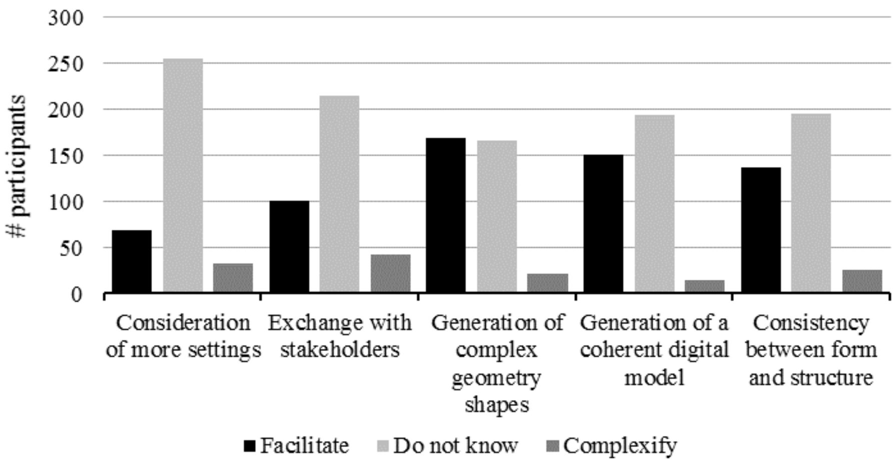

Fig. 5. Types of tasks and respective use (in % of respondents) of parametric tools.

Fig. 6 lists several impacts parametric tools have on the design process, and presents how participants evaluate this impact (from "it facilitates" to "it complexifies" through "I do not know"). Looking at the proportion of "I do not know" answers, we can observe how underestimated the impacts of parametric tools can be. However, when respondents have an opinion, black sticks indicate they believe parametric tools make it much easier to generate shapes with complex geometry and generate a coherent numerical model that keeps and coordinates changes all along the process. More generally, participants recognize in a significant way that parametric tools facilitate different aspects of the design process (taking into account more parameters, exchanges between stakeholders, consistency of form and structure).

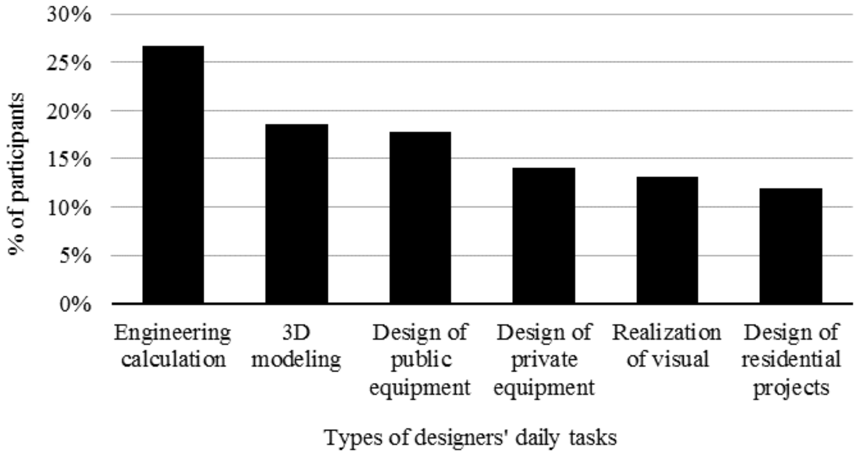

Fig. 6. Influence of parametric tools on several parameters of the design process.

When looking at how those results divide according to the frequency of use, other interesting observations arise. Those who do *not* yet use parametric tools think they can facilitate the generation of shapes with complex geometry (39.6%) and think that those tools could facilitate different aspects of the design process in general. 35.7% of them think parametric tools help to generate a coherent model that keeps and coordinates the modifications all along the design process. But more fundamentally, almost 60% of the non-users prefer not to pronounce in regard of the impact of these tools. Fig. 5 and 6 again confirm how underestimated the advantages of parametric tools can be.

On the other hand, among those who state using parametric tools, a large majority consider that they facilitate the design process in general and particularly the generation of complex shapes (86.4%) and the generation of a coherent model (75%).

Comparing to Fig. 2 that revealed that traditional digital tools are not considered as promoting the diversity of shapes produced, this new generation of parametric tools seems to remain a possible solution to rediscover a diversity of forms in the day-to-day design process, even for small and medium architectural firms.

This observation also correlates with another question asked to close the survey. Participants had to classify six main difficulties one can encounter (or expect, in the case of non-users) when using parametric tools. In first position (the most crucial problem from the point of view of 44.3% of the respondents), we find the slow and laborious learning of the software. This is indeed one of the problems encountered when using software in general. Second (for 34.3%) is the difficulty to stay up to level because the updates are frequent and the trainings expensive. Then two difficulties are highlighted (for respectively 18.6% and 30.5% of the respondents): the fear of losing control on the designed shape in favor of software, and the difficulty to reach easy interpretation of formal results at a technical and structural level. Additionally, the methodological workflow and the decreased speed of execution associated with the use of parametric tools seem to be considered less crucial for designers (fifth and sixth position for 34.3% and 50.5% of the participants).

If we compare the difficulties encountered by those who already use this category of tools, and the difficulties anticipated by those who do not yet use them, they are quite similar. However, fear of losing control of the shape decrease sharply in importance (from position 3 for 18.7%, to position 5 for 15.4% of participants) when designers use these parametric tools. We can therefore draw from those observations that what actually repels most users is the slowness and the difficulty to learn and to remain at level. This highlights the need to promote training on new techniques and technologies by the representatives of the sector.

4 Discussion

Our first research topic is concerned with the current use and perception of digital tools in Belgium, where firms are mostly of small and medium size. Our results underline that Belgian architects still use a traditional combination of software, mostly one commercial package for 2D design and another one for 3D modeling. Architects mostly agree that digital tools have strongly facilitated different aspects of their architectural practice such as speed of execution of projects, exchanges with stakeholders and implementation of projects, but they state digital tools have not promoted any diversity in the shapes produced. Considering these statements, we formulate two additional questions: are parametric tools accessible to every architect and can they restore freedom of creativity?

Researchers generally report the influence of parametric tools and the growing interest architects have for them, given the new perspectives they open in terms of workflow and diversity of morphologies. But these studies are carried out in large and renowned architectural agencies. Our paper underlines that Belgian architects do not currently work a lot with complex 3D or parametric tools, and feel remote from these new design support tools considered as designed for – and more adapted to - larger offices working larger-scale projects. Our survey indeed shows that half of the designers even never heard of the term “parametric modeling”, while 87.5% of them state not using parametric tools and only one seventh feels concerned by the arrival of tools called "parametric", such as the plug-in Grasshopper©. However, a trend shows that the larger the size of the office architects belong to, the most they know about parametric design and the most they feel interested in these tools. This disinterest expressed by smaller structures’ architects obviously leads to misunderstandings of what is at the core of parametric process and what parametric design might offer. The non-users cannot give a complete definition of what and why parametric process is interesting, mostly associating it to a mathematical process dedicated to large agencies. On the contrary, 95% of users give a correct definition, shared and understood by the community of users.

While parametric tools are mostly used for engineering calculations, the design of residential projects is the least affected sector while it represents almost 40% of the daily architects’ work in Belgium. Additionally, the paper looks into how parametric tools shape the way architects master the design process. All designers and even more users largely agree they ease the design process at different levels and, above all, 86% of the users agree parametric tools contribute to the diversity of shapes conceived.

Our results eventually shed light on the fact that parametric tools already freed the creativity of renowned offices and that, when adopted by SME's them, these new generation of tools have similar effects on their design processes. The transition to these tools is a bigger, more complex step for SME's to overcome but has the potentiality to ease freedom of expression for designers.

5 Conclusion and Future Work

This paper looked into the challenges architects working in small and medium firms face when dealing with digital tools, and more specifically parametric ones during their design processes. It underlines how their perception and understanding of these tools all along their day-to-day practices diverge from the current trends discussed in literature, especially in regard to the practice of larger architectural firms.

Future work will concentrate on two areas. Firstly, we will implement the same survey in other European countries in order to test and eventually validate and amplify the trends already identified in this paper. This may also lead to the emergence of digital culture trends. Secondly, we will deepen our understanding of current working strategies by interviewing and observing selected offices that answered positively to the possibility of further contact and on-field observation. This last phase will help us detect how to sensitize small and medium offices to new technologies, researching whether we should help Belgian designers adapting their processes or rather push for software adaptations and continuing training programs.

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Polymorphic Adaptation

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Abstract. Polymorphism, the ability of a substance to exist as multiple, different, crystalline solids is a subject of much interest in the fields of chemistry, pharmacy and crystallography. In some cases, polymorphs can be found to interconvert, usually in response to changes in the physical environment such as changes in temperature or pressure. The ability of structures composed of identical building blocks to interconvert is relevant to the field of architecture where architectural artefacts may require to respond to transient demands. Here we describe the phenomenon of polymorphism and the relevance to the architectural field, together with the development of a bespoke software plugin to allow polymorphic crystal structures to be used in design.

Keywords: Collaborative Design Research, Polymorphism, Digital Form Studies

1 Introduction

This paper illustrates the phenomenon of "polymorphism", a widely studied concept in the science of crystallography, and articulates the potential to utilize this phenomenon to design adaptive physical systems for architectural applications. The term polymorph is derived from the Greek words *πολυ* ("polu") which means many and *μορφη* ("morphē") which means form, thus translating as many forms. In crystallography, polymorphs are solid, crystalline substances with identical chemical composition but different atomic or molecular arrangements. Different polymorphs of the same substance often exhibit considerable variation in their physical properties. Polymorphism thus presents itself as an important principle as it illustrates that chemical composition alone is not enough to determine the physical properties of a crystalline substance, and highlights the significance of structure in relation to properties [1-4]. This paper discusses how the characteristic of polymorphic substances to exist in multiple forms (crystalline arrangements) and to transform from one form to another under certain conditions may find potential applications in design.

Architectural artefacts must often respond to transient demands. These demands could be environmental, in which a change in external temperature and humidity may require a corresponding change in architectural features to maintain comfortable internal ambient conditions. The demands could also be spatial or structural, in which the same space must serve different programmatic functions at different points in time, or they could be optical, where the same space requires modulation in its levels of transparency. This paper suggests that adapting and applying some of the principles of polymorphic transformations will help to address the above situations, by informing design research in the field of adaptive architecture in the following ways:

- by systematizing how designers understand the relationship between structure and physical properties;
- by interpreting the transformation from one (polymorphic) structure to another, for a variety of polymorphic geometries;
- by providing arrays of a variety of components that can be assembled into a variety of tectonic arrangements.

2 Polymorphism

An understanding of the geometric principles that underlie the arrangements of the building units (e.g. atoms, ions or molecules) in crystalline materials is key to understanding the phenomenon of polymorphism. In the fields of chemistry and crystallography, the spatial arrangements of the building units in crystal structures are rationalized through two fundamental principles – periodicity and symmetry [2]. It is the differences in spatial arrangements, and hence the differences in these two mathematical principles, that determine the varying physical properties of polymorphs.

Atoms and molecules in crystal structures inhabit space in regular arrays and exhibit long range periodic order. Crystal structures are typically represented in terms of a lattice, which is a geometrical abstraction of the actual structure. A lattice is made up of a collection of nodes, positioned at integral or specific fractional coordinates, with each node signifying the three-dimensional periodic replication of a structural motif, which represents a collection of atoms, ions or molecules. The repeating unit of the lattice defines the unit cell. The unit cell is an imaginary volumetric entity, which tiles space continuously when translated in three dimensions to build the lattice. For three-dimensional lattices, all unit cells are parallelepipeds. There are only seven different classes of parallelepiped that can tile three-dimensional space without gaps. These seven forms are defined as the seven crystal systems: *triclinic, monoclinic, orthorhombic, tetragonal, trigonal, hexagonal* and *cubic*. In a crystal system, the nodes may be located at only integer coordinates (termed primitive), or both at integer coordinates and well-defined fractional coordinates, in which case it becomes *centred*. Centring types include: base-centred (with nodes located at the cell corners and at the centres of two parallel faces), face-centred (with nodes located at the cell corners and at the centres of all six faces), body-centred (with nodes located at the cell corners and at the centre of the cell), and rhombohedrally-centred (with nodes located at the cell corners and at two points along the longest diagonal, and arising only for the hexagonal crystal system). We note that only certain centring types occur within a given crystal system, and their combination yields the 14 Bravais lattices, which are the 14 different types of unit cell that are possible in three-dimensional space [5-8].

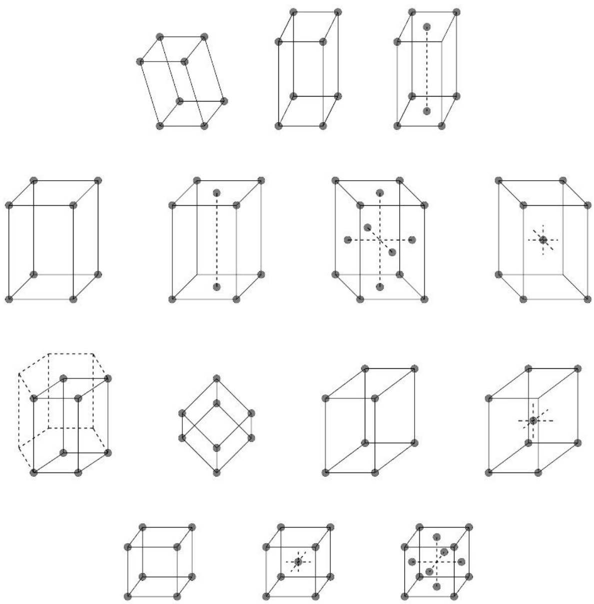

Fig. 1. Bravais lattices

Furthermore, within the unit cell, the positions of the constituent atoms and molecules are often related by a combination of symmetry elements, which include operations such as translation, reflection in mirror planes, rotation and inversion. Only certain combinations of these symmetry operations, in relation with the unit cell types, allow for the continuous tiling of space. Each allowed combination of symmetry operations defines a space group. In total, there are 230 space groups in three-dimensional space. The largest group of atoms within the unit cell which are not related to each other by any crystallographic symmetry operation is called the asymmetric unit. When the symmetry operations of the space group are applied to the asymmetric unit, the complete contents of the unit cell are generated [5].

Transformations between different polymorphic forms are often associated with a change in the Bravais lattice type and space group. For instance, shifting of certain atoms can result in a change of unit cell type – say from the *monoclinic* to the *tetragonal* crystal system, a change in unit cell dimensions along one or more axes, and/or a change in the number of atomic or molecular units per unit cell. These geometric transformations arise from changes in the nature of interatomic or intermolecular interactions, which are associated with alterations in interatomic or intermolecular distances and relative orientations of molecules. In turn, these structural changes are generally associated with changes in physical, mechanical, electromagnetic and optical properties.

The case of polymorphism in chemical elements is termed allotropy. For example, diamond and graphite are allotropes of the element carbon. It is interesting to note that these two materials exhibit very different physical properties and yet they are both constructed only from carbon atoms and hence have identical chemical composition. In graphite, the carbon atoms form hexagonal layers with weak interactions between adjacent layers, whereas in diamond, each carbon atom is bonded to four neighbouring carbon atoms in a tetrahedral arrangement [9].

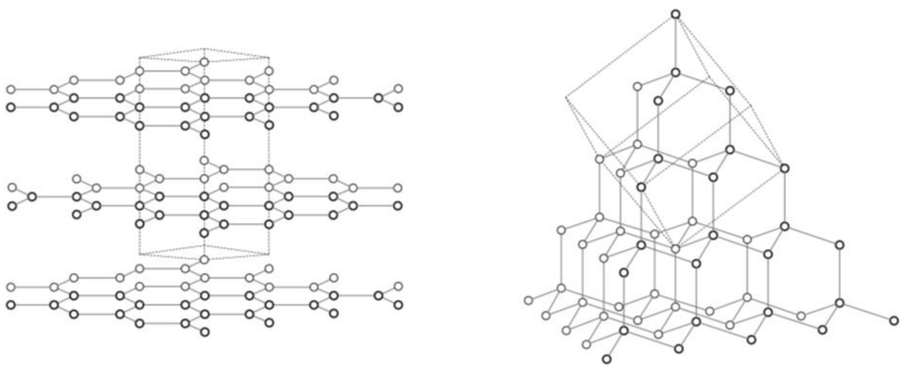

Fig. 2. (Left) Crystal structure of graphite, (Right) Crystal structure of diamond

Graphite has a hexagonal lattice (unit cell dimensions: a = 2.46 Å, c = 6.71 Å, where 1 Å = 1 × 10^{-10} m) and space group $P6_3/mmc$. Diamond has a cubic lattice (unit cell dimension: a = 3.56 Å) and space group $Fd\overline{3}m$. The weak interactions between layers in graphite give rise to the softness of this material, while delocalization of electrons within each layer gives rise to the electrical conductivity and colour of graphite. On the other hand, the strength of the bonding in three dimensions gives diamond its hardness, high thermal conductivity and refractive qualities [10-11].

Under a specific set of physical conditions (i.e., temperature and pressure) only one polymorph of a substance is the *most* energetically (thermodynamically) stable form. All other polymorphs are less energetically stable than the stable form, and may be expected to undergo a polymorphic transformation into the more stable form. In some cases, however, the energetic barrier for this transformation is so high that the polymorphic transformation is very slow. The diamond/graphite system represents an example of this type. Graphite is the stable polymorph under ambient conditions, and therefore, according to the laws of thermodynamics, all diamonds should transform to graphite. However, the energy barrier for the transformation from diamond to graphite is so high that no conversion of diamond to graphite occurs on normal human timescales.

3 Polymorphic Transformations

Polymorphism and polymorphic transformations represent a vast subject within the physical sciences. As an example of how such transformations may be relevant to design, we now discuss a specific classification of polymorphic transformations that is generally found for extended inorganic materials: reconstructive *versus* displacive transformations. Reconstructive transformations involve rearrangements that include breakage of bonds and creation of new bonds. Displacive transformations, on the other hand, involve only relative changes in positions of the atoms, for example through rotations or changes of bond lengths. While reconstructive transformations are typically slow (due to a high energy barrier) and often irreversible, displacive transformations are typically rapid (due to a low energy barrier) and often reversible [12-13].

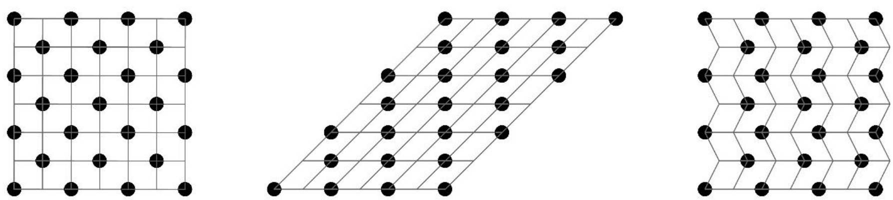

Fig. 3. Martensitic transformations: transformation of the structure on the left may produce the two structures on the right

A specific type of displacive transformation, observed for certain materials, is the martensitic transformation. It is found in metals, alloys and ceramics and has been used for applications in multiple fields. For instance, in some alloys such as nitinol (a nickel/titanium alloy), martensitic transformations lead to a *shape memory effect*, in which the sample can restore its original shape after deformation. This property leads to applications in medical and engineering devices, such as orthodontic files, and has been used to create new materials for actuation (such as ferroelectrics). Martensitic transformations are also observed in life forms. The tail sheath of the T4 bacteriophage virus is constituted of protein molecules in regular arrays, the realignment of which causes the tail to expand and contract. On the other hand, similar transformations in bacterial flagella lead to various versions of left and right handed helical coiling. Because martensitic transitions are reversible, require low energy for actuation, and are often structurally continuous, they are potentially a very effective model for applications in the field of adaptive design [14-16].

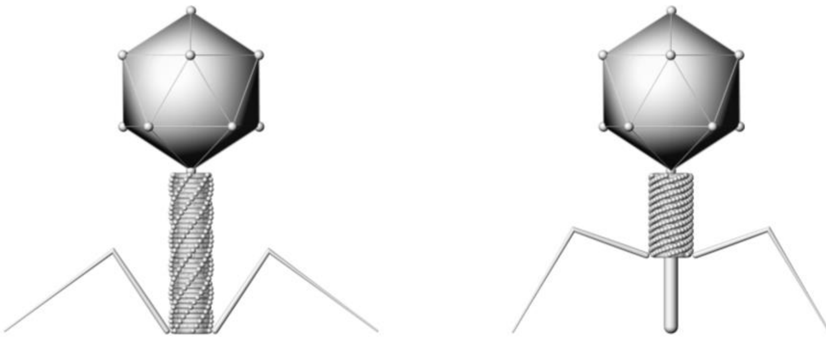

Fig. 4. T4 Bacteriophage virus prior to and upon attachment to host cell.

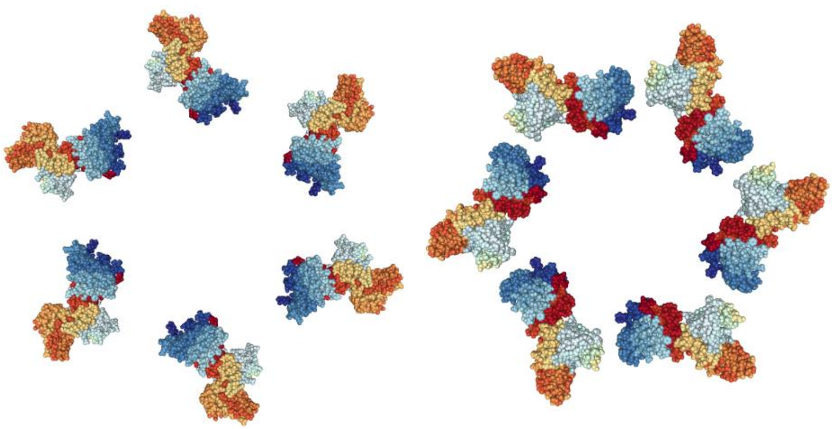

Fig. 5. gp18M protein from the tail of the T4 Bacteriophage virus in expanded and contracted form [17]

Another special category of crystallographic transformations, relevant to applications in adaptive physical systems, are transformations that result in mechanical changes.

For example, photomechanical crystals display changes in mechanical behaviour in response to the external stimulus of light [18-20]. Strictly speaking, many of these transformations are not polymorphic transformations, as the stimulus induces chemical changes in the crystal such that the molecular components are different before and after the transformation. In polymorphic transformations, on the other hand, the molecular components remain identical before and after the transformation. A variety of mechanical responses are known to arise in such crystals, including bending, twisting and cracking. In some cases, crystal explosions can even occur as a consequence of structural changes at the nanoscale generating extreme forces of stress and strain within the macroscopic crystal.

As an example, crystals of *cis*-4,4'-dibromooctafluoroazobenzene are found to bend away from a source of blue light (with wavelength 457 nm) [18]. This bending is caused by a chemical transformation (in this case, a *cis*-*trans* isomerization). The two isomers of the molecule occupy different volumes of space in their respective crystal structures, with the *trans* isomer requiring a greater volume than the *cis* isomer. When the blue light is shone on the crystal, the *cis*-*trans* isomerization occurs mainly on the crystal face nearest to the light source, causing an anisotropic expansion of the crystal. Thus, the crystal face nearest to the light source expands more than the crystal face furthest from the light source, and the resultant anisotropic expansion of the crystal leads to the bending process observed.

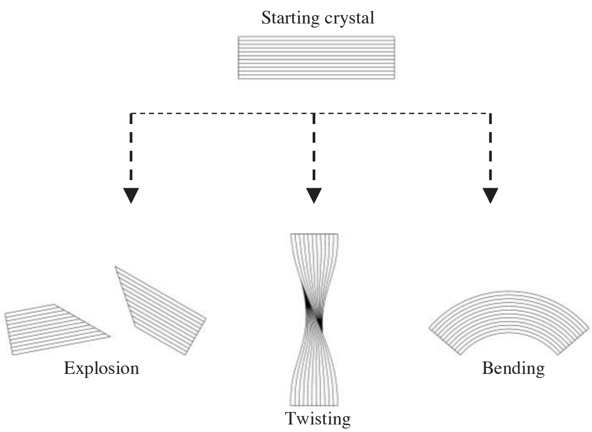

Fig. 6. Schematic diagram describing photomechanical phenomena in crystals

4 Interpretive Mapping of Transformations

In order to be able to translate the concepts of polymorphic transformations within the field of design, it is imperative to map the transformations between different polymorphic materials for any case documented in the fields of chemistry and crystallography. We note, however, that the actual physical mechanism of polymorphic transformations is often not well understood, and is the subject of much research. The pathway of the transformation may be expected to occur in different ways for different polymorphs, and different mechanisms are expected to be applicable in different cases. The types of interatomic and intermolecular forces that operate at the atomic/molecular scale in crystals are not necessarily the types of force that are relevant at a macro-spatial scale. The mechanism of transformation will, therefore, fundamentally differ at these contrasting scales, with transformations at the macro scale often having non-chemical interpretations.

To allow for the development of design applications, our research team has created a digital interface that simulates polymorphic structures, while allowing their geometries and transformations to be manipulated in real time through design criteria. This digital interface is part of a wider software application, which is the product of an ongoing research collaboration focusing on crystallographically inspired architecture. The collaboration brings together architects and scientists at Cardiff University and is funded by the Leverhulme Trust. The project proposes that crystal nano-structures possess valuable physical properties, and a multi-scale potential with possible design applications. It thus aims to make the wealth of information stored in crystallographic datasets available to the community of designers and architects, by developing a bespoke software application which offers a CAD based platform to study the structures and properties of crystalline materials. The bespoke software application embeds the principles of lattice types and space group symmetry to simulate the logic of crystalline arrangements and computes forms at various scales within this process. It begins by importing the asymmetric unit of a crystal structure, applies the symmetry operations of the space group to generate the contents of the unit cell, and translates the unit cell periodically in three-dimensional space to generate the crystal structure. *Rhino*, a widely used NURBS based platform, serves as the host environment, while *grasshopper* serves as its associated visual programming software and the plugin application is coded with *python* [5]. The component being developed on polymorphic transformations is embedded within this logic.

4.1 Component 1

The first approach to mapping polymorphic transformations is focused on the movement of individual atoms from the unit cell of the first polymorph to the unit cell of the second polymorph. As input, the component uses a Crystallographic Information File (denoted CIF). CIFs are standard text file formats which record various geometric properties of crystal structures, and are available in crystallographic databases such as the Cambridge Structural Database (CSD), the Protein Data Bank (PDB), and the Inorganic Crystal Structure Database (ICSD). The bespoke application reads the input file to plot the crystal structure within *rhino*. The atom positions are plotted as points or spheres, and the interatomic connections are modelled as lines. The polymorph component inputs two CIFs, for the first and second polymorphs, in such a way that their unit cells are aligned with each other in a structurally relevant way, and enlists atoms according to atom type within each structure. It then plots the trajectory of the nearest displaced atoms according to atom type, from the unit cell of the first polymorph to the unit cell of the second polymorph, and re-parameterizes the collective transition onto an input slider. Further, it records the changes in interatomic connections while the transformation occurs.

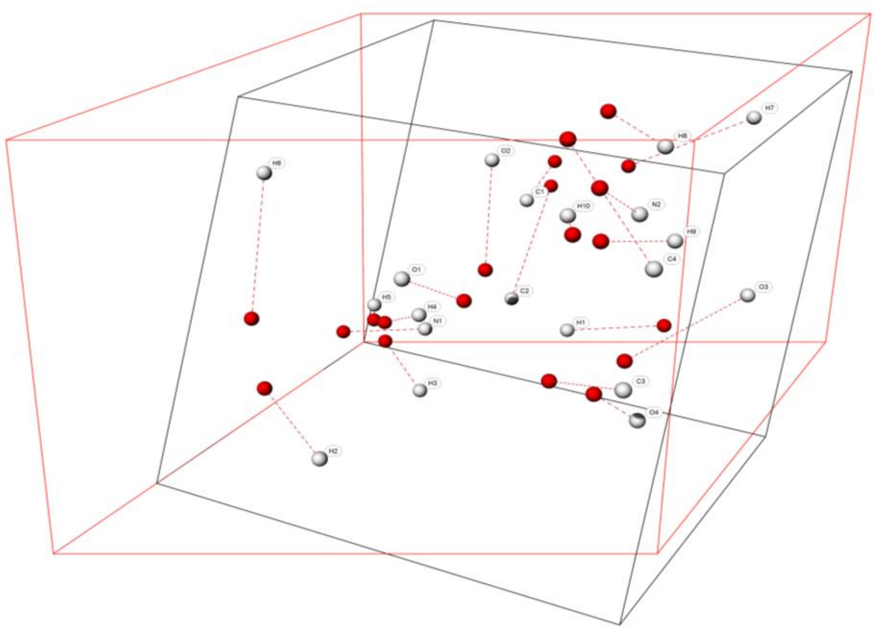

Fig. 7. Atomic positions in and displacement trajectories between two polymorphs of glycine

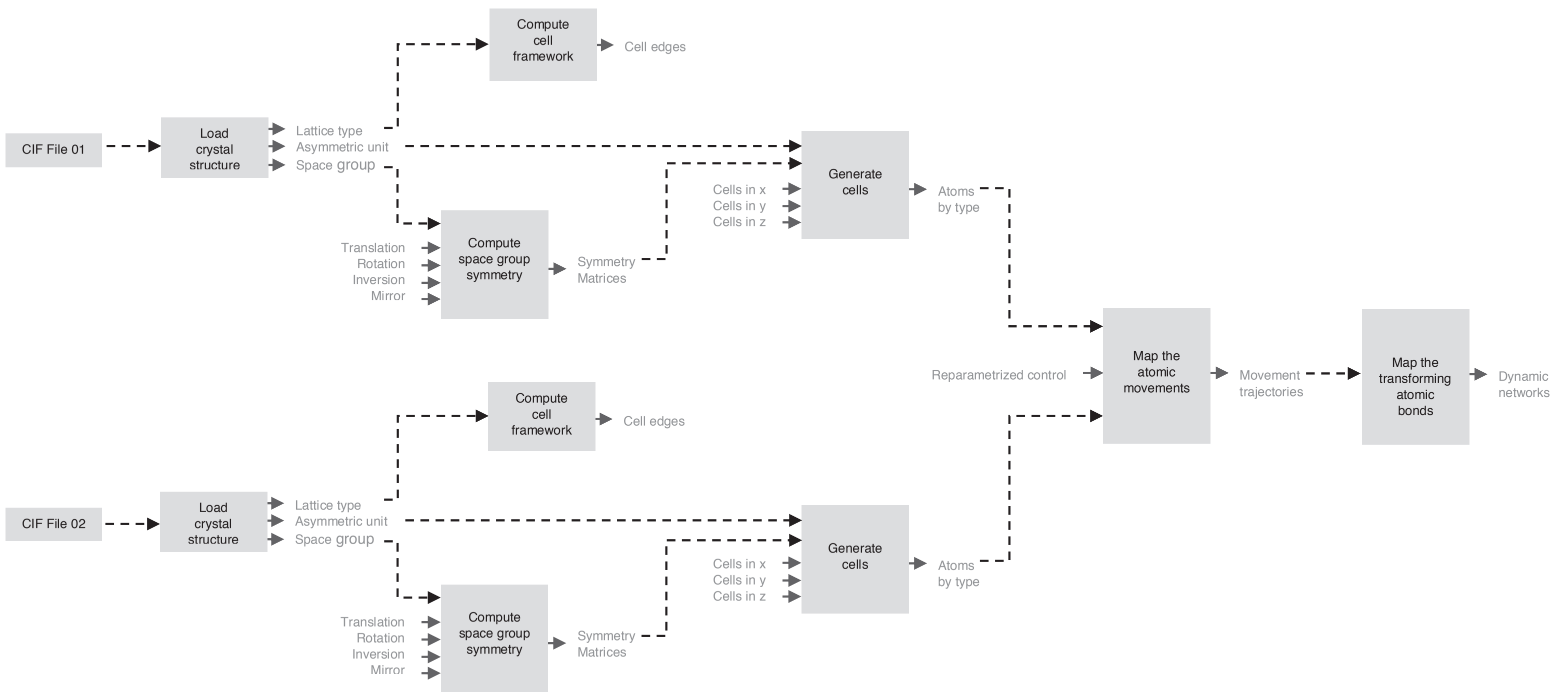

Fig. 8. Component 1 Workflow

4.2 Component 2

The second approach to mapping polymorphic transformations is derived from the concept of atomic nets and polyhedral units. For example, all the polymorphs of silica (chemical formula SiO_2) comprise SiO_4 tetrahedra, in which a silicon atom is located at the centre of the tetrahedron and an oxygen atom is located at each of the four corners of the tetrahedron, with each oxygen atom shared by two SiO_4 tetrahedra [21]. In the different polymorphs of silica, such as tridymite, cristobalite and the well-known mineral quartz, these tetrahedral motifs are arranged differently. The different structural arrangements correspond to different unit cells and different space groups, and give rise to differences in physical properties.

This component uses a CIF as input, and outputs a list of atom types. It then allows the user to specify the central and peripheral atoms for the polyhedral units. A library of observed interatomic distances allows the central atoms to connect only to those peripheral atoms that fall within the prescribed distance ranges. The networks between these peripheral atoms in a unit describe the faces of the polyhedron. The component then maps the trajectories through which the central atoms move and through which the orientations of the polyhedra change, on moving from the initial polymorph to the final polymorph.

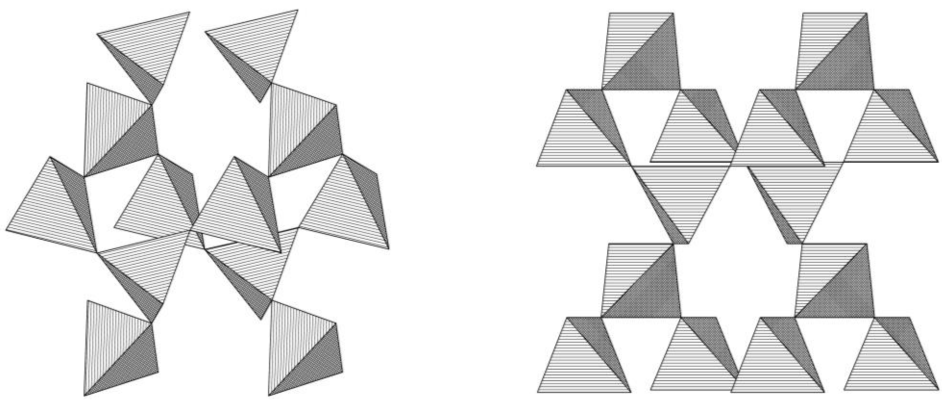

Fig. 9. Tetrahedral SiO4 units in polymorphs of silicon dioxide (silica), generated with the bespoke component. (left) the alpha quartz polymorph of silica and (right) the beta quartz polymorph of silica

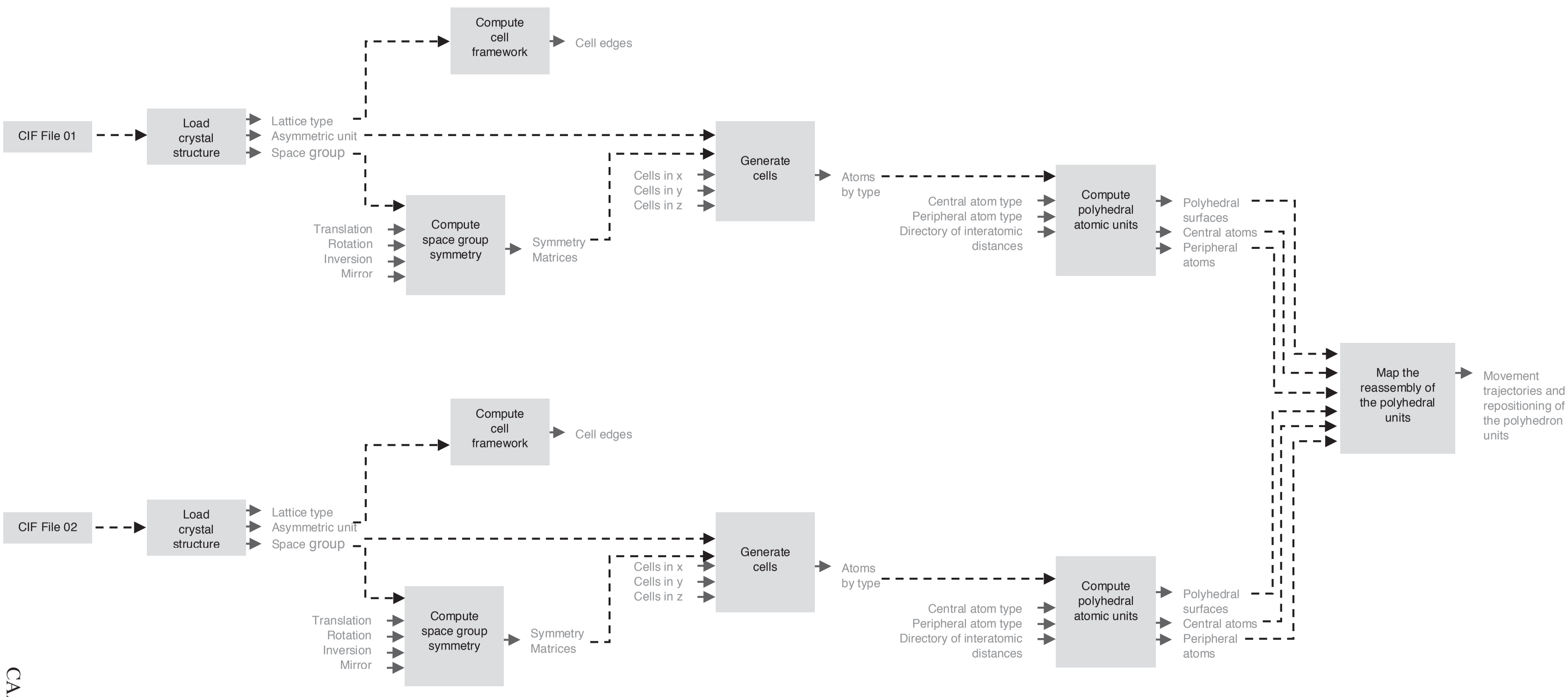

Fig. 10. Component 2 Workflow

4.3 The Application of Polymorphism in Design

As illustrated so far, polymorphism in chemistry has a geometric foundation. The concept of polymorphism is also used in fields such as biology (where its definition is genetic) and computer science (where its definition is based on data typologies). We believe that the concept of polymorphism can be applied further afield, and therefore we propose a geometric polymorphism derived from, but not restricted to, the principles that govern polymorphism in crystalline materials. This area of application would constitute a broader use for the concept of polymorphism, in which it is used as an instrument to develop new designs for structural and spatial configurations. Clearly, this application is inspired by the work of crystallographers and mathematicians in developing polyhedral assemblies as descriptors of crystal structures at the atomic level. The following definitions allow for the development of design principles based on polyhedral assemblies:

Local rules of component connection: Polyhedral components may connect face to face, edge to edge or vertex to vertex. Within these categories, further possibilities may arise based on the symmetries of the polyhedral components themselves. Some prominent types of coordination polyhedra are the tetrahedron and the octahedron. Figure 11 demonstrates a few connection types between two saddle polyhedral units [22] (the modular octahedral component here is derived from combining four irregular saddle tetrahedra).

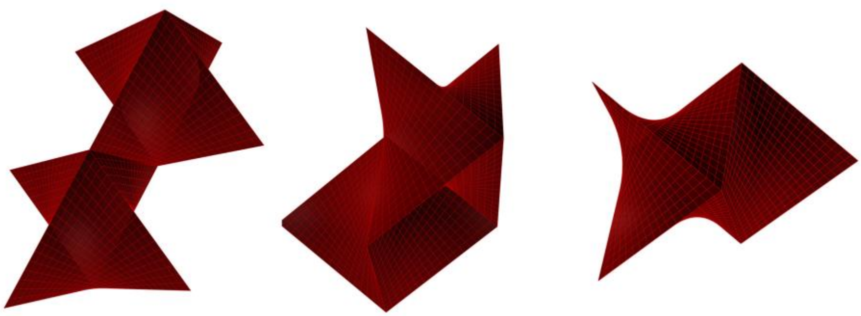

Fig. 11. Connection types between two saddle polyhedral units

Global strategies for polyhedral assembly: The arrangement of the polyhedral components and the directions of assembly further influence variations in the global structures obtained.

We have developed an interface with which designers are able to control parameters (such as component connection type, grid and component size, building units, and directions of assembly) to evolve a range of different structures from the same building blocks. This method facilitates a rule-based generative approach to work in coordination with the designer's intuitive control, and enables the development of a tectonic physical system with multiple combinatorial possibilities.

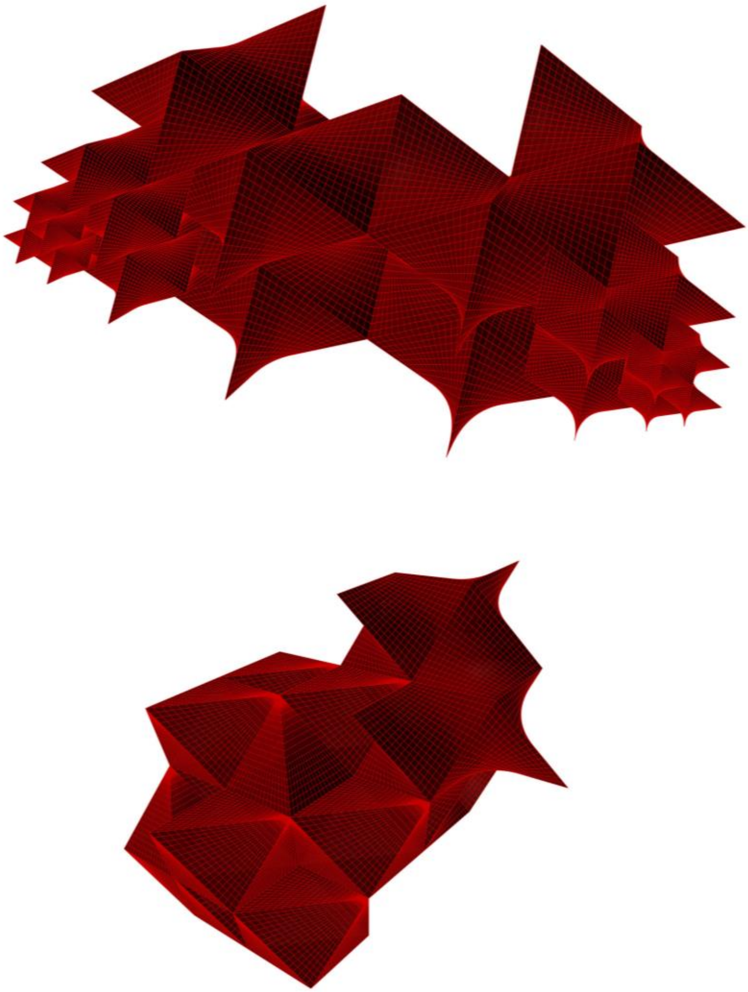

Fig. 12. Variable global structures developed from saddle and flat polyhedral units

5 Conclusions

From Gordon Pask's ideas of conversational machines in *Colloquy of Mobiles* in 1968 [23], to Philip Beesley's *Hylozoic Ground* in 2016 [24], the last few decades have witnessed considerable interest in the design and development of transformative physical systems. However, both the search for architectonic systems and the range of mechanical transitions explored so far remain somewhat incomplete and arbitrary.

The research described in this paper, on the other hand, aims to direct our understanding towards the fundamentals of adaptation through the phenomenon of polymorphism, where nature offers a model of structural transformations which lead to optimization of a number of properties, which are now discussed.

Fig. 13. 3D printed saddle polyhedral components

Structures: In the phenomenon of polymorphism, a substance is able to adopt more than one structural arrangement in the solid state (one of which is stable under a particular set of conditions while any others are metastable), with differing properties. An understanding of how nature arranges chemical components in space in multiple ways, and an understanding of the advantageous properties offered by each polymorphic structure, may provide a framework for developing component based architecture. Applications may be found within material, spatial or programmatic aspects. For example, in the design of micro-latticed materials or building space-frames, a repertoire of alternative configurations may offer insight into the relationship between geometry, density, weight-transfer directionality and load-bearing capacity. In the design of modular housing units, it may offer a variable vocabulary which may be reassembled with distinctive programmatic or microclimatic advantages. The second approach in our bespoke software, derived from the concept of atomic nets and polyhedral units, opens up this realm of combinatorial possibilities in the development of components for tectonic arrays.

Transformations: With regard to the first approach for mapping polymorphism, which is focused on the movement of atoms from their positions in the initial polymorph to those in the final polymorph, displacive and martensitic transformations become more immediately relevant for applications in adaptive physical systems. In this category of transformations, atoms move in a directed, regular and concerted manner, resulting in substantial changes in the overall structural arrangement. Similarly significant structural rearrangements are also found in the context of biomolecules. In the T4 bacteriophage tail sheath or bacterial flagella discussed earlier, modest geometric changes at the molecular level induce advanced mechanical movements in the organism. Further development of these concepts by exploiting this component may lead to new geometrical arrangements for sensing and actuation in the design of objects and spaces.

Stimuli: Various environmental factors (e.g. temperature or pressure) can induce polymorphic transformations in crystalline materials. Multiple transformations can occur within a series of polymorphs in response to a changing stimulus, with each polymorph representing the most stable structure under a particular set of conditions. Studies of these phenomena may provide insight into developing feedback and conversation in the transformative process.

The bespoke interface developed in our research allows polymorphic geometries to be simulated and manipulated in real time, leading to interpretations on polymorphic transformations, and giving the user a degree of intuitive control. This research is thus intended as a foundational platform, which offers a digital interface for a global community of architects and designers to study polymorphism as a source from which to test previously unexplored possibilities within the field of adaptive design and component-based tectonic systems.

Acknowledgements. We thank the Leverhulme Trust for funding this research project (Grant no. RPG-2014-420).

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Algorithm Driven Design

Comparison of Single-Objective and Multi-Objective Genetic Algorithms in the Context of Housing Design

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Abstract. This paper aims to present a dynamic multi objective genetic algorithm (MOGA) framework for the purpose of generating 3D mass models in the context of housing design. The proposed MOGA framework contains static and dynamic modules such as regulations, environmental condition analysis as static, behavioral models, designer-specified goals, domain-specific goals based on building types as dynamic modules. Moreover comparison of two algorithmic approaches, implementation of a single and multiple objective genetic algorithms are compared in terms of variety and usability of the generated design solutions, fitness approximation performances and the speed of the algorithms (running time). In the scope of this study, the potentials and limitations of the proposed MOGA framework in 3D form generation, its advantages over single objective genetic algorithm are discussed, conducted with a case study.

Keywords: Multi-objective, Genetic Algorithm, Housing Design, Mass-model

1 Genetic Algorithms in Architectural Design

Studies in computer science on natural evolution metaphor have leaded emergence of well-established algorithms. As a result a diverse range of methodologies, techniques, and concepts have emerged such as genetic algorithms, evolutionary algorithms and artificial ways of mimicking natural selection. The noticable increase in the use of algorithms in architectural design process also overlaps with the Carpo's 'Digital Turn' conception [1] which indicates the transformation in the way of thinking and making in architecture since early 1990s. Genetic algorithms (GAs) which was mainly developed for machine learning and optimization problems [2, 3, 4, 5] further bred various methodologies and new ways of thinking for different contexts. Although the theoretical contributions can be traced back in 1970s [6, 7] and there have been discussions on the potentials of GAs in conceptual design process since 1990s [8, 9], earlier implementations of GA in architectural design have been focusing on well-defined design problems and optimization processes. In relation with the reflection process of GAs onto architectural design, three considerations are listed below:

Representation problem: How design knowledge is represented and translated into computer affects the whole process and the design outcomes as well. In the very beginning of the algorithm development, flexibility of the assumptions, variables and fitness function matters. The more flexible fitness function is defined, the more population among design alternatives might be selected for the further steps.

Rigidity of the method and concepts: Well-defined algorithmic structures and their related concepts such as genotype, phenotype, fitness function, crossover, selection, mutation, etc. have been inherited from computer science. New visionary contributions in which architects play a pioneering role in the conceptualization process are needed.

Domain-specific or objective-specific nature of GAs: There might be difficulties in approaching the well-defined and ill-defined design problems simultaneously. Here, the terms well-defined and ill-defined refer to Hayes'and Ormerod's definitions for problem-solving strategies [10, 11]. Non-dominated sorting algorithms have a potential to partially respond to providing a shared ground for evaluation of different goals simultaneously

This study aims to contribute to developing better understanding and awareness in regard to the third problem: multi-objectivity in GAs and simultaneous execution of multiple inputs. The wide-ranging adaptation of GAs in architectural design is mostly focus on hybrid combination of two initial genotypes based on definition of a fitness function. The flexible fitness function is defined, the more population among design alternatives might be selected for the further steps. If multiple fitness functions are connected to each other in a serial way, each time there will be reduction based on this singular penalties which will cause elitism. However, regarding the nature of architectural design process, more iterative and recursive decision making environments are needed. Multi-objective genetic algorithmic dynamic modules have potential to response the required flexibility. User interfaces giving opportunity to add new customized modules are crucial in the case of multi-objective genetic algorithms (MOGA), apart from the simultaneous connection of different design goals. This study presents an integrated multi-objective genetic algorithm framework proposal, its implementation in a housing design project in comparison with the outcomes achieved from single-objective genetic algorithms.

2 Towards Non-Routine Design: Evolutionary MOGA

The concept of multi-objective genetic algorithm (MOGA) was first introduced by Schaffer, in his paper entitled "multi objective optimization with vector evaluated genetic algorithms". Schaffer [12] contributed towards engagement of multi optimization objective problems and genetic algorithms. Following this research several multi objective evolutionary algorithms [13, 4] have been studied under different topics and titles. "Multi-objective Genetic Algorithm" (MOGA) was introduced by [14], "Niched Pareto 6 Genetic Algorithm" was introduced by [15] "Random Weighted Genetic Algorithm" (RWGA) by [16] and "Nondominated Sorting Genetic Algorithm" (NSGA) by [17]. In the second half of 1980s and 1990s, while there have been a considerable progress in the specification of the multi

objective approaches, these methods were mostly developed and used by engineers in defined problems of sorting and optimization. New contributions continued in the following decade such as “Strength Pareto Evolutionary Algorithm” (SPEA) [18], “Pareto-Archived Evolution Strategy” (PAES) [19], Fast Non-dominated Sorting Genetic Algorithm (NSGA-II) [20], Multi-objective Evolutionary Algorithm (MEA) [21], Rank-Density Based Genetic Algorithm (RDGA) [22]. Introducing the “Adaptive Weight Sum Method”, Kim and Weck [23] pointed out the future directions of the multi-objective genetic algorithms:
“We propose a new adaptive method, based on the weighted-sum approach, for multiobjective optimization. In this approach, the weights are not predetermined, but they evolve according to the nature of the Pareto front of the problem” [23, p.150]

Briefly, genetic algorithms (GAs) are capable of responding to the problems which involve multiple objectives. However, As Rosenman [24] stated, until mid 2000s GAs had been used for optimization and machine learning problems with a few exceptions. To mention, Frazer’s [8] theoretical contributions or Elezkurtaj and Frank’s [25]’s explorations in the implementation of artificial evolutionary approaches in architectural floor plan design might be considered as promising studies from 1990s. As one of the earlier theoretical contributors, [24] discussions in terms of adaptation of GAs into non-routine design process have opened new directions.

The accumulation of experience not only in application of GAs in design but also usage of various computational approaches in design resulted with a significant paradigm shift in 2000s. Therefore beyond the consideration of GAs merely a sorting and optimization method, new approaches and interpretations were emerged in which GAs were became active agents of integrated design approaches. Instead of being used after most of the design decisions are taken, GAs and later MOGAs reflected onto the conceptual design processes [26, 27]. For instance, [26] “a forest of columns” assumption led an expansion in the meaning of GAs towards a metaphorical interpretation. Scheurer’s [26] approaching GAs in form-finding process and structural optimization also affected the definition of initial parameters and earlier phases of design process. Since 2000s, the tension between non-routine nature of design and routine characteristic of the engineering method GAs resulted with various novel approaches involving multiple and nondominated objective strategies. On one hand, finding a set of non-dominated solutions among multiple objectives can be still considered as a routine process in which all the parameters are expected to be defined from the beginning, the boundaries of the solution space and/or number of the outcomes are finite. On the other hand, simultaneous search for different parts of the solution space have potential to respond to complex problems via creating a finite number of but diverse set of solutions.

3 A Framework Proposal for MOGA in Housing Design Design

A framework proposal for multiobjective genetic algorithm (MOGA) is introduced in this section. The proposed framework (Fig. 1) consists of modular components, therefore it is possible to add, remove or update any module if required. The implementation of the framework was developed in Rhino Grasshopper environment conducted with scripting and add-ons including Rhino/Octopus and Rhino/Galapagos. Figure 1 shows the selected objectives and their sub-components such as regulations, physical environmental parameters as static, behavioral models, designer-specified goals, domain-specific goals based on building types as dynamic modules. As it is explained in Section 4 in detail, the gray sub-components (Fig. 1) are defined and used in the implementation model.

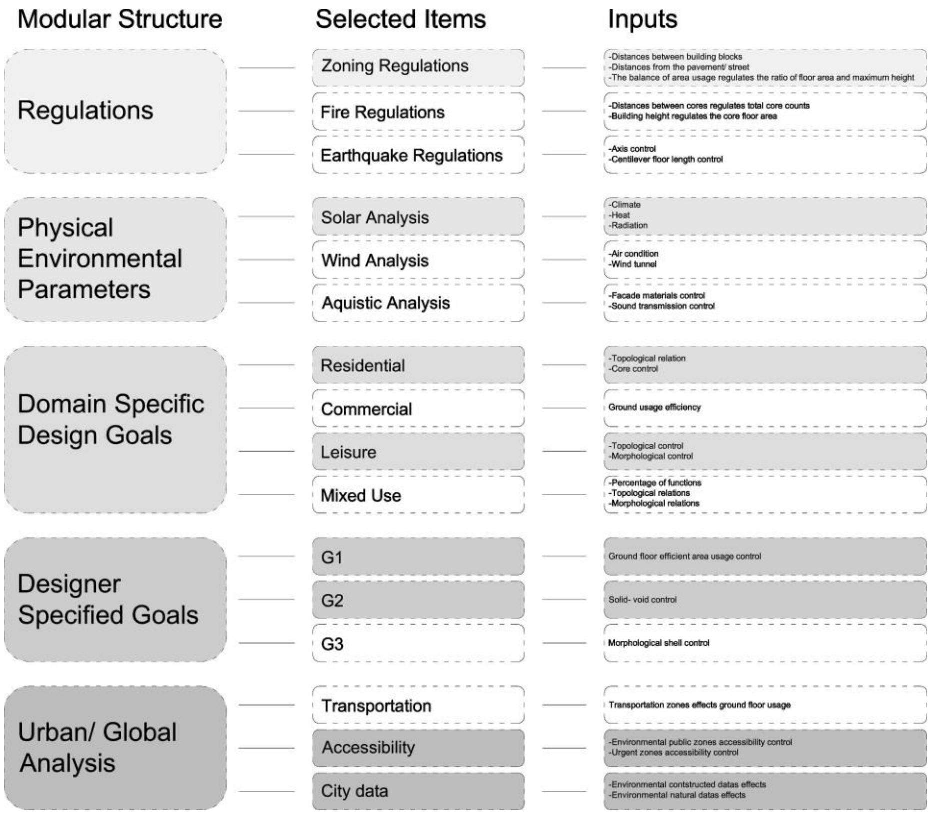

Fig. 1. Algorithm schema for the proposed framework

The regulation module is related to the context-depended design requirements. The number of the sub-components and definitions might be different in each architectural design process. In the scope of this study, zoning regulations of the selected site for housing design was used. Designer Specified Goals module can be considered as one of the most flexible module which can be developed, adapted or changed according to subjective design criteria. The selection among the design solutions according to the fitness functions are made simultaneously. However, the modules have different impact factors affecting the results. Moreover these impact factors can be changed by the users interactively. In the implementation process the MOGA framework was firstly defined by using multi objectives in Rhino/Grasshopper environment and Octopus add-on. In order to compare the performance of multi-objective and singular-objective approaches, later the algorithm was converted to single objective genetic algorithm (SOGA) (Fig. 2).

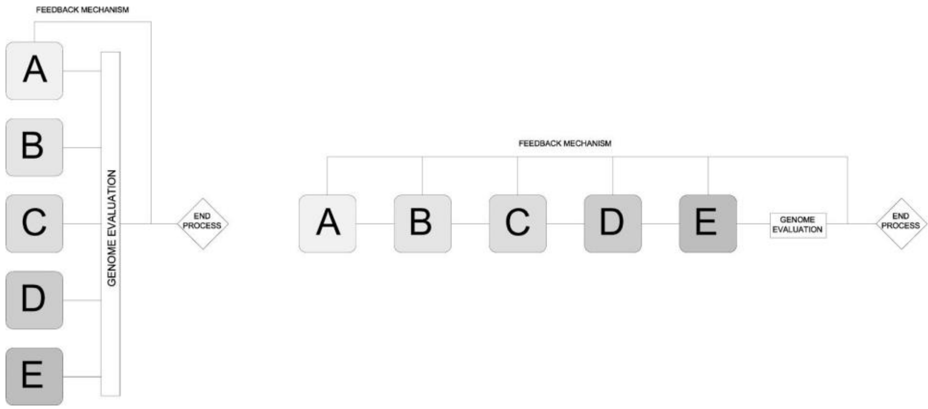

Fig. 2. Octopus(MOGA) vs Galapagos(SOGA) algorithm process diagram

In the conversion process multiple fitness functions are connected to each other in a serial way, each time, there is a level of reduction based on these singular penalties. Adapting the algorithms to Grasshopper components (both in Octopus and Galapagos), each objective's weight was defined in a range. In this step, in order to convert MOGA to SOGA, [28] weighted sum model was used (Fig. 3).

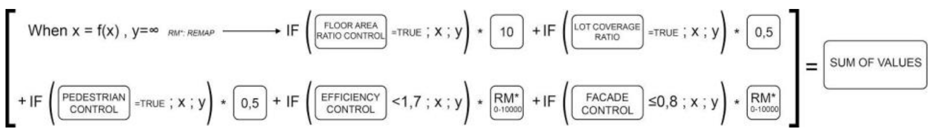

Fig. 3. Implication of Weighted Sum Model

4 Implementation of Single and Multi Objective Generative Algorithms in Housing Design

The case study involves implementation of the proposed framework for MOGA in Rhino Grasshopper-Octopus and SOGA in Grashopper-Galapagos. The MOGA and SOGA models are used for the purpose of generating 3D model alternatives at a defined site, Fikirtepe. Variety and usability of the generated design solutions, fitness approximation performances and the speed of the algorithms (running time) of the models are compared.

4.1 Selected Site and Problem Definition

Fikirtepe was chosen as a case study area in this project. Fikirtepe, as a settlement area consisting mostly of one storey residence, is located in Istanbul-Kadıköy in Turkey. Fikirtepe was declared as an urban transformation zone by the Law on the Transformation of Areas under Disaster Risk (Law No.6306, 31.05.2012). As it is in the urban transformation zone, the floor area ratio is fixed at 4.00 which was to encourage contractors, and rapidly changing urban identity is making design conditions difficult. Rapidly changing urban identity shortens the deadlines of designs and the high floor area rate limits morphological diversity. For these reasons, Fikirtepe was determined to benefit from the computational methods in the early phase of the design process for generating housing design proposal. Using computational design methods brings not only time optimization and variety, but also a rich pool of solutions, including well-defined natural parameters that are not normally well defined but intuitively used by designers.

Fig. 4a. Fikirtepe Location in Istanbul **4b.** Design site location in Fikirtepe

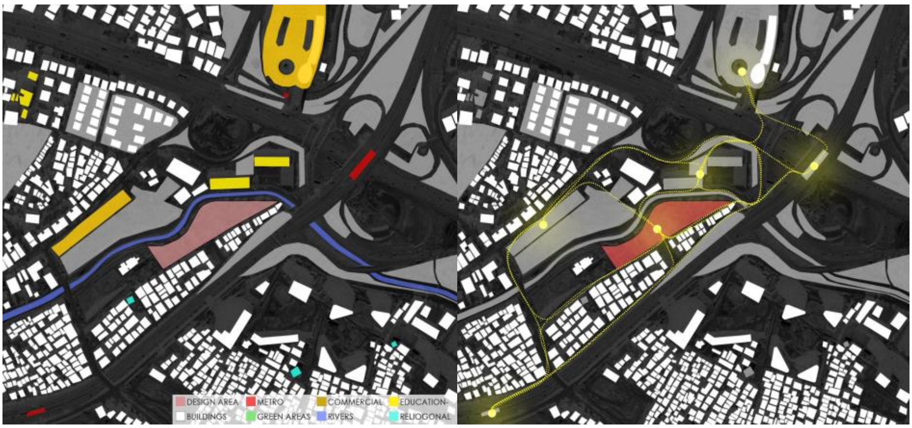

Fig. 4c. Design Site and Neighbourhood Relations **4d.** Design Site Pedestrian Connections

In the beginning of the design process, the 13133 m² floor area and the maximum construction volume of 33739 m², 4700 m² as cession of territory for municipality, 80m as a maximum height and the regulation values were accepted as predefined criteria.

4.2 Parameterization of the Design Objectives

In the scope of the case study, 5 modules and 8 sub-components are used as individual deisgn goals with their own fitness functions. The distances between the building blocks (b), the distances to the boundary of the constructible area (a), the floor area ratio of the site (FAR) and the maximum height (hmax) are selected as regulation parameters. An additional objective is defined by the authors for checking the effectiveness of site usage at the masterplan level. As an environmental control module, an existing solar analysis tool is integrated with the algorithm. Another module used in case study is an agent-based pedestrian movement simulation. Connections between the selected area and the existing street nodes are used as a basis for the creation of pedestrian movement simulation. In terms of domain specific design goals, housing units are selected and defined as a node in a matrix-based layout. Pedestrian movement simulations between different objectives were carried out only once at the beginning of the evaluation process due to heavy load. The objectives are checked in the tolerance range to maintain beneficial results. These criteria of the design objectives and sub-components are formulated below:

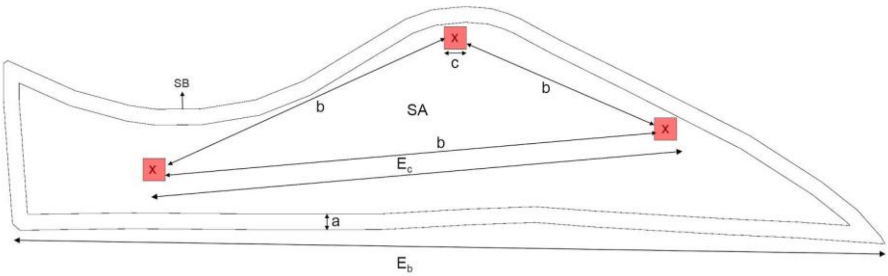

Fig. 5. Site notations

SA= Site area
SB= Site boundary
FAR= Floor area ratio
CAV= Constructable area volume
LCR= Lot coverage ratio
CoT= Cession of territory for municipality
hfl= Floor height
hhs = High structure limit
hmax= Maximum height of constructed building
SM= Solar Mass
Eb= Longest edge of the outer bounds of the design site
Ec= Longest edge of the outer bounds of the current modules
Fb=Modularization of outer bounds of the facade silhouette
Fc= Modularization of current bounds of facade silhouette
a= Constructable area distance
b= Distances between high rise attraction points of building blocks
c= Module axis measurement
n1=Number of total modules
n2=Number of floor modules
xm= Rising points coordinates

4.2.1 Regulation Module

Regulation criteria are coded based on the constraint defined by local municipalities (Fig. 6a) in zoning regulations sub-module. A boundary shape was created to describe a volumetric constraint to represent the constructible area (Fig. 6b). This zoning regulation sub-module checks whether the generated floor area is in the tolerated range (Fig. 6c). The number interval is calculated based on the given zoning regulation. The total constructible area was checked with an additional tolerance constant to adapt it to Galapagos interface (Fig. 6d).

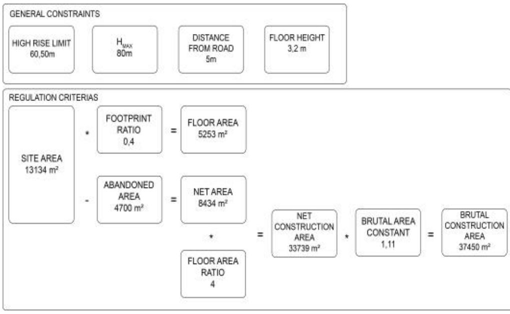

Fig. 6a. Regulation criteria

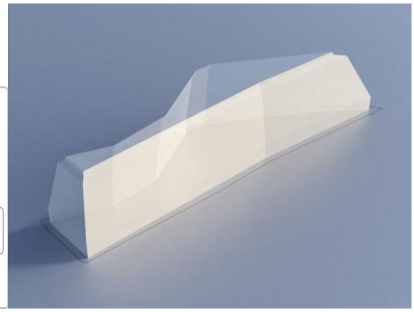

Fig. 6b. Constructable volume

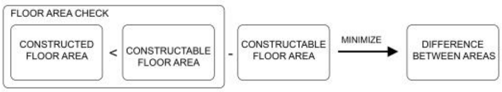

Fig. 6c. Constructable floor area

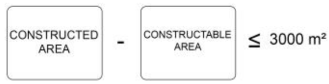

Fig. 6d. Constructable area

The formulas used in the zoning regulation sub-module's algorithm are shown below:
To maximize the constructible area

$$|[(SA-CoT)*FAR]/(c^2*n1)|<3000 \qquad (1)$$

To check the lot coverage check

$$(SA*LC)-n2>0 \qquad (2)$$

To create the constructible area volume

```
Loft (Move (Offset SB curve x=distance when(x= 0 to
[integer(hhs/hfl)] and y=5 If {x≤4,y,[(x-4)*0.5+y]})) in
Z direction x = distance when (x=0*hfl to
[integer(hhs/hfl)]*hfl) + (Move(Offset SB curve
x=distance when (x = 0 to integer[(hmax-hhs)/hfl]) 15 +
(x*0.5) in Z direction  x=distance when (x=hhs to hhs
+{3* integer[(hmax-hhs)/hfl]}                          (3)
```

4.2.2 Physical Environmental Parameters

The solar performance of the outputs are restricted by a dynamic solar control mechanism based on the location information of the site (Fig.7).

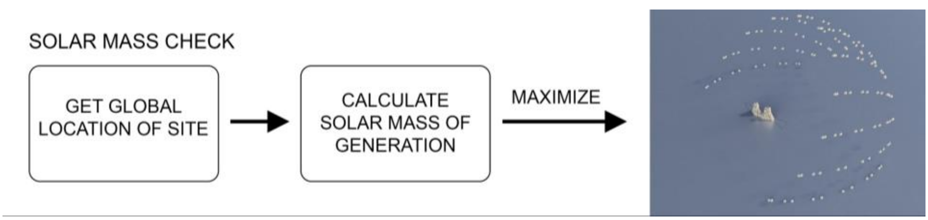

Fig. 7. Checking the solar efficiency ratio [28]

Maximizing the solar efficiency

$$-\sum SM \rightarrow MIN \qquad (4)$$

4.2.3 Domain Specific Design Goals

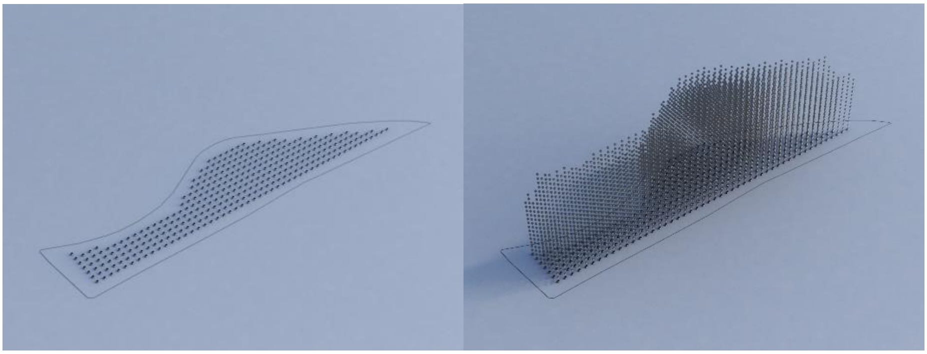

Fig. 8a. Defining The 2D and 3D Axis Systems [28]

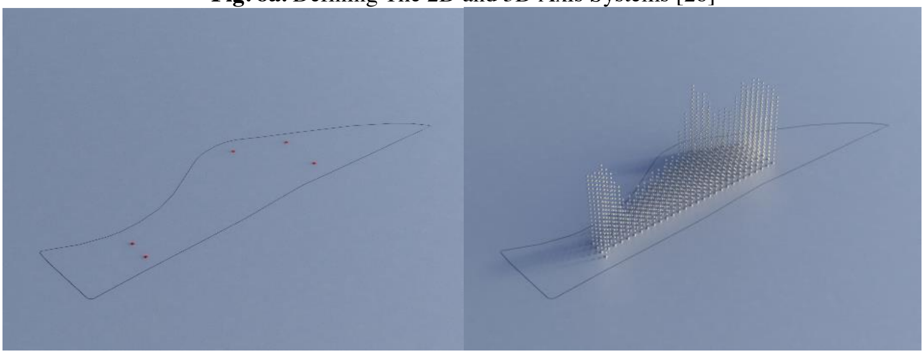

Fig. 8b. Representing attractor points in 3D [28]

A gridal axis system is constructed to represent to modules of housing units. The grid nodes are multiplied in the Z direction to create a 3dimesional axis system. (Figure 8a) Rising attraction points as a dynamic gene-pool is constructed (Fig. 8b)

```
Multiplication of modules in Z direction x=distance when
[x=0 to (Intersection in Z direction xm rays with CAV)]
                                                     (5)
```

4.2.4 Designer Specified Goals

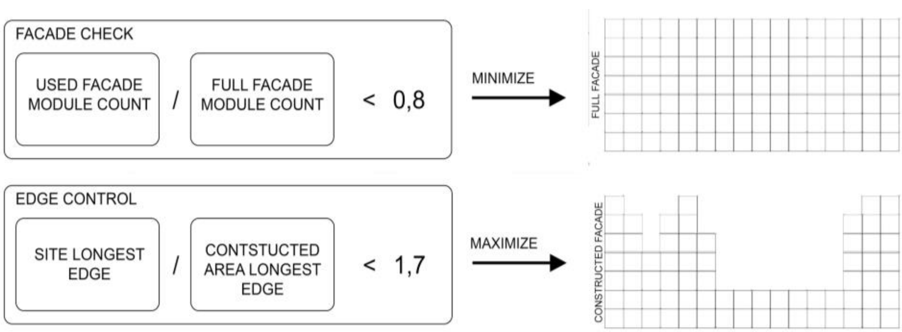

Fig. 9. The density checker objective [29]

A facade density system was developed to calculate the percentage of full-to-empty areas of products. The use of the construction site was limited to a fixed value to avoid inefficient solutions (Figure 9).

$$Fb/Fc<0.8 \text{ and } (Fb/Fc)\rightarrow MIN \text{ (Figure 9).} \quad (6)$$

The edge checking system is generated to prevent inefficient usage of the site

$$Eb/Ec<1.7 \text{ and } (Eb/Ec)\rightarrow MIN \quad (7)$$

4.2.5 Urban- Global Analysis

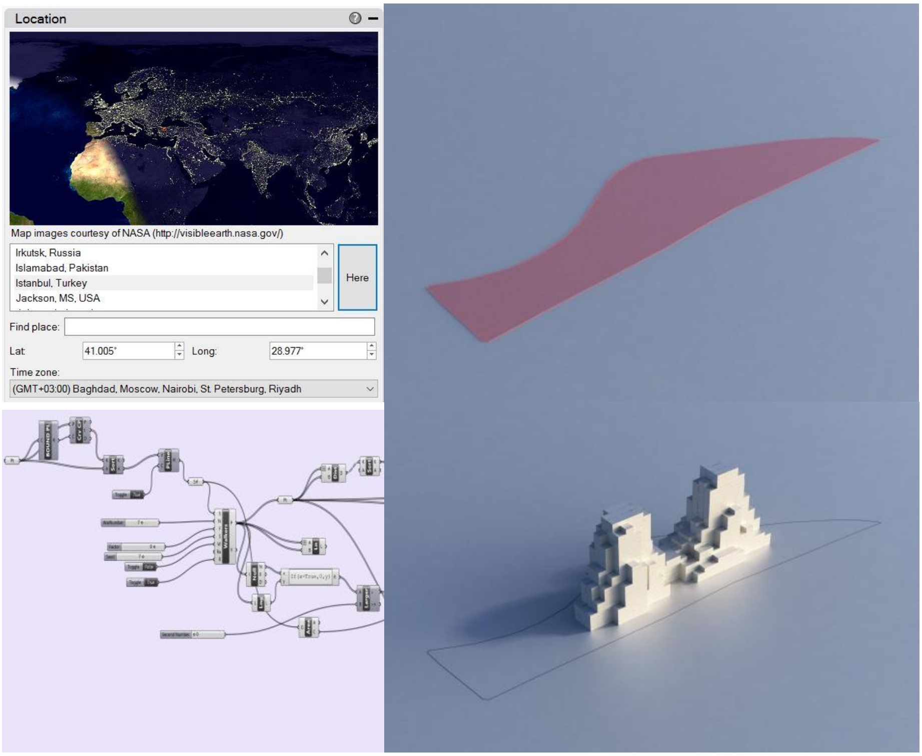

Fig. 10. Urban/Global Analysis [29]

Location and topographic information are derived from the rhino interface. The borders of the site are defined in the Rhino interface. Pedestrian analysis was created using environmental parameters. The circulation area was maximized. Applying site restrictions to borders (according to the law) to create a constructive volume of the site. The final result was gathered from pareto frontal solutions (Fig.10).

5 Finding, Outcomes and Evaluation

Based on the design objectives explained in Section 4, both MOGA (Octopus) and SOGA (Galapagos) were set to run 10 hours same settings. The findings and outcomes are discussed below.

5.1 MOGA (Octopus) SOGA (Galapagos) Outcomes

Selected outcomes derived from MOGA are shown below (Fig. 11). Number of the generations are shown on the left, 3D mass models shown in the other columns. Pareto optimal non dominated solutions are represented as final result of each generation. A wide range of variations are derived from SOGA compared to MOGA.

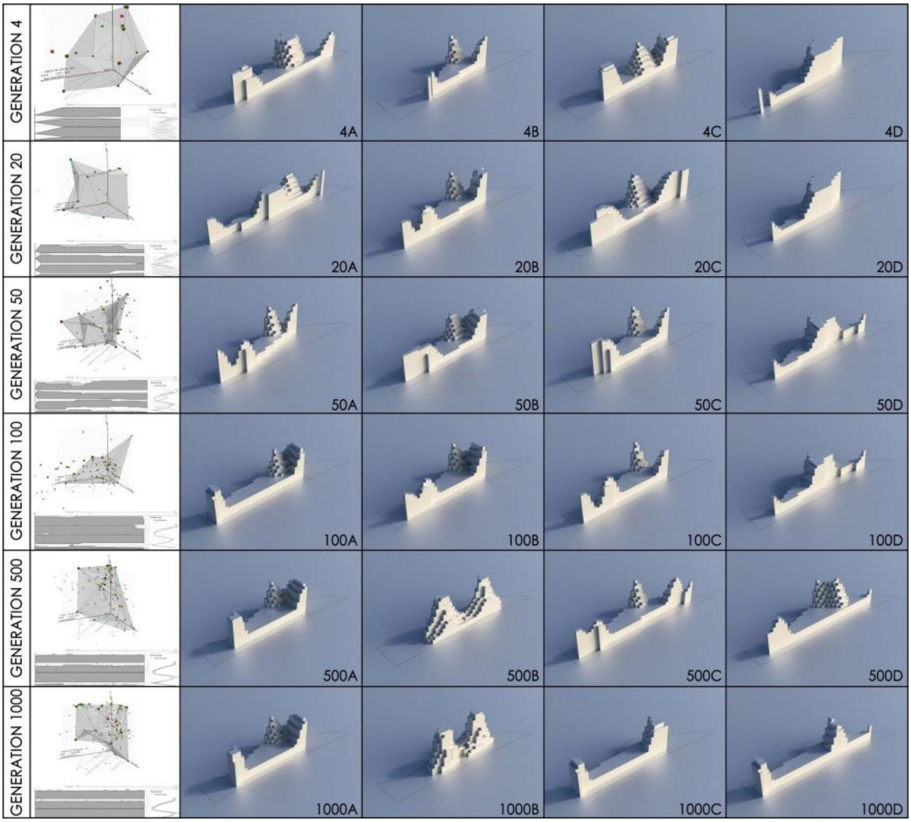

Fig. 11. Final outputs of Octopus generations [29]

SOGA(Galapagos) outcomes were sorted by generations shown below (Fig. 12). For each generation best of four solutions were represented in the diagram on the left column of Fig. 12. The solutions get closer to the fitness function by early 92 generations. At this generation the outputs matched with the fitness function very well and the morphological similarities between them were also high.

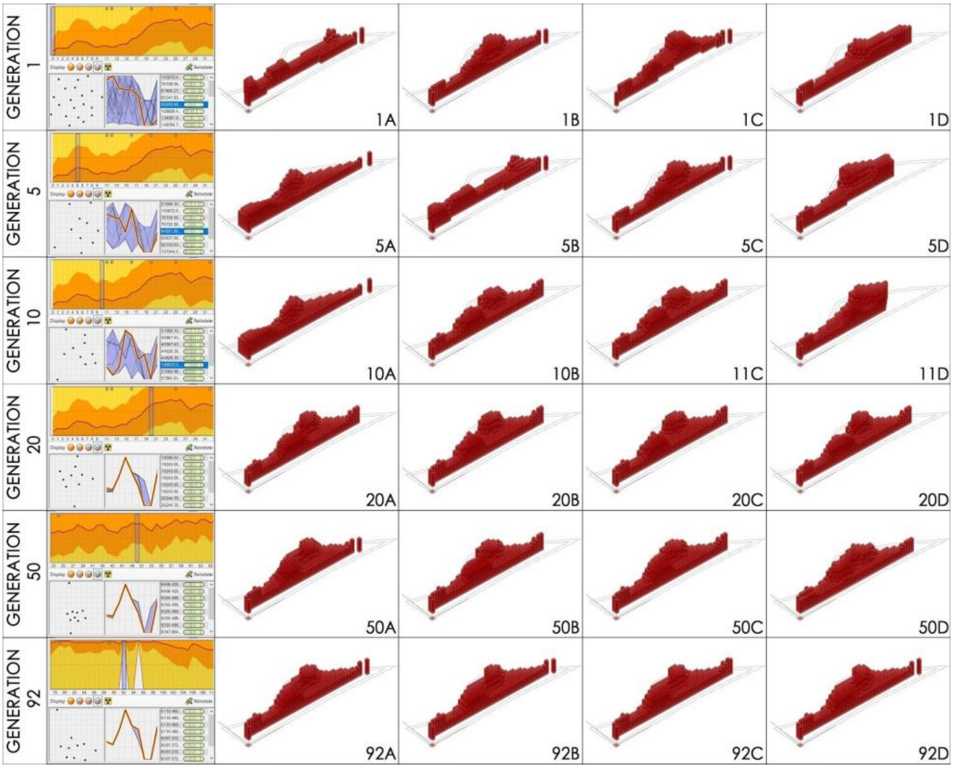

Fig. 12. Galapagos generations 1 to 92

As it is seen Fig. 12, in SOGA the system gained a kind of equilibrium state after the 92th generation, on the other hand MOGA (Fig.13) still provides a degree of variety for the design solutions in the higher generations. The more the components of SOGA gets closer to the fitness function, the earlier formal explorations are finalized. In the scope of this stud, from the point of design or user, dealing with a diverse range of outcomes can be accepted as an advange of MOGA.

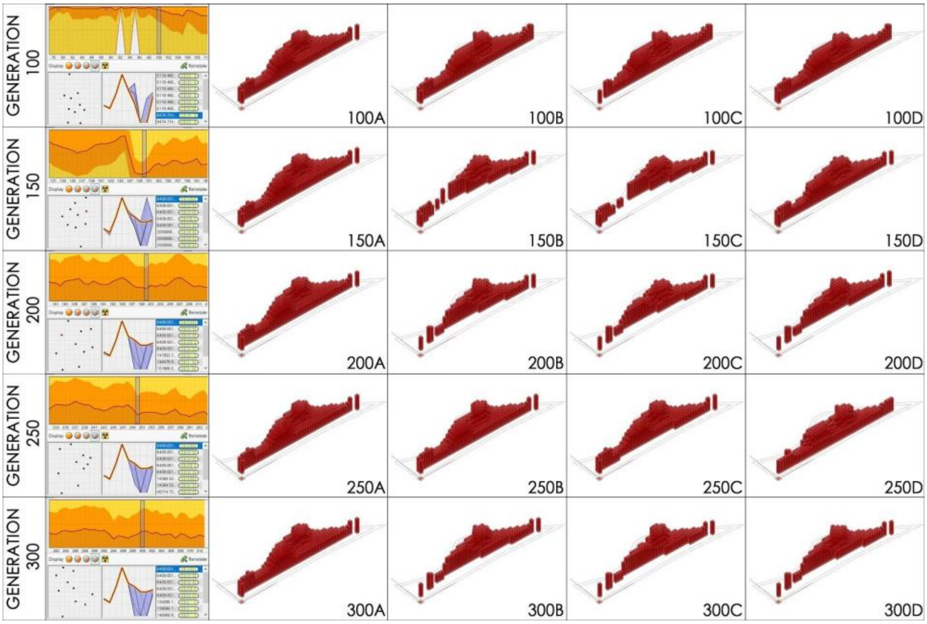

Fig. 13. Galapagos generations 100 to 300

When the generations between 100th and 300th are examined, it was observed that the outputs are getting far from the fitness function by effect of mutations and after a while it stays stabilized. After 10 hours of calculations Galapagos has stop process at 312th generation.

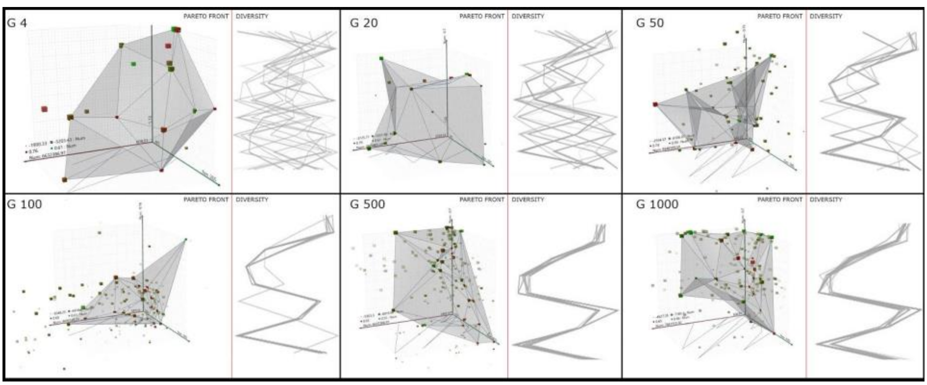

Fig. 14. Relationship between the pareto front fitness function and generation pool, Octopus

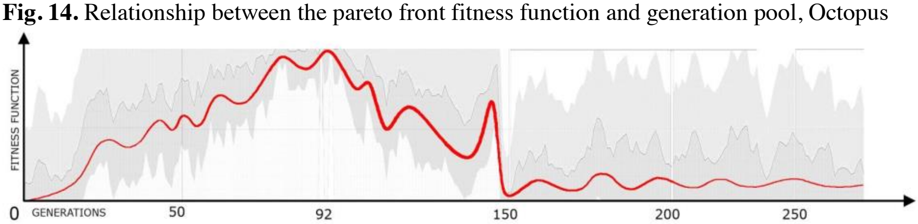

Fig. 15. Relationship between the fitness function and generation pool, Galapagos

The diagrams above shows the process of Octopus and Galapagos. They both have meet the fitness function needs. When they examined it can be say that Octopus keep finding a pareto front mesh which meets the needs of fitness function at any generations, but Galapagos reaches and loses the fitness function and got stabilized after a while.

5.2 Comparison of MOGA and SOGA in the Context of Morphological Relations

The evaluation of the outcomes of MOGA and SOGA is shown in Table 1 below:

Table. 1. Comparision of Octopus and Galapagos

MOGA (Octopus)	SOGA (Galapagos)
Using SPEA2 MO Algorithm	Using Basic Genetic Algorithm
The solution space is 3D	The solution space is 2D
Outputs has a wide range of variants	Outputs has a limited range of variants
More generations needs to reach the fitness function	Less generations needs to reach the fitness function
A non dominated pareto front pool is generated between generations	A dominated objective pool is generated between generations
Has default tools to define objectives and penalties	System needs to be optimized to define objectives and penalties
Many outputs can be baked while using the program	Only 1 outcome can be bake using the program
Let user see different density of objectives simultaneously	Focuses defined objectives and limits the potentials of variables

Comparing two algorithms, some differences are gathered which is shown above. These results show that using MOGA and SOGA is relatively effects the design process, in the case studies it was seen that more alternatives are gathered in the MOGA system, which are evaluatable in the generation process. In other hand, SOGA system is faster at one single problem solving but the generation results are not evaluatable during process. Also MOGA system try to get better results using a pareto front mesh and allow user see possible results, while SOGA system only use a section of that mesh.

6 Conclusion and Discussion

This paper presents a framework proposal for a multi objective genetic algorithm

(MOGA) and its comparison with a single objective genetic algorithm (SOGA) in a case study. The proposed MOGA and SOGA framework contains static and dynamic modules such as regulations, environmental condition analysis as static, behavioral models, designer-specified goals, domain-specific goals based on building types as dynamic modules. The modules are selected in relation to the housing design context in the given site, however in another site or another design task the modules might be organized in a different way by other researchers. Putting it another way, the proposed framework can be adapted to different design contexts by adding, subtracting or modifying objective criteria. Fitness function can be defined in different design areas according to needs. The use of both non-dominated multi-objective genetic algorithms and the use of a dynamic / adaptive modular framework can help build expertise and experience in similar design areas, especially in design offices, in early steps of the design process.

It became a common knowledge that the flexibility of the initial parameters and fitness function in the multi optimization design problems have a crucial impact on the richness of the solution space, in this study particularly 3D mass variations. Results of the case study confirm that multi-objective genetic algorithm have advantage over singular objective genetic algorithm in terms of meeting the required flexibility in design process. SOGA provides solutions focusing on the best generations of one selected hill, on the other hand in MOGA search in global hills goes on. This property of going on searching in global hills led possibility of getting closer to better solution alternatives. Moreover, apart from the simultaneous connection of different design goals in MOGA possbility of changing the weights/impact factor of the design goals interactively creates a better interaction between design alternatives and the designer.

The alternatives obtained from the application of SOGA in case study can be criticized in terms of morphological similarities. The reason for this is the dependence to the initial assumptions, such as the regulation objectives and also Galapagos' solving process. The maximum floor area and the use of constructible volume are strictly defined in the selected site, but the results would be different in another study. If the architect is expected to produce design alternatives within a limited time on a given site, the proposed framework has the potential to look for 3D image possibilities and give quick feedback to the designers.

Finally, Octopus and Galapagos both have potentials of gathering outputs in the multi optimization design processes with little differences. Octopus can generate in a wide range of alternatives which can be beneficial in form search problems and Galapagos have a strong meet the needs of fitness function faster than Octopus. So in some cases Galapagos could be preferred to get faster solutions and Octopus for variety.

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CAMBRIA: Interacting with Multiple CAD Alternatives

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Abstract. Computer-aided design (CAD) tools aim to assist designers in their professional work, one key aspect of which is devising, evaluating, and choosing among multiple design alternatives. Yet, with few and limited exceptions, current tools handle just a single design model at a time, forcing users to adopt various ad hoc tactics for handling multiple design alternatives. Despite considerable prior work, there are no general, effective strategies for supporting design alternatives. New tools are needed to develop such strategies: to learn how designers' behavior changes with support for multiple alternatives. In this article, we describe CAMBRIA, a multi-state prototype tool we developed for working with multiple 2D parametric CAD models in parallel. We describe the outcomes of an analytical evaluation of CAMBRIA using the Cognitive Dimensions framework.

Keywords: Computer-aided design • CAD • Parametric CAD • Interaction design

Pedagogical Approaches to CAAD

Virtual and Augmented Reality in Architectural Design and Education

An Immersive Multimodal Platform to Support Architectural Pedagogy

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Abstract. Virtual Reality and Augmented Reality research in the architecture field show a variety of possible uses of systems to accompany designers, laymen and decision makers in their architectural design process. This article provides a survey of VR and AR devices among a corpus of papers selected from conferences and journals on CAAD (Computer Aided Architectural Design). A closer look at some specific research projects highlights their potentials and limits, which formalize milestones for future challenges to address. Identifying advantages and drawbacks of those devices gave us insights to propose an alternative type of system, CORAULIS, including both VR and SAR technologies, in order to support collaborative design to be implemented in a pedagogical environment.

Keywords. Augmented Reality, Virtual Reality, Design Education, Architectural Design

1 Introduction

In 1994, Milgram and Kishino [1] coined the mixed reality concept, illustrating a scale of realities, ranging from the real environment to the virtual environment, including both Augmented Reality (AR) and Augmented Virtuality (AV). Our focus will be on VR and AR, specifically their use in architecture. Both offer alternative types of design representations and have a high potential to enhance architectural ideation and design. Development of VR and AR didn't go as fast as expected, mainly due to technical issues and the cost of devices supporting those types of reality. VR can be experienced either with a HMD (Head Mounted Display) or within an immersive room. The commercialization of affordable HMD to support VR like the Oculus Rift, the HTC Vive, the Samsung Gear VR or the low-tech Google CardBoard, to name a few, makes it more accessible for institutions, universities or architecture studios to access and benefit from VR technology. Immersive spaces like CAVE's [2] or Panoscope[1] inspired platform still represent high investments for institutions or firms but had shown its worthiness. On the other hand, AR applications are available on a range of display devices, including easily accessible ones, like smartphones and tablets. The portability of those devices makes it suitable to develop on site applications to assist designers, workers and decision-makers to deal with design and construction issues.

In the first part of the article, a survey on research papers proposing VR and AR applications in architecture will give us an overview of the multiplicity of possible uses, for example to support immersive design, to visualize on-site simulations or to enhance collaboration. Existing survey articles on VR or AR research in the AEC (Architecture Engineering and Construction) field already gave a good overview of this research domain. Freitas and Ruschel's study [3] draw statistics about the evolution of VR&A research between 2000 and 2011. Portman, Natapov and Fisher-Gewirtzman's work [4] focused on the use of VR in architecture, landscape architecture and urban planning, synthetizing opportunities and challenges depending on each discipline. Wang's survey [5] of AR applications in architecture underlined the variety of user's interactions, display devices and tracking technologies, summarizing issues and challenges for future developments. Schnabel, Wang, Seichter and Kvan [6] proposed a theoretical framework to classify 7 types of realities, including VR and AR, that they exemplified with existing applications, showing how those can enhance urban and architectural design. Our quantitative study of more than 130 papers completes these previous ones. In the second part, platforms or projects' prototypes, that are analogue to our own, will be described, to point out their potentials and limits. Those references' analysis enabled us to define a framework for our application. In the last section of this article, we will introduce CORAULIS, an immersive multimodal platform designed by our laboratory research team that will be built in our university by the end of 2017. We intend to use this system as a design representational environment to support design review sessions during studio courses in the architectural design program. Finally, we will explain our motivations to develop such a tool, and underline the potentials, the challenges and limits raised by an equipment like CORAULIS.

2 General Overview

The two cornerstones of VR are immersion and interaction [7]. Both are rarely completely achieved but remain VR's applications objectives and goals. VR gives the possibility to experience sensations and movement in an artificial environment that is a simulation of some aspects of the real world [7]. Concerning the field of architecture, VR applications' utilizations are wide, from design itself, construction and project's communication as well as collaborative decision-making. For Schnabel, Kvan, Kruijff and Donath [8], the manipulation of virtual environments during the design process pushes designers to better perceive space, for example its fluidity and functionality, without using 2D representations.

[1] http://panoscope360.com/ consulted 01/09/2016

On the other hand, AR systems combine the real and the virtual, and support a real time interaction and 3D registration [9]. AR applications in the architecture domain can be developed through a large type of systems, implementing HMD AR, Tangible AR, SDAR (Smart Device AR) or SAR which all include the merging of the real environment and virtual information using different techniques. The democratization of the use of smartphones and tablets opens a window for on-site AR to support interior design, building refurbishment or construction management. SAR and Tangible AR offer other types of use during the design process. SAR gives a chance to experiment on site, scale 1:1 design by displaying virtual data on the physical space, including walls, floors, desks or real objects [10]. For example, Raskar et al. office of the future [11] depicts how the use of common physical surfaces can serve as display screens to immerse users in a VE, supporting a remote collaboration. Tangible AR ameliorates collaborative design and the efficiency of decision making thanks to the accessibility of the design data represented in a more intelligible manner. The advantage of SAR compared to AR is that there is no added display interface like a tablet or a HMD.

The review of a corpus of articles from the Cumincad (Cumulative Index of Computer Aided Architectural Design) database outlined research conducted in VR and AR in architecture. The final papers were selected from the following conferences: ACADIA (Association for Computer Aided Design In Architecture), ASCAAD (Arab Society for Computer Aided Architectural Design), CAADFutures (Computer-Aided Architectural Design Futures), CAADRIA (Conference on Computer-Aided Architecture Design Research in Asia), eCAADe (Education and research in Computer Aided Architectural Design in Europe), SIGRADI (Sociedad Iberoamericana de Gráfica Digital). Two additional journals were covered, namely IJAC (International Journal of Architectural Computing) and Design Studies. 'Virtual Reality' and 'Augmented Reality' were used as key words in the Cumincad database, and on all the articles found (620 hits for VR, and 142 for AR, 01/09/2016), 122 were selected depending on their content (78 for VR and 55 for AR). Articles proposing studies on CVE (Collaborative Virtual Environment), VDS (Virtual Design Studio) or desktop virtual reality were put aside. In fact, articles on CVE and VDS show how the use of shared virtual environment can support remote synchronous collaboration. In most cases, the virtual environment is displayed on a desktop, which we consider as non-immersive representations, explaining why we didn’t include it in our quantitative survey on VR.

All papers were semantically classified into six different categories. They were defined before surveying the articles and correspond to the features that we considered in the development of our platform’s proposition. We intend to describe the current VR/AR research context where our proposition integrates, in order to point out its particularities. Some of the categories like collaboration, or education were reviewed previously by Freitas and Ruschel’s in their study [3]. Our proposed themes are the followings:

- Communication and collaboration illustrates articles proposing the use of an application to enhance collaborative design and communication between decision makers (designers, contractors, laymen).

- Education represents papers where pedagogical issues are dealt with, for example a proposition to include VR or AR applications in a course curriculum.

- Representation focuses on the appraisal given by the types of visualizations offered by VR and AR applications.

- Sense and cognition regroups articles where the effects of VR and AR devices on the cognitive load or the multiplicity of senses stimulated simultaneously are highlighted.

- Design category rallies papers where systems were developed to accompany designers' creative process.

- System (hardware or software) corresponds to research articles precisely describing the device or application, like the software architecture.

Most of the articles are belonging to several categories (Fig.1).

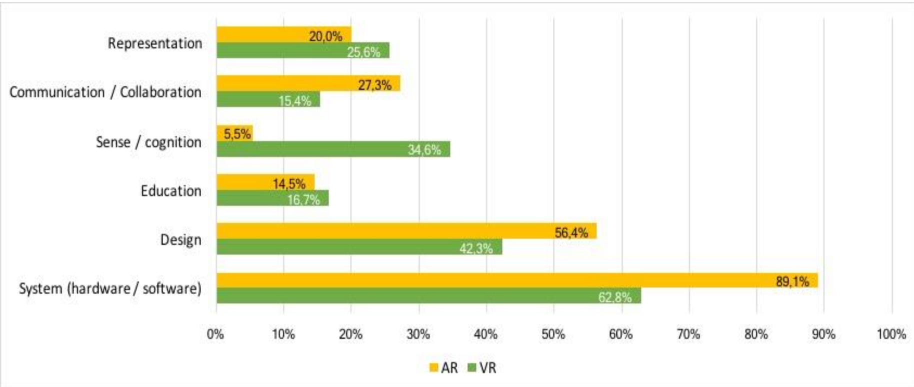

Fig. 1. Prevalence of the focus topics of the reviewed articles

The system's concept, either the hardware or software, is the most recurrent topic for both AR (89.1% of the AR papers) and VR (about 62.8% of the VR papers). In fact, most articles described the design process of the device as well as its potential or user tests results. Only 1/5 of the corpus focuses exclusively on the system. Design is the second prevailing topic as it was the focus for 56.4% of the AR papers and 42.3% of the VR ones. We noticed that research on applications' impacts on sense and cognition is more popular for VR applications that for AR ones, which seems relevant considering the immersive characteristic offered by VR visualization. The few papers on AR that are part of that category are putting forward cognitive load reduction thanks to the use of tangible interfaces to interact with the virtual world. Considering that VR technology is more developed than AR, this can explain the differences for that category. Communication and collaboration is the less prevalent focus for VR papers, while it is the third most addressed in AR ones. Indeed, tabletop tangible AR and on-site AR are brought forward for their easy-to-use characteristics and sharable quality favoring co-design between the users. On the other hand, the use of HMD for VR can be considered as a limit for collaboration since it affects users' communicational behaviors, particularly because it prevents primary natural non-verbal communication like eye contact. Fewer papers deal with pedagogical implementations. A lot of systems were tested by design students (architecture or interior design), but only the outcomes of its uses concerning the design activity are considered, and barely the effect on education. 40% of the total corpus described user experiences results, which was enriching to understand the limits and benefits of each study.

From this sample of articles, we can distinguish different display systems: using a HMD, a CAVE or an immersive screen for VR applications and implementing a HMD, a smart device / screen or any surface (SAR) for AR applications. Depending on the type of system used, the purpose and goals of the applications vary as shown in Table 1.

Table 1. Purposes and uses of VR and AR applications in architectural design, depending on the display system

	Display	Prevalent topics	Uses	Examples
VIRTUAL REALITY	HMD	> Design > Sens / Cognition > Education > Representation	> Immersive sketching and design > Sensitive experience > Remote collaboration > Spatial evaluation	[14] CAP VR [29]
	CAVE	> System > Design > Representation	> Scale 1:1 design > Spatial evaluation > Visualize simulations	[12, 26]
	Immersive screen	> Design > Sens / Cognition > Education > Representation	> Immersive sketching and design > Local and remote collaboration > Spatial evaluation	HYVE-3D [17, 18, 19] VizLab [27]
AUGMENTED REALITY	HMD	> Design > Communication	> Visualize simulations > Game oriented collaboration between designers > Remote collaboration > Merging digital and tangible	ARTHUR [32,33] BenchWork [35, 36] MxR [13]
	SDAR or screen based	> Design > Representation	> Visualize simulations > Reduction of design cognitive load > Including project management > On-site design > On-site technical data visualization	[34] [40] video-datAR [42] [43]
	SAR	> Design > Representation	> Scale 1:1 design > On site design > Seamless assessment of several design possibilities > Merging digital and tangible	SARDE [46,47,48]

In the next section, our focus will be on some of the applications referenced above, that were developed to assist designers alongside their design process, to support either ideation, simulation or evaluation.

3 VR and AR Tools for Architectural Design

VR in design can be employed for VRAD (Virtual Reality Aided Design). This implies the interoperability between digital models (CAD – Computer Aided Design) and virtual models (models built in/for a VE – Virtual Environment) which points out one of the technical complications of VRAD environment's usability in this context. Designing in an Immersive Virtual Environment (IVE) is not a common practice in architecture, although it is quite developed in industrial design, in the automobile and aeronautic sector, to reduce cost production of scale 1:1 prototypes. Fuchs, Moreau and Guitton [7] explain that designers working with VRAD tools have to add more information to the model than when they design with CAD tools. Indeed, the behavior of each element has to be defined in the VE. The advantages of VRAD, according to these authors, are: creativity enrichment, contextualization of design outcomes or product, change of virtual models scale and explicitness of virtual representations, which favors the integration of the end users in the design process.

Several studies on the implementation of VRAD environment were conducted to assess its potential for early design stage activity [14], or to evaluate the impact of immersive full-scale design [15, 16]. Dorta's research team has worked for years on developing an immersive design platform, the Hybrid Ideation Space (HIS) and lately the HYVE-3D (Hybrid Virtual Environment – 3D) to promote immersive ideation and synchronous collocated or remote design collaboration [17, 18] (Fig.2).

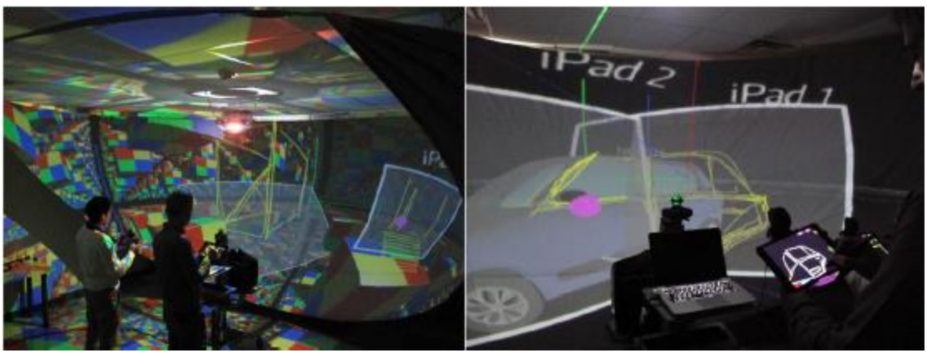

Fig. 2. Hyve-3D in use (source [18])

The Hyve-3D offers the possibility to draw directly in the VE displayed on the 360° screen, using an Ipad which also serves as an interface for navigation like walkthroughs and diverse interactions with the VE. It acts as an immersive working space for designers who can sketch with a natural designer's tool to design in a digital environment. The fluidity between sketching and digital visualization enhances the user's design flow, and consequently the quality of the design outcome [19]. For Schnabel, Kvan, Kruijff and Donath [8], remote design collaboration was also their intention in implementing the Virtual Design Studio between students from the University of Bauhaus of Weimar and the University of Hong Kong. In that case, only one student at a time was in the VE, wearing a HMD to experience VRAD design activity. He/she was always in audio contact with the other members of the team, who were seeing the scene on a display monitor. The experiment showed that the collaboration between students was effective and that immersive designing upraised their experience.

As far as using VR during the architectural design process is concerned, to date, there are no relevant studies of its use in a real practice situation. Nonetheless, some professionals integrate immersive VR in their daily design activities as illustrated in Demangel's interview in Dezeen magazine[2]. However, experiments where VR integration for design activities was tested with professionals or students in architecture are well documented. Those studies focused either on the benefit of VR for students to understand structure and construction [20], on the comparison of different VR systems [21], on the implementation of a new working environment or framework for designers [22,23,24], on the evaluation of remote design collaboration [25], or on the integration of VR in the curriculum for design courses at architecture schools [26,27]. On that last topic, it seems relevant to illustrate two of those studies. Kalisperis et al. [28] made an experiment at Penn State University with the aim to enrich the design process with the use of an immersive space (V-shaped screen). Students from 2nd and 3rd year of architecture took advantage of the platform for a semester for a specific course, as well as some of the 5th year, to work on and present their final project. The study showed how students adapted the platform setting depending on their needs, either for design or communication. The second research experiment took place at the College of Architecture and Planning of Ball State University. For three years in a row, the CAP VR environment, composed of a HMD, served as a design environment for 2nd year students [29] (Fig.3).

Fig. 3. CAP VR environment (source: https://capvrenvironment.wordpress.com/)

Results showed that students using this immersive environment to visualize their projects, enriched their spatial experiences, and enhanced their design outcomes. Students judged the CAP VR environment as beneficial for their design process. Although a few authors published on the advances of the use of VR in architecture to

2 http://www.dezeen.com/2015/04/27/virtual-reality-architecture-more-powerful-cocaine-oculus-rift-ty-hedfan-olivier-demangel-ivr-nation/ consulted 09/05/2016

propose a framework for VR in architectural design or education [30, 31], that lack of research illustrates a potential gap to fill in the future.

As shown in the quantitative approach, collaboration and communication are one of the main qualities brought out from using AR applications for design activities. Only a few studies were made in situ, in real practice cases, but many systems were tested by professionals within research laboratories that are worth detailing. Experimentations using ARTHUR highlighted different behavior's patterns in design collaboration with or without the AR system [32,33]. The sharable quality of the information displayed was brought forward to support design efficiency. In that case, users wearing a see-through HMD, were able to generate new shapes and display agent behavior like pedestrians by using a PHO (placeholder object), a pointer or with gestures. Those features helped them in their design decision-making, thanks to the visualization of alternatives solution and dynamic simulations. Another study, from Gül and Halici [34], depicts different behavior's patterns in collaborative design depending on the workspace used, in that case an analogue model environment or a SDAR environment. They argue that using their SDAR application, the efficiency of idea generation and design development raised thanks to a reduction of designers' cognitive load. To offer a collaborative design environment was also the challenge of the BenchWork system using TUI's as well as a HMD [35]. Users can visualize their design, create new shapes and scribble notes inside the virtual environment. This device was tested to evaluate its interface's usability. The results showed that handling several cubes with markers instead of a 3D pen for interactions, enhanced collaboration within the designer's team [36].

The CDP (Collaborative Design Platform) offers a relevant visualization setting combining a tangible tabletop system and a SDAR application in the last version of that prototype [37]. In this scenario, users can place foam mock-ups on the augmented table and in the meantime, visualize the 3D models of the whole urban area as well as 3D simulations like wind or shadows through a tablet (Fig.4).

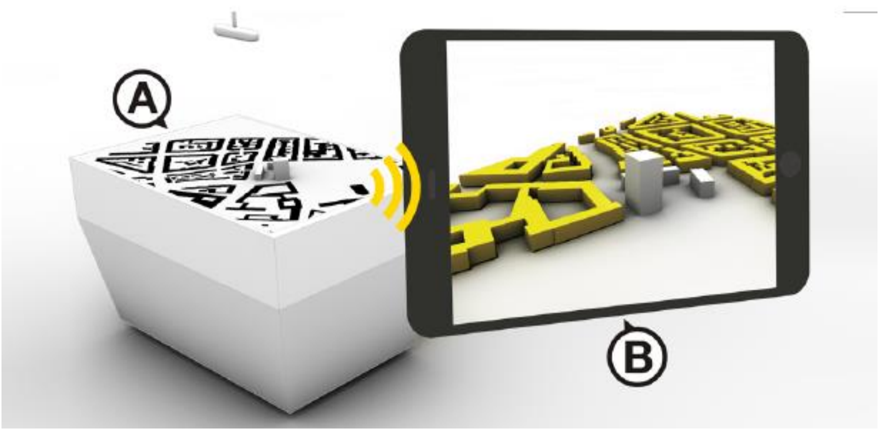

Fig. 4. Collaborative design platform with augmented tabletop and SDAR (source [37])

The aim of that interface is to facilitate design collaboration and active participation thanks to the tangible interface provided by the foam mock-ups, and to ease the design's decisions making process by augmenting the proposals with simulations. SDAR applications' potentials have been multiplied by the large commercialization of smartphones and tablets. Their uses vary from interior design as proposed by Hsu [38] who identified three models of SDAR, namely, filtered reality to arrange furniture into the room, parallel reality to visualize an entire portion of the room with augmented data and projective reality which consists of projecting a texture on the wall to see installations and wiring. SDAR systems are suitable for on-site AR, and have potential for integrating information technology for building refurbishment [39, 40], building management and construction [41] or future project's visualization [42, 43]. Linking BIM (Building Information Modeling) and AR is also a way for the actors of a design project to take advantage of an alternative way to represent technical data on a smart device, facilitating discussions between professionals and laymen [44, 45].

On-site design is the goal of several SDAR applications described before. Tonn, Petzold, and Donath [46] shared the same intentions by proposing a SAR application for 1:1 scale design for interiors. The system provides an environment for both color design and image based design (Fig.5).

Fig. 5. SAR application for on-site design and visualization (source [44])

A pointer and GUI projected on the wall assist the user to change colors and textures, to draw lines and to place images, for example a window or a door. A user study, comparing four methods to make propositions for a color design, that were traditional 2D plans on paper, 2D Photoshop visualization, 3D digital model and SAR, showed that the use of 3D models and the SAR application for that task were perceived as more positive tool than the two others [47]. A complementary user study highlighted that the visualization of design alternatives and 3D spatial perception was increased while designing with the SAR system, instead of traditional pen and papers [48].

In design education, tangible AR is brought out as a system to enrich design in the studios because of the interactivity that it offers [49]. Indeed, TUI's and AR provide a link between tactile action and visualization. In that way, students can learn by active experimentation. Moreover, the interface is shareable, which means that it can support collaborative learning. Designs' propositions are augmented by information on buildings, for instance, distances between buildings. The Luminous Planning Table concept supported the same idea, with environmental data visualization: traffic, wind, shadows and glass reflection [50]. Other types of exploitations of AR applications range from teaching of building physics, to the enhancement of student design in the studios through an AR representation of their design proposals or the improvement of 2D panels presentations with the use of SDAR to complement 2D representations of a project with dynamic and interactive ones [51]. An implementation of SAR for students in interior design, with the SARDE system (Spatial Augmented Reality Design Environment), showed that it supported their design decisions, and gave them more confidence to present their project [52]. The aim was to narrow the gap between what students think and tell about their design and what they actually show through their design representations. That last issue was not completely reduced with the SAR system, even though students felt that they better understood the connection between their 2D representations and the full scale one. Nevertheless, thanks to the SARDE device, students were able to design on site, and remodel their proposition.

As well as for VR and education research, only a few papers dealt with a framework to implement AR in the design education curriculum. Chen and Wang [49] made a proposition for an implementation of Tangible AR to increase and facilitate knowledge transfer and skill development. More recently, Morton [53], suggested that implementing AR systems in design studios could improve students design learning process since multiple solutions can be assessed faster and in a seamless way. Moreover, the author explained that linking BIM and AR provides alternative possibilities of data representation that students could benefit from during their learning process.

As we have seen, relevant research was conducted in order to provide suitable devices and applications to support the architectural design process. The intentions are either: to augment collaboration between the actors of a design project (remote and collocated); to increase designer's representation of his design by enhancing his embodiment in the EV; to provide a more natural interaction with the design object to enrich ideation; or to facilitate design activities by reducing the cognitive load required to evaluate design solutions. Depending on the end user and the objectives of the application, the physical and technical features are adjusted (display mode, user interface, number of users). The representation type differs in accordance with the display. SDAR applications mostly offer top down views on the scene, whereas HMD VR provide first person immersion in the VE.

Only a few papers focused on the appraisal of VR and AR use in terms of design education which offers an opportunity to develop a framework for the use of applications to support design learning. Many propositions focus on enriching design activities, which can be a part of design education process. However, for a pedagogic implementation, the application's features should be adapted. For architecture students, the design studio is the cornerstone of their curriculum. The CAP VR and the BenchWork systems were oriented to support design studio sessions, as well as the Luminous Planning Table. Except for that last example, the communication between students and teachers is hindered because users are wearing a HMD. Only one type of design representation is used for each of those device: immersed first person view for the CAP VR, and top down view for BenchWork and the Luminous Planning Table. Nonetheless, architects always work with multiple design representations. In the following section, we will underline the importance of the use of a variety of external representations' modalities during studio sessions.

Considering the significance of communication and representation, we will argue why exploiting the potentials of VR and AR can support architectural design learning. Merging enhanced top-down and first-person views of the same scene within the same immersive platform can provide a suitable representational environment for the critique sessions.

4 Towards an Immersive VR and SAR Platform to Support Design Learning

Designing moments during the critique sessions help students to learn how to design, either by seeing their instructor designing or by experiencing collaborative design with their tutor [54, 55]. During design studio critique, students and instructor discuss design issues which drive the evolution of the students' designs [56]. Designing can be performed during the session, by either the student, the instructor or both. This moment is pedagogically important, which is why, collaboration and communication should be a primary concern. Conversations on design issues and potential solutions revolve around design representations. Miscommunication between students and instructor can penalize the learning potential of the discussion. The lack of constructive communication is driven by misunderstandings, that can be a consequence of the gap between the design expertise of both student and instructor, as well as a difficulty to synchronize the student's and the teacher's mental model of the design object.

Designing implies the manipulation of multiple types of representations. Indeed, architects work simultaneously in a synthetic and analytic way, which explains why they need to use a variety of design representations. The variety of points of view on their design enables them to deal with specific details in parallel to global concepts. Goel [57] established a connection between design phases and the types of representation used for a specific design activity. He considered two kinds of transformation of the design representation: a change in a concept or a detailing of an existing concept. External design representations perceived by the designer impact the design process evolution [58]. Design knowledge is embedded into external design representations, and their manipulation influences the direction taken during the design process. Therefore, handling representations during the critique session affects the overall student design process and its outcome.

Experienced architects have spatial representation skills allowing them to switch naturally from a planar representation of space to a 3D representation of the same space. It implies that while designing a project in a 2D plan, with a pencil and a sheet of paper, they mentally and seamlessly construct the spatial representation of that space. Nevertheless, students in architecture are still novice in manipulating their design representations. They are used to produce several representations (for example a section, a mock up and a plan) of the same object, that sometimes do not correspond to each other. The issue with traditional representations (plans, sections, 3D models, mock-ups, renderings) is that they are disconnected. It means that no link or synchronization is kept between the diverse representations of the same object.

We underlined several issues that could lead to a diminished pedagogic experience during the critique sessions: the difference of expertise between instructor and students in handling design representations and accurately representing the design object; misunderstanding and miscommunication due to a lack of synchronization of the student's and tutor's mental model of the design object. We believe that by modifying the representational environment used during critique sessions, enhancing it with VR and AR technology, it could benefit each session learning outcome for the student.

Systems using both VR and AR on the same device are not that common. However, Schubert, Anthes, Kranzlmuller, and Petzold [59] and Wang [60] already made that proposition to use both technologies to provide designers the possibility to switch from exocentric to egocentric view within the same physical space. The first example is an alternative configuration of the Collaborative Design Platform presented earlier. In that case, the table top is connected to a CAVE environment (Fig.6). On the other hand, the ARUDesigner concept is to use the same HMD to switch from a view of a table top in AR and the first person view in VR (Fig.6).

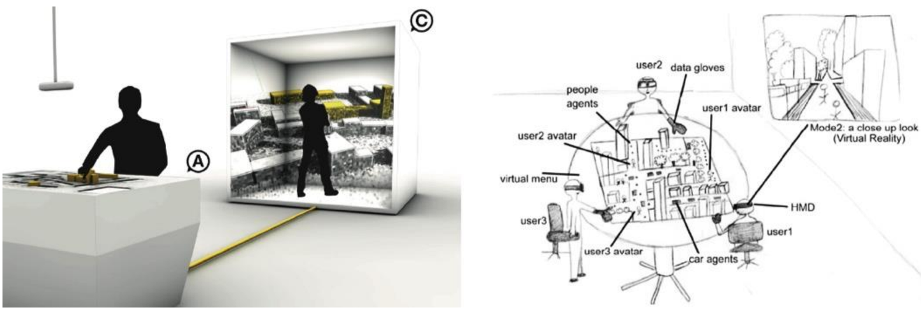

Fig. 6. (Left) A possible CDP configuration with the augmented tabletop (A) and a CAVE (C) (source [59]) (Right) Concept of the ARUDesigner project (source [60])

Both projects included simulations (wind flow, shadow cast, agent-based simulations) to help users assess their design propositions. With the ARUDesigner project and the Collaborative Design Platform, designers can experience both representations within the same space, and the connection between those representations is held since the same virtual model is used to create the visualization layers that are displayed.

As we mentioned before, designers need to handle design representations at multiple scales and from diverse points of view to perform analytic and synthetic cognitive activities that are inherent to the design process. Moreover, for a pedagogical use, we have to consider the synchronization of those representations to enhance their comprehension and ease the communication between the participants of the critique session. Using traditional media, no simultaneous link between distinct representation's prop like a 2D section and a 3D digital model are kept. Our proposal is to offer, for design studios, an immersive design representational environment providing synchronized top-down view and first-person view on the student's design, mixing VR and SAR techniques that will support user interactions in both spaces. By providing a dynamic interaction between a top down enhanced view on the project (analogous mock-ups enriched by an SAR application) and an immersed first person view (immersive VR), we intend to smooth the transition from one representation to the other one. Featuring this asset, we expect the design process during the session to be improved. Indeed, each user will access both egocentric and exocentric views within the same immersive space that will favor the collaboration within instructor and students. Moreover, it will facilitate individual spatial comprehension of the design, and this could reduce the gap between the critique participants' perceptions of the design object.

CORAULIS platform will support immersive VR thanks to its 360° screen, providing visual and aural immersion as well as SAR (4 of the 10 beamers will be use to project textures in the center of the platform). In our case, SAR will be used to map printed 2D plans or sections and mock-ups display on the tabletop. The same virtual model will provide input data for both SAR projection and the immersive first person view projected on the circular screen. We consider the representational environment offered by our platform as an illustration of the WIM (Worlds in Miniature) metaphor, coined by Stoakley, Conway and Pausch [61]. In the WIM paradigm, both exocentric and egocentric views on the building are displayed in the virtual world. The concept is to facilitate 3D objects manipulation in the virtual environment by representing a miniature replica of the life sized scene visualized in a HMD. Users can seamlessly interact with objects in both representations. The WIM metaphor supports a better visualization of space. It can help for navigation and orientation, and offers diverse objects' selection possibilities. Within CORAULIS platform, the miniature replica will be the augmented tangible objects, either mock-ups or 2D plans (Fig.7).

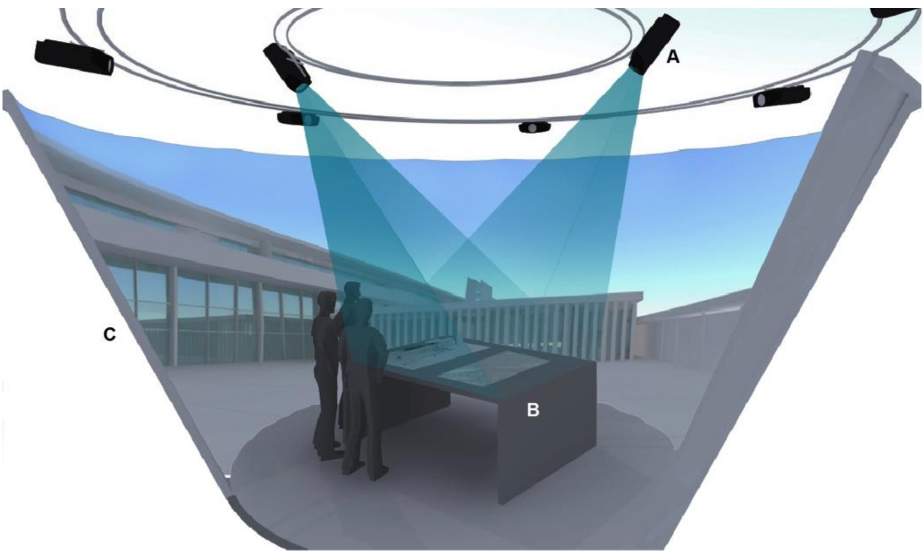

Fig. 7. Possible configuration for CORAULIS (A: beamers for SAR, only two are represented in the image, B: tabletop with augmented plans and mock-up, C: immersive screen)

To maintain the WIM paradigm concept, both visualization environments will act as navigation and interaction interface. Our challenge will also be to keep a synchronization between the SAR tabletop and the full-scale egocentric view of the same scene, projected on the 360° screen. Our application framework to be used in CORAULIS is composed of three modules: the virtual model module, the visualization module and the interaction module, as outlined in Fig.8. The virtual model will be based on a 3D model importation (a BIM model for instance). Simple simulations will then be generated and regrouped with the texture layer, in a conceptual simulation layer. The same virtual model is exploited within the visualization module that includes the SAR layer and the VR layer. The interaction module offers navigation within the virtual model either by walking or flying, as well as a GUI interface to activate simulations' layers.

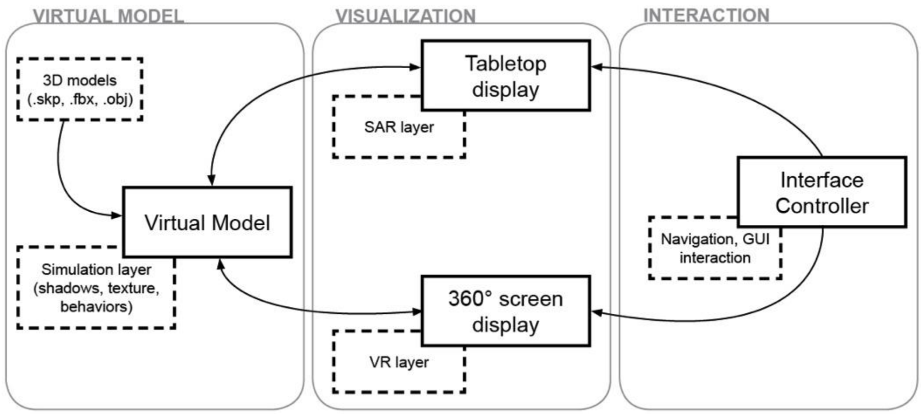

Fig. 8. Application framework for CORAULIS

During the critique session, the first part consists of the student presentation. He could navigate in the scene to support his idea. Within the navigation mode, participants will see an avatar moving on the tabletop projection while the first person view is changing according to the position of the avatar in the 3D virtual model. If needed, the simulation layer could be handled through a GUI displayed either on the screen or the table top. The efficiency of the proposed design solution can be discussed based on the shadow cast. If the time setting is changed, the shadow simulation will adjust accordingly in both views. The framework we proposed is a preliminary version of what can be implemented. For example, TUI's interactions could be developed by moving mock-up elements to try alternative possibilities, displaying modifications in the egocentric view in real-time. Primitives, like cubes representing building outline, could be generated and arranged within the virtual model with the GUI, and appear in the VR space and be represented by their shadow cast in the SAR space.

The proposed framework is specific to address local collaborative design activities in a pedagogic setting. The challenge raised by such a system and platform is to take advantage of both VR and SAR technologies: the feeling of embodiment for VR and the sharable quality of the augmented tabletop for SAR, to support design and co-design. Design is a collaborative activity, which includes individual moments of ideation. We aim to provide a platform for both individuation and collaboration by creating an environment that corresponds to the particularity of designing activities during studio critique sessions. Our system will work without a HMD which seems more relevant to offer a suitable environment to support collaboration and communication. The first-person view and full scale immersion will improve users' understanding of the student's design object. The consideration of the human scale perception of space is essential in architectural design and will help instructor and students to evaluate their design propositions. Moreover, the enrichment of tangible object (mock-ups) with SAR, offers an alternative and accessible way to visualize technical data that designers rely on. Compared to other devices that removed physical representation of the object being designed, our aim is to favor merging digital and physical representations. Architects usually work from a top down view or a bird-view that is why conserving that type of representation seems essential. Both egocentric and exocentric representations will be viewed in the same space. Complex design actions, to be processed and achieved, rely on representations switch including a change of format, scale or level of detailing. The switch will be addressed within that dynamic and interactive way to smooth the transition from one media to the other. The platform is not yet constructed, so the limits of the framework are not clear. The interaction/controller interface to handle those multiple representations is a challenge to undertake. Indeed, the cognitive load needed to interact and apprehend the whole system could affect the performance of the users. Users experiments will be conducted in order to assess the usability of our framework in such a pedagogic context.

5 Summary and Discussion

This article provided an overview of applications of VR and AR in the field of architectural design. A high diversity of devices and systems have been developed in laboratories, however, in real practice, there are still few studios or firms benefiting from those technologies. Nevertheless, user studies showed the potentials of VR and AR applications in term of ideation, collaborative design, building management and design education. Only a few of those systems were designed to support design critique sessions in term of pedagogic outcomes. We can distinguish six families of systems that were used for either design studio sessions:

- HMD VR, for example the CAP VR system
- Immersive screen based VR, like the HYVE-3D
- Tangible AR, as illustrated by the Luminous Planning Table
- HMD AR as proposed by the BenchWork system
- SDAR (no example of SDAR use for design critiques were find in our survey)
- SAR, as exemplified by the SARDE system.

The CAP VR environment proved to be efficient to enhance the quality of students' design. Student's immersion in the virtual model of their design augmented their spatial comprehension and enriched their design's evaluation. However, the communication with the tutors wasn't seamless because students were wearing a HMD. The Hyve-3D offers a perfect environment for co-ideation, either collocated or remote, during the critique. Both 2D and 3D representations are exploited, although no physical representation can yet be integrated in the platform. On the other hand, the Luminous Planning main feature was the augmentation of tangible mock-ups. The intention of that device is centered on representations to enrich the critique and discussion more than to promote designing during the session. The drawbacks mentioned by students were that simulations' display (wind, shadows, traffic) oriented the design process. The BenchWork system was used by students only in the studios. Its objective is to offer a better collaboration space for co-designing. As well as for the CAP VR, communication can be obstructed by the wearable device. The SARDE system suits onsite, scale 1:1 interior refurbishment design but cannot be applied for architecture (building scale). Its use was also centered on improving students designing process, without considering student/instructor communication. Our proposition is an alternative to those devices. Our system, blending both VR and SAR technologies, aims to benefit from the assets of each of them. For a pedagogic use during the critique sessions, it seemed relevant to use an immersive screen for VR instead of a HMD, in order to conserve natural communication behavior. Students have to manipulate all kinds of representations types, physical and digital, which is why augmented mock-ups and plans appeared to have a high potential. CORAULIS will propose a design environment providing multiple enhanced viewpoints of the design object and seamless navigations and interactions in all of the representation spaces, that are merged in a single physical environment. Our future work will be to assess the effects of the use of our application in CORAULIS during a design review in an architectural studio at our university. This experiment will be run in the following year, and will serve as a test-bed to investigate the potential of VR and SAR for design critique, the limits of its usage and suggest guidelines to enhance design pedagogy in the architectural studio.

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Imitation in Action
A Pedagogical Approach for Making Kinetic Structures

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Abstract. One of the problems in teaching students how to design kinetic architecture is the difficulty of helping them grasp concepts like motion, physical computing and fabrication, concepts not generally dealt with in conventional architectural projects. In this paper, we introduce a pedagogical method for better utilizing prototyping and explore the role prototyping plays in learning and conceptualizing design ideas. Our method is based on building the learner's sensory experience through iteration and focusing on the process as well as the product. Specifically, our research attempts to address the following questions: How can architecture students anticipate and feel motion while they design kinetic prototypes? How do their prototypes enable them to explore design ideas? As a case study, we applied our methodology in an 8-week workshop in a fabrication laboratory in Cairo, Egypt. The workshop was open to young architects and students who had completed at least four semesters of study at the university. We describe the pedagogical approach we developed to build the sensory experience of making motion, and demonstrate the basic setting and stages of the workshop. We show how a cyclical learning process, based on perception and action -- copying and iteration -- contributed to the students' learning experience and enabled them to create and improvise on their own.

Keywords: Kinetic Architecture, Digital Fabrication, Sensory Experience, Computational Making, Imitation

1 Approach

Inside the growing movement to go beyond static architectural tectonics and build skin configurations that include kinetic and adaptive structures, problems still arise regarding the pedagogical role in teaching such complex structures and methods to young architects. The skill sets and knowledge now required from students of architectural design have expanded to include prototyping, making and physical computing. As stated by Frazer and Fischer (2005), architecture is being modeled as "logic states in space and time" where computers and architecture are interchangeably constructed and computed in an intelligent and interactive environment. This typically implies that architects now need extensive knowledge in the areas of human-computer interaction, programming, mathematics, computer science, robotics, electronics mechanics, and other areas.

In this interdisciplinary context, the architect/designer no longer follows a linear workflow and reductive process of simple hierarchical problem solving (Diniz 2015). He/she becomes an orchestrator integrating different concepts, viewpoints, disciplines and methodologies and technologies. As a result, architects need to understand and feel comfortable with prototyping, both for static and kinetic structures.

The significance of the role of prototyping in architectural design and making of kinetic structures have been discussed widely. While educators have explored a variety of methods to teach students to design and make kinetic architecture, most attempts have focused on the product rather than on the learning process. Some educators have focused on asking students to design certain mechanisms and then add elements such as electronics (Fox and Hu 2005). Other designers have attempted to classify motion types (Schumacher, Schaffer and Vogt 2010).

Later attempts have explored the notion of experience prototypes, prototype conceptualization, and prototypes as a vehicle for research through design and for design exploration in education (Diniz 2012). An inevitable transition occurred in architectural education as emphasis shifted from design ideas and concepts such as case-based design and representation to processes such as performance-based design, mutation and animation (Zaero-Polo and Moussavi, F. 2003; Kolarevic 2003; Aranda and Lasch 2006; Oxman 2008; Diniz 2015). This transition automatically led to a shift in mindset and the palette of skills necessary to conduct such processes as physical computing, programming, scripting, and algorithmic thinking.

In this paper, we explore a new way to teach students the skills necessary to create kinetic systems that change shape according to contextual or climatic changes. Our inquiry entails how they learn to imagine and materialize tangible elements such as structure and materiality, and intangible elements such as motion. We first adopted Fox and Hu's approach (Fox and Hu 2005) in our pedagogical strategy. We also introduced the learning process as a holistic design activity, rather than as a discrete set of skills.

Tim Ingold argues that art and technology should be treated as one, as the ancient Greeks considered both as *practiced skills* (Ingold 2001). Imagining motion, and then designing and making it is an acquired skill gained through the action of making. With this in mind, we aimed at building students' practical skills, which they could then apply in designing and making any kinetic structure.

To do this, we adopt I^3, a three-layered operation for making and learning that is based on *Imitation, Iteration and Improvisation* (El-Zanfaly 2015). Through I^3, students build their sensory experience and acquire the technical skills needed for design and making. We argue that I^3 is particularly useful because it requires integrating computational design with additional components. I^3 is a hands-on process that focuses on process rather than product.

For the purpose of this study, we designed a workshop that we called *Kinematic and Responsive Architecture and Fabrication Technology* (KRAFT). We describe below the workshop settings and its stages, outlining the approach we developed to build the necessary sensory experience. We then highlight the act of copying or imitation, and discuss how the notion of imitation-in-action affected the design and learning process of the students. Finally, we present our main findings and conclusions.

2 Workshop Process and Outcomes

2.1 Workshop Stages

The workshop took place at the first community-based collaborative space and fabrication lab in Egypt. It was open to young architects and students who had completed at least four semesters of study at the university. We also collaborated with the Department of Architecture at Ain Shams University and with a team at an independent architectural hub. Twenty students had not been previously exposed to digital fabrication tools or elements related to responsive environments such as microcontrollers, materials and motions were participated.

Our workshop represented was the first attempt in Egypt to teach students how to design and make responsive and kinetic architecture. The workshop was conducted in 24 sessions over a period of 8 weeks. Learning by doing (Dewey 1997) was one of the main methods implemented in the workshop. We also asked the participants to present their projects' storyboards and ideas about how people might react to their projects and why. This helped the participants not only to focus on the aesthetics, materiality and motion of the structure, but also to design for user experience. We conducted the workshop in 6 different stages: (1) introducing relevant literature, (2) working with active shapes and active rules, (3) working with digital fabrication and analyzing precedents of kinetic structures, (4) imitating and copying as a creative act, (5) introducing concepts of physical computing, and (6) prototyping to design and fabricate a responsive wall system.

First, we introduced the students to related literature on digital fabrication, kinetic structure components and responsive environments. In order to familiarize them with KRAFT, we needed to review some basic topics within the readings, such as architectural robotics, tangible user interfaces, ubiquitous computing, digital fabrication and responsive architecture. We then introduced them to *active shapes* and *active rules* (Fig. 1), which represent guidelines for designing architectural kinetic structures, where rules based on shape grammars (Stiny 2011) are used for capturing motion and design (El-Zanfaly 2011). Active shapes and rules provide a method for the designer to describe and design novel kinetic structures through different transformations (Fig. 2).

Based on Shape Grammars, the rule A -> t(A) is introduced. (A) means an Active Shape, that is a physical shape with motion observed or created by the designer. t(A) means a new Active Shape produced by applying one or more transformations t on the original Active Shape to produce a novel motion (El-Zanfaly 2011).

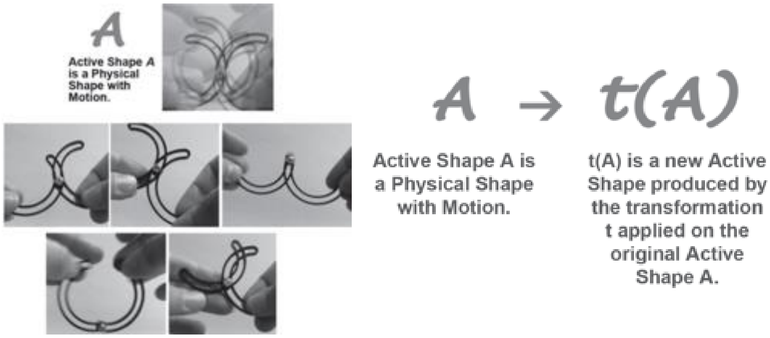

Fig. 1. Right, Active shape. Left: Active rule, showing a transformation applied on the active shape (El-Zanfaly 2011)

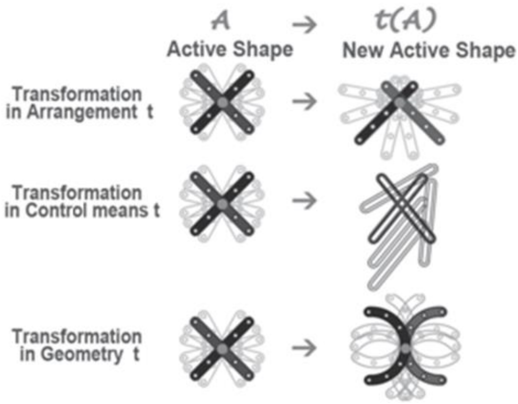

Fig. 2. Examples of types of transformations (transformations in arrangement, control and geometry), which could be applied to the active shapes to produce novel kinetic structures (El-Zanfaly 2011)

In the third stage, the participants were introduced to digital fabrication methods and techniques, with hands-on exercises and access to a laser cutter and 3D printer. As Mine Özkar (2007) argues, digital tools and fabrication machines often overwhelm students and thus impact their design process. With this in mind, at this stage we focused on analyzing some examples of already built responsive and kinetic structures. We discussed the materials used, the assembly of the parts, and the fabrication methods used; we believed that helping students to familiarize themselves with the steps in designing responsive architecture would reduce the students' anxiety when it came time to approach their own projects.

In the fourth stage, we asked the participants to imitate an existing kinetic structure and its motion by first drawing and then fabricating it. It was important here to allow the participants to select an example to replicate. We intentionally provided students with an image of the project only; we did not provide diagrams or blue prints from the original structure. In the fifth stage, we explored the implementation of the Arduino micro-controller for the prototyping of smart and responsive skins and surfaces, with specific focus on interfacing between digital and physical worlds and programming different forms of sensors and actuators to control physical elements. Finally, the participants were asked to integrate what they learned in all stages to design and fabricate a responsive wall system. In the next two sections, we discuss the student works in stages 4 and 6, which contained most of the hands-on work and best illustrate how the participants progressed in their work and arrived at their final outcomes.

2.2 Imitation and Copying as Creative Act

In this specific stage (stage 4), we introduced the act of copying. We asked students to copy an already built mechanism or concept of a moving structure in any scale. Through this process, students see something new whenever they copy or imitate a part. They learn to analyze and focus on structure, material behavior and mechanisms, and how pieces come together. Copying an already built structure enables the students to learn from tangible objects and connect aspects such as materiality with intangible aspects such as motion. We asked the students to choose an example and fabricate it so as to gain hands-on technical skills through imitating and to get the "feel" of motion and materiality (Ingold 2001). The students did not have to build the whole structure; we asked them to imitate and build a structure in motion with any material.

Below we describe briefly five example prototypes from the students' work: (1) Origami Structure, (2) Walking Beast, (3) Mechanical Iris, (4) Expanding Circle, and (5) Kinetic Sine Wave. The *Origami Structure* project involved inspirations from folds and origami (Fig. 3). One student described her design of the origami structure as one that transforms from a 2D to a 3D structure. She also gave functionality to the designed structure; *"....it may be a responsive curtain which can divide space, or outdoor furniture unit which can appear from nothing (2D plan to 3D unit), or it may even be a decorative wall which can interact with users."*

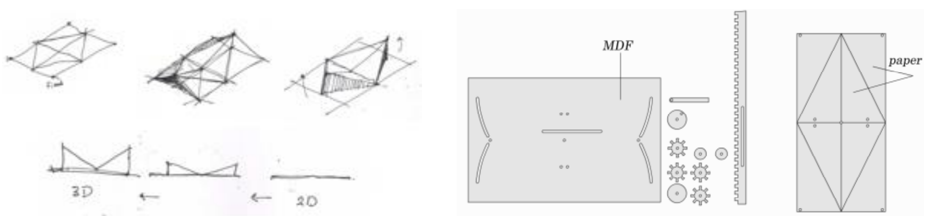

Fig. 3. Origami Structure drawings

In her description of the final structure and motion (Fig. 4), she described the structure as consisting of two main parts, in which the first part is "*origami paper –*

it's fixed from one point at the middle to the wooden plate," and the second part as *"paper's edges start to move when we use the crank slider and push the two gears in the wooden plate*".

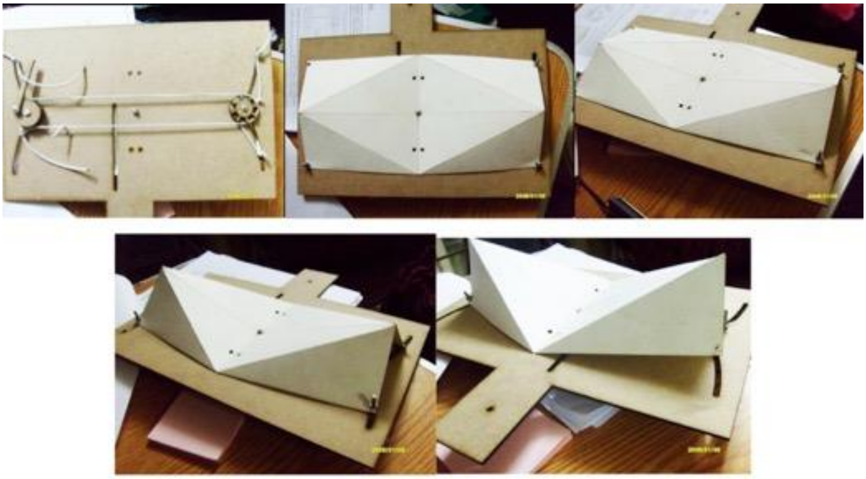

Fig. 4. Structure and mechanism of Origami Structure

In the *Walking Beast* project, two participants working together decided to imitate the motion of Theo Jansen's mechanism "Strandbeest" (Patnaik 2015). They designed the element and fabricated it using the laser cutter (Fig. 5). In their presentation, they explained how they studied the motion of the walking legs of some of Jansen's beasts and the motion of these kinetic sculptures. They found a new way to fabricate the continuous motion of the element using the laser cutter during their assembly of the pieces.

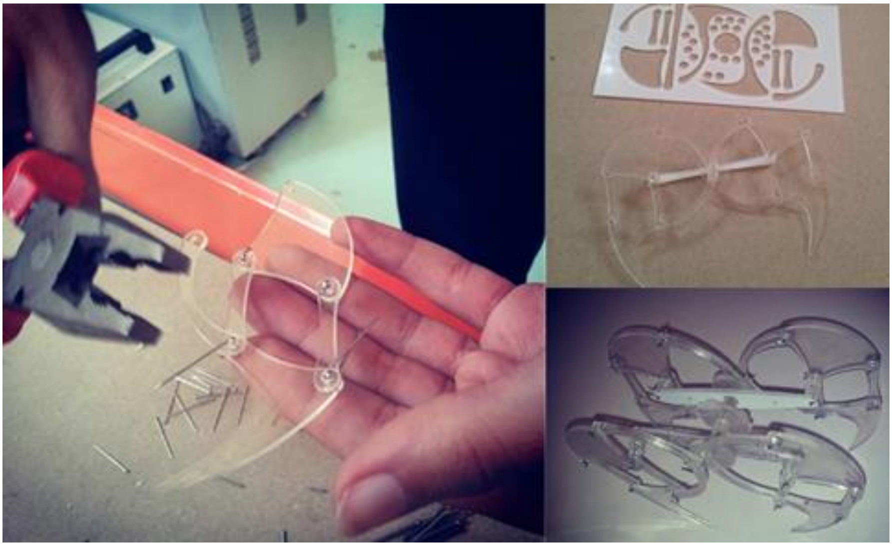

Fig. 5. Structure and mechanism of *Walking Beast*

In the *Mechanical Iris* project, two participants, working separately, developed a mechanical iris from scratch. The first participant designed the motion and pieces to imitate a specific type of motion captured from a video of a responsive window aperture. The structure involved a circular geometry with a double-layered guide for controlling the opening and closing of an internal aperture (Fig. 6). He made several iterations until he developed his own final geometry and motion (Fig. 7).

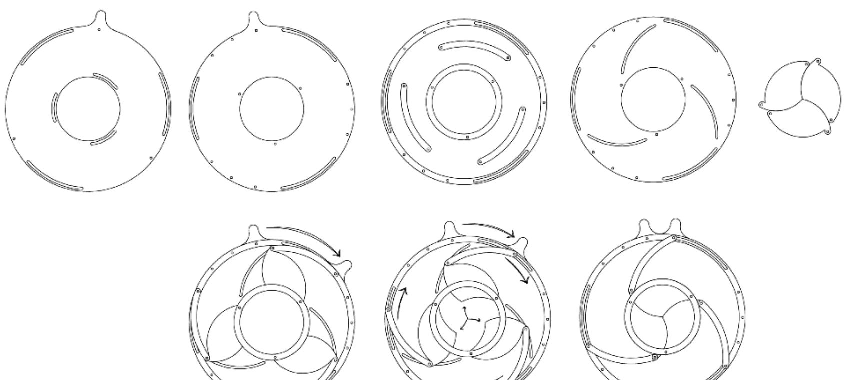

Fig. 6. *Mechanical Iris* drawings (Project A)

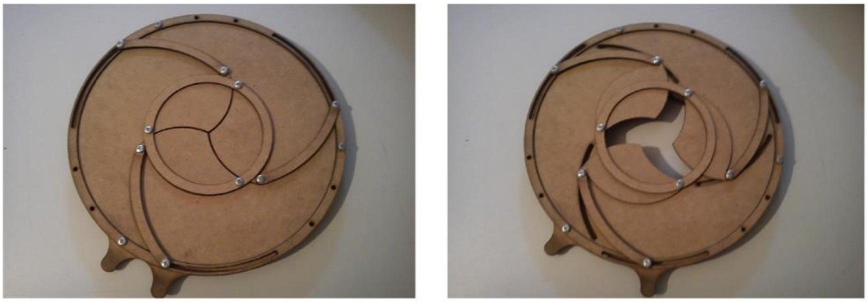

Fig. 7. Structure and mechanism of *Mechanical Iris* (Project A)

The second participant also worked on a mechanical iris. She was also able to replicate the motion of opening and closing with another mechanism using gears (Fig. 8). The mechanism also involved a double layer of circular geometry with motion guides and two circles that acted as gears for guiding the overall motion (Fig. 9). In both projects, the participants were able to create the same motion they attempted to imitate, but using different mechanisms and techniques.

Fig. 8. *Mechanical Iris* mechanism, final structure and motion (Project B)

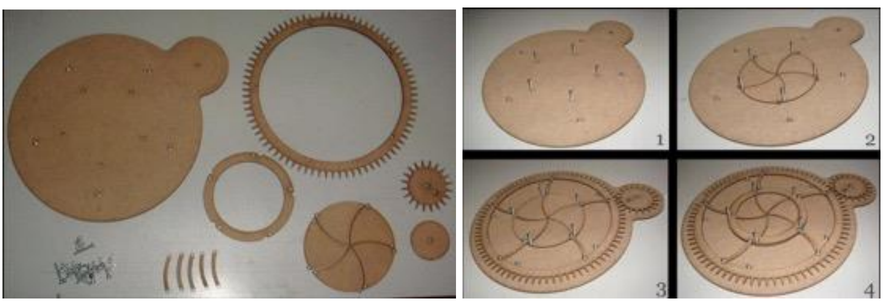

Fig. 9. *Mechanical Iris* detailed components and assembly (Project B)

In the *Expanding Circle* project, one participant designed an expanding circle that returned to its shape once it was pulled. She used a rubber band to pull all parts together once the circle was expanded (Fig. 10).

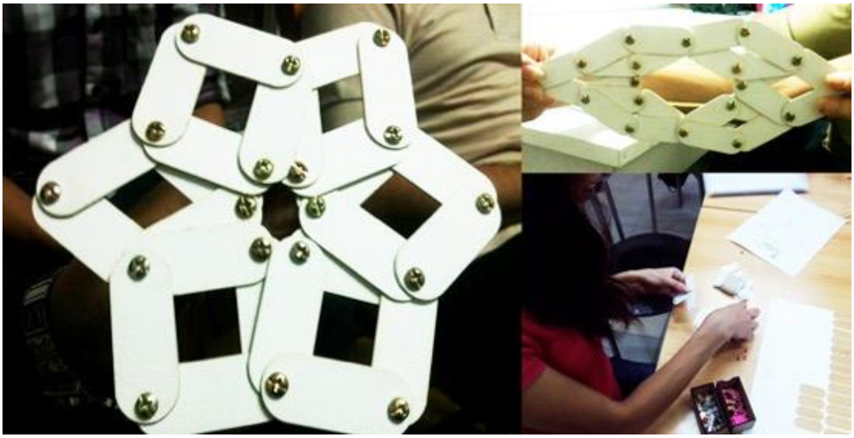

Fig. 10. Structure and mechanism of *Expanding Circle*

In the *Kinetic Sine Wave* project, the participant imitated the Reuben Margolin Nebula structure. The student's sketches show that he designed the motion and parts from scratch (Fig. 11). He was able to produce his intended motion after a couple of iterations. Using pulleys and threads, he was able to pull the structure made of wooden circular rings according to several 3D sine wave motion types (Fig. 12).

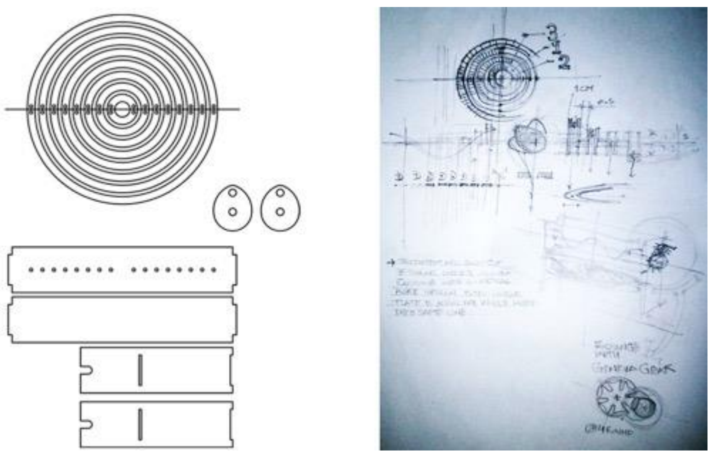

Fig. 11. *Kinetic Sine Wave* sketches and drawings

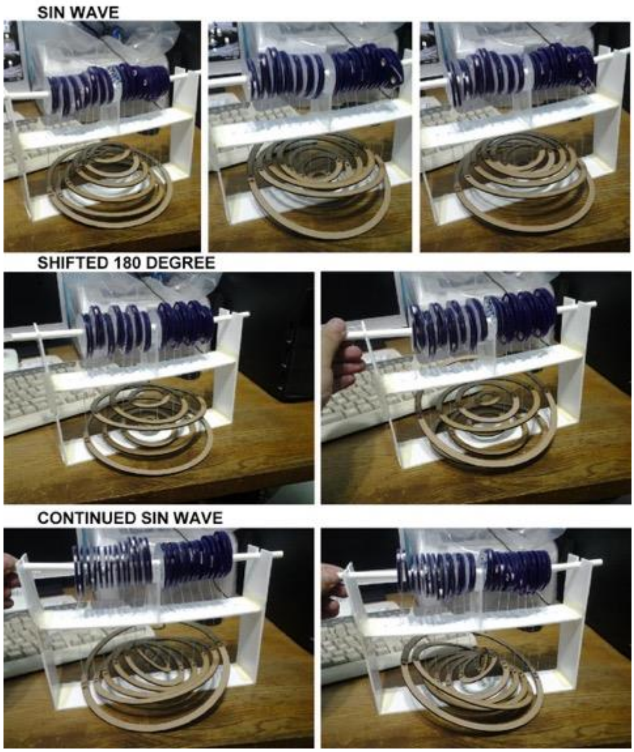

Fig. 12. Structure and mechanism of *Kinetic Sine Wave*

2.3 Architectural Scale: Expandable Mashrabeya

In this final stage, and after introducing the Arduino programming environment for the prototyping of smart and responsive skins and surfaces, we asked the participants to design and fabricate a wall component that represented an element of responsive architecture. The goal was to create a modular wall unit representing an exterior or interior wall that could be controlled using microcontrollers, sensor feedback systems and actuators to adapt to changing parameters. We specifically asked the participants to design scenarios for interaction, motion and reaction using this sensor network data.

The participants worked in 3-4 person groups on their projects. Each group picked a specific theme. Group projects were asked to specify and articulate their responsive architecture systems, i.e. whether they focused on responding to environmental conditions, lighting, acoustics, occupancy levels, user behavior and interaction, circulation patterns, and so on. The participants were asked for project proposals and presented them during three sessions with discussions and feedback. Each student proposed a project individually; then they formed teams based on mutual interest.

In one of the projects, the group suggested a wall system that opens and closes to control lighting and ventilation according to an ancient, well known Arabic wooden structure called the *Mashrabeyah* -- a carved wood lattice matrix that was used in Arabic houses to allow for ventilation and sunlight, and simultaneously allowed for indoor privacy. The group first studied different geometries and patterns in existing Arabian houses. Then they studied and tried different mechanisms to produce maximum motion with the least number of motors.

The group designed a unit with five gears, which controlled linear sliders to open or close the unit and adjust the units as well (Fig. 13). This unit required only one motor. The students worked on optimizing the numbers of motors required by changing the geometry of the units and its controllers (Fig. 14).

Fig. 13. The basic kinetic modular unit of the *Expandable Mashrabeya*

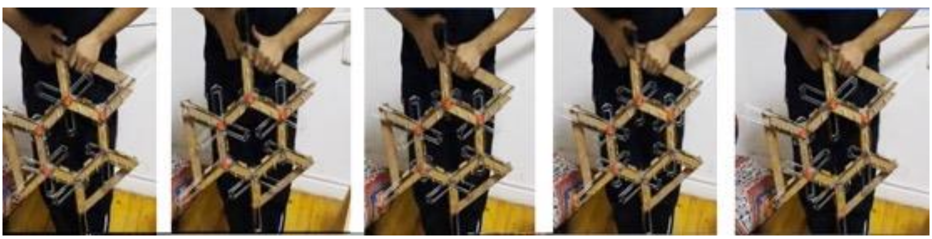

Fig. 14. The modular unit requiring only one motor to make five gears work

3 Discussion

This paper addressed a set of questions related to teaching students how to anticipate motion *while* designing and making. It provided a pedagogical framework for helping designers to first acquire the *feel* of motion and materiality, then apply this sensory knowledge to their design ideas. The *Imitation and Copying as Creative Act* approach, I^3, was introduced to help the students make moving structures. The general results showed that students were able to create kinetic structures using this approach. The introduction of active shapes and rules helped break down the sensory experience into explicit steps that allowed students to perceive kinetic motion and expand conventional grammar into dynamically changing possibilities The cyclical operation of perception-imitation-action employed by students throughout the workshop changed their perspectives and produced varying levels of complexity in terms of design. Some participants adapted the original structure along more predictable lines, as in the mechanical iris and expanding circle. Others showed an adaptation of the original examples with more complexity, as in the origami structure, the walking beast, and the kinetic sine wave.

Most students used several combinations of these transformations. As their design ideas iterated cyclically, they continued to *see* their active shapes *as* potential new active shapes. This allowed for innovative schemes that often exceeded the initially imitated-as-is image, and consequently led to novel kinetic elements. In the final stage, the students further augmented the I^3 operation. They started to include environmental, cultural and user experience considerations. The process of Imitation in this workshop was not limited to the geometrical *image* of the Mashrabeya, or even a direct translation such as in the mechanical iris.

The Mashrabeya project showed how far students could progress through the learning process. In this case, the developed mechanism featured a complex outcome based on the sensory experience learned during the workshop. This outcome combined the perception of active shapes and their expected transformations, together with an adaptation of the conceptual basis of the Mashrabeya – rather than mere geometry – and a complex kinetic optimized mechanism. The final design outcome – or *integrated system* – appeared to be more than the 'sum of its parts.' We conclude that the *perception-imitation-action* cyclical operation established groundwork for multiple levels of reflection, conceptualization, and learning, and led to this integration. These levels include (a) direct adoption of motion, materiality, and structure to conceptualize a prototype; (b) decomposition of the sensory experience into explicit rules of motion; (c) continuous reflection and adaptation to generate developed and complex prototypes; and (d) integration and appropriation of prototype to conceptualize and generate novel design ideas.

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Meno in the Studio

Design Computation in a Pedagogical Dialogue

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Abstract. Competence in learning comprises combinations of knowledge, skills, and attitudes. Yet it is difficult to articulate and assess the learning objectives for attitudes. This paper focuses on the role of computation in providing an instrumental medium for attitude development and assessment in the design learning settings of the future. Our study draws from a passage on a mathematical inquiry in Plato's Meno and makes a case of its aspects of visual reasoning and learning as reflection in action. Reporting on attitudes observed in an inquiry conducted with similar role play with foundational design students, we show that analog computation with visual rules supports the externalization of mental processes in basic design exercises and endorses beginning practices of accountable designing.

Keywords: Attitudes, Foundation Studio, Shape Rules

1 Introduction: Learning as Recollection and/or Reflection

A foundation studio in university level design education is a primary setting for first-year students to start acquiring design skills. A part of what students acquire is developing an attitude for establishing accountability for their designs by the way of using reference points and relational thinking. Accountability is a trait generally sought at the institutional level in the higher education context and is understood as "answerability for performance" [1]. Accountability entails an ethical dimension in learner-centered higher education [2] and subsequently in professional life. Findeli [3] identifies this dimension in design education in addition to that in practice and profession, and as a general morality to be adopted independent of the design domain. As students increase awareness towards the values of certain actions, they accomplish attitudes along with reasoning and the development of reflective skills [4].

We propose that a visual-rule-based computational perspective on design is instrumental for developing attitudes based on two points. Firstly, visual rules, as defined by Stiny [5], stand for self-imposed constraints defined and followed through by a designer for adding to, subtracting from or transforming designs. Introducing visual rules as reasoning tools in design studios allows the students to explicate their design reasoning and consequently develop awareness and understanding [6]. Secondly, rules that visually capture the stages of a transformation, externalize it for sharing and questioning the instances of design and production. Donald Schön [7] describes design as a reflective dialogue with the design situation and provides a further dimension of understanding that specific situation by reflecting upon reflection-in-action. Visual externalization of the design thinking process supports reflective practice and consequently, we argue, the formation of some attitudes in design learning.

Following Schön's example, this paper draws from a passage from Plato's Meno [8], a Socratic dialogue. While the full breadth of pedagogical values and Plato's theory of learning as recollection inherent in Meno as well as all implications of the dialogue deserve special attention and discussion, our focus is on the part concerning the drawing of shapes on the ground. This part of the dialogue provides an illustration of development of an understanding, and reflection plays an indispensable role in it.

From a design thinking perspective, Schön [9] acknowledges that the dialogue in Meno is constructed upon several interwoven kinds of learning processes including demonstration, learning by doing, imitating reflectively and reflection-in-action. The interaction between Socrates and the boy on verbal and visual representations is similar to the interaction between the instructor and the student in design studio. Schön recognizes the "learner's paradox" in Meno in parallel to the experience of learning to design: "Like Meno, the design student knows that s/he needs to look for something but does not know what that something is. S/he seeks to learn it, moreover, in the sense of coming to know it in action." [9].

In the part of the dialogue with the boy, Socrates makes a point on recollection in learning as he questions the boy on doubling the area of a square. The inquiry turns out to be instrumental in developing reasoning in a systematic and visually supported process. The geometric constructions on the ground are used to describe the reasoning process as shapes are combined and transformed. The boy's gradual grasping of the relational system underlying the shapes helps in his developing reasoning and judgment. The story in the dialogue is an individual's understanding-in-action. Similarly, visual rules that externalize a relational system in individual design processes are tools not only to control the relations between shapes but also for novice designers to develop an understanding of design thinking. In Meno, the boy implicitly learns the relation of the squares in the Pythagorean theorem. Similarly, forms in designs are of a constructive and relational nature. A spatial relation is specified whenever any arrangement of shapes is recognized perceptually to be as such. Drawing rules as discrete steps of a computation formalizes thinking and generative processes of design as previously developed and applied extensively within the frame of shape grammars [10-11].

1.1 Interpreting *Meno* from a Computational Perspective

Shape rules are visual representations of the objects' descriptions in a computation process. The mathematical relations described in the *Meno* dialogue are visual and invoke representation with shape rules. Previously March [12] and Stiny [5] have acknowledged the relationship between Plato's mathematics and visual calculating referring to the anthyphairetic ratio of the diagonal and the side of a square sqr2:1. Here, we show the shape rules for the *Meno* dialogue about how to achieve a square two times larger than a given square (Fig. 1).

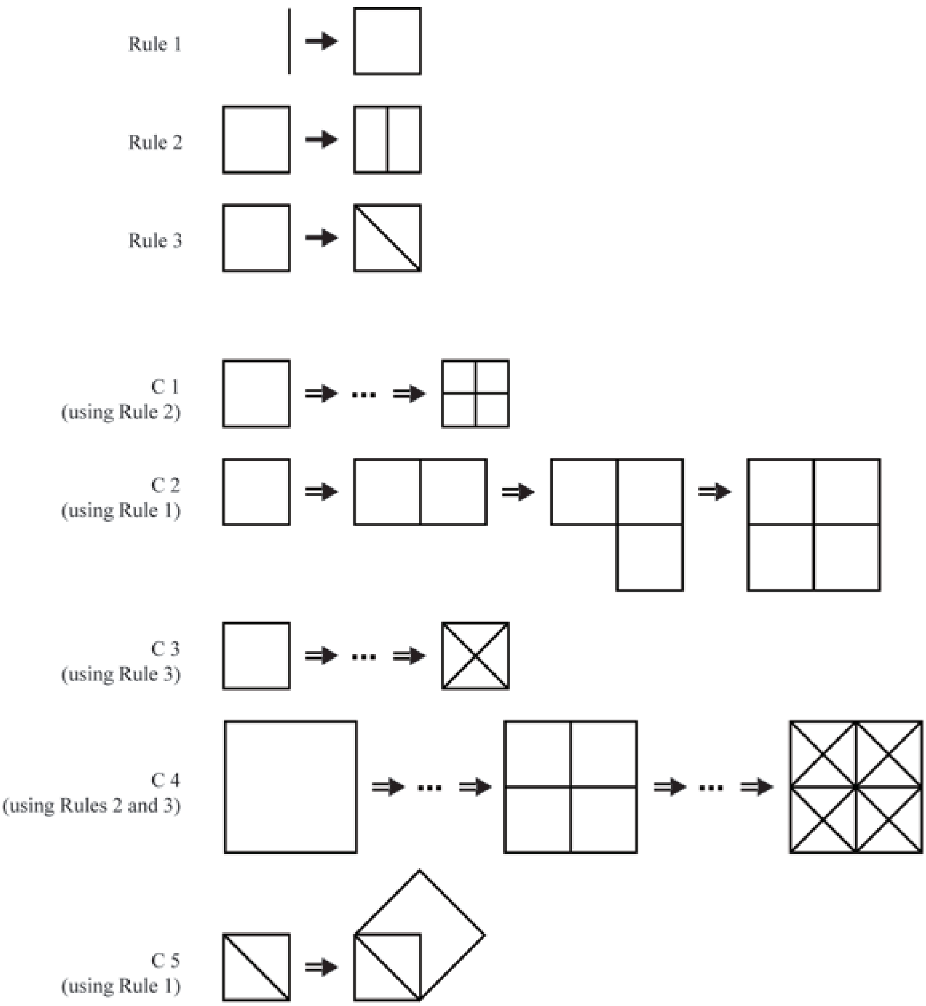


Fig. 1. Meno's three visual rules and different visual computations from the dialogue.

Throughout the dialogue, Socrates directs questions at the boy about spatial relations. Rather than the result, he asks for the means for them and makes the boy trace the course of logic and arrive at a certain level of understanding. The original dialogue does not include any images, but it is assumed that Socrates performs it by depicting the drawings on sand, and many publications have introduced images in line with the text.

The dialogue commences with Socrates asking "Tell me, boy, do you know that a square is like this?" while indicating that it is composed of four equal lines (of 2 ft length) [8] as illustrated in Rule 1 (Fig. 1). The next line of the dialogue "And these ones going through the center are also equal?" [8] corresponds to Rule 2 that illustrates the notion of "center". Rule 2 allows for perceiving "larger and smaller versions of" the square area [8] when applied recursively as expressed in Computation 1. The square area is subsequently divided into two and four equal areas. Socrates ensures that the boy sees this and how the area relates to the sides of the rectangles: "Now, if this side were two feet and this side two feet also, how many feet would the whole be? Or, if this one was two feet but this one only one foot, wouldn't the area have to be two feet taken once? When this one is also two feet, there would be twice two?"[8] Socrates then proceeds to doubling the initial square by adding. Rule 1 is applied consecutively to one "length" of the initial shape resulting in a rectangle as shown in the second step of Computation 2. Socrates introduces learning as recollection each time he reminds the boy of the shape rules defined in previous steps. Iterating Rule 1 in Computation 2 results in a square but one that is too large rather than the double. Towards the end of the dialogue Socrates reveals the solution of the problem at hand: "But we need to produce double. Now isn't there this same line, going from corner to corner, cutting each of these areas in two?" [8] As an alternative to Rule 2, Rule 3 divides the square area into two equal parts with equal lines that go through the center. The iteration of Rule 3 transforms the square into four equal areas as in Computation 3. If it is applied together with Rule 2, the result is a composition of triangles. In a further step in Computation 4, Rule 3 is applied again to result in even more triangles. Socrates then asks for a recollection of Rule 1: "So there will be these four equal lines, enclosing this area?" [8] Computation 5 illustrates how a diagonal from each of the four smaller squares is perceived as the side of the new square. The dialogue ends by Socrates recapitulating the reasoning for how the double area comes into being from the diagonal as now also perceived by Meno: What do you think, Meno? Is there any answer that he gave that was not his own belief? [8]

2 Playing Meno in the Design Studio

In early years of an architecture curriculum, students are engaged in the studios with various abstract tasks to define relations between forms. Sharing a formal vocabulary in discussing these relations facilitates reasoning while learning in dialogues similar to that of *Meno* where the instructor guides students to reflect. We conducted a short experimental study composed of three stages (distributed over the course of three months) with eleven volunteering second-year architecture students at Epoka University in Tirana, Albania. Students had a previous experience on working with shape rules. The dialogue of *Meno* served as a guide to understand the relational nature of design as well as to formalize the students' individual design thinking processes as conducted in the assigned design tasks. The stages of the experiment were as follows:

- **Stage 1** (first day): Students are asked to read the dialogue and interpret the moves with shape rules. They are encouraged to reflect on the dialogue and make use of the rules in a 2D composition. The composition is based on given elements, the sizes of which have to be determined by them. (individual task)
- **Stage 2** (after 3 months): In a role-play, students have to convince a "client" to purchase a 2D composition, produced by one of their fellows in Stage 1. They are encouraged to discuss in a group and verbalize their thoughts on the formal properties of the composition. (2 groups)
- **Stage 3:** Students are asked to work in pairs and make a short design task, by using the same element sizes as in the design they commented on in Stage 3. (4 pairs)

The design briefs of Stage 1 and Stage 3 consist of two-dimensional compositions with the contrast of black and white in a figure-ground relationship. The technique is cutting the black shapes and pasting them on the white background. Shapes are chosen from the dialogue: a square and triangles of two sizes. The set displays proportional relations of the sides (Fig. 2).

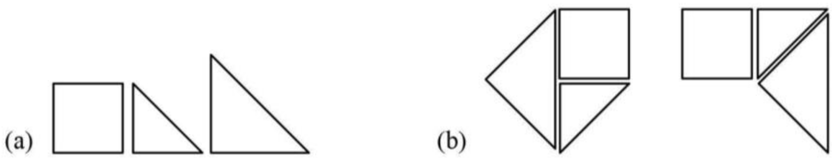


Fig. 2. Shapes (a) the students are asked to work with, are derived from the dialogue. They have a certain proportional relation between their elements, allowing the shapes to be combined as in the two examples illustrated in (b).

2.1 Externalizing an Individual Design Process through Shape Rules

In Stage 1, nine students are asked to read and perform the passage from *Meno*. They are then asked to make a 2D composition as an individual task, by reflecting on the shape transformations and relations passing in the dialogue. Students have to judge and decide on their own about the constant size of the shapes to be used. Similar to the visual reasoning Socrates directs the boy through in the dialogue, visual rules and computations represent students' reasoning processes of the design tasks conducted in studio. Following is our interpretation and externalization of the student S1's design process through shape rules. The interpretation starts with the general organization of the canvas, to proceed with part-to-whole relationships identified in the composition.

Student S1 has organized the whole canvas area to a grid of 7 x 10 units (Fig. 3). The size of the unit is determined by the smallest triangle. In the given shapes, the smaller triangle is half the size of the larger one (Fig. 4). Similar to what Socrates refers to in "And so there would be larger and smaller versions of this area?" [8], shapes appear in different sizes.

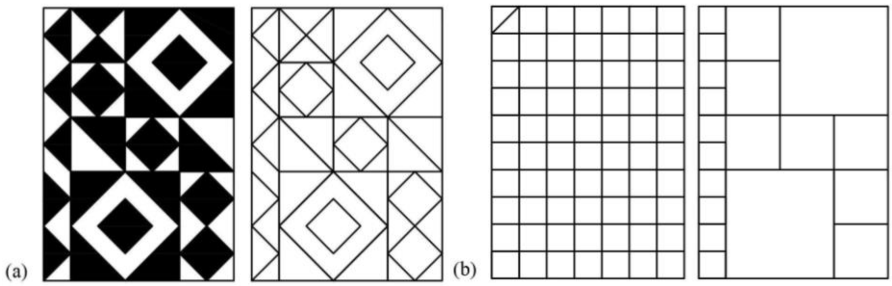


Fig. 3. (a) Studio work of student S1, as done with shapes and tones/weights, and redrawn by taking only the boundaries of the shapes. (b) The underlying grid and its adaptation to S1's work.

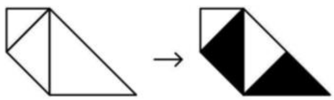


Fig. 4. A shape rule identified in S1's work assigns tones to the shapes, which enables perceiving the large triangle in terms of its halves.

In a further step, the square grid is reinterpreted. S1 has grouped four adjacent squares into a larger square resulting in a combination of 1-unit and 2-unit square systems in the first run, and a combination of 1, 2 and 4-unit square systems in the second run. The grid system developed by the student helps in reading different parts of the composition proportionally related with one another. At a first glance, the individual parts strike attention because S1 has followed the grid rigidly. However, in a second instance, the act of recursively sizing the square elements displays repeating units with some variation.

Visual Relations and Emerging Squares

The process of creating an emergent square out of the constraints of the given elements is achieved by either combining other shapes, or/and by playing with the contrast between figure-ground relationships. Such combinations of shapes lead to squares of varying sizes and orientations (Fig. 5). Although the square is one of the three assigned shapes, it is possible to define squares of varying sizes, similar to what Socrates by relating shapes and enclosing square areas according to Rule 1: *"And so a square has these lines, four of them, all equal?"* [8].

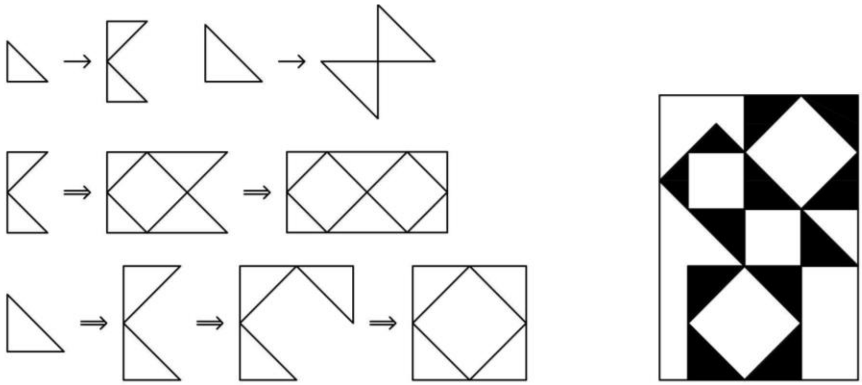


Fig. 5. Student S1 has achieved new squares of varying sizes as highlighted, through possible combinations of the assigned shapes, which enclose square areas.

Another way student S1 has used to define squares is by applying Rule 3 "*And these ones going through the center are also equal?*" [8]. The student has played with the figure-ground relationship achieved when a triangular shape sets a relation with the background. The combination of the figure and the ground make possible perceiving squares of different sizes and orientations as shown in Fig. 6. The student's eye picks up the lines that make a square in many shapes on the canvas.

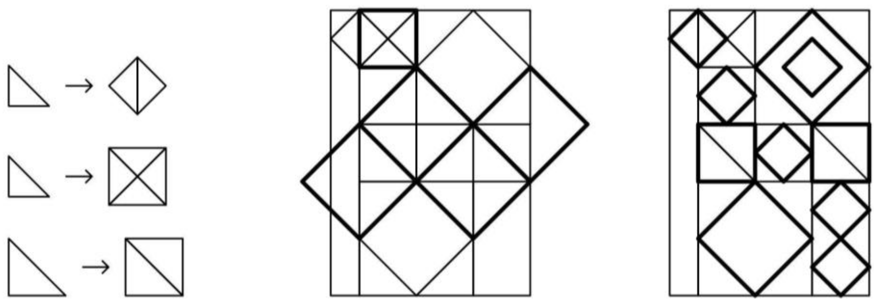


Fig. 6. (a) Referring to Rule 3 of the dialogue, student S1 has proposed different combinations of the given triangular shapes by playing with the figure-ground contrast, resulting in newly perceived square shapes as illustrated in (b).

The motive of the dialogue passing between Socrates and the boy was based on the quest for a square two times larger than a given square. It is possible to perceive this relationship in two different interpretations in the work of student S1. Computation 5 defined towards the end of the dialogue represents two moments: (1) how two squares relate in terms of size, and (2) how two lines relate with each other: the diagonal of the smaller square, becomes the side of the larger square. Starting with the latter, it is possible to perceive this relationship all over the composition. Student S1 has considered the outcome of Computation 5 as a new rule that produces a unit, composed of two overlapping squares, the half of the smaller being embedded in the larger one. The new unit has been used in three different scales, though the student has defined discrete relations between parts, which do not repeat. In Fig. 7 we have identified the possible rules that might have been used by the student to obtain her work. There is a single instance when student S1 has applied Rule 8 recursively twice, resulting in overlapping squares, increasing in size and shifting (as shown in the first row). Another way of interpreting Computation 5 is when the new unit repeats within itself, by increasing in size as well. This shape rule is used in three different scales (Fig. 7).

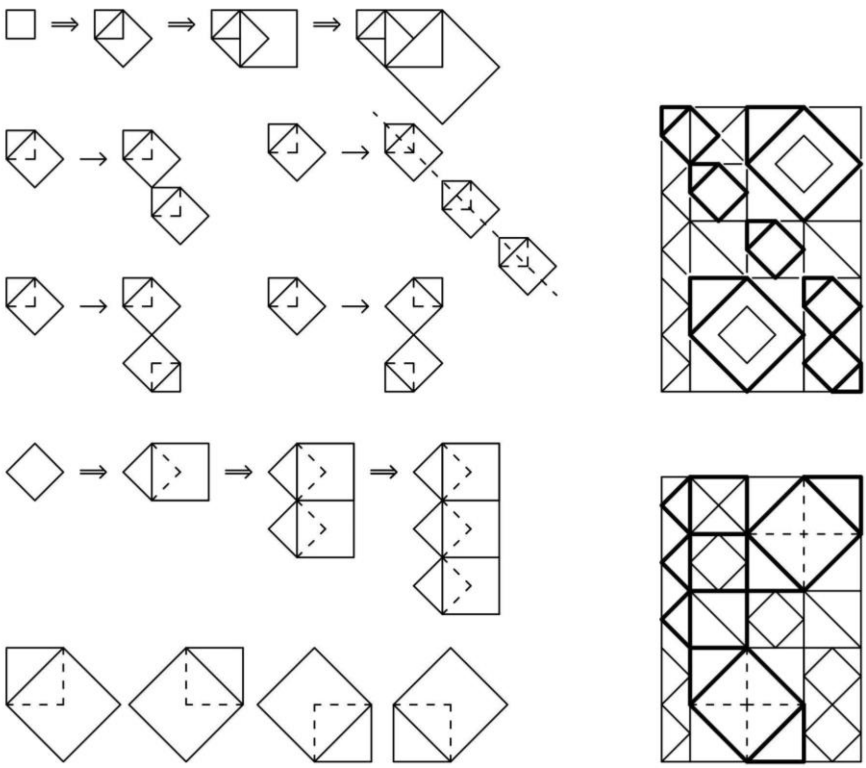


Fig. 7. Possible rules, transformations, and computations that might have been used by the student S1 to obtain her work.

The whole composition is rich in terms of the explorations of the potentials of the shape relations mentioned in the dialogue. It serves also as an example to show how the student is being accountable to herself first, by controlling the spatial relations of a composition through shape rules. In Fig. 7 one may follow how the student is defining relations between shapes, which are not necessarily resulting from the content of dialogue. The same unit is repeating and relating to itself in different ways (Fig. 7): three units are translating along an axis, the units combine in a glide reflection or in double mirror symmetry. Taking in consideration only the outermost boundary of the new unit, the shape repeats along the side three times. However, judging on how student S1 has assigned tones to the parts, it weakens the unity of the three units. Each part stands as a separate exploration.

There is another instance of how she has interpreted Computation 5 in her composition: two squares relate by recursively doubling the size of the square element, and repeating a square within a square (Fig. 8).

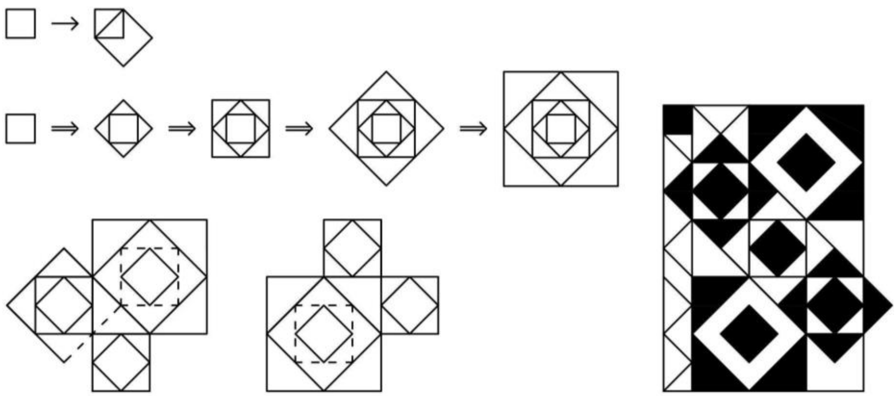


Fig. 8. S1's new rule represents the relation between a square and the one double its size evokes another rule: a square within a larger square of double size. The image to the right shows the iterative use of this shape rule within the composition.

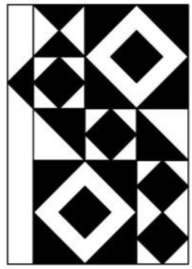
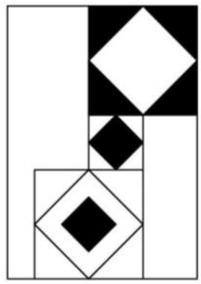
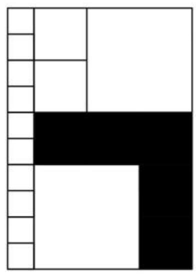
Exemplified in the case of S1, our assumption was that students learnt to apply visual rules and in the applications acknowledged emerging shapes and rules, which they used to consolidate the form relations, they started their explorations with.

2.2 The Issue of Accountability

We conducted two other stages of the experiment three months after Stage 1, with the aim of validating, near the end of the semester, the attitudes that we suppose students have acquired in Stage 1. Students were organized into two groups for Stage 2 and into four pairs for the consecutive Stage 3. The transcribed protocols of the dialogues between students are analyzed to see how students reflect on their fellow student's design process and their attitudes towards using shape rules while talking about form relations. Working in groups/pairs during this experiment was an advantage because students' dialogue and verbalization of the process occurred naturally. Moreover, talking stimulated students to explain their reasoning towards being accountable to their fellow.

The design episode of Stage 2 consisted of a short role-play lasting 5 minutes. Students were expected to convince another student in the role of the "client" to purchase the 2D composition produced in Stage 1 by student S1. They were encouraged to discuss in-group and verbalize their thoughts on the formal properties of the composition. No emphasis was put on using shape rules. The parsing of the protocol for both teams is straightforward, as the experiment was of short duration. We focus our attention only on the units in which students refer to the relations between parts and the referential system inherent in the composition.

Table 1. A selection from the protocols in Stage 2 (coding for the student roles is P: pair, S: student, C: client)

Student	Protocol	Composition
P1S1	[The design has started with small triangles and squares, and by contrast, they form other big squares and triangles] [These two bigger squares relate by the contrast in the smaller pieces]	
P2S1	[The small square is composed by the contrast of white and black triangles] [There are four triangles, which form this big square and this central square we perceive as white area] [… anywhere you look you perceive a square]	
	[We can perceive a square, and another bigger square, scaled one. It has some kind of scaling that we can perceive it easily] [… this big square is formed of four small ones]	
P1S1	[It has some geometrical rules. It has another rule too]	
P2C1	[I am not convinced yet, is there any rule to re-produce it?]	
P1S2	[… this bigger module is repeated two times]	
P2S1	[We have repeating elements, the small squares]	
P2S1	[… the small square is the unit of measurement to place the other pieces together] [… you can see some reference lines, they run diagonally and they help position and form other figures]	
P2S2	[They give reference to create another shape (pointing to the lines running diagonally)]	

One last design task followed in Stage 3. This time the process was reversed: whereas in Stage 2 students were asked to identify relations of a finished design by talking, in Stage 3, students were asked to make use of what they understand as a relation by doing a composition in pair. The design task was similar to what they did in Stage 1, except now the canvas area was smaller. The work duration varied from 4 to 10 minutes. A selection from the protocols of Stage 2 is arranged in Table 1 along with the possible shape rules appertaining to the conversation and of Stage 3 is arranged in Table 2.

Table 2. Selection from protocols in Stage 3

Theme	Student	Protocol
Grid	P3S1	[Let's start with a square so that we form a grid]
	P4S1	[Let's start with this grid over here: there are these diagonal lines but also straight lines]
	P6S1	[I think with these we have like a grid]
Unit	P3S2	[Let's measure the canvas dimension in terms of the chosen square. It is almost 5 to 3 squares]
	P5S1	[I think we should start with one of the pieces for reference]
	P6S1	[I think we can use it as a module]
Defining a square	P5S1	[We want to define by juxtaposition squares via triangles]
	P6S1	[…add a small triangle on the white area so that it forms our unit of measurement, the square]
	P3S1	[…as the sides (of square and small triangle) are equal we can create another square]
	P6S1	[I think we may achieve a bigger square through the combination of these triangles and the small square...my aim is to create a reverse square, this is black and this is white through juxtaposition]
Defining shape relation	P6S1	[We should create a relationship between this square and these small triangles because as we see the side of the triangle is equal to the side of the square]
	P3S1	[It would be better if we use another shape, which takes reference from this diagonal]
		[…we may repeat the large composed square but shifted towards the edge of the paper]
		[I think it should have one-to-whole relationship and I don't see it here]

Some observations related with Stage 2 and Stage 3 of the experiment are as follows:

- Most students arranged the organization according to a grid (3 out of 4 pairs: one of the students in one pair, which apparently did not refer to any specific grid, was not a participant in Stage 1 and had not read the dialogue). Students used the given shapes as the unit of measurement or the unit of the grid, and mentioned this aspect explicitly in the protocols (refer to Table 1).

- Most students defined emergent squares of different sizes based on figure-ground relations between the given shapes and the new emerging ones. (Two of the students who did not participate previously in Stage 2 did not define emergent squares while doing the design task of Stage 3. However they could identify squares of varying sizes verbally.)
- In both cases above, students' experience with the dialogue seems to be influential on how they act in the process.
- During Stage 1, only one student drew shape rules to represent the relations mentioned in the dialogue and how the given shapes relate with each other. Differently most students defined relationships between the given shapes verbally: "this side of the triangle corresponds to this side of the square…" While talking to one another in Stage 3 about rules of relationships, rather than pointing to the shapes or doing the composition tacitly, students made use of rules as a mode of communication in between them. Most students knew how to go on with the composition whenever their fellow stated a rule. When encouraged to talk, it seems that students utilized their knowledge of visual rules.

2.3 A survey on Studio Learning

In comparison to the sequence of studies with second year students, we "played" the Meno for a whole term during Fall 2016, in the foundation design studio consisting of forty first-year architecture students. The objective of the studio was again the integration of shape rules in design studio pedagogy and assessing their role in instigating attitudes of accountability and sharing in collaborative design practices. Differently than the second year students, these students were exposed to visual rules for the first time.

The design assignments are organized in one of the following modes: (1) individual work and (2) pair and share (work in pair). In the first mode, the students are let free to develop their own rules on possible relations, based on the class discussions of formal principles. Visual rules stand for self-imposed constraints defined and followed through by the students for adding to, subtracting from or transforming certain design arrangements (or organizations). The second mode is characterized by exclusive collaborative design processes [13]. Students exchange their designs to interpret through visual rules the possible design decisions taken by their respective fellow. The pair of students works individually by negotiating and by keeping track of rules of relationships used by the fellow. Through this approach, when repeated in a sequence of assignments, students are expected to reflect on the collective and individual process comparatively, in terms of what rules they used and how changed their own rules on the way.

This part reports on the students' feedback collected through an online self-report questionnaire conducted at the end of the semester. Forty first year architecture students were asked to complete the questionnaire, out of which thirty-four submitted. The questionnaire is composed of an open-ended questions part and a multiple-choice part where students respond to each item with a value on a 5-point Likert-type scale, ranging from 1: “not at all true of me” up to 5: “very true of me”.

Table 3. The process of coding and grouping into themes the findings from the open-ended questionnaire.

Theme	Initial coding	Student Report Statements
Accountability	relational design thinking thinking about the consequences of an action know-why reasoning based on arguments	[You need to think about the relations that your design represents, the reason why it was created in that way.] [I used to think that background for example, or the way how we put something somewhere wasn't so important /But now I think and I have learned that even background has its own meaning.] [My way of thinking has changed a lot in terms of “if I do this what's next”] [Whenever I start a design task I always ask myself, why?] [The most valuable aspect of this course are: being reasonable (giving a reason for every action that I do), and being organized.] [Also a very valuable aspect of this course is teaching us that all our proposals should be based on concrete arguments.]
Understanding/Meaning making	visual reasoning reflecting on and learning from own mistakes learning by doing understanding by externalizing the reasoning through visual rules	[I thought that we were doing something meaningless but now I can understand and can read visually what we have done.] [I'm actually really glad that even if my work isn't classified as a good work, I understand my mistakes and how to improve them.] [We can learn by practice and by reflecting on our assignment and our mistakes. By passing time I believe that we will understand what we have learned.] [I used to think there wasn’t needed to explain the rules I have used in my composition/ but now I think that visual rules are important and help us a lot.] [Using visual rules in terms of relationships is a valuable way to understand what we do have in our minds and also to improve ideas that we have for each composition.]
Sharing in Collaborative Practices	learning by sharing with peers developing awareness by comparing with peers reflecting on personal and peer work multiplicity in design ideas	[I consider the work with my friends as a good way to learn more. I can easily compare works with each other. I can easily evaluate my work and reflect on the things I have done and how can I improve it.] [We can learn by practice and by reflecting on our assignment and mistakes. By passing time I believe that we will understand what we have learned.] [Even others' failures and achievements affect my works.] [Working in pair offers more design possibilities.] [Working in groups, which mean more ideas for different assignments.] [I also find precious the fact that we can learn from and with each other because in this way we develop our skills better.]

Referring to the first part of the questionnaire, students were asked to write down their reflections on how their thinking was before and how it has changed after the course. The data analysis procedure consists of identifying statements of the students, which refer to the possible dimensions of attitude construct. In a second step, the statements are grouped according to their commonalities and labeled with an initial coding. The analytical process of the initial coding resulted into separate themes such as: understanding/meaning making, accountability, sharing in collaborative practices, transfer of knowledge, change in perspective and organization/management (skill). We focused only on those categories, which are directly related with the learning objective as stated in this paper. The procedure of identifying codes and assembling them into separate themes is presented in Table 3.

The second part of the questionnaire was an adapted version of the *Learning Strategies Questionnaire* as developed by Pintrich [14]. The original questionnaire uses a social-cognitive view of self-regulated learning. It assumes that learning strategies are not static traits of the learner, rather "learning strategies can be learned and brought under the control of the student" [15].

Table 4. Quantitative data collected from the multiple-choice questionnaire

Learning Strategy	Categories	Mean	Min.	Max.	Sample Question
Resources Management	Effort regulation Peer Learning	3.5/5	1.9/5	4.5/5	[I try to understand the material in this class by making connections between what the instructors comment on my work and the other friends' works.]
Cognitive Strategies	Reflection Elaboration Organization	3.8 /5	1.9/5	5/5	[I reflect while doing a composition by identifying rules of relationships, to make sure I understand what I have done.]
Metacognitive Strategies	Awareness Self-regulation	3.8 /5	2.6/5	4.5/5	[I try to think what I am supposed to learn from this studio rather than just finishing the assignments when studying for this course.]

The objective of the test is to measure the effect of making visual rules part of the students' learning strategies. We adapted it to include terms such as compositions, design works, studio and visual rules, to fit the studio context and the learning material used. It also contained questions regarding students' use of different cognitive and metacognitive strategies as well as student's management of different resources as proposed by Pintrich [14]: cognitive strategies include reflection, elaboration and organization as strategies for selecting and constructing relations among the information to be learned; metacognitive strategies refer to the awareness, and control of cognition which assist the learner in understanding the material at hand, integrate with prior knowledge and continuously adjust one's cognitive activities. Managing a resource, in our case, refers to peers as a source for learning from each other. We analyze the results in terms of the mean, minimum and maximum value within a group (Table 4). The mean value for each group of questions is calculated on individual basis and then as a group.

The data analyzed from the questionnaire provides evidence of a general awareness among students with reference to the pedagogical method followed. Most of them are able to talk about the relational feature of design thinking, similar to the group of students who performed in Stages 1, 2, and 3. However, the students who were exposed for a whole term to visual rules, even if it was their first exposure to them, report a higher level of accountability: "The most valuable aspect of this course is being reasonable (giving a reason for every action that I do)". It is surprising to see that students are able to talk about how their understanding has increased by externalizing their design reasoning through visual rules and reflecting on what they have done. Reflections are often seen as the internal processes of isolated individuals, however students report on developing awareness by comparing and reflecting on their peers. An indispensable part of this awareness forms by sharing. These findings are complemented with the quantitative data collected from the second part of the questionnaire. The mean value for each category indicates that more than the average of the first-year students share a similar awareness towards the contribution of visual rules in their studio learning.

3 Discussion

At the beginning of the paper, we posited a learning objective for design attitudes in foundation studios in using references and establishing relations of various elements of design in connection with accountability. In this paper we focus on accountability as attitude at the individual student's level for answerability for performance during a design process. We directly relate accountability with reasoning during a design process, and how that reasoning is coupled with validating arguments or justifications.

The main theme of the *Meno* dialogue is whether virtue can be taught. The implications of the original text can be manifold. In our reference to it, we focus on the passage where Socrates converses with a boy who in turn comes to understand the Pythagorean theorem through reasoning with shapes drawn on the ground. Drawing parallels to the visual reasoning Socrates directs the boy through, we posit that visual rules and computations represent students' reasoning processes in the studies conducted in the studio and guide them towards an understanding of relational design thinking.

In the studies conducted, the design elements given to the students (Fig. 2) were suggestive of certain form relations. Their sides had the ratio of sqr2:1 just as the lines drawn on the ground in *Meno*. This proportional relation is sought, iterated and utilized in the works of all students who also answered to the directive that they create new squares of different sizes. The process of creating an emergent square out of the constraints of the given elements demanded an understanding of a series of relations between the forms. In a way, each student enacted a version of the dialogue with the boy in *Meno* and the assignment brief served mainly as the guide. The difference in the case of the design studio is that the productions are not the mere revelation of a mathematical relation but multiple instances of the same relation between squares and triangles of different sizes and orientations. The variation that each student creates attests to their understanding of a relation and its variations. The control they may or may not employ in generating these variations is a further step in their understanding of design thinking with references.

The visual rules for each student's work show that the mathematical relation can be represented in different instances. In a pragmatist take, a student can focus on the relations between triangles whereas another one on a pair of triangles or a square, depending on the visual composition they are developing. The common denominator to all rule sets in the study is the emergent square of a new size from the hypotenuse, or the diagonal. This is inherent in the brief and in almost all of the rules. The students already had basic knowledge of visual rules. As they explained their reasoning through visual rules, they were able to compare individuals' different takes on the same phenomenon, and the production of variations. Eight out of ten students based their compositions on grid organization that they varied.

Initial questionnaires showed that the students became aware of not only the relations between shapes and group of shapes in individual works but also in between works across the class. Students were firstly accounting the designs for themselves by formalizing their reasoning based on their individual interpretation of the dialogue. In this way, they could keep track of their actions, reflect on the possible outcomes and understand what is going on. A student commented on this situation by drawing a parallel with *Meno*: " Like *Meno*, we go through a similar thinking process: it starts with a task, followed by an assumption. In later steps you understand that the assumption may not be right and turn back to one previous step. This process repeats until you arrive at a solution".

The accountability makes the process transparent to the fellow students as well, making way to the sharing of knowledge and common understanding in the studio environment. The study shows that in the course of three months, students already develop a practice of using visual rules to communicate design decisions with peers. Nevertheless, the assessment of the contribution of these collective practices on the improvement of personal attitudes requires future analysis conducted over longer periods and in different settings.

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Challenges in Raising Digital Awareness in Architectural Curriculum

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Abstract. The issue of bringing digital technology into architectural education necessitates a paradigmatic change. Achieving this change within a conventional framework presents a number of challenges. However, challenges are presented by the rapid change of technological tools and the frustration of updating the architectural scholarship, especially for schools with a traditional curriculum. This paper focuses on a case study of an update in the architectural curriculum for a CAD course. An approach to understanding the impact of digital tools and methods on digital awareness and a sustainable development of the students and pedagogy are presented, discussed, and demonstrated. Based on questionnaires, the students' learning outcomes are evaluated.

Keywords: Digital Awareness • Architectural Curricula • Learning Outcome

Augmented and Virtual Reality Environment Studies

The Expansion of Virtual Landscape in Digital Games Classification of Virtual Landscapes Through Five principles

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Abstract. This research established classification system which contains five principles and variables to classify the types of the virtual landscape in digital games. The principles of the classification are *Story*, *Space Shape*, *Space and Action Dimension*, *User Complexity* and *Interaction Level*. With this classification system, our research group found the most representative types of virtual landscape in the digital game market through 1996 to 2016. Although mathematically there can be 288 types of virtual landscape, only 68 types have been used in the game market in recent twenty years. Among the 68 types, we defined 3 types of virtual landscape as the most representative types based on the growth curve and a number of cases. Those three representative types of virtual landscapes are *Generating / Face / 3D-3D / Single / Partial*, *Providing / Chain / 3D-3D / Single / Partial* and *Providing / Linear / 2D-2D / Single / Partial*. With the result, the researchers will be able to establish the virtual landscape design framework for the future research.

Keywords: Digital Game, Virtual Landscape, Game Design, Game Classification

1 Introduction

Numerous terms such as virtual landscape, virtual land, cyberspace, digital landscape and so on have been used to describe a virtually designed space or an environment. However, those terms have been used sporadically, without enough attempts of defining them with consensus. Therefore, instead of simply adopting the definition of the *virtual landscape* from previous researches, this paper defines it by comprehending the dictionary definition of both *virtual* and *landscape*. Following the dictionary definitions, the word “virtual” contains ‘temporarily simulated or extended by computer software’ in its definition, and “landscape” means ‘the land’s forms of a region in the aggregate’ [1-2]. In a combination of those two definitions, a *virtual landscape* means ‘landforms and components of a region in aggregate, that are temporarily simulated or extended by computer software.’ Unlike any other media describing an unreal space such as novel, painting and stage design, a virtual landscape can drive interactive action to the player. Because of this unique characteristic, designing virtual landscape requires designers to understand "space." Painting a picturesque drawing or writing an article describing utopia doesn't require the artists or authors to consider the interactive activity between the user and environment. Unlike those media such as painting and so on, designing a virtual landscape, just like designing space, asks skills to design the space considering interactions between users and the space itself. However, yet it is impossible to find any standard and specific methodology nor procedure to design a virtual landscape so far. Numerous studies and researches have been covering only technical ways to develop backgrounds of games; none of them suggested the meaningful design method of virtual landscapes. As the virtual landscape shares its characteristic of interactive space with the *real space*, it is convincing to adopt the design methodology or procedure from real space to virtual landscape. Numerous area of studies such as landscape architecture, architecture, and urban planning have a deep understanding of the interactive space and retained several confirmed design methodologies. If it is possible to adopt those methodologies successfully to the area of virtual landscape, new and efficient way to design the virtual landscape can be rise.

Moreover, as the complexity of virtual landscapes in video games increases, a need for a unified design methodology rises. Rollings & Morris (2004) mentioned that if the developing game requires a certain amount of assets, an unified design methodology is needed [3]. Unlike the conventional design methodologies for real space, the new virtual design methodologies differ due to diverse and various methods of interactivity regarding the spaces. Which means, though there are several different conditions such as weather, the height of the region, every real space shares same condition of dimension, laws of physic and time flow. Not like those real spaces, virtual landscapes in various digital games has their own characteristics of space. Different gravity, various dimensions, and other natural conditions. Therefore, a modular design methodology is required to adjust and adapt to the various types of virtual landscapes; an effective classification system will be needed to establish such a modular design methodology.

Furthermore, based on such classification system, the goal is to seek and verify a proper design methodology for specific types of virtual landscape. Also, analyzing the data in chronological order, the research will allow projecting the upcoming types of virtual landscapes in order to establish corresponding design methodologies. For the last, by combining the principles of virtual landscapes, designers will be able to design virtual landscapes those have never been developed so far.

2 Methodology

In order to understand the landscape in digital games, this research extracted design requirements of the virtual landscapes, built them as principles and verified the principles through analyzing the landscapes of existing digital games. The first step to do so was the establishment of the classification principles. Through the literature reviews of game-design books, we extracted the five mandatory principles of virtual landscape design. On the second step, our team conducted a validity test of established classification principles. Lastly, this paper chronologically analyzed virtual landscapes of 385 digital games with those five principles.

2.1 Establishment of the Classification Principles

Establishing the classification principles was the first step of this paper. As we mentioned previously, clear and accurate principles are required to figure out the types of virtual landscapes in digital games. In order to stand those practical principles, we tried to verify the requirements of designing digital games landscape through literature review. Our research team thoroughly researched existing books and papers concerning *video game design* to extract the mandatory elements of virtual landscapes in digital games. Five principles were derived as the most commonly and importantly discussed in previous researchers or designers in the field of landscape design in digital games. In other words, the frequency of the appearance of design requirements – here called the principles – represents their importance.

As these principles are the most important and considerable for the designers, at the future research, design methodology for the landscape design will be established based on these five elements.

2.2 Examination of Established Classification Principles

In order to verify the acquired five different principles of virtual landscapes, this research built a database of 19,752 items. Our research team gathered those digital games from two major platforms; 7,229 games from the PC game platform STEAM (http://store.steampowered.com), and 12,523 games from the console game platform Play Station 1-4 (Table 1).

Afterward, fifty games were randomly sampled from each platform, and a classification test was conducted for the total of 100 digital games. Two researchers were asked to categorize the virtual landscape from the games into five different categories. The number of unable-to-be-classified games would reflect the validity of the classification principles.

Table 1. Description of the database our experiment

Platform	Market	Number of games
PC	STEAM	7,229
Console	Play Station 1,2,3 and 4	12,523

2.3 Chronological Analyzation of the Virtual Landscape Types in Games

Based on the five verified classification principles, virtual landscapes shown in digital games in recent 20 years, from 1996 to 2016, was tested. Digital games were extracted from the website Game Rankings (www.gamerankings.com) where games are scored based on review scores from both offline and online sources. Game Rankings, owned by CBS Interactive, has rated more than 14,500 games through the calculation of the review sites that are determined reliable. Three hundred eighty-five games were extracted based on the most highly rated by Game Rankings in recent 20 years and was tagged by the team member for the types of spatial conditions. The tagging process was revised twice by our research team member, and the data was extracted enough to be analyzed. The extracted games mean that they were popular and received the most reviews in each era.

3 Acquisition of Five Principles

Based on the information from twelve books, there existed five different elements that compose various forms of virtual landscapes: *Story*, *Space shape*, *Space and action dimension*, *User complexity*, and *Interaction level*. Such principles can be described as in Table 2.

Table 2. Principles of virtual landscape design mentioned in books

	Story	**Space Shape**	**Space and Action Dimension**	**User Complexity**	**Interaction Level**
Fullerton (2003) [5]	O	O	O	O	-
Rogers (2014) [6]	O	O	-	O	O
Schell (2014) [7]	O	O	-	O	-
Crawford (2003) [8]	O	-	-	O	O
Apperley (2006) [9]	O	-	-	-	O
Ervin (2001) [10]	-	-	O	-	O
Kalay & Marx (2005) [11]	-	-	O	-	-
Lecky-Thompson (2003) [12]	O	-	-	-	-
Rollings & Morris (2003) [13]	O	O	O	O	O
Adams & Blandford (2003) [14]	O	O	O	O	O
Kim et al. (2013) [15]	O	-	-	O	-
Jang (2015) [16]	-	-	O	-	-

Each reference described the importance of each principles to design the virtual landscape. Numerous authors of the books considering game design have been continuously mentioning and emphasizing the importance of a *story* in game design. For example, Fullerton mentioned the story is one of the most important resources one should consider before designing the digital game and its environment [5]. Rogers, Schell, Crawford, Lecky-Thompson, and Apperley also made the same statement that story requires the deepest consideration when one try to design the terrain at the digital games [6-8], [9], [12]. Rollings & Morris mentioned that at the very early time in video game industry, the game designers were separated into two factions [13]. One insisted the game story is the most important in digital game design and the other insisted the opinion that story never effects to the player and it is not needed at all. However, with the success of game titled 'DOOM (1993)', designers realized that story is the key elements in a digital game design [13]. Also, Schell pointed out if one can design the story of the game with a structure of ludology by using the plot point, the quality of games will be raised [8]. Adam & Blandford and Kim also described the story is a counter resource to consider at game design [14-15].

Space shape was also one of the key factors when designing a virtual landscape. Fullerton used the term of 'edge' to classify the shape of spaces [5]. By reading the edge of space, they can be classified as linear, agent, or network (p.177). Rogers simply classified the shape of a 3D game to corridor and island (p.267). Schell classified shape of space in five conditions, *linear*, *grid*, *web*, *spot* and *face* [7]. Rollings & Morris spared a lot of pages on space shapes. They questioned whether the typical side-scroll game is linear because of the degree of freedom to the players [13]. They mentioned sports games are good examples for the *spot* typed space (p.380). Also, they suggested several design tips design the *linear* space in a digital game more efficiently.

Space and action dimension was also described essentially in those books. Fullerton tried to classify the dimension of the game by the types of viewpoints [5, p.307]. Ervin, who approaches the realistic 3D simulation games in his writing, mentioned that the dimension in games is crucial when designing digital games. Kalay & Marx wrote the importance of dimension in digital games and tried to classify them with their style and flexibility [11]. Rolling & Morris classified the space in digital games with 'dimension,' 'edges' and 'axis and the time flow' [13]. Jang (2015) also described the importance of dimension in digital game numerous times. As this principle decides the movement of the character and the viewpoint and effects to the whole design process, one should consider deep enough before start designing (p.29).

Fullerton, Crawford, and Rogers tried to classify the *user complexity* with the behavior of the user. Rodger classified those behaviors to competition and cooperation [6]. Also, he mentioned that if one game contains a certain amount of players in one place, the designer should consider about the housing and the habitat space (p.467). Schell suggested designing the social community and its territory space based on the sociology and anthropology from the real world [7].

For the *interaction level*, Roger mentioned that the medium *video game* had been developed its interaction level from an island to sandbox as a metaphor [6]. Apperley described the interaction level between the environment and the user in detail [9]. He tried to classify the interaction level of the virtual landscape in three levels. At the first level, the user remains as an observer to the world and can't cause any interactions. Second, like labyrinth and maze, users are trapped in the sealed space and only can interact with limited level. For the last level, users can interact with space freely [9]. He also mentioned that a virtual landscape is a scheme to manipulate the user with interaction (p. 168).

With those researches, we could verify those five principles are the most important principles when one is designing the virtual landscape in digital games. However, those references only suggested principles very ambiguously, and it is needed to be organized with more precise details. Therefore we arranged the design variables of each principle (Table 3).

Table 3. The five principles and their variables

Principle	**Story**	**Space Shape**	**Space and Action Dimension**	**User Complexity**	**Interaction Level**
Variable	Representing Generating	Spot Linear Chain Face	2D-2D 2D-3D 3D-2D 3D-3D	Single Group Massive	None Partial All

First, "Story" is a component of a virtual landscape that provides a story to a character in a narrative manner. Stories in digital games can be categorized into two types: *representing* and *generating*. *Representing* story means that the developer actively provides the designed story to the users, while a *generating* story only provides an environment to the user, and the user has to generate stories by their own. Depending on rather the game contains the fixed ending or not; it can be classified as a *Representing* or *Generating* story. As the *Representing* contains a strong story line, it has a fixed ending with it. However, the *Generating* doesn't have any certain ending nor fixed one. For example, until the end of the game player can't know how the sports game ends.

"Space Shape" means structures of implemented virtual landscape. The structures can be divided into *spot*, *linear*, *chain* and *face*. This later determines the overall structure and masterplan of the form while designing the virtual landscape. Each condition can be determined by the edge of the space and the flexibility of player's direction. *Spot* contains fixed edge of the space and free movement of the players. It means that the game players can move freely in the limited area. A *Linear* shaped space contains fixed edge of the space with forced movement to the players. Players are forced to move in certain directions in a limited space. Super Mario Bros. (1985) is a case with *linear* space type. The player only can manipulate the character in a fixed direction, left to right. A *Chain*-shaped space is a combination between *Spot* and *Linear*; players can run both activities of spot and linear in order. Technically, a *Face* shaped space has a boundary of the game playing space. However, players cannot recognize the boundaries that limit the game space. Also, players do not have any forced direction in a *Face*-featured space.

"Space Dimension" and "Action Dimension" means corresponding implemented dimensions and movement dimensions required for the user to control the character within the space. It can be divided into four types: *2D-2D*, *2D-3D*, *3D-2D*, *3D-3D*. These elements determine the vertical resource factor for the future design methodology implementations. If the environment at the game requires two axes (XY) for the designer to build and requires 2 axes (XY) for the players to play, it will be categorized as *2D-2D*. If the game contains more than 2 layers of 2 axes filed together and requires 2 axes for the players (XY), that game can be categorized as *2D-3D*. The game with 3 axes (XYZ) for the designers to build the game and 2 axes (XY) for the players to manipulate will be categorized as *3D-2D*. For the last, the game with 3 axes (XYZ) for the design and 3 axes (XYZ) for the manipulation will be defined as *3D-3D*.

"User Complexity" means the simultaneous occupancy of the users within the space. This can be separated into *single*, *group* and *massive*, and will determine the feasibility of the public space within the virtual landscape design. The *Single* game runs with single player only and doesn't need designers to consider about applying any community or public space. If the game holds more than two players sharing same or facing goals, it can be categorized as *Group*. In this case, designers should consider how to apply public and community space in the design. The game runs by more than two groups of players and holding various goals in the game is *Massive*. As the *Massive* contains a large number of players at one time, designers need to consider about community, public and even habitat space to design.

Lastly, the "interaction level" means the rate of interaction between the virtual landscape and the user. Classified into *none*, *partial*, and *all*, this element forms the interaction layer for future design methodology. *None* is a type player can't cause any interaction with environment resources. In this type, the environment resources are covered with so-called the 'invisible wall' and only works as a boundary of void space. If the player can interact with only designed resources, is *Partial*. To design this type of game, designers need to consider about the characteristic and depth of interaction on each environment resources. Players can interact with every environment resources in type *All*. In this case, the game is built in particle level which means the world is based on unified units and designers are building the environment by filing them. In this case, designers need to consider the condition and spread of particles in the world.

These five elements will set-up for an overall design approach for the future virtual landscapes. Future developing design methodology will be based on the Layer-cake method by Ian L. McHarg from the area of landscape architecture [17]. Each of the five principles will be adopted as layers to fabricate the masterplan. Following Table 4 contains summarized descriptions about the principles and variables conditions.

Table 4. Classification Conditions

Principles	Variables	Description
Story	Representing	Player follows the given story line (close ending).
	Generating	Player generates a new story (open ending).
Space Shape	Spot	Player freely moves around in a limited space that has boundaries.
	Linear	Player is guided to a move toward certain direction in a limited space.
	Chain	Combination of Spot and Linear. The player is allowed to move freely in a spotted space, and moves to the next

		spotted space to play further.
	Face	Unlimited space with player's free movement
Space and Action Dimension	2D-2D	Requires two axises (XY) to build the world, and requires two axises (XY) to the players to play the game
	2D-3D	Requires 2 axes (XY) to build the world and requires more than 2 layers of 2 axes (XY) to the players to play the game
	3D-2D	Requires 3 axes (XYZ) to build the world and requires 2 axes (XY) to the players to play the game
	3D-3D	Requires 3 axes (XYZ) to build the world and requires 3 axes (XYZ) to the players to play the game
User Complexity	Single	Player is the only one in the game (a single player at a time)
	Group	More than two players play the game together, sharing same goals.
	Massive	More than two groups of numerous players play the game simultaneously, with various goals.
Interaction Level	None	No interaction between the player and the environment except as the boundary of a void space
	Partial	Player can interact with designed limited environment resources in the space
	All	Player can interact with every environment resources in the space

4 Validity of the Classification Principles

The validity of the proposed classification principles can be verified according to the result that every one-hundred-randomly-selected-games were able to be classified without failure. The details are in Table 5.

As shown in the table, none of the cases was classified as 'etc.' This means every sample – the games randomly retrieved from STEAM and the series of Play Stations – was able to be classified with those five principles and their variables. This fact that there was no exception when classifying those games with our five principles and their variables shows the effectiveness of five principles we suggested to classify the virtual landscape in digital games. Furthermore, these classification principles classify digital games without any overlap, therefore it will be possible to classify digital games without any confusions in the future research.

Table 5. Results of the classification test

Principles	Variables	Percentage (%)
Story	Generating	47
	Representing	53
	etc	0 *

Space Shape	Spot	49
	Linear	30
	Chain	12
	Face	9
	etc	0 *
Space and Action Dimension	3D-2D	41
	2D-2D	41
	3D-3D	18
	2D-3D	0
	etc	0 *
User Complexity	Single	75
	Group	24
	Massive	1
	etc.	0 *
Interaction Level	Partial	51
	None	44
	All	5
	etc.	0 *

* No overlap among variables of each principle

5 Chronological Analysis of Virtual Landscapes

5.1 Chronological Analysis of Five Principles

Fig. 1. shows the trend of the *story* in virtual landscapes represented in video games in recent 20 years. Thanks to the technical advance, games could carry rich data, and therefore the game industry built *story-representing* game intensely during 2007 to 2014. However, recently two sorts of story – *generating* and *representing* – are both equally balancing together with stabilized market needs. This tells the users in digital games are equalizing balance, and future design methodology for the virtual landscape should be able to consider both of types together.

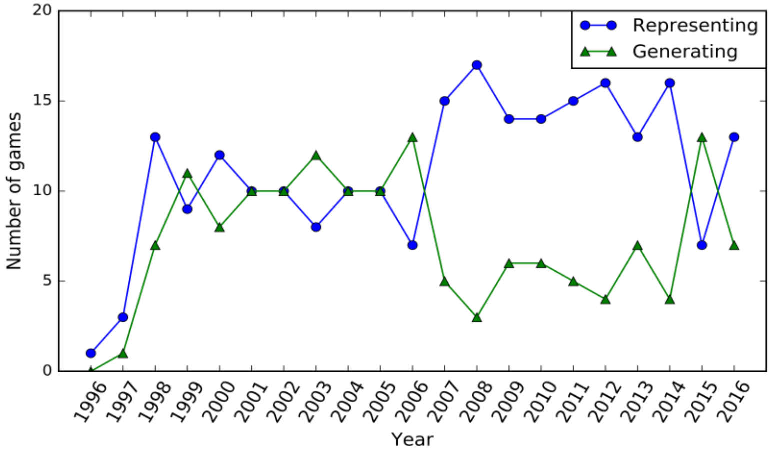

Fig. 1. *Story* in video games

Changes in *space shape* from 1996 to September of 2016 are shown in Fig. 2. Compared to stark differences of the popularity of *space shapes* in the 1990s, the types of *space shapes* in early 2000s seem to be distributed because of a limitation of the hardware; developers were only able to construct spot typed virtual landscape in the early period. With technical advance, spot typed virtual landscape in decrease and facial space has been raised. This phenomenon shows the complexity of virtual landscape in future will be raised and will require a more systematic approach to design them.

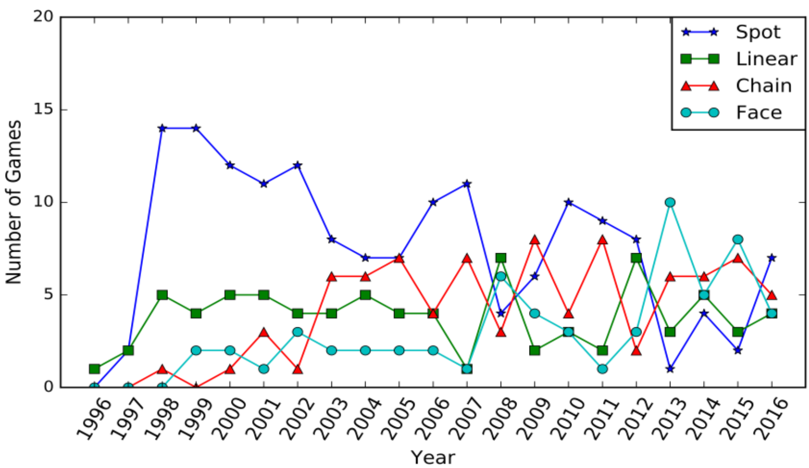

Fig. 2. *Space Shape* in video games

In terms of *space and action dimension* in a video game (Fig. 3.), the needs for the 3D-3D game always has been high on the market through the time. On the other hand, the amount of 3D-2D game has been decreased with time, and it is possible to think those type has been evolved to 3D-3D type.

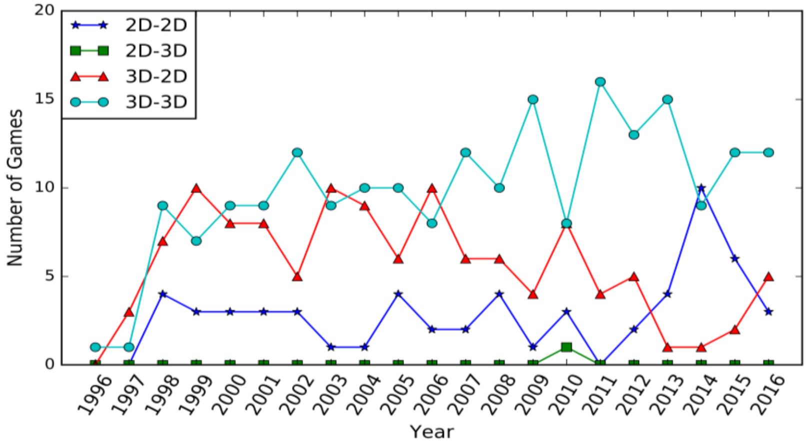

Fig. 3. *Space and Action Dimension* in video games

Fig. 4. described the trend of *user complexity* in video games. Though with advancing network technology through the early 2000s, still most of the digital games are in single play. However, it is true that single games are decreasing and massive, group games are rising. Which means in future, designers need to consider how to add the complicated social spaces in the virtual landscape.

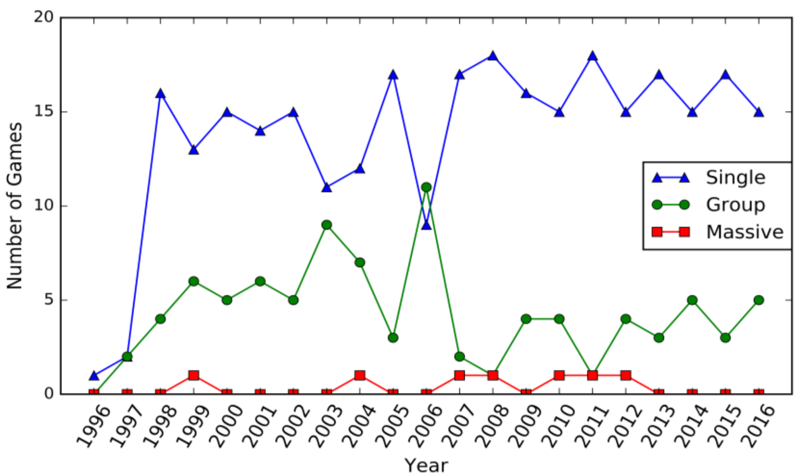

Fig. 4. *User Complexity* in video games

The *interaction level* shows clear evidence of technical advance (Fig. 5.). With technical advance, *interaction level* keeps rising, and non-interaction leveled games are on a consistent downtrend. However, still, it is a burden to interact with every aspect of the virtual landscape, type all is still in low level. If the hardware of computer develops at a high level in future and able to describe the particle based model, not the rendered model, it will be possible to generate all interactive virtual landscape.

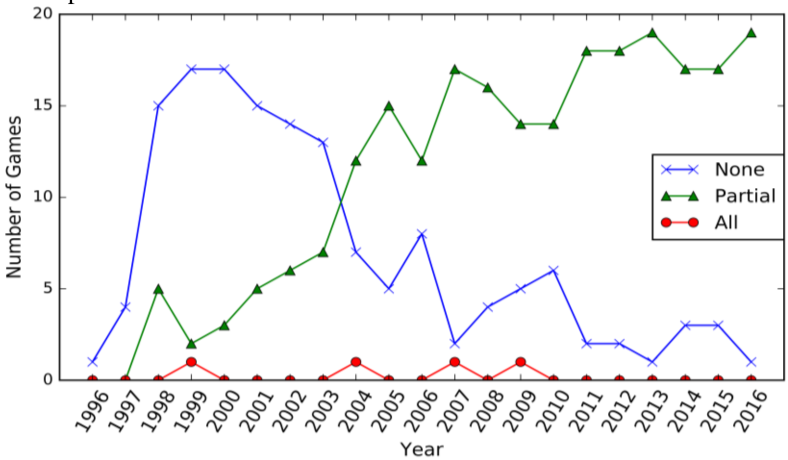

Fig. 5. *Interaction Level* in video games

5.2 Trend of Virtual Landscapes Types

Theoretically, based on the five classification principles, 288 spatial types of virtual landscapes can be created in games. However, only 68 variations of those have been appearing repetitively from the 385 games released within last twenty years. The ten most commonly appearing combination addressed in as chronological manner are shown in Fig. 6.

Through the figure, it is possible to read the trend of the virtual landscape through time in the market and also to find the representative types of virtual landscape. There have been only five to seven types of virtual landscape commonly used in the market through the time since 1998. This phenomenon implies that the game company and the designers prefer to use a qualified type of virtual landscape only. Also, this implies that various types of the virtual landscape have not been introduced to the market and there is rich potential to develop in the near future.

List on the right in Fig. 6. contains the most common types of virtual landscape in the order. But the list only delivers the sum of all cases and needed to be analyzed with time flow. For example, the first case; *Representing/Chain/3D-3D/Single/Partial* has the largest amount of all but is decreasing dramatically since 2013. On the other hand, *Generating/Chain/3D-3D/Single/Partial* type is growing its size aggressively and indicates the potential in the near future. For the last, the case *Providing/Linear/2D-2D/Single/Partial* never showed any dynamic growth but also the demand for this type in the market never died. The condition for this type can be said as a steady seller.

One of the most interesting part with the ratio between each type is that after 2015 the ratio is becoming stabilized to an equal amount. This movement shows the demand of market is bringing adhesion and need to consider those cases as representative types of virtual landscape in the near future.

5.3 Three Representative Types

This research claims that the three representative types of virtual landscape are "*Generating / Face / 3D-3D / Single / Partial,*" "*Providing / Chain / 3D-3D / Single / Partial,*" and "*Providing / Linear / 2D-2D / Single / Partial*". Table 5 shows the characteristics of those three types of virtual landscape in digital games. Because of type 1, which is "*Generating / Face / 3D-3D / Single / Partial*", is showing the most aggressive growth among the others, deserved to be a representative type. The type 2 (*Providing / Chain / 3D-3D / Single / Partial*), which is in a downtrend, still has the biggest volume of all and could be a representative type. For the last, *Providing / Linear / 2D-2D / Single / Partial* (type 3) has a steady need for the market and could be one of the representative types of virtual landscape.

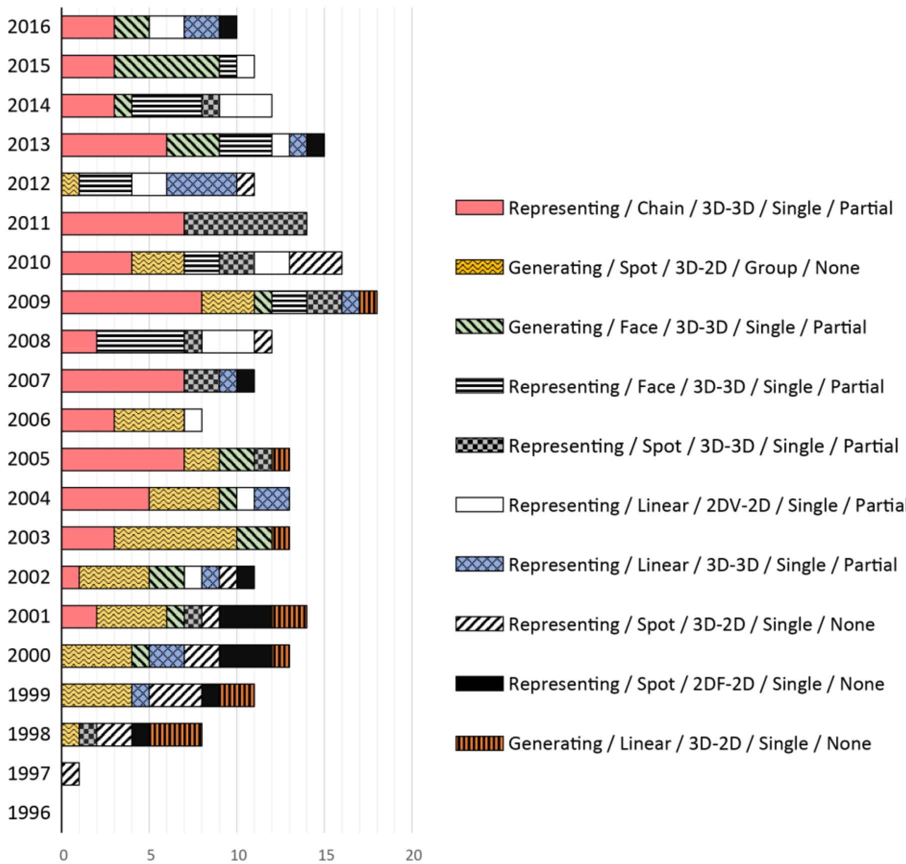

Fig. 6. Trend of 10 types of the virtual landscape in video games

Table 4. Representative types of virtual landscape in digital games

	Story	Space Shape	Space and Action Dimension	User Complexity	Interaction Level
Type 1	*Generating*	*Face*	*3D-3D*	*Single*	*Partial*
Type 2	*Providing*	*Chain*	*3D-3D*	*Single*	*Partial*
Type 3	*Providing*	*Linear*	*2D-2D*	*Single*	*Partial*

There are numerous examples of digital games in each type. For example, GTA 5 (Rockstar Games, 2013) is a good example of type 1 (Fig. 7). This game, which became a multi-playable online game with the additional upgrade and downloadable contents, was originally designed as a single player.

Story	Space Shape	Space and Action Dimension	User Complexity	Interaction Level
Generating	*Face*	*3D-3D*	*Single*	*Partial*

Fig. 7. GTA 5 (2013) as an example of Type 1

The player in such condition of virtual landscape, they can make their own game story with environments resource on the terrain freely and can access wherever they want. In GTA 5, the player can hang freely around the virtually designed city and is capable of doing based on the designed interactive objects and characters. With the advance of the computer, this type of virtual landscape is evolving network based multi-playable virtual landscape. Shortly, this type of virtual landscape will be replaced by "*Generating /Face /3D-3D /Massive /Partial*" type.

For an example of type 2 (*Providing / Chain / 3D-3D / Single / Partial*), Naughty dog designed 'Last of us' on 2013 with Play station 3 platform. This game carries a deep story through the game and having typical chain shaped space with it. With several updates and downloadable contents this game became an online playable multi-game, however, was originally designed for a single player. With a partially interactive interaction, the user can only manipulate designed objects on the virtual landscape. As this type of virtual landscape is story based and requires many props and actors to be placed in order, a precise design methodology is needed.

Virtual landscapes of both type 1 (*Generating* / *Face* / *3D-3D* / *Single* / *Partial*) and type 2 (*Providing* / *Chain* / *3D-3D* / *Single* / *Partial*) require various resources to the designers to consider in the design process. Unlike designing a landscape architectural plan in the real world based on the naturally existing environment, game designers have to consider about every resource in the terrain to design these virtual landscapes. In other words, naturally-created geographical features such as hills, cliffs, valleys, and even the law of physics such as gravity should be planned in designing virtual landscapes. The game designers even need to plan the brightness of the sun, sounds of rain drops and the pattern of the constellation at the night sky. As those kinds of works are both delicate and time-consuming, only few game design companies with enough manpower can develop the game.

Story	Space Shape	Space and Action Dimension	User Complexity	Interaction Level
Providing	*Chain*	*3D-3D*	*Single*	*Partial*

Fig. 7. Last of us (2013) as an example of Type

Providing/Linear/2D-2D/Single/Partial (type 3) (Fig.8) is one of the oldest types of virtual landscape in digital game history, and it has never vanished during the past 30 years. Like a steady selling books, this type of virtual landscape always had a certain amount of market looking for it. Super Mario Bros. (Nintendo, 1985) is a good example of this type of virtual landscape. The virtual landscape of type 3 contains a simple combination of environment resources. Therefore, it doesn't ask for advanced and delicate consideration to the designers compared to type 1 and 2. However, as it is a linear space and rhythmical flow is required, design methodology based on the human cognition from the field of landscape architecture can be adopted in future research.

Through the examples of the three representative types of virtual landscape, it was possible to find the reason to establish the virtual landscape design framework for the future research. The three types of virtual landscapes had different design requirements depending on their variables of each 5 principles. Therefore, this paper suggests that the elements of each variable should be defined to form a firm design framework as our future work. Moreover, we expect the framework that includes the 5 principles, their variables, and related landscape elements to be a concrete guideline for game designers to plan the exhaustive virtual landscapes.

Story	Space Shape	Space and Action Dimension	User Complexity	Interaction Level
Providing	*Linear*	*2D-2D*	*Single*	*Partial*

Fig. 8. Super Mario Bros. (1985) as an example of Type 3

6 Conclusion

The interesting fact is that, during the mid-2000s, as the GPU Fill rate speed increased and the 3D rendering technologies advanced, the advanced visual effect played the most important role to lure the market, providing only a very specific type of spaces. This, however, changed as time passes by; now the various types of spaces are gradually balancing evenly. This means that each type of spaces has established markets of their own, and is now stabilized. Such development of various types of spaces reminisced when post-modernism was accepted by the modern art and architecture. This raises the needs for a balanced establishment of design methodology for future virtual landscape.

The results of this research are expected to provide insights in detail to the game designers and other researchers as follows. First of all, this classification methodology provides the main structure for construction of systematic design method of a virtual landscape in digital games. By combining the classification principles, game designers will be able to clarify the detailed characteristic of a landscape in their designing digital games. With an understanding of their landscape, they can comprehend which design methodology is needed to run the systematic design process. For the future research of this study, the research of adopting the design methodology from the area of architecture, landscape architecture, and city planning to the digital game will be run based on this classification research.

Secondly, the designers could develop digital games in diverse and novel forms by simply making combinations of variables from our classification method. As this research refers, even though 288 types of digital games are possible according to the classification theory, there have been only 68 types of digital games developed since today. In other words, we can insist that more than 200 types of games are yet developed. This approach of systematic classification method, our research team expect our method to expand the scope of novel digital games.

Finally, we expect our classification method, elements as variables and game types derived from the method to be referred by further researches. According to Apperley [9, p.154], a classification of computer games can be based on how they represent – or, perhaps, implement – space. It means that the classification of space and landscape in the digital game can directly lead us to the classification of the digital game itself. Since now the classification of digital games has been unclear and inconsistent by utilizing keywords without enough consideration of certain standards. The lack of systematic approach toward elements and types of digital games has been an obstacle to many researchers to study digital games. Therefore, this research provides the possibility of systematic classification of digital games relatively clear and rigorous enough to be used in diverse research of digital games.

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Lincoln Cathedral Interactive Virtual Reality Exhibition

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Abstract. This paper demonstrates a workflow converting terrestrial laser scan (TLS) data into an interactive virtual reality (VR) platform. A VR exhibition prototype of Lincoln Cathedral was created to validate the established workflow in terms of the technical and visual performance, usability, and functionality. It combined TLS data and storytelling to produce a shareable platform, inviting opportunities for public engagement, and to facilitate custodians with the tools to maintain the building's heritage. The paper discusses the use of open source software and suggests future work.

Keywords: 3D Laser Scan, Virtual Reality, User Experience, Building Heritage

1 Introduction

Lincoln Cathedral is a fine example of Early English Gothic style architecture; it displays a wealth of architectural craftsmanship, with historical significance embedded in its maze of linked and layered spaces. It survived a fire (1141) and an earthquake (1185) and was the tallest building in the world until 1549. The cathedral has, on average, four million visitors each year and it spends approximately 1.5 million pounds on annual repairs and restoration of the building's fabric [1]. A recent project to restore the Bishop's Eye window cost £400,000 alone. Many spaces inside the cathedral have restricted access due to narrow staircases, or due to a need to maintain the original building fabric. One way to increase audience participation at Lincoln Cathedral is to provide virtual access to such areas.

Over the past decade virtual 3D reconstruction and visualisation of historical buildings and heritage sites has become an efficient tool for analysing scan data, enhancing visitor experience, and contributing to the restoration of building heritage. Examples of virtual exhibitions include Roman heritage exhibitions [2] and Bronze Age exhibition at the British museum [3], or visualisation of industrial structure [4]. All utilise visualisation in the form of predetermined flyovers, or walkthroughs. Unfortunately, both forms of delivery rely on display screens and create a passive experience for the users, limiting their actions and experience.

This paper, instead, suggests an immersive virtual reality approach, combined with gamification, allowing users to fully experience virtual reality (VR) of a historical building.

Such virtual reconstructions have been enabled by improvements in terrestrial laser scanning (TLS) technology, including a large reduction in its cost over the last decade. TLS uses a low power laser to collect large 3D spatial point cloud data with millimetre precision; for example, Leica P20 collects up to a million points per second, each with 3mm accuracy. This technology allows for relatively quick conversion of real world objects into virtual space [4]. This capacity is deployed in projects such as Scottish Ten or Arc/k aimed at creating digital storage of all historically significant structures.

This paper aims to evaluate a new method for interpreting large scan data into a user- friendly platform, by utilising open-source and low-cost software. A prototype for an interactive virtual reality exhibition of Lincoln Cathedral was created, combining TLS data and storytelling to produce a shareable platform, inviting opportunities for public engagement. The method used, and the VR exhibition prototype produced, is evaluated in terms of technical and visual performance, usability, and functionality.

2 Virtual Reality Software and Devices

As one of the leading game making tools on the market, Unreal Engine 4 (UE4) was used as the main tool to develop the VR prototype in this research. It contains many advanced techniques and functions for creating interactive applications with high visual quality. The built-in visual programming tool, Blue Print, is easier to be handle compared with other gaming software on the market. For new users, its intuitive interface aids the integration of interactive functions, from grabbing and operating exhibits to teleporting the user between virtual scenes. The advanced material system and performance optimisation tools boost the high visual quality while saving the PC performance. Moreover, UE4 is an open source software and free with no condition in the heritage and architecture usage, which means the outcomes using UE4 are easier to be applied and pushed further by other researchers.

There were three available choices on the market during the time of this research; this research used a VIVE headset, developed by HTC. It was selected because its tracking technology is based on laser positioning, rendering it more reliable than other options that use cameras. It runs on a PC platform, which is more suitable for developing, researching and testing the prototype than game devices such as a PlayStation. The VIVE headset was the only VR device on the market available with two motion controllers – a vital feature for building and testing interactive functions in the prototype.

3 Interpretation of Scan Data to User-Friendly Platform

Many virtual reality exhibitions utilise traditional technology, such as freestanding displays, with interactivity limited to touchscreen devices. Our approach utilises fully immersive virtual reality, commonly used in the gaming industry and widely known for its entertainment quality. It has matured over the last five years, mostly due to OLED (Organic Light-Emitting Diode) development [6-7], reducing its main limitations: motion sickness and crude display [8]. The use of a head-mounted display (HMD) improves experience and navigation inside the virtual environment. The workflow for development of the interactive virtual reality exhibition can be divided into four parts:

1. Data collection
2. Data Visualisation: isolation; reduce complexity; patch & polish
3. Exhibition Narrative
4. Interactive functions: teleport, scale, slice, daylight manipulation, information text, voice over.

Our approach involves combining visuals extracted from the TLS data, using Geomagic software, simplified in Rhinoceros 3D (Rhino) software, and an interactive narrative curated using Unreal Engine 4 (UE4) software. This research differs from established research approaches [5] by integrating a gamification approach into the visitor's experience, and by introducing an interactive virtual tour guide and a spontaneous walk-through experience.

3.1 Data Collection

Data collection at Lincoln Cathedral was conducted using Leica P20 TLS (Fig 1), due to its speed and accuracy. TLS has almost completely replaced more traditional total station or photogrammetric approach [8]. TLS data - otherwise known as a point cloud - is very detailed, but it is a time-consuming task to remove outliers and spikes before the data can be used for a further production.

Fig. 1. Data collection at Lincoln Cathedral

3.2 Data Visualisation

Key architectural features were extracted and isolated from the main point cloud data and modelled independently (Fig 2), using global coordinates to maintain spatial relationship between objects.

Fig. 2. Isolated column extracted from the main nave

Isolated features were then imported into Geomagic (a scan-based design and processing software) to retain geometric accuracy and improves visualisation, this was achieved by reducing noise (mesh complexity) and patching holes (Fig 3).

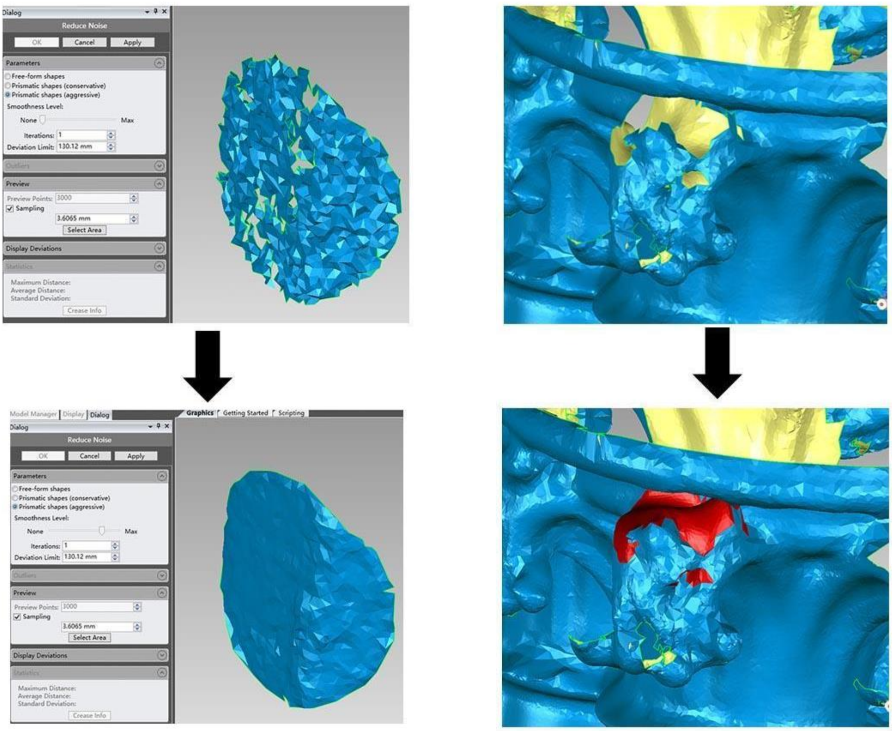

Fig. 3. Geomagic software used to reduce noise and patch holes.

3.3 Exhibition Narrative

Unreal Engine 4 is a free open source gaming software; it enables reasonably easy VR development compared to architectural 3D modelling and visualisation software, such as Sketchup, Autodesk Revit or Rhino. In the UE4 platform, an Actor refers to objects that can be placed in the scene; subclasses of Actors include StaticmeshActor, CameraActor, PlayerPawn, and LightActor. Components are used to classify static meshes, cameras and controllers, and can be attached to an Actor. Each Actor has its own BluePrint - a visual programming tool in the UE4 - used to manipulate events and variables belonging to each Actor's BluePrint. The refined models were imported and assembled in UE4 to create each scene.

For the purpose of this experiment, three scenes were created in the interactive VR prototype. The virtual tour starts with the visitor in front of the Chapterhouse of Lincoln Cathedral; here they are introduced to the infamous Lincoln Imp and acquainted with the basic VR interactive functions, such as looking around, walking and teleporting in the virtual reality world. Users can navigate between each scene guided by the mini-map, or the advice given by the mischievous Lincoln Imp (Fig.4).

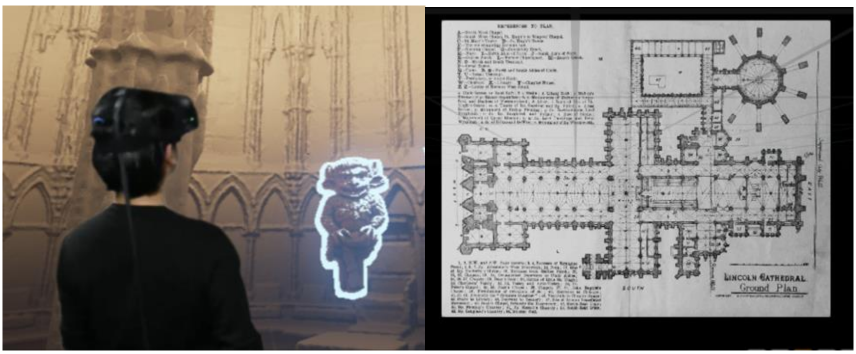

Fig. 4. Lincoln Imp and mini-map help the user navigate the VR environment

3.4 Interactive Functions

In the development of the prototype, six main interactive functions within UE4 were used: teleport; grab; scale; section; and appear/disappear. Transformative functions are new applications of VR of heritage buildings. In the Main Nave scene of Lincoln Cathedral, visitors can change the time of the day and interact with objects, such as columns, and obtain additional information (Fig. 5).

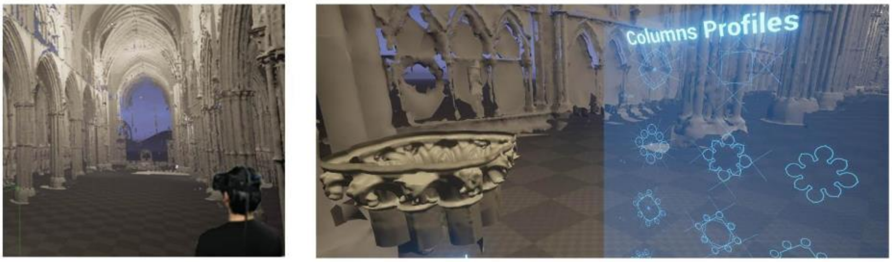

Fig.5. Main Nave scene of Lincoln Cathedral, with interactive information function

In the new Digital Model Exhibition scene, users can view architectural and historical objects isolated from their original location, offering various interactive functions, such as: grabbing, scaling, slicing (free sectioning) and rotating, to achieve an alternative perspective (Fig. 6).

Fig. 6. Digital Model Exhibition scene, with isolated objects and free section function

To study an object in detail, a visitor can grab an object, lift and scale it. It can be scaled to 1:1, allowing the visitor to walk through the object. Freely sectioning is a powerful function created in UE4, helping visitors to better understand complex architectural structures.

The dynamic mini-map (Fig 7) allows the visitor to navigate and teleport between the different scenes. Destination can be previewed before teleportation. The same mechanism allows historical documents and other media, such as videos seen in the VR exhibition scenes to be embedded into a scene, for users to interact with.

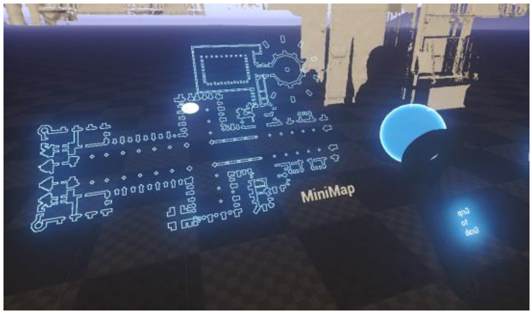

Fig. 7. Mini-map is used to navigate and teleport between scenes

4 Technical and Visual Performance

To improve the technical and visual performance of the interactive virtual reality exhibition, it was necessary to simplify the data, and control materiality and the level of detail.

4.1 Simplify Data to Increase Framerate

Once the interactive functions were operational, the first prototype was tested but it failed due to the complex meshes causing a low frame rate. VR displays require the graphics-processing unit to perform at a rate of 90 frames per second in order to avoid the screen juddering and causing motion sickness [8]. It was therefore necessary to simplify the meshes, using Rhino 3D software to reduce the mesh face count, and import back to UE4 to achieve a running framerate closer to 90 frames per second.

Simplification was an indispensable step to overcome the limited computer performance. This was completed in two separated stages (point cloud and mesh models) in manipulating the data during the workflow. Data had to be simplified to save time in the different stages, and to increase the display quality afforded by the limited computer performance. Simplifying the point cloud reduced the time required to process the raw data to a warped mesh model. Geomagic Studio software offered four commands under the sample section to achieve the reduction: Uniform, Curvature, Grid and Random. In this research, we found that Uniform was the most appropriate command to use, it allowed the designer to Keep Boundary, and provided a high control over specifying the different densities for the flat and curved areas separately.

Simplifying the mesh models helped to control the frame rate of the final product. Geomagic software was not as effective as Rhino software in terms of reducing the complexity of mesh models. More often than not, Geomagic resulted in “Not responding” during the reduction process, an outcome that never occurred with Rhino during the tests. Therefore, all the simplification of mesh models was completed using Rhino in the practical experiment.

4.2 Materiality

With modern laser scanners, color capture tends to extend data collection time by a factor or 2-3. In the case of Lincoln Cathedral, due to access restrictions and the visitors' schedule, color was not captured, with the exception of the wooden framework in an area of particular research interest - the Chapterhouse roof timber structure. In all other instances, material was applied to the refined models within UE4, which has an advanced, yet complex, material system. In UE4, an image applied on a mesh plane, or three maps (Colour, Specular and Normal) define material texture. The material system within UE4 is very powerful and goes beyond visually representing materiality; it helps minimize the amount of system performance required during an interactive function. For example, during the interactive function of sectioning a material texture can be reprogrammed to enable parts of the newly sectioned model to become transparent – making the sectioning effect without cutting and generating new models real time, reducing the amount of processing power required to run the function. UE4 is a leading platform in game design area and offers high quality visuals of materials used to represent historical buildings

4.3 Level of Detail

Due to the wide-angle perspectives in virtual reality, more objects have to be rendered compared to using a traditional display. Therefore, the complexity of the mesh models in the virtual reality scenes had to be controlled to a suitable level of detail (LOD). The effect of a shift in the level of detail can been clearly seen before and after the user focuses on an object (Fig 8). If the screen area is larger than a certain percentage (this value is set in the detail panel), the system will render the object in focus in full detail, and the background information will be distorted as a simpler version. The shift in LOD is dependent on the percentage of the pixels on the screen occupied by the object.

Fig. 8. Shift in level of detail, before and after focus on the Chapterhouse model

The LOD command helped to reduce the render load on the computer system. In general, the aim was to merge several mesh models, with different level of details, into one. Each object in the exhibit had many faces, and if those faces were not seen within a frame they were 'hidden.' This improves the performance. The shift in the

LOD is controlled by the user when they rotate their heads to observe something far from their vision center.

The LOD significantly improved the running performance of the interactive VR exhibition, yet maintained a detailed version of each single mesh model. Unfortunately, this function is sometimes problematic in its application to virtual reality due to the wide-angle distortion caused by wide field of view (FOV) in VR. This can mislead the LOD function into making incorrect shifting decisions. In VR cases, because of the wide-angle distortion, the further the content located from the image center, the more serious distortion will happen. As a consequence, the edge area on the screen is always dramatically stretched. That is to say, the objects will take more pixels when they are displayed near the edges of the screens. Meanwhile, content near the vision edges is not what the user attempting to see, but due to the area occupation is beyond set value, are likely to be shifted up to the detailed one as well.

5 Visitor Experience

The interactive VR exhibition prototype was evaluated to better understand its impact on the visitor's experience of Lincoln Cathedral. Initial observations from an empirical study of the prototype, involving four architectural students at the University of Nottingham, who compared their visit to the Cathedral with their visitor experience during the VR prototype. Additional feedback was gathered from Lincoln Cathedral Connected.

The empirical study of the prototype concluded that the interactive VR exhibition has potential to contribute to the conventional tour guide experience. It allows the audience member to inspect objects that are normally out of reach, or have limited visibility, such as the Lincoln Imp. The interactive functions provided a more illustrative method of visually exploring and analyzing the building, compared to traditional method of observing objects from a distance. Visitors get the opportunity to interact with the exhibits at a detailed level, which has the potential to enhance their understanding of the architectural and social history. The VR exhibition also has the benefit of being able to include archived material, such as scans of historical photographs, paintings, and video and audio recordings. The VR exhibition can also be accessed remotely, using a small floor space, which opens up the opportunity for user to explore the historic building from their own living room.

A video demonstration of the prototype was sent to Lincoln Cathedral Connected for review. Fern Dawson - Audience Development Officer of Lincoln Cathedral - stated:

'*I can definitely see the applications of this type of technology for visitor interpretation and the ability to access hidden spaces or features and to be able to zoom in and out and to rescale entire rooms or buildings*. '[9]

She explained that the public have been asking to see more of the traditional crafts like stonemasonry, joinery and glass, and praised the detailed model of the Chapterhouse roof structure. Being able to offer an interactive VR exhibition model was viewed by the committee as a potential outreach tool to engage with those who cannot visit the site in person. However, the committee felt that the prototype lacked a social aspect, and considered it to be an individual experience. They suggested that the prototype could be improved to cater for those who visit heritage sites for a more social experience.

6 Summary and Future Work

This paper demonstrates a workflow converting terrestrial laser scanner (TLS) into interactive virtual reality (VR) platform, which extends previous work in this area by promoting a more user-centric approach. The virtual reality enables curators to create rich narratives by guiding the visitor through virtual experiences, and custodians support in their endeavour to maintain the cathedral.

Use of gamification enables storytelling and guides visitor through Lincoln Cathedral in a similar way to traditional tour guides, making it easier for users to navigate the VR experience.

Such approach would be of most benefit to two groups: people who are unable to visit the Cathedral in person as well as current visitors. They can learn more about the building itself and interact with architectural features, mixing virtual reality experience with the normal visiting one. Both groups are also able to virtually access parts of the cathedral that have restricted access, such as Chapter House roof structure.

The demonstrated workflow has the advantage of being low cost due to a use of open source tools and standardisation coming with the use of common platform and approach. Use of detailed TLS data provides flexibility - the visual data can be simplified for a general audience (offering processing benefits for the general public as discussed above) and made complex and very detailed for specialised use (such as replacement of the architectural detail by stonemasons). This approach has received a positive feedback from Cathedral Fabric Committee. Colour information is very important for fabric maintenance and the authors of this research are looking at quicker and more inclusive data collection. Another improvement would be utilisation of a flexible moving data collection device (deploying an inertial system for self orientation) allowing for quick access to small spaces.

One of the limitations of the interactive VR exhibition is a lack of social interaction between members of the public. This aspect is missing from virtual reality, where each user is separated by the HMD. One way forward would be a combined virtual reality experience, where users can see and interact with each other, however this requires further work to fully understand all implications, including a better understanding of users interaction with the equipment. The next planned step in this research is to explore this concept in a VR exhibition, allowing the general public to both experience the technology and provide important feedback

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Integration of a Structure from Motion into Virtual and Augmented Reality for Architectural and Urban Simulation

Demonstrated in Real Architectural and Urban Projects

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Abstract. Computational visual simulations are extremely useful and powerful tools for decision-making. The use of virtual and augmented reality (VR/AR) has become a common phenomenon due to real-time and interactive visual simulation tools in architectural and urban design studies and presentations. In this study, a demonstration is performed to integrate Structure from Motion (SfM) into VR and AR. A 3D modeling method is explored by SfM under real-time rendering as a solution for the modeling cost in large-scale VR. The study examines the application of camera parameters of SfM to realize an appropriate registration and tracking accuracy in marker-less AR to visualize full-scale design projects on a planned construction site. The proposed approach is applied to plural real architectural and urban design projects, and results indicate the feasibility and effectiveness of the proposed approach.

Keywords: Architectural and urban design · Visual simulation · Virtual reality · Augmented reality · Structure from motion.

Studying Co-design
How Place and Representation Would Change the Co-design Behavior?

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Abstract. This paper reports the results of a protocol study which explores behavior of designers while they design in pairs using sketching (analogue and remote) and 3D modeling tools (co-located and remote) in co-located and remote locations. The design protocol videos were collected, transcribed, segmented and coded with the customized coding scheme. The coded protocol data was examined to understand the changes of designers' co-design process and their activities of making representation in four different settings. This paper discusses the impact of location and types of representation on collaborative design. The paper concludes that designers were able to adapt their collaboration and design strategies in accordance with the affordability of the used digital environments.

Keywords: Collaborative design · Remote sketching · Augmented reality · Virtual worlds · Protocol analysis

Generative Design Systems

Interactive Design of Shell Structures Using Multi Agent Systems

Design Exploration of Reciprocal Frames Based on Environmental and Structural Performance

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Abstract. This paper presents a continuation of research on the prototyping of multi-agent systems for architectural design with a focus on generative design as a means to improve design exploration in the context of multiple objectives and complexity. The interactive design framework focuses on coupling force, environmental constraints and fabrication parameters as design drivers for the form finding of shell structures. The objective of the research is to enable designers to intuitively generate free form shells structures that are conditioned by multiple objectives for architectural exploration in early stages of design. The generated geometries are explored through reciprocal frames, and are evaluated in an automated fashion both on local and global levels in terms of their structural and environmental performance and constructability. The analytical results along with fabrication constraints are fed back into the generative design process in order to more rapidly and expansively design explore across complexly coupled objectives. The paper describes the framework and presents the application of this methodology for the design of fabrication aware shell structures in which environmental and structural trade offs drive the final set of design options.

Keywords: Generative Design, Parametric Design, Multi-Agent Systems, Digital Fabrication, Form Finding, Reciprocal Frames

1 Introduction

Modernisms' influence in the 20^{th} century pioneered and made pervasive mass-standardization to accommodate the need for rapid and inexpensive erection of buildings and in doing so shifted the attention away from non-uniform nonstandard structures and forms. While shell structures have been used for centuries in architecture and engineering given their capacity to efficiently cover large spans, however the design, modeling and analysis of shells has remained a challenging topic given their complex geometries [1]. The design exploration of these structures are not conceived of in a linear process, requiring extensive iteration as well as close collaboration between architects and engineers [2], further making the process less interactive and suited for rapid iterative design exploration. Additionally, the development of new knowledge regarding these types of structures has historically been dependent on extensive physical testing; the establishment of sophisticated building techniques which consequently increased the cost for their realization [3] [4] [5].

However, with the rapid development of computer aided design and modeling tools we have seen a rise in the development of non-standard building forms, including free form shell structures [6]. In parallel a reinvigorated interest in revisiting traditional building techniques through digital craftsmanship and digital technologies is notable [7] [8]. Recently, in concert with a myriad of digital tools that facilitate the handling of complex geometric constraints, a number of computational methods have been appearing, where structural concepts and material constraints are integrated as design drivers for the form finding of complex geometries [9]. Moreover the widespread application of digital fabrication techniques and robotic construction, has made the realization of complex shell structures economically and technically feasible and has broadened our capabilities to include design of material and construction processes [10].

The paper presents an evolution of our research on a Multi Agent Systems (MAS) framework which aims to solve the challenge of bringing into the form finding process a set of complexly coupled and often divergent design objectives, here environmental parameters and materialization constraints. While this may imply less perfected shells in the case of structural objectives, such as minimization of material and load distribution, the work sees integration of multiple analyses as critical for the generation of non-standard architectural forms which necessarily include multiple objectives.

Despite the fact that the increased availability of new tools has enabled designers to design complex and free form geometries, in most cases little feedback relating to the structural or environmental performance of the geometry is provided to the designers interactively in the early design stage [11]. Moreover there is a lack of integrated methods and design systems which combine form finding with manufacturing parameters and environmental aspects like shading and lighting [12]. The use of disparate software for different analyses, fragment the design process among different disciplines and most frequently generated geometries are further rationalized multiple times for environmental, structural and/or construction processes separately and independently [13]. As a result of this lack of integration, the design cycle latency increases creating inefficiencies from concept design to design development and finally construction. Our work focuses on the implementation of a MAS approach, where the formulation of design behaviors for the form finding of shell structures is based on the decomposition of a given problem into different design agencies (i.e. structural agency), and is further based on their coupling with multiple analytical processes early in the conceptual design phase. The objective is to enable designers to design explore much more rapidly and extensively and to form find based on the combination of structural, environmental and material parameters though a bottom up design approach. Through the evaluation of both local and global behavior of the reciprocal frame shell system the designers can define rules which condition the form and result into geometric data representations which can be developed through design automation and non deterministic methods and finally more easily communicated across different expert disciplines.

The paper is structured through a survey of literature for existing form finding methods as well as for identifying the key design parameters and constraints associated with the realization of shell structures using reciprocal frames. It then identifies the gaps, from which we describe how the relationships of form, force and environmental parameters are utilize and validated in simulations via a MAS approach for the generation and evaluation of non-standard geometries with complexly coupled structural, environmental, and fabrications objectives. Finally, a conclusion and discussion is provided regarding the MAS methodology for the design of shell structures through analysis of both global and local geometries and the intended next steps.

2 Background and Precedents

Shell and space frame structures have played a significant role in architectural design given their spatial and geometrical qualities and can be loosely classified into: a) lattice space structures (discrete elements); b) continuous (slabs, shells, membranes); and c) biform space structures (combination of discrete and continuous parts) [14] [15]. Space structures can provide large unified spaces while still being highly efficient in material usage. This is mainly achieved through their complex geometric description, which has proved to be one of the main challenges in their design, modeling and analysis. In order to address the challenges, practitioners and researchers have developed analog and digital apparatuses to empirically form find space structures over the years. Through the systematic study of scaled physical models most notably researchers such as A. Gaudi, H. Isler and F. Otto, have managed to design, analyze and construct fairly complex shell structures [16] [17]. Additionally, F. Candela pushed the boundaries of structural shell design by seeking 1:1 solutions, which by virtue of geometry could limit the amount of necessary calculation for their erection [18] [19].

With the use of digital tools and computation the potential to integrate multiple types of design information as well as fabrication and material constraints into an interactive design and multi objective optimization workflow has now become more productive and interactive [20] [21]. Given the increasing availability of computation, the use of simulation for structural behavior early in the design phase, is considered a viable methodology for architects and engineers to manage engineering constraints in much more interactive, design exploratory, and intuitive fashion [22]. Emanating from the work of these precedents a number of design computing and simulation tools have been developed for aiding designers to understand the relationships between form and force to further the design of free form shell structures. Kilian, using particle spring systems, established an interactive virtual hanging string modelling environment while other researchers have used dynamic relaxation methods which allow for real time exploration of funicular shells [23] [24] [25]. Block, introduced the Thrust Network Analysis (TNA) method, which extends a graphics statics approach for the form finding and calculation of compression only vaults [11]. Of important note, these innovators use computational methods and simulations instead of the previous luminaries' reliance on physical models. In doing so they have laid the ground work for others to shift our research efforts towards computational affordances such as more accuracy, more rapid iteration, and scalability of material testing. It has also enabled a greater ability to integrate often asynchronous and conflicting design domains and objectives.

Reciprocal frames, also called nexorades, are defined as a structural system of mutually supporting interwoven elements (nexors) [26]. In nature we encounter the principle of reciprocity in structures such as birds' nests where simple discrete elements are interwoven to form complex geometries but also in micro scale organisms such as cocolithoropes, where calcareous plates, cocoliths are interlocked in a spherical fashion around a central cell. In architecture, reciprocal frames have a long tradition and appear in China and Japan around the 12th century, while in Europe V. Honnecourt introduced the system in the 13th century [5] [27]. Leonardo Da Vinci studied reciprocal frames systematically for different applications including for bridges, ceilings, and roofs; and subsequently a number of architects and practitioners investigated alternatives of the system. S. Serlio and J. Wallis looked into the adaptation of the system for the construction of flat roofs, while others developed and patented a similar system for the construction of timber roofs [14]. The reciprocal frame system requires a minimum of 3 structural elements and is based on the principle that one element supports and gets support from the rest of the elements on the structure. The overall form of a reciprocal frame structure is dictated by the way the elements are interwoven with one another. Recently, reciprocal frames have received the attention of architects and engineers because of the potential that computational methods offer to design, analyze and optimize such structures [27]. The adaptation of reciprocal frames to form shell structures, is made interactive through the use of computational design aids enabling the simulation of the geometrical configuration of the frames. The description of the final geometry is now possible with the use of non-regular frames, characterized by different unit cell shapes and dimensions, or with non-regular topology, and or with variation in the dimensions of bars and position of joints [28] [5]. The generation of reciprocal frames using genetic algorithms and dynamic relaxation methods have been researched as well as methods based on shape grammar rules and tiling theory [29] [30] [31].

While there has been a resurgence of interest and research on reciprocal frames they have not been thoroughly studied, here conjectured to be mainly due to their complexity in terms of number of elements, and therefore number of complex calculations. Although single objective or simple configurations have been studied and successfully realized (with different numbers of elements and materials) complex reciprocal configurations with parametrically varied reciprocal units that respond to more than structural constraints still remain largely unexplored. In most of the previous work the connection between the nexors is considered fully regular or rigid and little work has been focused on the geometry and behavior of the joint or in our case the joints (given purposeful non planarity and overall formal irregularity). While the research on the generation and systemic behavior of regular and planar reciprocal frames on 3D surfaces has progressed this is also where the literature presents a clear gap [32] [5] [14] [31]. Additionally, in surveying the literature of form finding few examples exist inclusive of integrated workflows which combine structural form finding with environmental parameters such as lighting and shading with fabrication constraints [12]. Despite the maturity of digital design and the field of design computation, there remain but a few examples in the field where combining numerical analysis with a generative design system is explored [33]. The integration of the reciprocal frame into a multi-objective design exploration workflow where irregularity is specifically addressed through a MAS and generative computing is unique.

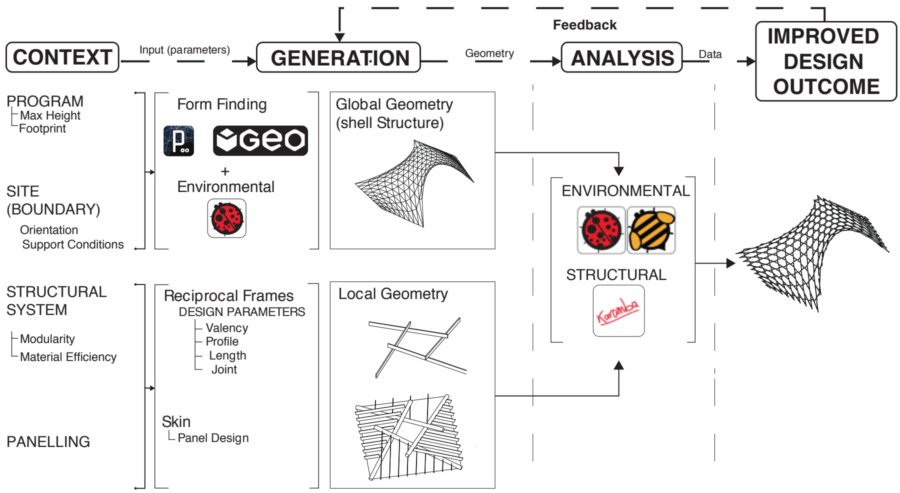


Fig. 1. Workflow diagram illustrating a Multi Agent System approach including the tools implemented from initial design conditions, to form generation, analysis and materialization.

3 Research Objectives and Hypothesis

Our research objectives include the ability to facilitate the design and construction of geometrically intricate yet efficient, comfortable, and fabricatable shell structures inclusive of combining environmental and structural analysis in the form finding process by coupling them with a modular yet parametrically variable structural system based on the principle of reciprocity. The research hypothesizes that our generative design system can improve the design exploration, generation, and optimization of such structures by providing designers with interactive tools that incorporate structural and environmental feedback with that of constructability. It is further hypothesized that through the use of a MAS for design methodology novel design outcomes will become achievable in terms of previously unattainable levels of geometric and multi objective complexities through the characteristics of the automation and application of a multi agent systems approach. The objective of this stage of the work is to further evaluate the generative design methodology which combines form finding techniques with conceptual environmental and structural analysis tools via a MAS. A goal is to be able to provide practical solutions for the design and construction of free form geometry using reciprocal frames (nexorades), by exploring suitable configurations for their construction. This design exploration and optimization is performed through local and global generation, simulation and analysis of 1) the shape, cross section and joint conditions of the elements (nexors), and 2) structural analysis and environmental analysis of the reciprocal fames. The purpose of the work is to enable designers to generate shell structures that are pareto optimized across multiple objectives rather than purely driven by structural parameters. This is a critical distinction in that the work trades off pure structural efficiency in favor of and to include other efficiencies and hence the need for incorporating generative design, MAS based optimization and design automation.

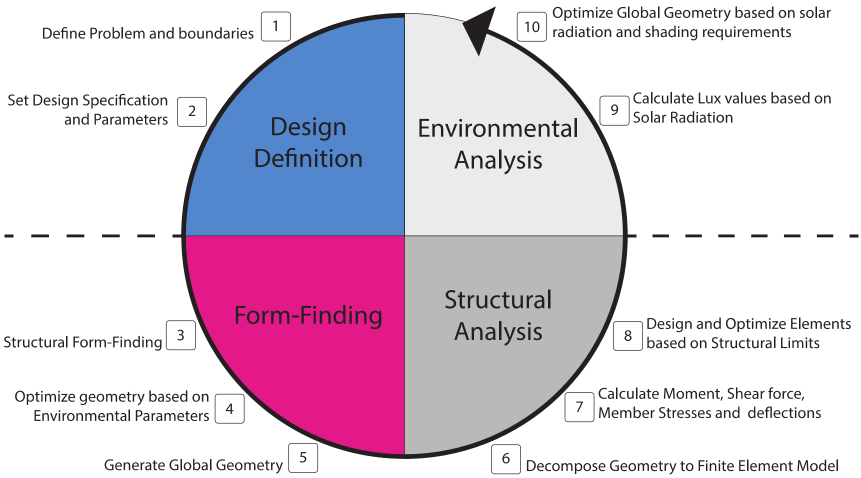


Fig. 2. Diagram illustrating the sequence of the methodology including the feedback of the design, form finding, and analysis steps within the MAS for design.

4 Methodology

In this section the description of the steps in our MAS for design workflow are described in detail (see Fig. 1). The computational design methodology is applied to shell structures and their realization using reciprocal frames. The aim is to develop an approach that shifts away from pure form finding a single objective, towards a more integrative multi objectives design exploration inclusive of environmental parameters and fabrication constraints. This is done in order to influence the geometric exploration of shell configurations where the other pragmatic parameters are given greater weight in the pareto optimization for the architectural design and search of reciprocal frame structures. In order to more efficiently manage divergent objectives for driving the form finding inclusive of environmental parameters a bespoke design and optimization application is developed to generate design alternatives through utilizing open source software and libraries within Processing and IGEO and through the linking of our applet to commercial software packages through Rhinoceros 3D, Grasshopper, Ladybug, Honeybee, and Karamba [34]. The links and interactive feedback between these different platforms and programs is established by a set of custom interfaces. These interfaces and scripts are written in Python, which provides for establishing communication across the different data representations inclusive of geometric and the analytical properties and drivers. The MAS for design workflow is structured through four main phases (A-D) each with a series of steps (1-10) as can be seen in Fig. 2.

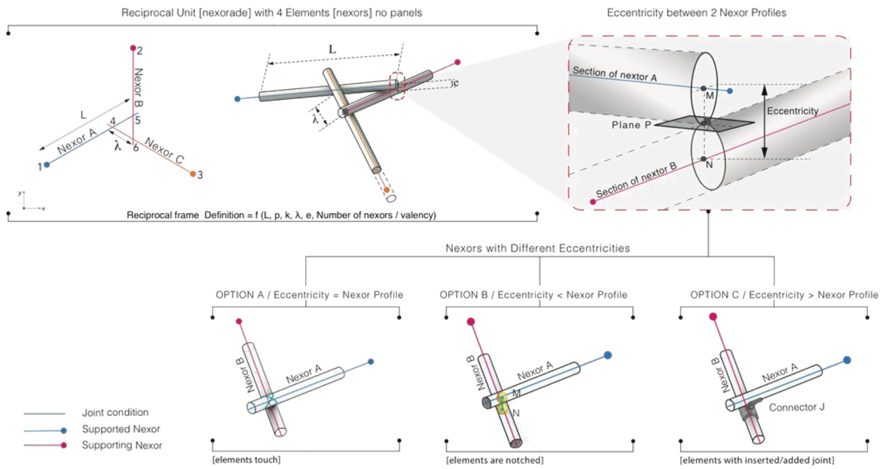


Fig. 3. The diagram illustrates the logic of reciprocity and the parameters of the reciprocal frame element (nexor) and unit (singular nexorade frame). The different eccentricities illustrate a variety of joint conditions and fabrication solutions (ties, pins and 3D printed non-standard couplings).

In phase A steps 1 and 2 a set of global and local design parameters are defined inclusive of footprint area, support conditions, environmental conditions such as location and orientation, and as well as the main parameters of the reciprocal frame topology represented by number (integer), type (discrete nexor geometry option described below) and size (length, width, and depth) of elements. Phase B steps 3 through 5 are the form finding of the shell structure using our MAS modelling and pareto optimizing method. In this phase each point is modelled as an agent which has a weight and tension value when connected to other agents, as well as an environmental sensitivity factor, which defines how much the agent is affected by the environmental objective. The global geometries (nexorades) are design explored generatively and in an automated fashion through different topologies, different support conditions and nexor connectivity options. The form finding process is influenced by solar path positions in order to capture global behavior with respect to an environmental result: how much direct sunlight during the morning hours, or shadow during afternoon hours is provided by the nexorade. In phase C steps 6 through 8 the structural elements are modelled as geometry agents which interact based on the principle of reciprocity so that each sub system can then be assumed to be statically determinate and in equilibrium. Sequentially structural analysis is performed on all reciprocal frame nexors for their deflection and stress distribution both locally and globally for the nexorade for maximum deflection, and sums of stresses overall. Depending on the global geometry and structural performance of the design alternative a specific configuration at this stage can be selected or rejected by the designer. Fig. 3 illustrates reciprocal element nexor morphology and possible connections between the elements in the nexorade. Internal forces on each planar frame within the freeform polysurface of the global nexorade shell are related through the rules of reciprocity which then are adjusted iteratively by the system to meet these geometric rules and the structural static load capacities. In Phase D steps 9 and 10, an environmental analysis based on solar radiation is performed on each shell's global surface and below at the ground level. This is done in order to 1) drive the global geometry orientation towards the sun for gathering more light in case the shell is cladded with solar panels, and 2) to change the geometry of the reciprocal frames based on the impact below the surface where the amount of light that penetrates creates too much solar gain. The system cycles through phases B through D repeatedly either for a specified number of iterations or until a geometry is generated and evaluated as performing better both structurally and environmentally in a pareto trade off fashion. At each iteration both the global parameters, such as position of the agents and the local parameters including element size, joint type, and panel type are parametrically varied and a new geometry is generated. Better is defined by the designer who for instance may privilege the configuration to provide maximum shade while using the smallest available element profile for structural stability.

5 Design Experimentations

A series of experimental steps have been performed to date, including testing of the global and local system logics as well as tests to simulate the construction of the shells manually and in anticipation of robotic assembly. The research presents a focus on reciprocal frames, because as a structural system it relies on simple mutually supported structural elements that can be assembled into highly intricate configurations to form large aggregations and spans that have the capacity to create structural shells which can span many times the length of the individual structural elements. Konrad Wachsmann's research into large span space frames is one exemplar of the capability of the space frame, albeit not a reciprocal frame. The series of tests and experiments move towards proving significant design exploration and generative design and complexity affordances.

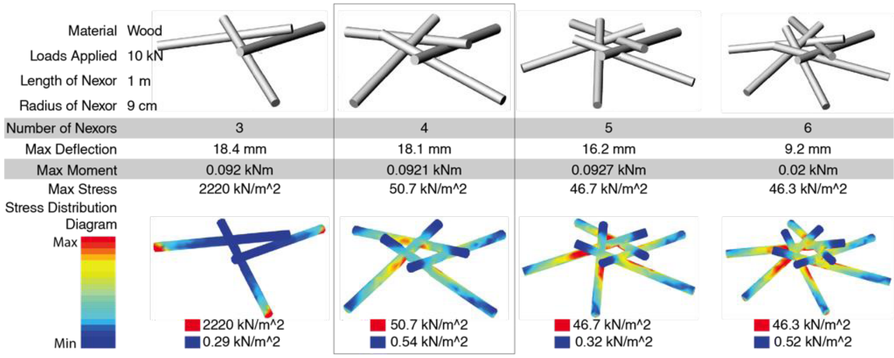


Fig. 4. The table illustrates the exploration of increasing nexor count from 3 to 6 elements into the singular nexorade (frame) and their resultant structural analysis in relative terms.

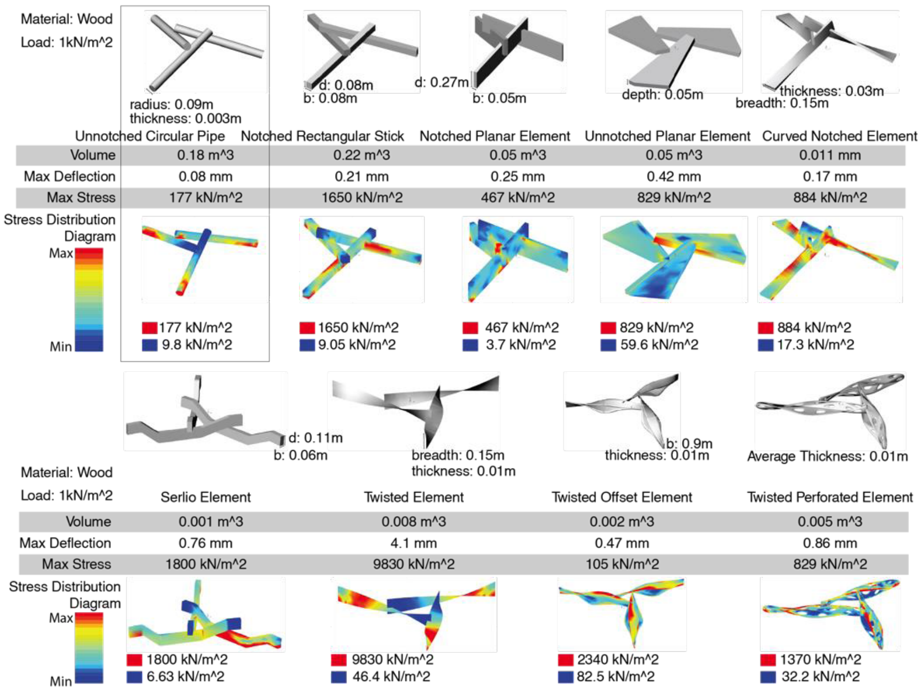
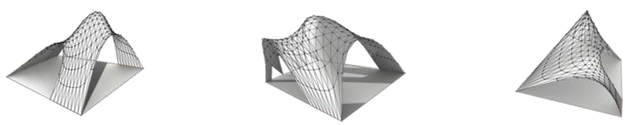


Fig. 5. The table illustrates the structural analysis of singular reciprocal frame units (nexorades) of similar element count (3) for 8 different element (nexor) geometries and joint conditions. The experiment included elements ranging from round to uniform rectilinear to non-uniform flat through to a series of non-standard nexor geometries.

One experiment focused on the design exploration of the topology of the nexorade frame through the change in integer values of nexors (see Fig. 4). Through these experiments the designers could more interactively understand the loading conditions y adding and subtracting the number of elements. A second step for the experiment on the nexor and singular nexorade was to design explore uniform through to non-uniform nexor designs and their performance. Fig. 5 shows eight nexor designs ranging from simple parametric round and rectangular cross section nexors to that of non-uniform nexors designs. O key question for this stage of the experimentation was whether the system would aid in the finding of nexors design that would be more efficient through non-standard cross sections, twisting and highly intricate geometric designs. Simple resting connections were assumed for these analyses. A third set of experiments was to analyze the performance of nexors in terms of their dimension and engagement lengths or valency with their neighbors (see Fig. 7). The analysis undertaken was to look for more optimal nexors or nexors options within a permissible range and how they accommodate stress, displacement and in which geometric configuration was valency more or less influential in the design decision making.

The next set of experiments moved from the local focus on nexors to that of the form finding of shells and the generation of nexorades influenced by the environmental conditions. Fig. 6 illustrates the structural analysis of a subset of three global configurations which have been form found structurally initially and then re-form found based on the solar radiation influence. From these configurations as illustrated in Fig. 7 the method then adjusts the global configurations to accommodate solar condition preferences set by the designers.



Max Span	60 m	60 m	60 m
Min Span	10 m	13 m	10 m
Max Deflection	1.02 mm	1.82 mm	5.83 mm
Max Stress	612 kN/m^2	347 kN/m^2	2266 kN/m^2
Max Moment	0.97 kNm	1.47 kNm	8.77 kNm

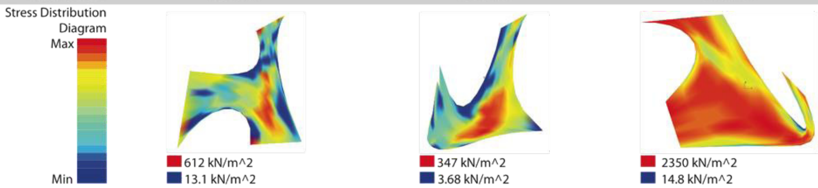


Fig 6. Illustrates 3 shell configurations in plan and perspective with an exaggerated influence and distortion away from the pure form found by virtue of the inclusion of solar path influence. The images below show the structural analysis in terms of stress distribution on their scaled spans.

Through the application of the methodology the designer chooses orientation and support conditions specifies design preference then the system generates the shell structures and discretizes iteratively the surface into panels which are the geometric proxies for the reciprocal frames alternatively explored based on the analytical results of different geometries of the reciprocal element (nexor). The performance of the global geometries are evaluated both structurally (total deflection and stress) as well as environmentally (total radiation on and beneath the structure). The work benchmarks the single objective of structure against the multi-objective of structure and environmental results. The analysis data is used for the iterative use and optimization of the global geometry then the reciprocal elements.

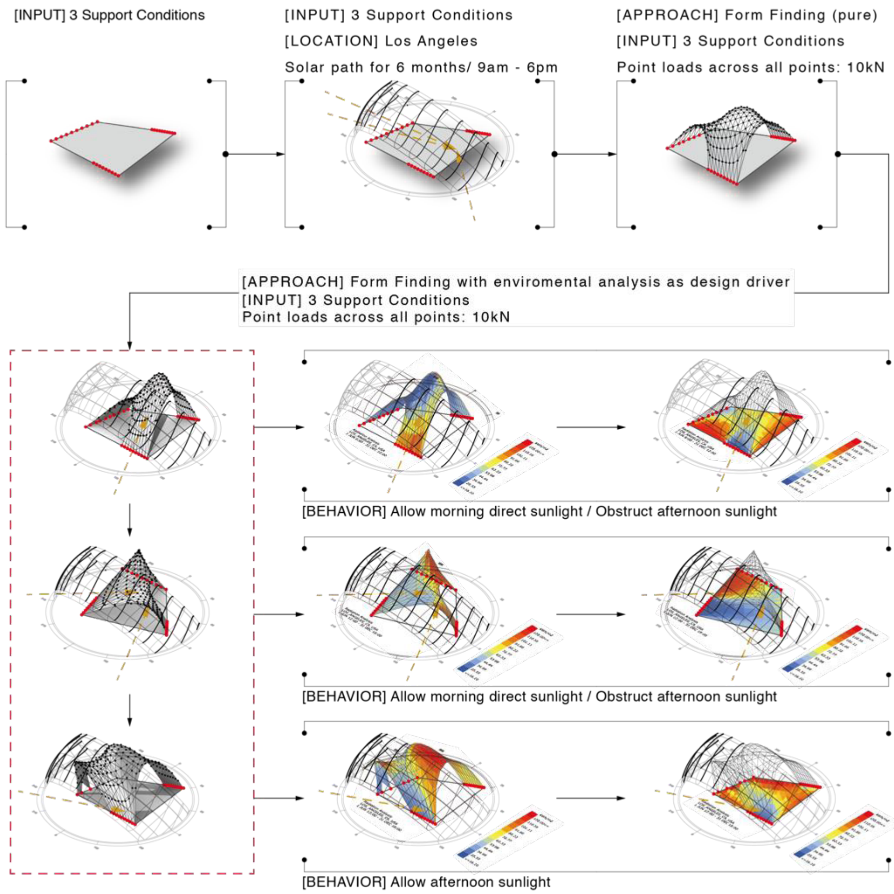


Fig. 7. The diagram illustrates the global input parameters for the form finding of the shell and then the combination of the environmental analysis and a resultant of three behavioral results.

At the beginning of the process the designer defines the a) support points; b) resolution of the mesh; c) critical solar positions; and d) environmental attraction sensitivity (see Fig. 7). The designer provides an outline of the area either in Rhinoceros or directly in Processing by providing coordinates; then provides input parameter values for material tension between particles and weight, environmental attraction value of each agent and count of iterations an agent/particle based solver can iterate. Once the geometry comes to a state of equilibrium the reciprocal frames are generated and the geometry is exported as NURBS to Rhinoceros 3D. The geometry is analyzed structurally for max displacement and deflection using the Karamba plugin in Grasshopper and environmentally for total solar radiation using Ladybug and Honeybee plugins. The analytical results are saved into a txt file that is fed back to the Processing applet. Based on the results the reciprocal nexor parameters change one step at a time and the simulation is run again. If the generated geometry does not meet the structural requirements, the global parameters are updated and the process restarts.

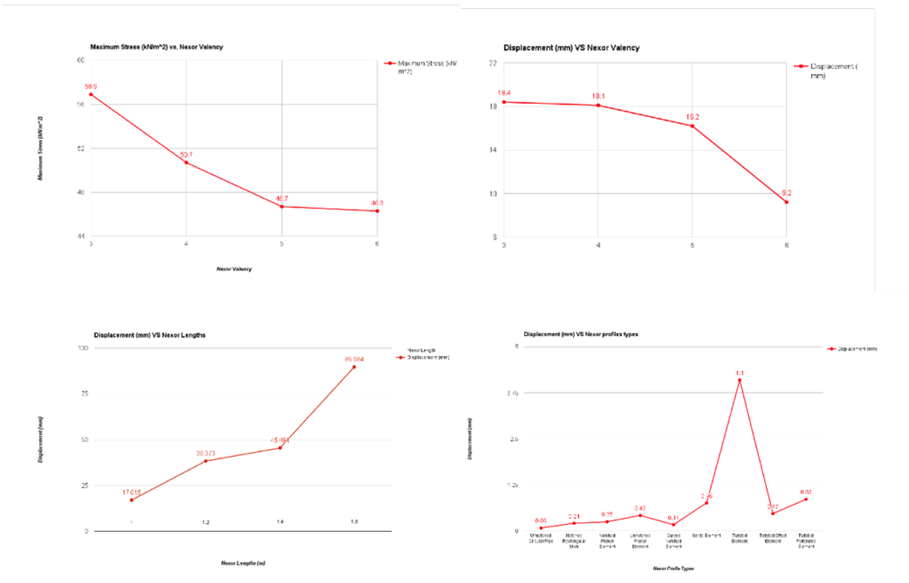


Fig. 8. Graphs showing maximum stress in relation to nexor valency, displacement in terms of nexor valency, displacement in relation to nexor lengths and displacement in relation to 8 nexor profile types from circular to irregular.

Another set of experiments has focused on developing the automated fabrication and erection of the reciprocally framed shells. This has been performed in two ways, one being a manual simulation and the second being through simulation of the MAS which generates frames for cementitious deposition. The simulation has included the constraints that industrial robotic arms have in terms of reach, clash and singularity as well as patterns for efficient use of multiple robots working in collaboration. Through these experiments the research has both begun to anticipate the tectonic and fabrication constraints and parameters for future full scale automation.

Fig. 9. An illustration of design exploring the erection sequence study performed manually (top); a set of simulated frames illustrating the cementitious deposition and resultant shading analysis (middle); and a set of 3 global configurations illustrating a variety of agent driven porosities (bottom).

6 Discussion and Future Steps

This paper presents the further development of a "Design Agency" research, specifically a MAS for design methodology that is based upon a multi objective optimization where multiple agencies interact to negotiate towards a more informed design. The research furthermore illustrates the complexity of reciprocal frames and the need for a bespoke design computing method to enable the designer to interact and design explore where the project is cognitively too complex with out the aid of computing in two primary ways: that of the complexity of the trade off in the analysis an that of the constructability of the shell in terms of elements, unique connections and overall non-standard form.

The contribution of the work enriches structural form finding with additional objectives, including environmental impact and those of the tectonic system. Of note is the conflicting nature of these objectives and yet how critical they are for architectural design from concept through to fabrication. The paper presents a demonstration of our methodology where the system successfully modifies the generation of shells inclusive of an environmental target by assigning different environmental behaviors to our agents. We utilize structural analysis of reciprocal frames locally in order to calibrate the agents' behavior for their application globally so that we can avoid the generation of bad performing geometries. This is achieved by generating and analyzing different structural element (nexor) designs and by analytically observing how different geometries affect the structural behavior of the element then frame then shell. The results so far indicate that the increase in the number of elements in a reciprocal unit significantly decreases maximum stresses and displacement, while the increase of the individual elements' length increase the displacement almost linearly. These results are encoded into the geometric agent behavior in order to steer design generations towards more optimal solutions.

The implementation of our tool to date is in progress and the data passing between the analytical and generative components of our methodology needs to be further automated. A current step is being taken to extend our methodology so that it includes the generation of perforated panels directly connected to reciprocal frames. The vision is to simulate the robotic construction of the shells both in terms of the nexor placements but as well as the nexorade in-fill for more optimal shading and light filtration. Another extension of the work, is to develop an intuitive web based user interface (UI) for generating and visualizing a gallery of design alternatives which contains analytical (i.e. stresses, displacement, environmental performance) as well as the possible range of formal geometric alternatives.

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Stair Design Using Quantified Smoothness

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Abstract. This paper introduces metrics to evaluate stair geometry and shows how these metrics can be used to develop versatile computational stair design tools for the design of smooth stairs. The proposed stair smoothness metrics are based on the angles between tread lines, the angles between the walk line and tread lines, and the dimensions of tread sides. Using these metrics in combination with evolutionary algorithms results in computational methods that are highly flexible: as opposed to common software tools that generate particular classes of stairs (such as helical stairs or u-shaped stairs), this approach could be used for any stair design. The proposed methods produce results that match or surpass the smoothness of manually designed stairs and enable the implementation of features that are not available in other design tools, such as obstacle avoidance. Applications of the proposed method are shown for both freestanding stairs and stairs with a predefined footprint.

Keywords: Stairs, Stair Design, Evolutionary Algorithms, Computational Design

1 Introduction

1.1 Stair Balancing

A major design consideration in stair design is how to deal with turns in direction. For walking comfort and safety as well as for aesthetic reasons, gradual transitions are typically desired [1], [2]. Stairs in which treads are locally adjusted to create smoother transitions are called balanced stairs or dancing stairs [3].

The process of balancing stairs involves rotating treads horizontally around the point where they intersect the walk line. Various geometric methods to execute this process manually exist [2], [4-6], of which the unrolled projection method is the most widely applicable, as it can deal with any angle between straight series of treads. This method (illustrated in Fig. 1) has been known for over 200 years [7] and can be found in various sources [6], including recent publications [4], [8].

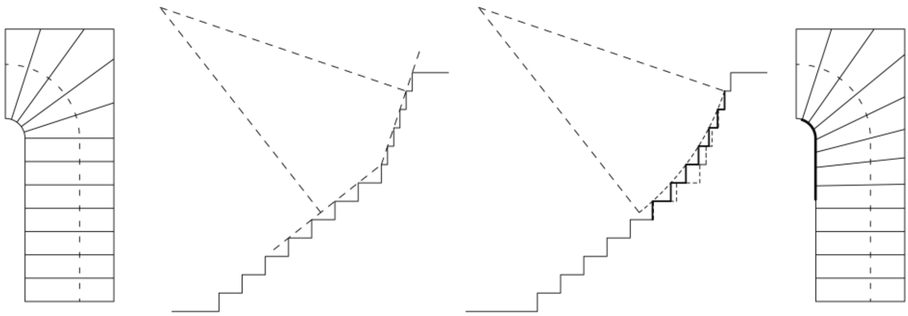

Fig. 1. Conventional balancing method using unrolled projection. From left to right: unbalanced stair; unrolled projection of inner side of stair, with construction lines needed to create an arc; balanced unrolled projection, created by shifting risers to the arc; balanced stair. The modified tread lines in the balanced stair are constructed by first transferring the tread dimensions on the inner side of the stair from the projection, then connecting these points to the original treads' intersection points with the walk line.

1.2 Stair Design Tools

In current software implementations, tools for the creation of various stair types (such as straight stairs, helical stairs and winding stairs) are typically implemented. However, although stair design software has been around for over 30 years [9], the choice of balancing methods tend to be limited (if present at all). Therefore, using manual methods may still lead to better results than what can be achieved using software tools. This is remarkable, as due to the high constraints that are placed on their geometry, stair design should be well suited to a computational approach [10-12].

2 Proposition

Balancing improves stairs in terms of appearance, walking comfort and safety, by making sure no sudden changes occur between consecutive treads. A balanced stair has more gradual changes between treads and exhibits a smoother appearance, as illustrated in Fig. 2.

Stair smoothness can be evaluated visually, but as it is based on geometry, it should be possible to evaluate smoothness numerically. Stair geometry can be generated programmatically, so as soon as design alternatives can be evaluated quantitatively, it becomes possible to develop evolutionary methods for stair design. As such methods do not depend on pre-existing conceptions about particular stair categories, they should be more flexible and more generally applicable than existing design methods. Because the result of such an evolutionary process will be a stair with high smoothness, the outcome should be a stair that is aesthetically pleasing, as well as safe and comfortable to walk on.

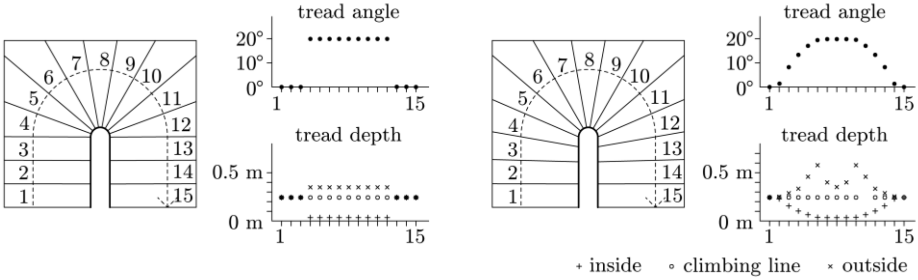

Fig. 2. Comparison of a stair with abrupt changes from straight segments to winding segments (left) and a balanced stair created with a method described by Reitmayer [5] and Wattjes [6]. Note how the tread angles in the tread angle diagram for the balanced stair (right) describe a smooth curve, as do the tread depth values on the inside of the treads.

3 Principles

The proposed stair generation approach is based on the following premises:

1. The rise height of all treads of a stair should be constant.
2. The going distance on the walk line should be constant.
3. Consecutive treads should not exhibit large tread angle differences.
4. Consecutive treads should have similar side depths on at least one of their sides.
5. The lines defining the front of treads should be as close as possible to being perpendicular to the walk line.

The *tread angle* and *side depth* (as mentioned in premises 3 and 4) are illustrated in Fig. 3, with α denoting the tread angle and *d1* and *d2* denoting the tread width. These properties are geometrically related and for freestanding stairs, they could be used interchangeably. In winding stairs, side depth is the property that most directly affects the visual smoothness of the hand rail and the side of a stair. However, for walking comfort, the tread angle is the more directly relevant property, as it is defines the change in tread orientation in relation to the walking direction.

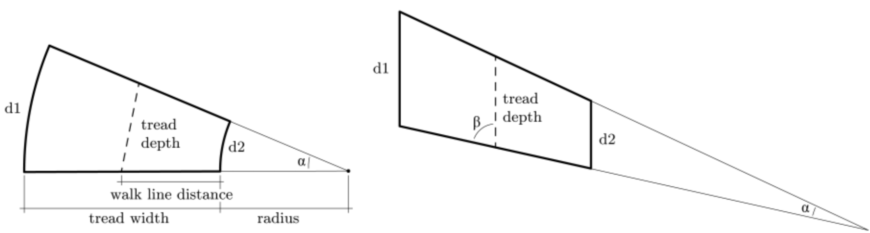

Fig. 3. A tread in a freestanding stair (left) and a tread in a balanced stair (right). In both cases, the angle α is defined by the lines that define the front and the back of the tread. The *tread depth* we use in our algorithms is illustrated here, but depending on the applicable building code, different definitions may need to be used. We will refer to *d1* and *d2* as *tread sides*.

As the word suggests, balancing is a trade-off of properties: balancing methods typically decrease the differences in tread side depth at the treads' shortest side, but as a side effect, the tread lines are no longer perpendicular to the walk line. This trade-off needs to be reflected in the definition of a smoothness metric.

4 Abstraction

In the proposed computational model, a tread is principally represented by the angle between the lines that define the front and the back of a tread (excluding the tread nose). The position of a tread is either defined by a point on the walk line, or in case of a free-standing stair, the position simply follows from the position and geometry of the previous tread. The sides of a tread are either defined by the stair's side lines, or in case of a free-standing stair, by arc segments. Although series of arc segments with non-constant radii have only G1 continuity, the resulting curves are virtually indistinguishable from curves with G2 continuity, as can be seen in Fig. 4.

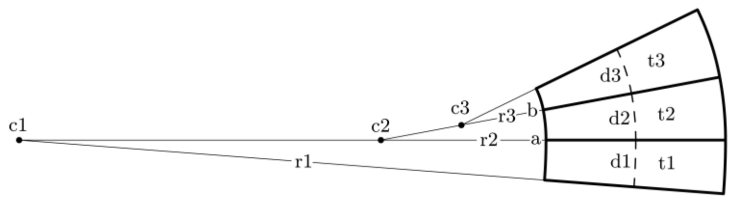

Fig. 4. Three consecutive treads, constructed by defining point *c1* and radii *r1, r2* and *r3*. Point *c2* is constructed on line c1-a, using given distance *r2*. As distances *d2* and *d3* are on the walk line, they should equal distance *d1* and thus angle a-c2-b can be defined. Note that center points for two consecutive treads are always on the extension of the shared line between two treads; therefore, arc segments that form the sides of treads are tangent.

Stair objects are defined by a series of constant values (stair width, start point, start direction, rise height, going, and optionally a walk line and side lines) and a list of tread objects. Tread angles are the only variable that changes during the generative process. Thus, the only data to operate on is a single list of numbers.

Any number of constraints can be linked to a stair object, for example the desired end position and end direction, particular fixed points on the stair, or obstacles that need to be avoided.

5 Smoothness Metric

As discussed in Section 3, various properties are relevant for a good stair design. We will only be looking at stairs with constant riser height and constant tread depth on the walk line, so premise 1 and premise 2 will always be fulfilled. This leaves three premises; for each of these, we describe a matching metric that a stair could be evaluated on. Depending on the type of stair, the spatial requirements and design intent, one or more of these metrics may be used.

5.1 Tread Angle Metric

According to premise 3, consecutive tread angles (as illustrated in Fig. 3) should be similar and changes should be gradual. Two consecutive small changes in tread angle are preferable over a single large one. Therefore, we sum the squared differences between pairs of tread angles:

$$A = \sum_{t=2}^{n} |\alpha_t - \alpha_{t-1}|^2 \tag{1}$$

A represents the tread angle metric, *n* the number of treads, *t* the tread number and α the tread angle for a particular tread.

5.2 Tread Side Metric

According to premise 4, the dimensions of tread sides (as illustrated in Fig. 3) of consecutive treads should only change gradually. For the curvature of a hand rail, relative changes in tread dimensions appear to be more closely linked to visual smoothness than absolute changes. Therefore we look at the proportion between treads, rather than absolute lengths:

$$D_s = \sum_{t=2}^{n} max\left(\frac{d_{s,t}}{d_{s,t-1}}, \frac{d_{s,t-1}}{d_{s,t}}\right)^2 \tag{2}$$

D_s represents the tread side metric, *n* the number of treads, *t* the tread number and *d* the dimension of the tread side for a tread with number *t* or *t-1* on either the left or the right side (*s*) of the tread. The values are squared as it is preferable to have many small changes instead of a few larger ones.

5.3 Tread Direction Metric

According to premise 5, the front line of a tread should ideally be perpendicular to the walk line. For this metric, we square the angles between the front line and ideal perpendicular line for each tread:

$$W = \sum_{t=1}^{n} \left(\theta_{tl,wl} - 90°\right)^2 \tag{3}$$

W represents the tread direction metric, *n* the number of treads, *tl* the front line of tread *t*, *wl* the walk line direction at tread *t* and θ the angle between a tread's front line and the walk line.

5.4 Combined Metric

To be able to numerically evaluate stair designs, relevant metrics need to be combined in a single smoothness metric. In order to control the influence of each metric, weighting factors are introduced. These can be set to 0 in case a particular metric is not to be used.

$$S = (a \cdot A + b \cdot W + c \cdot D_l + d \cdot D_r)^{-1} \tag{4}$$

Here, *S* is the smoothness, *a, b, c* and *d* are weighting factors and *A*, *W* and *D* are the metrics described above. For *D*, separate weighting factors can be set for the left and the right side of the stair.

6 Algorithm

The algorithm we propose is an evolutionary algorithm. The process starts by generating a stair object with the required number of treads. If a walk line is provided, the tread positions will be defined on the walk line. The initial tread angles can be set to any value. As at this point there is only one stair object, it is marked as the best candidate. Geometry output for this stair object can be created using the stair object's tread positions, angles and tread side lines, or if these are not given, by constructing treads one by one, as illustrated in Fig. 4.

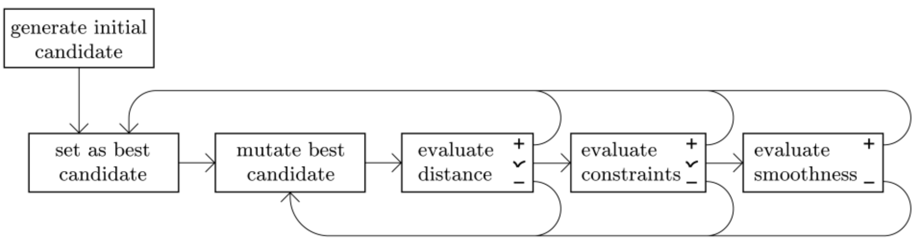

Fig. 5. Scheme of the proposed evolutionary process for free-standing stairs. In the evaluation steps, the tick marks mean that a goal has been met, while the plus sign indicates that even though the goal has not been met, the result is an improvement over the previously best candidate. A minus sign indicates that a candidate does less well than the best candidate and is to be discarded. The constraints evaluation step is optional and for winding stairs, the distance evaluation can be omitted.

Variations of the best candidate are generated by duplicating the object representing the best candidate and slightly modifying one or more angles in the new candidate's tread list. As illustrated in Fig. 5, goals for the algorithms are compared sequentially. In case of free-standing stairs, initially only the distance to the desired end position is evaluated and if a candidate's distance to the target point is smaller than the best candidate's distance to this point, the new candidate will now be designated as best candidate. Once a candidate with a target distance below the distance threshold has been found, the next goal comes into play. From this point on, the best candidate is only replaced by candidates that not only perform better on the new metric, but also fulfil the distance criterion. Once all other goals have been met, the smoothness of candidates is compared with the best candidate: the best candidate is replaced when a candidate is found that is smoother than the previous best candidate while also fulfilling all other goals.

The process can either run continuously until the designer stops it, for a fixed amount of iterations, for a fixed amount of time, or until no further progress has been made for a certain number of iterations.

6.1 Constraints

There may be additional design constraints that are not included in the smoothness metric. For example, one might want to specify a minimum tread side dimension, or for freestanding stairs, a particular angle at which the target point should be approached.

For such constraints, we add an additional step in the evolutionary process: before evaluating the smoothness at all, we first evolve the stair until it fulfils the additional constraints. From that point on, the current stair will be replaced by smoother candidates as long as they still fulfil all additional constraints.

On top of smoothness criteria and additional constraints, the designer may want to control a particular tread angle, or may want to exclude certain treads from being modified. This can easily be accommodated by excluding these treads from the perturbation process of the stair candidates.

6.2 Implementation

We implemented the algorithm described above in C# as Grasshopper components for Rhino [13]. However, the methods could be implemented in practically any language and environment. The Grasshopper components and the source code of our implementation have been released under the name Ammonite [14].

7 Application A: Winding Stair

In this example, we apply our method to the design of a winding stair with two winding sections. The contours of the stair in the floor plan are given, so we can draw a walk line and divide it evenly. Treads are then created at the resulting location and initially drawn perpendicularly to the walk line. After this, the algorithm described in section 6 will run, optimizing for some of the metrics described in section 5.

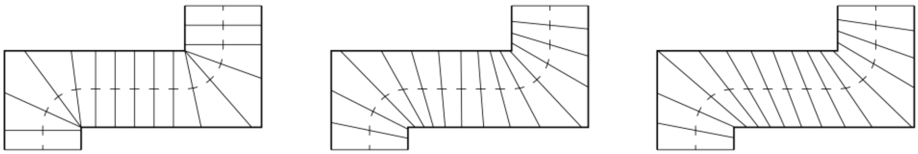

Fig. 6. A winding stair, optimized using metric *W* (left), metric *D* (right) and a combination of both metrics (middle).

When only using metric *W*, the tread sizes on both sides of the stair show a lot of variation and at some treads, the front and back line of the tread come together in a single point. This solution is identical to an unbalanced stair.

When only using metric *D*, the transition of tread dimensions on the sides is smoother. However, due to the geometry of this stair, many of the treads are skewed and far from perpendicular to the walk line.

By optimizing for a combination of metrics *W* and *D*, a good solution can be found. The weighting of the two parameters is done by the designer. As can be seen in Fig. 7, the balancing process not only influences the walking comfort, but also has a significant influence on the shape of the handrail, with balanced solutions exhibiting fewer kinks.

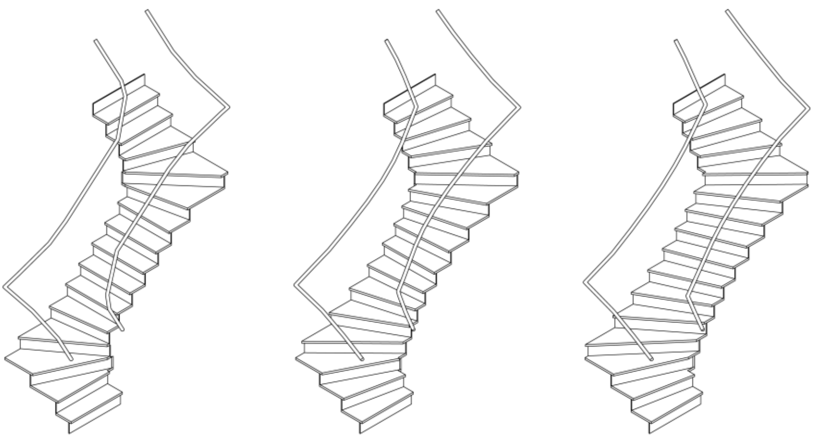

Fig. 7. Isometric views of the stair designs shown in Fig. 6. Large changes in tread sizes in the unbalanced stair (left) result in kinks in the hand rail segments.

8 Application B: Free-Standing Stair

In this example, we want to create a design for a free-standing stair with a fixed start point and start direction, as well a particular end point and end direction. The geometry of the stair will be generated algorithmically, by optimizing for smoothness metric *A* (as described in section 5).

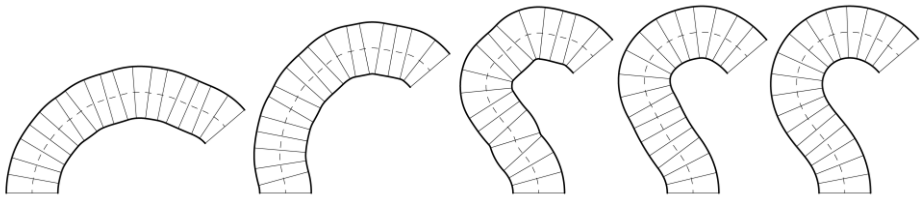

Fig. 8. Evolutionary process: in the first step, the position of the last tread is incorrect, but the direction of the last tread is already perfect. After a few thousand iterations, the distance to the target point is within desired range. From that point on, smoothness gradually increases.

The initial stair object is created in such a way that the sum of the tread angles equals the angle between the start direction and the desired end direction of the stair. Variations are created by first changing the tread angle of *n* treads by random amounts, and then subtracting the sum of these amounts from the tread angle of an unaffected tread. This way, all stair variations will approach the end point in the desired direction, which leaves us with only the end position as a constraint. Applying the method described in section 6 and Fig. 5 results in the process illustrated in Fig. 8. Results for various target points and target directions are illustrated in Fig. 9.

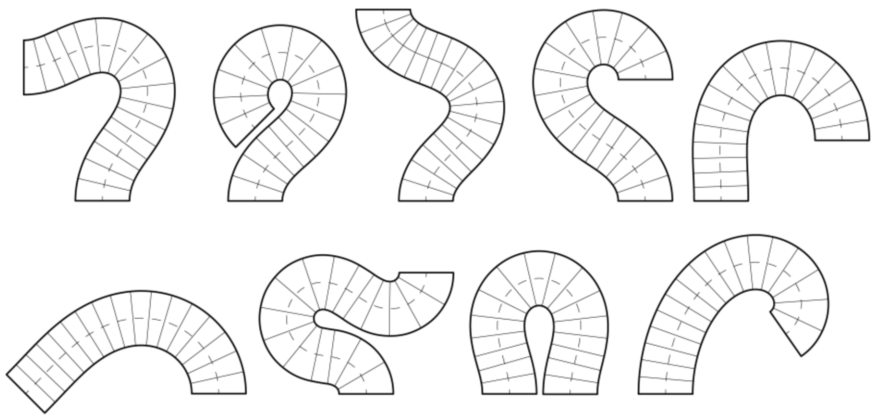

Fig. 9. Examples of stairs that are generated using smoothness metric *A*.

8.1 Obstacle Avoidance

Obstacle avoidance can be added as an additional constraint. Instead of just checking for distance to the target and smoothness, the evaluation of candidates is now a three stage process: first, the amount of overlap with an obstacle is compared with the current stair; if the amount of overlap decreases, the tread list is replaced. Once there is no overlap at all, the distance to the target point is used to compare solutions. Finally, when there is no overlap and the distance to the target point is within the desired range, smoothness will be improved. Examples of the outcome of this process are shown in Fig. 10.

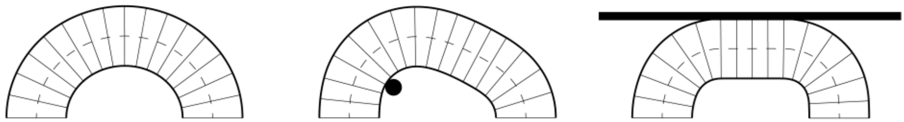

Fig. 10. Result of automatic obstacle avoidance, using a column (middle) and a wall (right) as obstacles. As a reference, the result without obstacle is shown on the left.

9 Results

9.1 Design Quality

Objectively comparing the results of our method with known good examples is difficult, as using the evaluation methods introduced in this paper would be an unfair advantage. Furthermore, for any given situation, there are multiple manual balancing methods that could be used, and there are also multiple combinations of metrics and weighting factors that can be selected when using our method.

When evaluating the results of our methods visually in plan, in unrolled section and in 3d, in our opinion the results are often very good. However, as can be seen in Fig. 5, there are situations where particular optimization metrics lead to less desirable results and the designer will need to experiment with various optimization metric settings.

9.2 Speed

The calculation speed varies significantly between scenarios. For stairs with 16 treads and a fixed walk line, metrics A and W can be calculated at a speed of 200.000 candidates per second using a single thread on a 2.7 GHz laptop processor. In practice, this means that the result can be displayed instantly. For metric D, line intersections need to be calculated and the speed drops to around 4.000 candidates per second. This is still fast enough to work interactively, but sometimes one has to wait for a few seconds before a good result has been reached.

For free-standing stairs, about 10.000 candidates can be generated and evaluated per second on the hardware mentioned above. However, convergence speed depends very much on the tolerance of the target point, because tight tolerances result in many candidates being rejected before smoothness is evaluated. An effective way to deal with this fact is to start with a large tolerance (for example 1 cm) and tighten it once a good solution has been found.

When using obstacle avoidance, many geometric intersections have to be calculated and the speed drops significantly, down to about 200 evaluations per second. However, it may well be possible that significant speed can be gained by implementing more efficient intersection checks.

The evolutionary process we propose is suitable for multi-threaded computation, so further speed improvements are possible. However, even the current computation speed already enables an interactive workflow.

9.3 Workflow

The methods we propose take far less time and also less skill and knowledge of the designer than manual methods. However, as the weighting of metrics influences the outcome, the proposed method should be considered a design tool rather than a fully automated process.

The tool can be used to address design challenge that to our knowledge cannot be solved with commonly used methods. This includes balancing both the left and the right side of a stair in parallel, designing free-standing stairs based on constraints only, and designing free-standing stairs with obstacle avoidance. Furthermore, the computational approach can be used to develop further interactive design methods, for example allowing the designer to manually control a particular tread position or orientation while the evolutionary process is running.

9.4 Robustness and Repeatability

So far, the methods we developed resulted in a solution in the vast majority of cases. Some additional checks proved to be necessary to ensure that the process would not get stuck on wrong solutions; for example, very large tread angles could result in intersecting tread lines, which should be avoided.

As variations are created randomly, there will be slight differences between solutions when starting with a different random seed. However, these differences are typically too small to have any impact on the design process. In some situations, the results of different seeds can be grouped in two sets of solutions, in particular in symmetrical or near-symmetrical conditions.

9.5 Applicability

A precursor to the work presented in this paper has already been used to aid in the design of a stair in the Forum shopping center in Helsinki (see Fig. 11). In this particular project, there were tight geometric constraints that would have been very hard to resolve with other approaches.

Fig. 11. A stair in Helsinki designed by SARC Architects. Development of design tools for this stair initiated the research presented in this paper.

10 Conclusion

We introduced metrics to evaluate the smoothness of stairs and showed how this metric can be used to develop evolutionary tools for stair design. Rather than automating the design of various known stair types, our method is more general and should in principle be able to deal with any stair type.

The methods we propose are fast enough to be used in interactive design tools. The implementation of the proposed methods is straightforward and additional constraints can be easily incorporated.

We have shown how our methods can be used to design free-standing stairs as well as winding stairs. For winding stairs, the left and right sides of the stair can be balanced in parallel, which is not possible using conventional methods.

Free-standing stairs can be generated based on just a user-defined target position and target direction. As an example of additional constraints that can be included in the evolutionary process, integrated obstacle avoidance has been demonstrated.

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Towards Intelligent Control in Generative Design

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Abstract. This position paper proposes and defines the nature of a framework, which explores ways of integrating control system (CS) with machine intelligence for generative design (GD). This paper elaborates about the implications of and the potential for impact on GD. The framework described in this work can be used as an active tool to drive design processes and support decision making process in early stages of architectural design. This type of system can be either automated in nature or adaptive to regular user input as part of interactive design mechanisms. The module of CS in the framework would allow additional guidance during design and therefore reduce the need of manual input to enable a semi-automated design practice for lengthy generative processes. This study on GD reveals emergent properties of the framework, for example the introduction of intelligent control allows guidance of GD to meet specified performance criteria and intended aesthetic expressions with reduced need for user interaction.

Keywords: Semi-Automated Design, Evolutionary Architecture, Generative Design, Architectural Optimisation, Artificial Intelligence

1 Introduction

As technological progress accelerates, there is an unprecedented growth in information [12] that provides opportunity for the establishment of contemporary design paradigms, generative design being one of them. While the impact of emergent innovative technology on design processes has a significant history in architecture [21], [34], [61], Mitchell predicted [41] that the extension of the use of computational design systems will change the way we practice architecture in radical ways and increase in computational power will transform the industry. In brief, the presented position paper elaborates on one trajectory of technological disruption that possesses the potential to transform the nature of GD to utilize it as support tool for decision making in architectural design.

Machine intelligence can be applied to architectural design in one of the following categories: (1) analytic processes feeding into predictive analysis to learn from realized designs for the design of future instances of a similar typology or design case, (2) intelligent building control, coined smart buildings, adding control features to architectural technology or kinetic features in buildings, or (3) intelligent control of generative processes, usually in form of optimization of potential design solutions towards specified performance criteria – coined morphogenesis in architecture [40], [50]. Because of the limitation of architectural optimization on the variation of decision variables, the proposed framework focusses on the integration of artificial intelligence technology for grammatical evolution of design solutions to increase the emergent design potential during architectural optimization.

In the same way, generative structural design of shell structures [5], [48] and structural nodes [13], [24], [45], [47], [62] may be improved. Form-finding for optimal structural solutions is addressed by two main streams: discrete structural optimization [7], [18] and continuous structural optimization [17], [64]. Even interactive structural optimization processes were explored in the context of parametric design environments [14], [27], providing invaluable insights on the limitations of parametric design and interactive exploration of the associated design space. While an exploration of these areas would be promising for application of the framework, it is beyond the scope of the provided argument to extend on the considerations related.

In this paper, we describe the framework for the development of a CS for GD based on machine intelligence and interactive evolutionary computation [39], [58]. The key aspects discussed are:

(1) the intelligent design framework for the integration of a novel interactive strategy to enhance semi-automated design generation
(2) the integration of a preference-based fitness function in the evaluation process of the search process in the context of early design in architecture
(3) the potential improvement of decision making in GD based on the guidance procedure that allows the designer to navigate the optimisation process

2 Background

For a review and comparison of other suitable generative algorithms that could be used as module in the proposed intelligent design framework, refer to the work of Singh & Gu [54]. Furthermore, the referenced work provides evidence on the use of a combination of different GD methods. Subsequently, different GD methods could be applied to advance the design to the next design state with different contextual specification.

The basis of the argument is the necessity to address designer's intent in automated design processes. Therefore, the GD process described by Mitchell [41] and presented in Fig. 1 is used as a foundation for the reasoning. This computational design process incorporates the cyclical nature of design tasks and differentiates essential activities during the design process. To summarize this approach, the design problem is analysed and structured to the current knowledge of the design process before a data structure is developed and implemented as a representation of the design problem.

Performance criteria, decision variables, constraints, parameters, geometric attributes and topological relationships are defined by the design case and specified for the implementation.

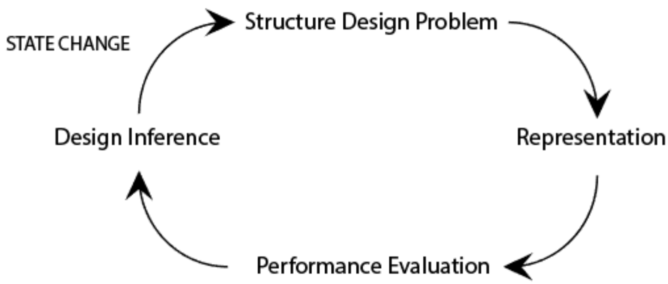

Fig. 1. GD process after Mitchell [41]

In the next step, the generative process is initialized and evaluated based on performance criteria. The choice of those criteria frames the decision-making process and reflects the design goals. Thus, the simulation methods used to evaluate the design and the decision variables are to be defined in the context of the desired trade-off. At this stage human and computational resources available for the GD need to be considered, especially when using expensive fitness evaluation. One key contribution of the intelligent control module outlined, is the reduction of the user and simulation effort during lengthy processes, while providing maximum flexibility for the designer to provide additional non-solution input.

2.1 Structuring Design Problem

Structuring design decisions is a crucial task during design processes. As tools frame design processes during computational processes, the choice of representation is crucial for the outcome of the process. The impact of the choice of representation used to describe design spaces is extensive and defines the set of phenomena we are interested in [15]. At this step, architectural expertise is required to define the hierarchy of functions, variables and parameters for a specific design case [2]. Based on the suggestion of Akin & Dave [2] to rethink those processes of representation construction as part of a control system, some aspects of the hierarchical assembly can be constituted based on the flexible representation of genetic programming.

It has been suggested that rule-based systems are an efficient way to encode architectural shapes [10]. These generative systems exhibit a range of degrees of emergence and volatility, depending on the set of rules or behaviours chosen to define the bottom-up process. Prior to the introduction of CS, the use of grammatical rules [6] and the generation of those rules [35] needed to be fully automated to efficiently exploit the emergent potential of GD.

The context of shape generation in architecture is broad with methods ranging from shape grammar [23], genetic algorithm [38], genetic programming [11], [59] and grammatical programming [10] to grammatical evolution [6]; [44]. Even if all those methods allow for the introduction of intelligent control, the presented framework focusses on the use of genetic programming and shape grammars.

The definition of performance criteria is dependent on the design task and specific to the application case. Three main decisions need to be taken:

(1) Specification of the criteria used for the performance evaluation
(2) Definition of constraints used as thresholds of the criteria's domains
(3) Goal weighting for the performance evaluation, specifying the relative importance between the criteria during the trade-off process

As design problems are wicked or ill-defined in nature, the result of the structuring process might be a preliminary trajectory of investigation that is used to generate knowledge about the design problem. In this case, the process would result in a more refined formulation of the representation in the following design state. In other cases, the optimisation process already leads to a computational model representing a feasible design solution.

2.2 Defining Representations

The qualities integrated in the representation of architectural design are of either geometric, topological or contextual nature [2]. Those aspects of the architectural problem need to be specified and encapsulated in the representation to define the design space. The representation is dependent on the chosen process of shape generation. This research paper focuses on the discussion of shape grammars and grammatical evolution [44], [46], because the multi-facetted nature of design problems suggests their efficiency in use for performance-driven design to define architectural shape, building features and plan layouts.

Grammar-based models of the representation of architectural shapes [1], [43] were explored in depth [19], [28], [57], [63] and the related challenges reported in other research in this area [29], [55] will be addressed by the proposed intelligent design framework. The lack of efficient control of shape grammar systems during interactive design processes is addressed through the introduction of a guidance mechanism controlling the periods of automation in broad interactive approaches will increase the efficiency of GD and reduce human effort.

During the control of GD, interaction between the artificial intelligence and human designer is facilitated through the common evaluation of the genotypic (representation and grammar rules) and phenotypic (interactive, multi-criteria optimization) expression developed during the framework development. Further insights, gained by reflection on the relationship between architectural genotype and phenotype [42] will inform the ongoing speculation promoted through the development of the proposed framework.

The combination of the use of flexible representation based on genetic programming for automatic shape generation [44] and control of the grammatical parameters and rules as described by Byrne [6] and Lee [35] are basis for the conceptualization of the presented framework for integration of intelligent control [65]. It will contribute through the introduction of additional strategic potential for support of decision making in early design stages and a novel mode of interactivity in GD using non-solution input as a reference for the guidance mechanism contributing to the fitness evaluation, which will be discussed in section 4.

2.3 Performance Evaluation

Numerous authors have argued that integration of simulation and optimization in architectural design generate novel designs, while simultaneously leading to significant performance improvements [3], [4], [9], [53].

The integration of performance simulation and multi-criteria optimization is facilitated based on the modular nature of the intelligent design framework. A variety of possible combinations of criteria could be introduced and some will be explored in future experiments. Repeated computational experiments to review the performance of design solutions are described by Burry and Burry [8] as virtual prototyping. The presented research extends this notion that is closely associated to parametric design setups for optimization in architectural practice, towards a semi-automated design practice to overcome the limitations associated with current visual programming environments.

2.4 Interactive Design Synthesis

The main contribution of the proposed intelligent design framework for digital morphogenesis using semi-automated design is the introduction of a preference-based control system using reference input to constantly reflect the preferences and requirements of decision makers that frame architectural design processes.

As the generated shapes by themselves contain no meaning when the process is initialized based on a random population, after the first iteration already a common creation of meaning takes place inside the framework. This creation of meaning is provided by interactive evaluation and the novel input mechanism on one side and the automatic evaluation of multiple criteria on the other side. Then, constraint satisfaction and semantic structure of the solutions are tested to make sure that the solution reflects the scope of the design problem and addresses all thresholds and limitations imposed on the decision-making process. Therefore, the interactive evaluation during every generation addresses only the solutions that are suitable as solutions to reduce user effort and computational expenses during fitness evaluation.

Performance-based GD related to Morphogenesis [31], [50], [51] will benefit from the adaptation of intelligent control, extending the designer's influence on the strategic exploration of the design space. Furthermore, the discourse about second-order cybernetics in architecture and the associated discussion about control of feedback loops through the designer, as intensively discussed by Thomas Fischer [20] will be revived through the reasoning on concepts of intelligent control and human-computer interaction.

The described framework takes the step from GD and semi-automated design using a CS for intelligent decision support during GD, as a novel way of human-computer interaction in early design stages of architectural design. In conclusion, this position paper speculates about a design framework through the introduction of intelligent control into decision making processes based on interactive multi-criteria optimization.

3 Research Methodology

The intelligent design framework builds on critical review of GD in architecture, engineering and computer science and simultaneously evolves theoretical considerations, implementation of active design tools based on system design methodology and strategic design exploration in form of case studies to reflect on the implications of the work on creative practice. The main modules of the framework are presented in Fig. 2. The green modules are already implemented, the module marked blue is currently under development, while the red modules will be implemented as part of the intelligent design framework. The goal of the study is to reduce designer fatigue during interactive GD by introduction of a CS alongside conventional fatigue reduction methods.

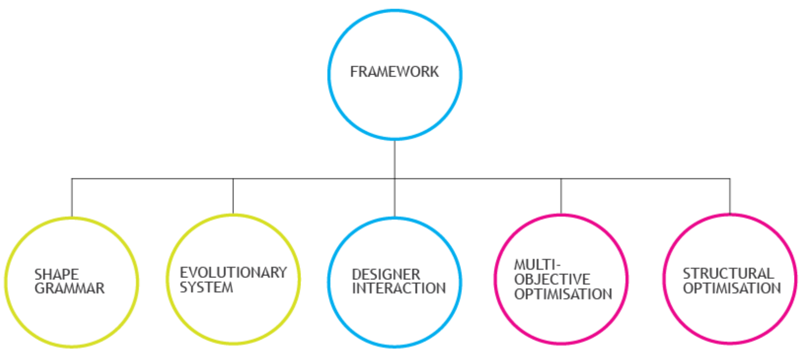

Fig. 2. Modular structure of intelligent design framework

3.1 An Intelligent Design Framework for Semi-Automated Design

The intelligent design system proposed in this research could be applied in a variety of different design-related fields, e.g. engineering, interior design, landscape architecture. The validation of the design system for architecture based on the exploration of various case studies is inside the scope of the research project and will be explored in the next iteration of the process. The implementation will be discussed in section 4 of this paper.

Basis for the development of the framework is a GD that is based on parameters, and rules or behaviours to build solutions computationally during a bottom-up process. In this context, artificial selection is an invaluable asset for the introduction of expert knowledge into the design process.

A point often overlooked, is that in the period between user inputs during a broad interactive approach, the generative process is fully automated and could be extended by introducing an additional guidance mechanism. In fact, this CS evaluates aesthetic qualities of the design alongside other specified performance criteria. Therefore, it addresses the core aspects of architectural design – form and function – about subjective preferences and allows GD to evaluate design solutions towards the codes of utility and beauty constituted by Patrick Schumacher [52].

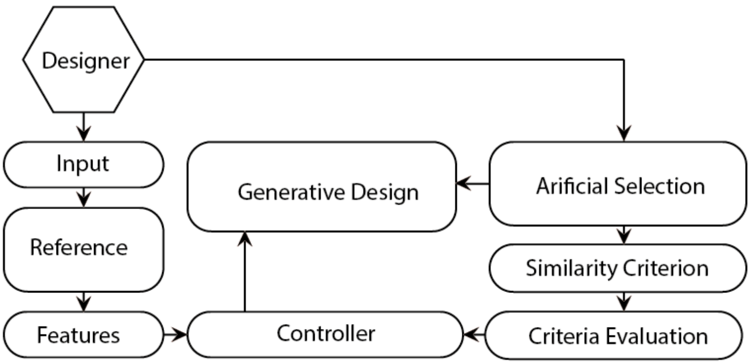

Fig. 3. Integration of Designer Interaction Module in GD

The CS is integrated into GD as part of the Designer Interaction Module as shown in Fig. 3. Here, a non-solution input is provided during initialization of the GD as reference for the controller to evaluate subjective preferences as part of the utility function. This research contributes to the architectural discourse in the context of GD with the proposal of additional guidance during lengthy design processes to minimize human effort, while increasing the amount and quality of user input to guide GD.

3.2 Intelligent Design System

For control of GD, an intelligent system is developed that uses either images as two-dimensional input or mesh geometries as three-dimensional input to guide the search process based on a set of features extracted from the input data.

To the end of a more direct and creative input to the design process, the reference introduced to the GD is continuously evaluated to provide additional robustness and stability. This is achieved by a constant comparison of the features extracted from input and output geometry to calculate a distance measure used as part of the fitness evaluation.

The intention is to provide an aesthetic guidance mechanism that allows the designer to introduce specific aesthetic qualities through the specification of a design reference. In addition, a multi-objective trade-off process integrates the aesthetic guidance with performance optimization towards specified criteria.

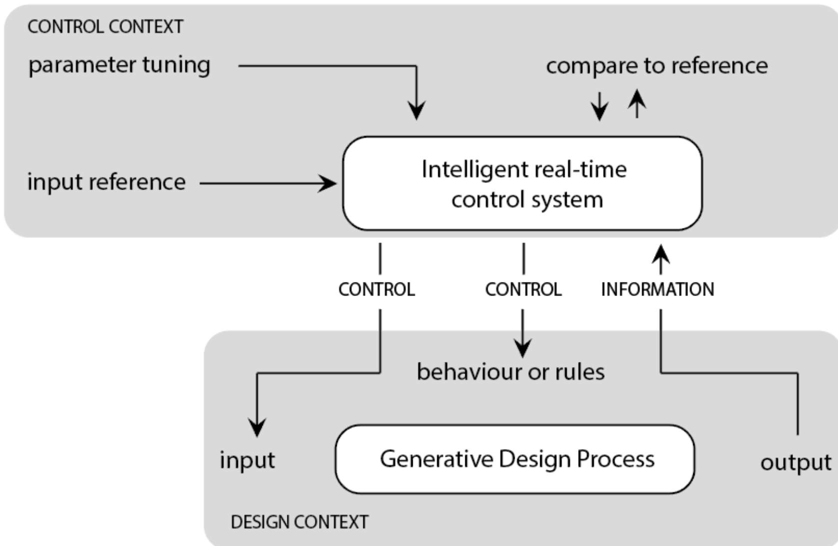

Fig. 4. Intelligent real-time CS for GD

The intelligent CS performs in a variety of calculations in real-time during the discrete time steps of the GD that works as a closed-loop system. A conceptual diagram of the CS is presented in Fig.4. In the next section of the research, we will discuss the agents, means and ends of the CS in greater detail.

3.3 System Identification Using Genetic Programming

The controller is based on a non-linear input-output model, because GD exhibits a non-linear system response that shows a discontinuous fitness landscape. Genetic programming systems as population-based methods fit well with complex fitness landscapes used to define the structure of a robust controller in a tree-based representation [37]. The application of CS in design systems can be used to integrate a reference to the performance requirements, system constraints and customer specifications of the specified design case [36].

Application to texture classification provides initial insights on possible implementation strategies [56] and considerations about aspects leading to increases in efficiency of image classification.

3.4 Learning and Knowledge-Preservation

The knowledge generated implicitly in the generative process is implicitly stored in the grammar representation used for the description of the solution. It consists of two connected aspects of the representation. On the one side the topological encoding of spatial relationships in the data structure and on the other side a feature-based encoding of the building components. Desired features can be enforced through their selection during the input process.

A mesh representation can be chosen for the development of the solution during the process, so that geometrical information about the shape and features of the design are stored in the representation directly. Therefore, any generative algorithm that can generate polygon meshes may be integrated into the framework. This link allows the use of different GD for distinctive design states and thus more creative freedom to the computational designer.

3.5 Genetic Programming

Genetic Programming is an evolutionary computing method first developed by Koza [33] that exhibits enormous flexibility in representation and can be used in a variety of tasks. It was used for shape generation [44], optimization [60] and space layout planning [26].

The symbol-based evolutionary system can be used to evolve computer programs and in this respect, evolution of controllers and classifiers are part of the systems capabilities. In the context of this research project, GP is used to implement the GD process based on shape grammar and genetic programming [44], [46].

The GP algorithm is based on an iterative, generational process that is structured in several steps. After generating an initial random population, a selection process takes place based on the evaluation of a fitness function. The selected individuals are then modified by the genetic operators of recombination and mutation. In a separate process, the best solutions of the generation are preserved by elitism. During the advancement of the generation, a new population is constructed based on the mated, mutated and preserved solutions.

A diagram of the implementation approach of the framework based on grammatical evolution of a strongly-typed grammar is shown in Fig. 5.

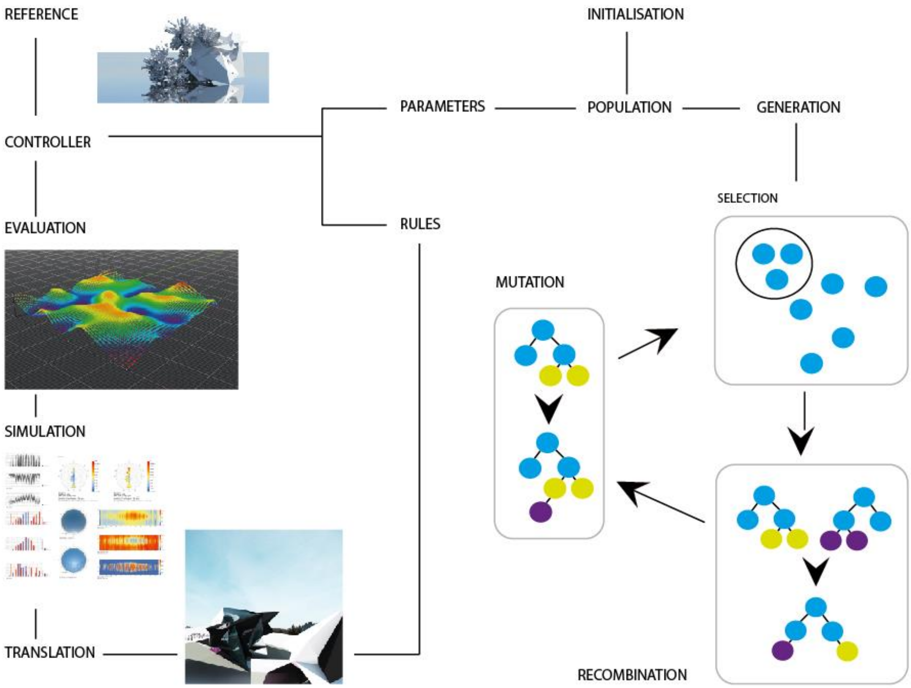

Fig. 5. GD based on Grammatical Evolution

Grammatical evolution is integrating the evolution of the rules or behaviours of GD into the evolutionary process based on either a string presentation or linear GP. Different combinations for the application of the rules or behaviours in a stages manner are explored during the co-evolution with the shape grammar representation, providing the data of the topology-based plan layout and the associated building features that describe a design space, usually in the scope of style or typology.

3.6 Implementation of Guidance Mechanism

An image upload allows the designer to upload a reference image. The features of the image are extracted using the SIFT algorithm available in the OpenCV library to identify the key points of the image.

During GD, the solutions generated are rendered as image files and the features matched to those of the uploaded image. This process allows to specify a distance measure that contributes to the fitness evaluation. It relates the reference image to the generated solution and guides the GD along the implicit aesthetics.

The necessary pre-processing of the images for feature extraction consists of resizing, blurring and omitting the colour information of the images. Through this process, the performance of the feature extraction algorithm is enhanced tremendously. The steps from source image (1) over blurring (2) and key point detection (3) to feature matching (4) are shown on an example in Fig. 6.

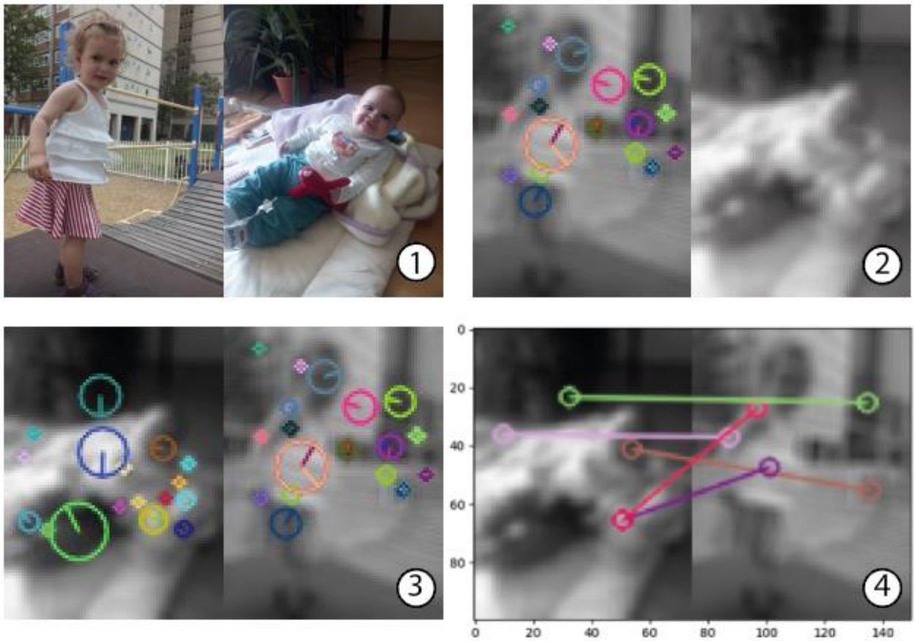

Fig. 6. Example of workflow for feature extraction and matching

During the GD, the user selects solutions as part of the fitness evaluation after a defined number of generations to adjust the guidance mechanism. This information is used for labelling a continuously growing set of training data for a Naïve Bayes classifier.

3.7 Classifier

During the last decades, machine learning experienced a growing attractivity in the scientific discourse and many new applications were developed. In the context of architectural design and engineering the use of expert systems was superseded by the introduction of classifier technology [49], because of the learning capacity of the system.

In machine learning, the term learning describes the capability of an agent to adapt its behaviour to an environment through an increase in knowledge. Therefore, performance improvements of the system are achieved over time based on the exposure of the agent to specific environments [32].

A classifier performs in different modes. In learning mode, a training set of properly labelled data is used to provide the classifier the possibility to learn the relationship between data and the labelling approach. In the context of this research, aesthetic criteria are addressed through the constant labelling of the solutions chosen by the designer as "desired" and "not desired" to train the classifier. The collection of the dataset for the classifier is continuously collected during the ongoing process, so that the evolution of the design can be adjusted based on the choices made during the artificial selection process.

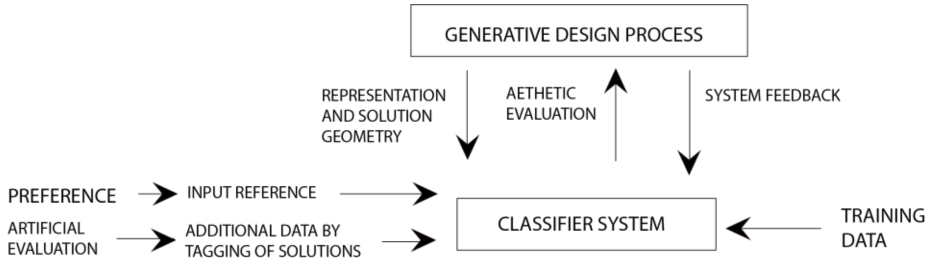

Fig. 7. Schema of a classifier integration

After successful training of the classifier, the CS is presented with the validation data set in application mode. Based on the learnt behaviour, the classifier evaluates the data and continues the learning process. The selection solutions presented for user evaluation is facilitated by the continuous update of the learnt model/classifier, so the system can be adaptive to changes hence more intelligent and requires less manual input. A schematic description of the process is given in Fig.7.

The Naïve Bayes classifier can work with comparatively small sets of training data and deal with noisy data efficiently. As the training data set might not be generated consistently in reflection of rational principles, but handled intuitively, the choice of classifier allows to accommodate for changes in subjective perception during the generation of solutions.

4 Framework Discussion

The focus on early stages of architectural design frames the following speculation about the implications of and the potential for designers to use the proposed framework during briefing, design and planning processes. During those decision-making processes, the design framework can be used to explore a variety of design solutions for goals with different weighting on performance criteria.

Linking to the tradition of automated design in architecture, the section is structured analogous to the seminal work of Mitchell [41] in the conclusions of his publication.

The modular framework for intelligent design for semi-automated design increases the efficiency of interactive GD through two modules. One is a similarity criterion that reduces the number of solutions that are reviewed by the designer and the other one a CS that introduces guidance based on aesthetic evaluation of the generated solutions.

As the learning process of the classifier is computationally expensive, a parallel implementation of the process might increase the efficiency of the decision support tool. In this context, the computation of expensive fitness functions could also be outsourced to a computer cluster to further improve GD. Extensive studies with finite elements (FE) or computer fluid dynamics (CFD) will gain more relevance, as the CS will help to reduce optimisation time by limiting the amount of solutions computed.

Keeping this scenario in mind, the proposed intelligent design framework can be used to provide guidance to these lengthy processes, which usually either prevent the feasibility of human interaction completely or accept delays based on the waiting time of the computational system, if the designer is not present.

User fatigue is one of the main concerns that are present in the current discussion about interactive GD. The proposed framework increases the efficiency of the GD and reduces the amount of manual work that is necessary for the designer to input through an increase in automation of the interactive aspect.

Another main aspect of the framework is the aesthetic guidance mechanism that extends the designer input and guidance potential during GD. The relevance of this aspect in based on the assumption that the designer using the intelligent design framework uses a rational decision making process based on criteria that can be either quantified or consistently applied during artificial selection.

5 Conclusion

In the context of architecture, multiple complex systems can be combined to generate a holistic design solution. Often a variety of experts participate in the development of sub-systems that contribute to the building performance. The modularity of the GD process that can be achieved based on a unified representation can facilitate a multi-level GD process that could be used to generate solutions for specific sub-systems in the context of a larger model.

Because of increasing costs and rising awareness for the climatic challenges of our times, performance requirements for buildings are constantly improving. Therefore, optimization processes will become mainstream technology in future design processes. Even if some performance criteria can be automated, the unique knowledge of architects about the philosophical, social and cultural aspects of design will not be automated. Semi-automated design processes using intelligent technology to provide means for interaction for designers during GD, integrate the extensive knowledge of the architect with the computational capacity of automated systems to evaluate complex trade-offs between conflicting criteria.

In early design stages, the specification of fabrication constraints, case-specific and site-specific requirements and stakeholder preferences are still in development. Thus, designer input is necessary to dynamically add those specifications using the designer's intuition. The proposed intelligent CS allows the externalization of some of these aspects through the specification of a reference input that incorporates an aesthetic expression, specific features and qualities in its representation.

In GD, the acceptance of generated solution by the designer is the main criterion for the application of optimization results. Additional input to the GD increases the potential acceptance, as the decision-making process is on side of the designer, while the GD supports the decision making through the provision of strategic data, the potential to explore different combinations of goals and criteria and the definition of a wide range of constraints on the representation, grammar and parameters.

6 Future Research

Future work will explore the application of a mesh representation for the generative process to store geometric features directly in the representation that is evolved during the grammatical evolution. This approach creates the possibility to use the output of one GD process as input for another one that modifies the mesh representation again. As an implicit knowledge storage mechanism, design decisions made during the development of one design stage can be transferred directly to the process used during the following design state.

The presented intelligent design framework extends strategically the application potential for interactive features of GD for architectural design. To these ends, a mechanism for guidance by aesthetic evaluation is integrated into the semi-automated search process for case-specific [22] and site-specific design. Multiple ways of implementation for a CS can be used to improve the efficiency of GD. While the presented framework builds on classifier technology with a medium level of complexity, less complex approaches like model-based and data-driven control mechanisms may achieve different results that might be more desirable in the context of specific design cases.

The proposed speculative framework can be applied in a variety of computational design methodologies, from diagrammatic approaches e.g. in space layout planning [26], [30] or activity representation [16] to three-dimensional shape generators [44]. In parametric design, the application of the framework might increase the efficiency of recently developed generative tools for shape generation, e.g. the genetic programming-based active tool implemented by John Harding [25].

In conclusion, the proposed intelligent design framework reveals potential for better performance of interactive design processes using GD by increasing the efficiency of user input. The main contribution of the framework is the use of non-solution input during the initialization of the GD process and the intelligent control of the GD based on feature extraction of the reference provided during this input.

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Dense Urban Typologies and the Game of Life

Evolving Cellular Automata

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Abstract. The ongoing rate of urbanization in China is the motivator behind this paper. As a response to the observed monotonous housing developments in Suzhou Industrial Park (SIP) and elsewhere our method exploits Cellular Automata (CA) combined with fitness evaluation algorithms to explore speculatively the potential of existing developments and respective building regulations for increased density and diversity through an automated design algorithm. The well-known Game of Life CA is extended from its original 2-dimensional functionality into the realm of three dimensions and enriched with the opportunity of resizing the involved cells according to their function. Moreover our method integrates an earlier technique of constrcuctivists namely the "social condenser" as a means of diversifying functional distribution within the Cellular Automata as well as solar radiation as requested by the existing building regulation.
The method achieves a densification of the development from 31% to 39% ratio of footprint to occupied volume whilst obeying the solar radiation rule and offering a more diverse functional occupation.
This proof of concept demonstrates a solid approach to the automated design of housing developments at an urban scale with a ,yet limited, evaluation procedure including solar radiation which can be extended to other performance criteria in future work.

Keywords: Evolutionary Design, Generative Urbanism, Integrated Strategy

1 Introduction

Accelerating urban development has been – and still is [1]- one of the key strategic plans of China in increasing its economic development. This strategy has worked well as an economic development tool but has also created a real estate market full of vertical towers, or horizontal sprawl, but always monotonously repeated- building arrangements for housing [Fig. 1].

Fig. 1. Repeated tower and horizontal sprawl at the case study HuDieWan and wider environs.

The towers, where the present paper focuses on, are essentially two dimensional in the sense that typical floor plans are simply extruded almost arbitrarily regardless of any context. To conform to existing building regulation the towers are just moved apart as much as needed to let enough sunlight reach the individual apartment while the speed of design forces the architects to rely on previously tested solutions. As such the efficiency of the land usage is very low and at the same time the architects lose the opportunity to explore the potential of the third dimension in the architecture produced. The case study under examination is located in the city of Suzhou in the Yangtze River delta and its new Industrial Park (SIP), constructed 25 years ago in a collaboration between the government of Singapore and the government of the People's Republic of China [2].

In Suzhou Industrial Park [13], the acceleration of construction of housing for urban population has eroded the agricultural land use in the area of Suzhou to about 1.5% of the total while the need for urban growth has not subsided [3]. Apparently, there is a discrepancy between the still increasing demand for housing supply and the very limited availability of land for new developments. A solution to this discrepancy can be the densification of existing housing developments. A higher density achieved through densification above ground – in the third dimension – would sustain the existing greenery within the developments whilst providing more living space. A densification whilst obeying existing building regulations would result in a more efficient land use while sustaining an equally high standard of living. We examined one example of a monotonous tower housing development, analysing the determining building parameters including building regulations and their impact on the actual planning and architectonic decisions made by the local planning office which led to the repeated tower pattern. The project then employed architectural computational techniques to investigate how to increase housing density. We transformed a standard cellular automata mechanism into an integrated generative and evaluative parametric system along evolutionary principles. In this paper we examine the possibility for optimisation of the building density, expressed as a ratio between maximised volume and to minimised footprint, along with the optimisation of the sun exposure of the surfaces of the building, expressed as solar incidence number, as per regulations.

A novel introduction into the proposed algorithm, is the parametric representation of the social condenser, a constructivist concept of overlapping and intersection of programs within a building, employed by in the 20th century by architects such as Rem Koolhaas & OMA, Ivan Leonidov, Mosei Ginzburg [4, 5]. We were able to produce results with increased density and similar parametric profile of the current residencies, thus in theory similar quality of life. Apart from the integrative nature another innovative part of the system is the inclusion of programmatic variety in three dimensions, thus breaking the functional monotony we encounter in Chinese megacities and walled communities [6]. The project is expected to provide an understanding of how housing density contributes to the sustainable development of the built environment of new towns like Suzhou Industrial Park, by stopping the transformation of land from agricultural and rural to urban [Fig. 2, 3].

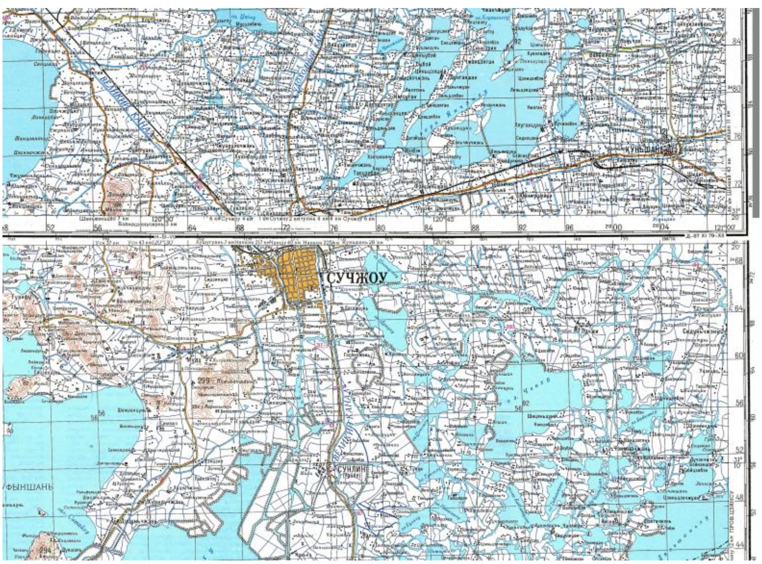

Fig. 2. Map of Suzhou area circa 1970: Soviet military map. Clearly visible is the difference between urban and agricultural land

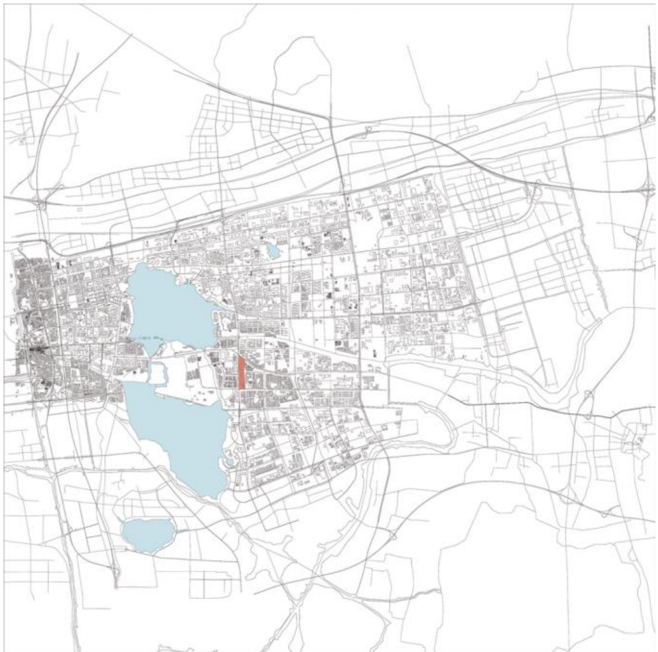

Fig. 3. Suzhou Industrial Park with red hatch indicating the location of the case study HuDieWan or Butterfly Bay compound.

2 Background

2.1 Cellular Automata

Cellular Automata are not new in the areas of designing dense towers or dense housing environments. Herr [7] has explored the mechanism of Cellular Automata as a tool for architectural designing and adapting an existing strategy of tower design with increased density. Subsequently Herr [8] has also explored the adaptation and exploitation of Cellular Automata in architectural design computation processes, ranging from the deterministic for generating a plan to the playful, conversational-with-the-designer use of Cellular Automata. Others such as Khalili & Stuffs [9], equally recently have used Cellular Automata as an engine for architectural design in dense housing conditions in the Netherlands, focusing on accessibility and light exposure, however at a significantly smaller scale and density than the present China study. In other earlier cases Kwaczyk [10] has looked into adapting Conway's game of life to develop three dimensional rules for architectural designs that handle functional requirements.

The rule based creation of morphologies by the Cellular Automata is not able to discriminate different individual according to their potential performance. Cellular Automata apply generative rules within a clearly defined framework but they are not able to evaluate whether any created individual performs differently towards certain performance criteria. Within a Cellular Automaton all solutions are equally valid since they are all compliant with the applied rules. However, the introduction of an evaluation algorithm connected with a search procedure allows to discriminate solutions based on performance criteria. The present paper drives cellular automata and their subsequent evolutionary evaluation using the basic parameters of the building regulation in the Suzhou Industrial Park.At the same time the novelty of our method extends to the use of the 'social condenser' as an urban center and functional diversification tool of the monotonous housing towers in SIP, and by extension China.

2.2 Simulated Annealing

The "Simulated annealing" algorithm as inbuilt into Grasshopper is a computational search algorithm which refers to a method in metallurgy where through the increase of temperature the bonds between atoms in a metal sample are weakened enabling them to take positions of lower energy state. As the sample cools down subsequently contained atoms form larger areas of stable metal grid than before. Analogous to this method, simulated annealing in computation as a search algorithm uses temperature as a controller for the search algorithm. The algorithm typically starts with an initial temperature T_i. The temperature T_i allows the algorithm to pick a random point of the solution space in a certain distance d. The distance d is proportionally related to the temperature T. Thus, through reducing the temperature T, the distance d also decreases and limits the search radius of the algorithm. By picking a random point q on the solution landscape and subsequently picking another point on the solution landscape within a certain distance d, where d is depended on the current Temperature T, the search algorithm compares the quality value q_i with q_i+1. If $q_i+1 > q_i$ the algorithm jumps to the point q_i+1 and resumes the previous steps. If $q_i+1 < q_i$ the algorithm typically stays at the position q_i and resumes with a different random pick within the set distance d. Yet to increase the variance and decrease the danger of early convergence to a local maximum of the solution landscape of the search function you could allow the search area to move even if $q_i+1 << q_i$. Reducing the temperature T step by step the related search radius d which determines the pick of the next iteration of quality comparison will be reduced and the search will narrow down towards the locally best result of the search. Typically the search comes to an end when a certain predefined temperature T or a predetermined quality value q_t is achieved.

The "Simulated Annealing" is a robust search algorithm which unfortunately doesn't guarantee to lead to the global maximum of the solution landscape, but it is efficient and successful in discontinuous and fractal solution spaces since the algorithm can overcome local maxima peaks and minima valleys in the landscape.

In the presented case, the fitness of the respective solutions is established through the evaluation of solar radiation and density as the ratio of volume to footprint using different simulation and geometric evaluation tools to establish a single value of quality q which can be fed into the "Simulated Annealing" algorithm to enable an efficient search for sufficiently good solutions.

The morphologic representation of the solution is the result of the applied Cellular Automaton which itself includes elements of randomness inbuilt into the growth algorithm but based on predefined starting conditions. The starting conditions which are to some extent the predetermining factors for the morphology of the solution are mapped towards the quality values of the fitness function. Depending on the results of the fitness function the initial conditions of the growth algorithm are adapted and the next (i+1) iteration of the morphological representation is grown and will undergo a fitness examination.

2.3 Evolutionary Methods

Evolutionary development is based on the selection of individuals from a larger group discriminated by their compliance to defined characteristics. Through the selection according to the characteristics these characteristics develop predominantly within the selected generations. Individuals can represent the entities or units in the before described groups or generations. The creation of individuals, in this case representing an instance of a potential tower, by the Cellular Automaton is based on few parameters such as the grid size, the height and number of floors and specifications of the "Game of Life" itself. These parameters contained in the genome of the created individual are mapped against a quality value which represents the individual's performance per the set solar radiation and density requirement. The before described search algorithm selects the best 50% of the created individuals and creates a new population through a randomized cross over recombination of selected individuals together with the selected individuals itself. This evolutionary process creates a dynamic solution landscape constantly improving driven by the discrimination within the search algorithm. The discriminating search algorithm simulating a metallurgic annealing process, will diminish the search radii as the 'temperature' decreases focusing on different areas of search within the solution landscape. Thus, the convergence of the process can be controlled through the speed of 'temperature' decrease and the number of selected individuals for reproduction.

The combination of the search algorithm and the evolutionary process are implemented in Rhino Grasshopper^{TM} and respective plugins thereof. The current implementation allows for population sizes of around 100 individuals to keep the system with an acceptable and reasonable response time using standard personal computation power, namely a 16 Gb Ram, i7 2200 Ghz laptop.

3 Research Methodology

3.1 Qualitative Markers

Using interviews with real estate agents of the region and the specific neighbourhood HuDieWan is based in, we attempted to establish the expected quality benchmarks that HuDieWan tried to achieve. These were: a production of a majority of 80% of one-child family units, that could also serve as affordable housing to be given to the community by the government, along with a series of apartments that serve as investment opportunities for middle class families in the area. We also attempted to evaluate the case studies' morphologies as qualitative factors including spatial configuration, spatial integration and functionality. The interviews with real estate agents, uncovered the modular and cellular nature of most of the housing complexes in SIP, revealing for example that most plans were similar, and only through uniting units by knocking down walls were they able to get any kind of diversity in plan. In this we wanted to make certain that the cellular and modular nature of Butterfly Bay/HuDieWan was a feature which is reinforced and enabled in other repeated tower patterns. Another notable feature of the design of HuDieWan was the fact that it was designed by a remote Design Institute, not a local one in Suzhou- It was designed by a design Institute in Shenzhen, perhaps making the case that similar strategies are employed all over China. However the low numbers of case studies in China that we had in our hands made it impossible for us to positively verify this as with the real estate agents. Other interesting facts, established by the interviews, was that some of the apartments were bought as investment by parents for their children, or that to get a custom apartment was only possible by combining and retrofitting 2-3 other apartments that had a typical configuration.

3.2 Case Study Butterfly Bay / HuDieWan Compound in Suzhou Industrial Park.

The project began with an examination of the volumes that repeated housing towers create in the Chinese urban landscape. By looking at the case study of Butterfly Bay though we discovered that the repetition of 10 cellular types of apartments defined the limited diversity of the towers. These cellular types, drove us to use cellular automata as the main engine in our generative system. Unclear termination rules in the cellular automata paradigm, i.e automata can run indefinitely, drove us to use evolutionary methods as optimization techniques.

The project examined one housing case study in Suzhou Industrial Park [Fig. 1, 3] and employed computational design methods to speculate about possible outcomes on increased density in SIP. The methods employed in the research were qualitative and quantitative in nature. [Fig. 5]

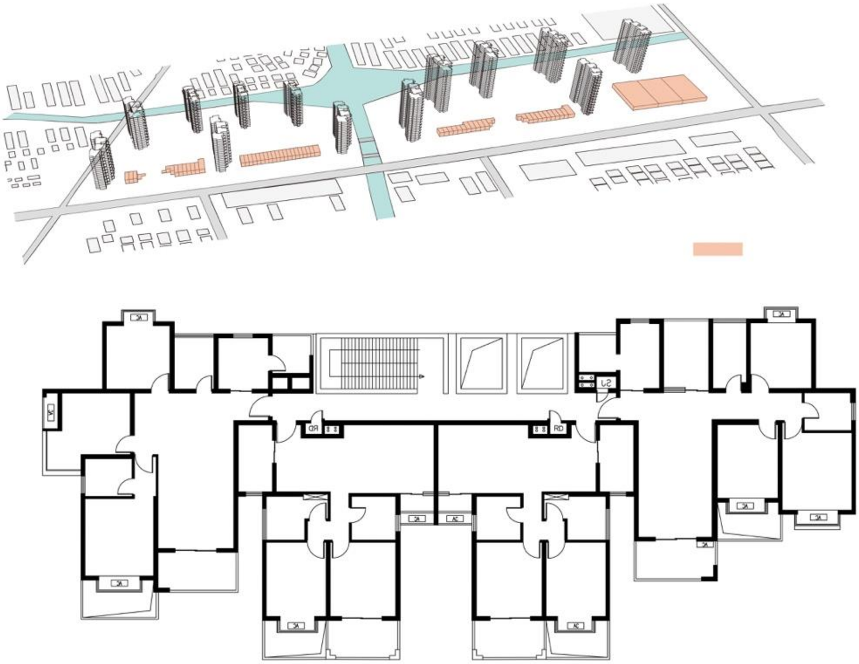

Fig. 4. Digital model of the residential area called Butterfly Bay / HuDieWan and typical floor plan

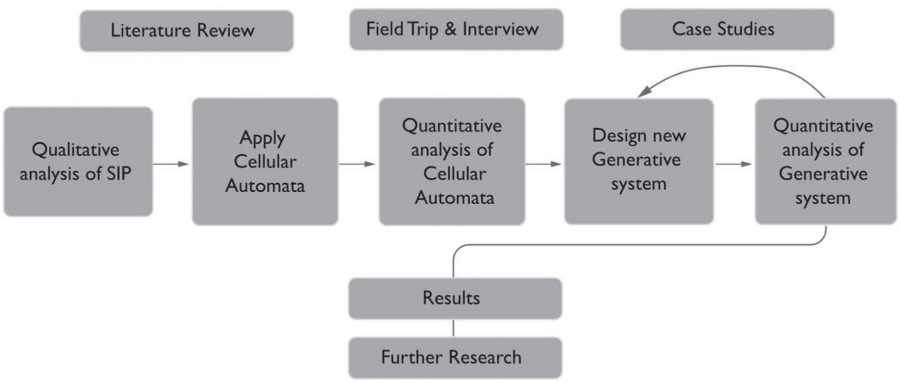

Fig. 5. Research Methods

3.3 Quantitative Research Objectives

The quantitative methods were focused in the speculative design experiment using computational design methods. Initial benchmarks were established by the Suzhou

Industrial Park case study Butterfly Bay to other known case studies in Asia, known for their effectiveness and high density.

Setting Parameters and criteria for the cellular automaton.

The basic parameter to be included into the algorithm are taken from the official building code for SIP [12]. 'Technical specification for planning and design of residential area in Suzhou Industrial Park' (In Chinese: 苏州工业园区住宅区规划设计技术规定). The regulation refers to the exposure of a residential unit to sunlight and the distance of the building to the site boundary. Table 1 indicates how the parameters are represented in the geometrical model and how their suitability or conformity is evaluated. Additionally to the building regulations the table [Table 1] includes parameter to establish the evaluation of the quantity of public space and the achieved density [14] of the respective proposal.

Table 1. Parameters and evaluation criteria

Parameters	Sub-Parameters	Geometry and definition in Rhino-Grasshopper	Evaluation
Building Regulation			
Site	Shape of Site	XY Polyline	minimum size
Lighting	hours of exposure per day	rectangular 2d area on side of wall & Line of sight from Sill to Sun	over 3 hours per day
Building Height	N/A	Z vector	>1.3 X width of S Facade.
Floor Height	N/A	Z vector	2.8 -3.5 m
Distance from site boundary	N/A	XY line Polyline	>15m
Cellular Automata			
Neighbourhood Rule	Game of Life	Cellular Automata: Born in a, Survive in u-v	Number of housing blocks
	Public Space	Void Space	ratio of housing to public space
Social Condenser	Shape of Condenser	Box XYZ Size; Centre Point; Type	Qualitative
	Condenser attraction	Sphere Service radius;	Distance of Cell from condenser

Other criteria such as fire truck and ambulance access, sizes and numbers of parking, being established in the building code are not considered at the current state.

3.4 Implementation: Rhino- Grasshopper

The computational modelling environment was Rhinoceros with Grasshopper handling the parametric and evolutionary roles. We used the Rabbit cellular automata plugin, with our own extension in the three dimensions. The evolutionary algorithms used were shape annealing and the Galapagos evolutionary solver. For the lighting simulation we used the Ladybug grasshopper plugin, connected again with the Rabbit and Galapagos solvers. To measure lighting we did not just restrict ourselves in the initial measurement at the sill of the opening, but established a grid of points on the surface of each cell that would measure incidence of light. This proved cumbersome and computationally expensive making the resulting lighting model difficult to handle and unresponsive.

The actual algorithm is a Cellular Automaton based on Conway's Game of Life extending it into the third dimension [Fig. 4]. In Conway's original algorithm a two-dimensional grid of cells is initially populated randomly by objects. Subsequently rules of density determine whether a cell will be generated, kept alive or be removed depending on the number of occupied or unoccupied neighbouring grid cells.

In the proposed novel extension of this cellular automaton each cell in the 3dimenional grid communicates with the neighbouring 25 cells determining whether or not a cell lives or dies. This also includes the consideration of cells that are not sharing a surface but share a corner. For evaluating the neighbourhood we use the 3d concept of the Moore Neighbourhood. We parameterise the rules in this form: if a cell has K neighbours then a new cell is generated, with the usual minimum K=2. If the cell has N-M neighbours, then the cell dies because of loneliness or from being overcrowded. N represents the full Neighbourhood of 25 voids that the individual cell can have as neighbours while M represents the number of voids actually occupied by Cells. The subtraction N-M represents the voids still left after we have counted all occupied cells [Fig. 6].

The second amendment to Conway's cellular automaton is the introduction of a variety of architectural function to each of the cells. This allows to diversify the functional and volumetric arrangement of the building spatially in three dimensions [11]. To explain our strategy in this, we have to first explain the functional arrangement of 'Neighbourhood Centres' around SIP and the subsequent strategy that we employ in extending their framework in three dimensions. During the design of the Suzhou Industrial Park, Singapore authorities transferred knowledge and urban design guidelines to the Chinese authorities, either directly or via training of architects and urban planners. One result of this knowledge transfer is the establishment of Neighbourhood Centres, places in the urban grid that are engineered to centralise various disparate functions in one location that cannot be found anywhere else at a distance of 400meters. As a consequence the monotony of the housing estates is intensified as functional diversity is established only in the Neighbourhood Centres. These centres do not always resemble the literal centre of the neighbourhood in terms of urban configuration but are essentially a block which combines service functions.

The closest articulation of the concept is the social condenser, a space that combines disparate functions, without any need for coherence or explanation of relevance. A function is needed for an area so therefore it is added or pre-programmed by the planners. In certain cases like neighbourhood centres in the Higher Education Town, the centres are located jointly with other supra-local functions, like a kindergarten, a school, a police station, a hospital, and a community centre [Fig. 7].

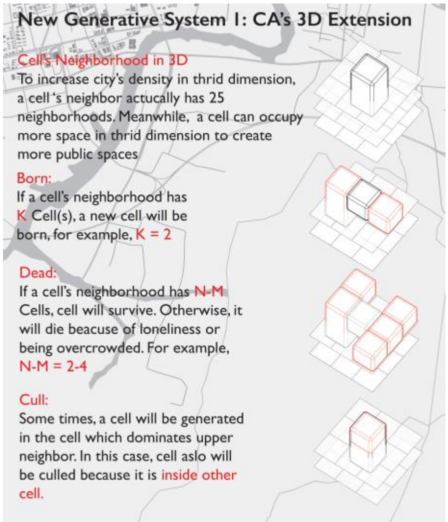

Fig. 6. Extension of CA game of life in three dimensions.

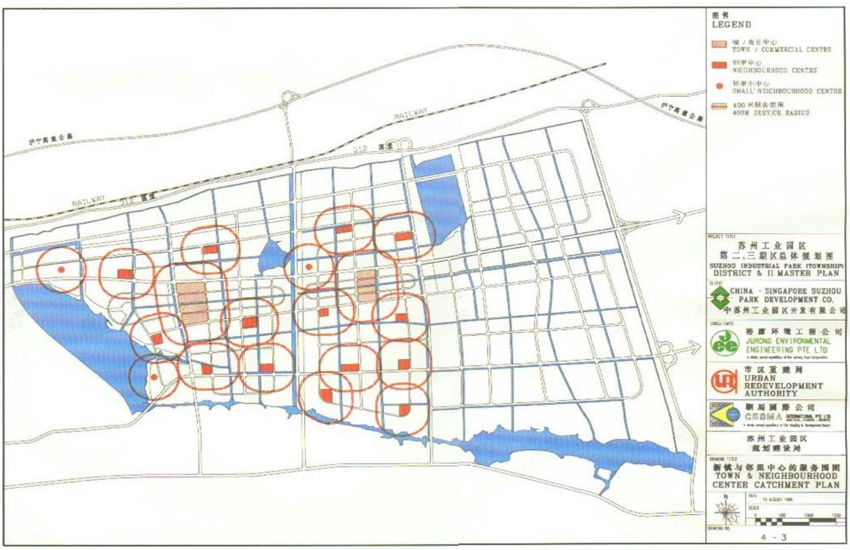

Fig. 7. Neighbourhood centres as social condensers dispersed on the SIP grid-east (source: SIP Masterplan 1994)

The main articulation of our algorithm in terms of the social condenser is the extension of this strategic operational device into three dimensions. Instead of building a generative system only for housing the prescription of the algorithm is to drive the generation through the careful positioning of the social condenser, i.e hyper-local functions, within a three dimensional grid. The grid then can be filled with the housing functions one desires and evaluated according to their proximity to the social condenser. One can imagine an initial placement of the social condensers as if on grid with a standard distance between them at the initial positioning, where the distance starts to vary according to the generative system parameters [Fig. 8].

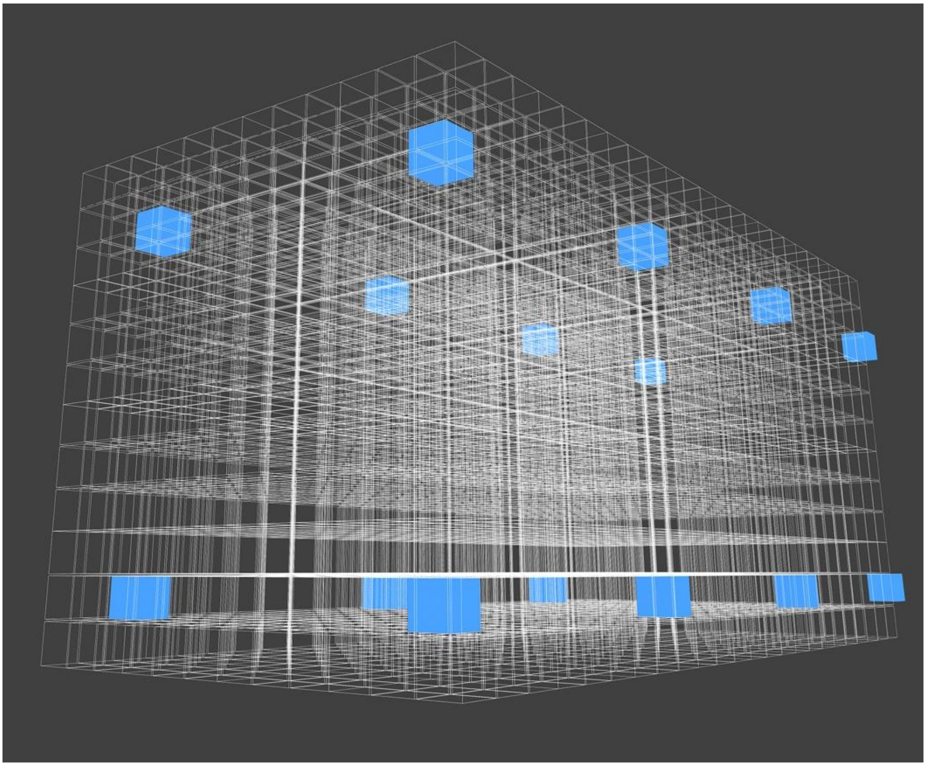

Fig. 8. Social Condensers placed on a three dimensional grid instead of a two dimensional urban one.

The current proof of concept presented in this paper employs a fitness function with a multi-objective optimisation consisting of two parameters: the maximisation of density together with the maximisation of sun exposure of specific cells. Based on the same initialising parameter in the Cellular Automaton, the evolutionary algorithm was set up to maximise floor area and building volume by sustaining sun exposure of every cell at a minimum of three hours daily, since this is a crucial element for obtaining building permission within SIP. Measuring the available building volume in relation to the site footprint we find that the algorithm increased this ratio from 31% at the initial generation of towers to 39% in the conversed state of the evolutionary algorithm. Sustaining the number of hours of daylight exposure this can be interpreted as an increase in efficiency of site usage by maintaining the same quality of residential units at least in terms of daily sun exposure.

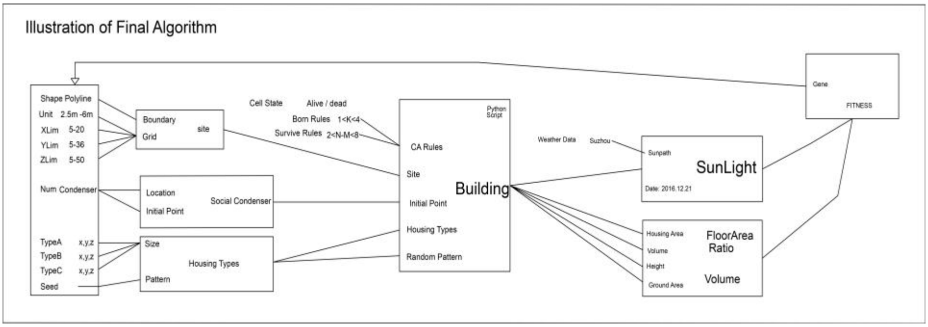

Fig. 9. Diagram of the algorithm including morphology generation and quantitative evaluation.

4 Results – Discussion

Applying the extended rules from Conwell's Game of Life together with the performative evolutionary process through evaluation and discrimination the algorithm was able to create solutions which comply with the set building regulations - defined solar radiation for each residential unit - whilst increasing the density which is measured by the ratio of the footprint to usable area. Besides this, whilst complying with the set restrictions and requirements the evolutionary Cellular Automaton created solutions of architectural diversity and increases the efficiency of the respective land use [Fig. 10].

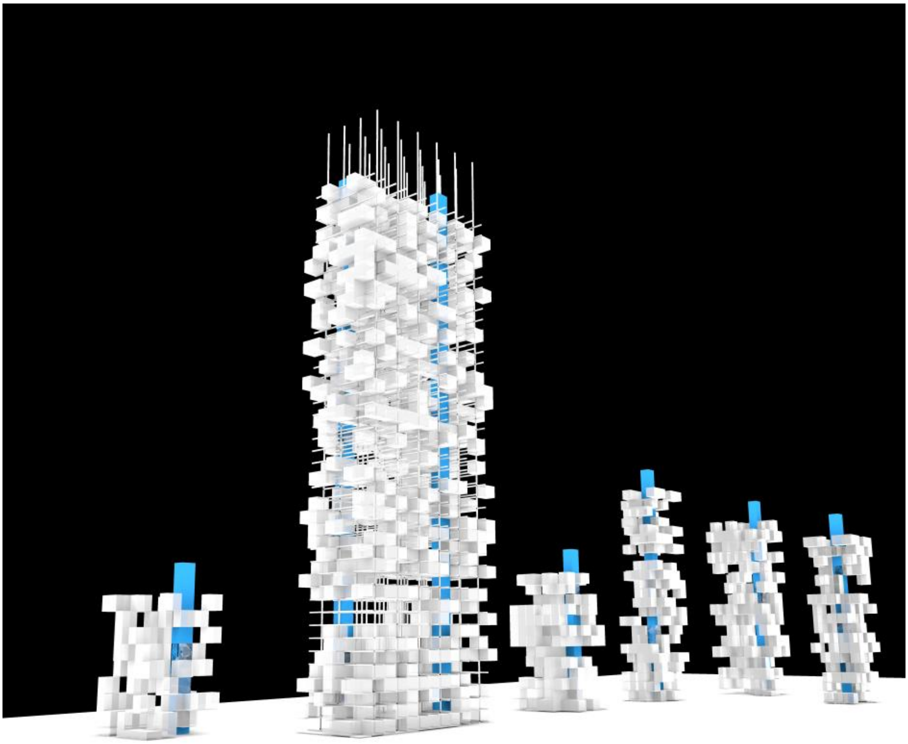

Fig. 10. Maximum Height tower in comparison with towers of multi-optimised genomes

For the moment the created cells are of equal dimensions but of different architectural functions which allow the accumulation of different functional cells into specific units such as residential units. The introduction of the “social condensers” the accumulation of different cells can be guided. The “social condenser” cells specified and placed by the designer will attract a certain group of cells respectively.

Architectural diversity in the global shape of the tower was achieved by the inclusion of the social condenser into the grid of the cellular automaton. Since the “social condenser” cells act as attractors adjacent cells with similar function around these cells are being melt into larger entities [Fig. 11].

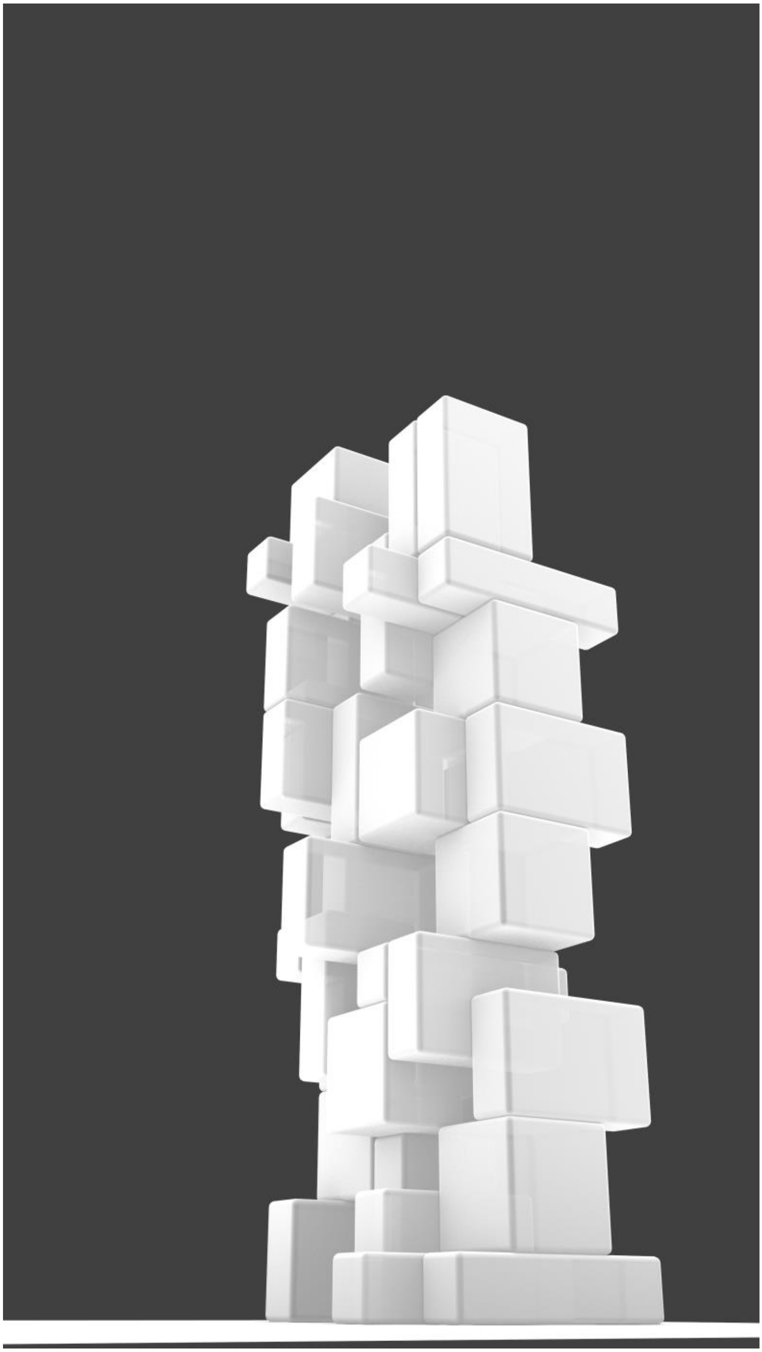

Fig. 11. Social Condenser Schematic Result: The tower diversifies in three dimensions even more, while functions coalesce together.

Technically the implementation of the condenser cells was achieved through a python script generating the points in the grid for the social condensers. In future work we consider to incorporate the generation of the condensers in the cellular automata mechanism, requiring multiple types of cells incorporated into the morphogenetic mechanism.

The introduction of types of cells according to functional activity is run in a parallel algorithm to the cellular automaton and transferred manually into the main model, importing them by hand rather than automatically. While this is an obvious weakness in the automation of the mechanism, nonetheless it allows for architectural intervention and authority within the system. It allows for developing rules of design where the cells do not just get deleted or created according to density, but in a more grammatical fashion get moved around to coalesce according to function and structural logic of the architectural design strategy. Thus the designer can create a living-room cell, a bedroom cell, kitchen cell, bathroom cell, circulation cell etc. The complexity of the algorithm grows exponentially as the type of cell needs to be taken into account. The social condenser cells act as centres of attraction around which the algorithm will accumulate cells preferably. For the coalescence of the cells we propose two main strategies. In the first strategy the accumulation of cells depends exclusively on the adjacency of cells to the condenser cells regardless of the similarity of their function [Fig. 11].

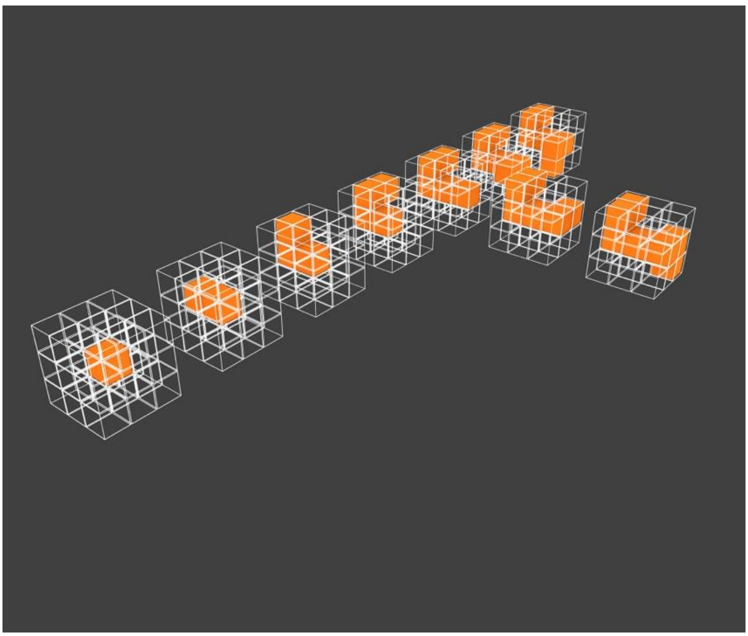

Fig. 12. Coalescence strategy without considering function but neighbourhood to social condenser cells.

The second strategy considers the similarity of the cell's function and accumulates cells of equal or similar function into larger cells. [Figure 12] By using the second style of aggregation, the algorithm proceeds in developing solution made out of the aggregated, multi-cell boxes. For now the dispersal of different function happens as a percentage, however we would like to develop it to the stage where the algorithm designs apartments bottom-up from groups of functions.

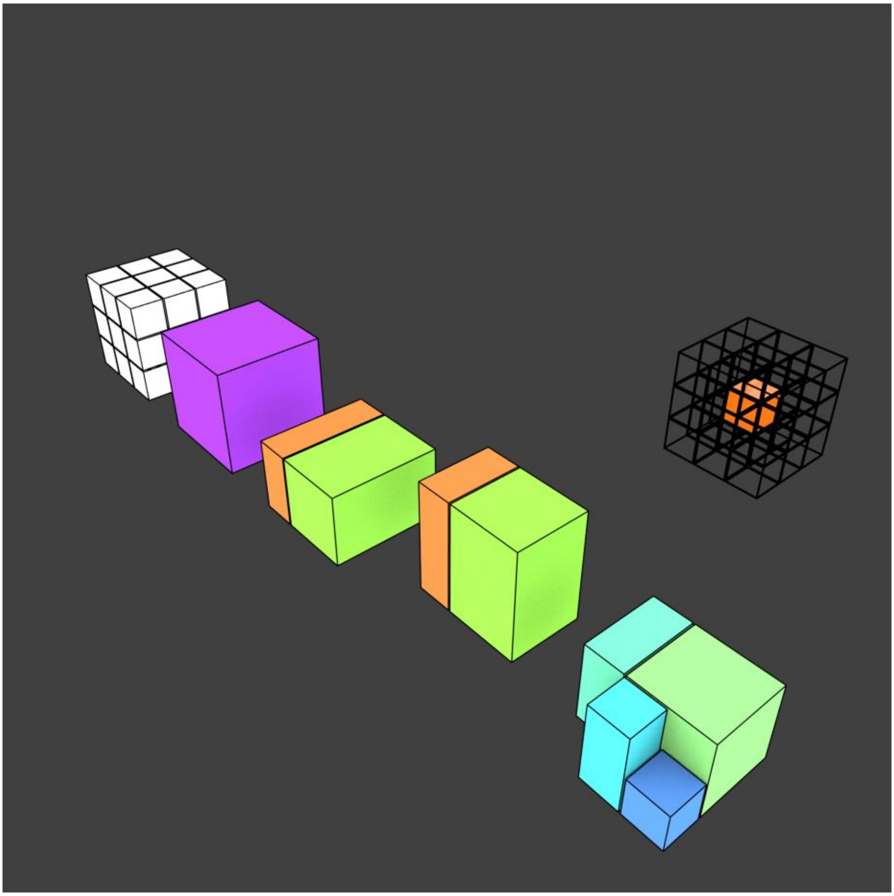

Fig.13. Coalescence of cells around social condensers according to identical or similar functions.

5 Conclusions & Further Development

We have demonstrated that it is possible to design a generative and evolutionary parametric system, integrating programmatic function, floor area, and sunlight exposure along with a performative evaluation thereof. We proposed an automated system that is capable of developing large three-dimensional housing blocks, with functional and architectural diversity, increasing the density of the housing whilst retaining the size of a given footprint and the set requirements of sufficient sunlight exposure. The quality of the proposed design uses the available land more efficiently whilst providing a diverse architecture with at least the same amount of sunlight exposure per day for each unit as the current implementation. We will continue to develop the system with the inclusion of basic structural and circulation evaluation functions, and we hope to expand and test the system using other building regulations, for example the UK's where lack of appropriate housing is a social issue. Further potential of the system lies also in developing a tool that evaluates the building's financial performance, from cost of construction to the price of sale or renting to make a profit in a specific time. The novelty of the method lies in the extension of the cellular automata mechanism with functions and types of cells, along with the three-dimensional dispersal of the social condensers. The introduction of an evaluation algorithm allows for discrimination of less performing individuals and enables an evolutionary development process within the rule based cellular automaton.

Further development is needed to integrate the allocation of the social condenser and the cellular automata into one single integrated algorithm. However, the implementation of an operational strategic architectural device such as the social condenser in three dimensions using computational tools contributes to the understanding of computational tools as a continuation of architectonic strategy; we argue for a strategic integration of performative tools as part of the genuine design process rather than a posteriori attained and measured performance. Thus we envision that a continuation of this system will lead into an integrated tool, combining the parametric generative system and a multi-parametric evaluation, helping architects and planners deliver competitive designs within fast developing environments.

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SILVEREYE– the implementation of Particle Swarm Optimization algorithm in a design optimization tool.

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Abstract. Engineers and architects are now turning to use computational aids in order to analyze and solve complex design problems. Most of these problems can be handled by techniques that exploit Evolutionary Computation (EC). However existing EC techniques are slow [8] and hard to understand, thus disengaging the user. Swarm Intelligence (SI) relies on social interaction, of which humans have a natural understanding, as opposed to the more abstract concept of evolutionary change. The main aim of this research is to introduce a new solver Silvereye, which implements Particle Swarm Optimization (PSO) in the Grasshopper framework, as the algorithm is hypothesized to be fast and intuitive. The second objective is to test if SI is able to solve complex design problems faster than EC-based solvers. Experimental results on a complex, single-objective high-dimensional benchmark problem of roof geometry optimization provide statistically significant evidence of computational inexpensiveness of the introduced tool.

Keywords: Architectural Design Optimization (ADO) · Particle Swarm Optimization (PSO) · Swarm Intelligence (SI) · Evolutionary Computation (EC) · Structural Optimization

Rethinking Design in Digital Context

Models of Subjectivity and Intentionality in Computational Architecture

From Centralized to Distributed Approach

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Abstract. Triggered by the dominant criticisms on the formalism of current computational approaches and algorithmic modes to form generation, this paper challenges this view on computational design methods that are claimed to be incapable of embracing subjectivity and artistic expression, which in turn lead to data-driven forms as outcomes of pure calculations and rationalistic procedures. Providing a discussion and a framework on the disregarded dimensions of subjectivity in computational design processes, it proposes a tripartite model – *centralized*, *partial* and *distributed* approach to computational design – to understand and assess the condition of subjectivity and intentionality and reveal a possible shift from a centralized approach to a distributed one.

Keywords: Subjectivity, Design Intention, Computational Design

1 Introduction

The subjectivity of the architect and its related modes of design thinking repeatedly come to a point of question with advances in technology, which is further emphasized by the involvement of computation and associative methodologies in the design process that requires a rationalization of procedures both mentally and operationally. In the turn of the century, with the developments in computer science and increased capacity in information processing provided by the computational paradigm, the studies on computational design display great interest in complexity management. While, the aim is to cope with the intricacy of data, the '*improved means and methods used in complexity management do not reduce but rather increase'* the complexity of design problems [1]. In order to respond to the rapidly changing status of tools and mindset, an epistemic choice in favor of rationalization with avoidance of subjectivity and intentionality has been made [1]. This condition leads to a determination in the dominant mode of computational thinking towards design confirmation in the form of rationalization, optimization and efficiency, instead of exploring new ways to deal with subjectivity, intuition and artistic expressions of the designers.

The computational thinking requires an unambiguous translation of ideas into quantitative data. On the other hand, according to Zeynep Mennan, the qualitative notions of human thinking are claimed to be against the mathematical nature of computation, which creates a problem, as well as a challenge, of encoding subjectivity and design intention in computational processes [1]. As she points out, this condition originates from the epistemic opposition between subjectivity and rationalization, which repeatedly appears parallel to the gap between human and computational thinking [1]. Problematization this current approach to computation, the aim of this paper is to discuss the disregarded dimensions of designer's subjectivity and intentionality in computational processes.

2 The Dominant Approach to Computational Design

In the book *The Electronic Design Studio* (1990), George Stiny distinguishes the creative act of designer from the role of computational procedures, which are problematic with their structured nature by stating that: *'Designers do many things that computers don't. Some of these are bad habits that the stringencies of computation will correct. But others are basic to design, and cannot be ignored if computation is to serve creation and invention.'* [2]. He then emphasizes the importance of ambiguity in design, '*where it fosters imagination and creativity, and encourages multilayered expression and response,*' which computational procedures cannot incorporate due to the structured nature [2].

In the foreword of the book *Expressive Form* (2003), William Mitchell approaches the problem of dominant computational approach from a pragmatic-formal level. He associates the formal tendencies with which the software provides, an '*economy of shapes*' that suggests the availability and ease in the creation of some forms with certain methods, while its expansion and restructuring has been made through the advancements in computer technology at the turn of the century. [3] In the book, Kostas Terzidis – who is the author – defines the problem from a methodological perspective [4]. He notes that:

'What makes computation so problematic for design theorists is that it has maintained an ethos of rationalistic determinism -the theory that the exercise of reason provides the only valid basis for action or belief and that reason is the prime source of knowledge- in its field. Because of its clarity and efficiency, rationalistic determinism has traditionally been a dominant mode of thought in the world of computation. The problem with this approach is that it assumes that all computational activities abide by the same principles. In contrast, intuition, as defined in the arts and design, is based on quite different, if not opposing, principles [...] This mode of thought comes in contrast to the dominant computational model where methodical, predictable, and dividable processes exist.' [4]

Terzidis reveals that the world of computation, in which a more rational, confined, organized, and methodical model exists, is resistant to such characterizations belonging to the human world, where '*intuition has been an underlying assumption for many design activities*.' [4]. Elaborating on this division, he claims that the mathematical processes can easily be translated into quantitative methods, thereby, can be controlled through computation, whereas *'manipulations, evaluations, and combinations of these processes are qualitative processes and as such can be handled by the architect.'* [4]. As he continues, on the point that we shift our design modes from manual to computerized, there occurs a necessity to '*integrate the two seemingly contrasting worlds, that of intuition and that of computation*.' [4]. The outcome of such reconciliation may provide an alternative to the dissolution of subjectivity.

In a similar way, Axel Kilian considers computation to be in many cases *'an obstacle [...] in translating design intent'*, since; *'it lacks the fluidity of human thoughts.'* [5]. And he proceeds arguing against this dominant view by stating that:

'Design should not be solely about the execution of established processes but about querying the understanding of the factors involved. This is a much more complex task and it goes far beyond the traditional geometric and numerical representation of current computational practices but it happens in designers minds regardless of the involvement of computation.' [5]

By extension to this, Kilian proposes to see the critic of the dominant approach to computational design not as *'a glorification of human designers'* but as *'a reminder of the respective strengths and weaknesses of the different approaches,'* and not to perceive them as competing processes but *'a potential collaboration between design in the mind and its externalized computational processes.'* [5].

2.1 Challenging the Nature of Computation

Computational methods are regarded as rational because of its '*mechanistic nature*,' and parallelwise, they are considered as incapable of '*artistic sensibility and intuitive playfulness in their practice*.' [4]. However, it is possible to claim their subjectivity, but since, subjectivity and objectivity are simultaneously emanated through the act of coding, it is a different king of subjective construction that we are no longer able to detect with the conventional cognition of form. This results in a highly embedded subjectivity and design intention existing within the act of code writing, which may or may not be expressed in the geometric definition of form. Thereby, the visual unreadability of subjectivity in the outcome of code and the condition of being too generic results in such claims that computational methods are incapable of including subjective design thought processes.

In her recent paper 'Mind the Gap: Reconciling Formalism and Intuitionism In Computational Design Research', Zeynep Mennan explains the dominant attitude towards this problem as an epistemic choice in favor of rationalization over subjectivity and intentionality, and she reports that the criticism of the dominant mode of computational design led to a re-appearance of subjectivity together and against an increased formalism in the field of computation [1]. Rather than staying in the limits of optimization and rationalization in form control, designers started to explore other potentials by combining the mode of scientific reasoning and human reasoning, so that, '*the gap*' between computational rationality and the expressivity and subjectivity of the designer could be joined [1].

Roland Snooks observes that based on the analytical and generative capacity of computational thinking, the algorithmic approach is an agent-based bottom-up approach where there is no pre-determined idea of form, and form is dependent on the capability of the architect to '*encode architectural intent within the operation of the algorithm.*' [6]. As he explains, algorithms are used as generic templates for architects and they are '*abstract formal generators operating on an appropriated logic, devoid of any recognition of the architectural problem or proposition.*' [6]. Recent attempts reveal that such reconciliations are possible, between creativity and reason, between the subjectivity of the architect and the rationality of computational procedures [1]. Therefore, a new model in which subjectivity and design intention is being encoded within the operation of algorithm is replacing the dominant computational model.

Although this research has been triggered by the dominant criticisms on the formalism of current computational approaches and algorithmic modes to form generation, it challenges this view on computational design methods that is claimed to be incapable of embracing subjectivity and artistic expression, which in turn leads to data-driven forms as outcomes of pure calculations and rationalistic procedures. Then, it aims to demonstrate the possible ways to achieve different methods that deal with this problem with the assumption that subjectivity and intentionality of the architect has not been replaced or dissolved in computational processes but rather has been *embedded* within the design process and become *indirect* and *invisible*.

3 A Tripartite Model for Computational Design

In order to assess the condition of subjectivity and intentionality in computational design processes, this research proposes a tripartite model as an interpretation of the terms *centralized*, *decentralized* and *distributed* models of network, which are initially diagrammatized by Paul Baran in 1964 [8] and defined in the field of computation, network and communication sciences for management and organization of information [9] (Fig.1).

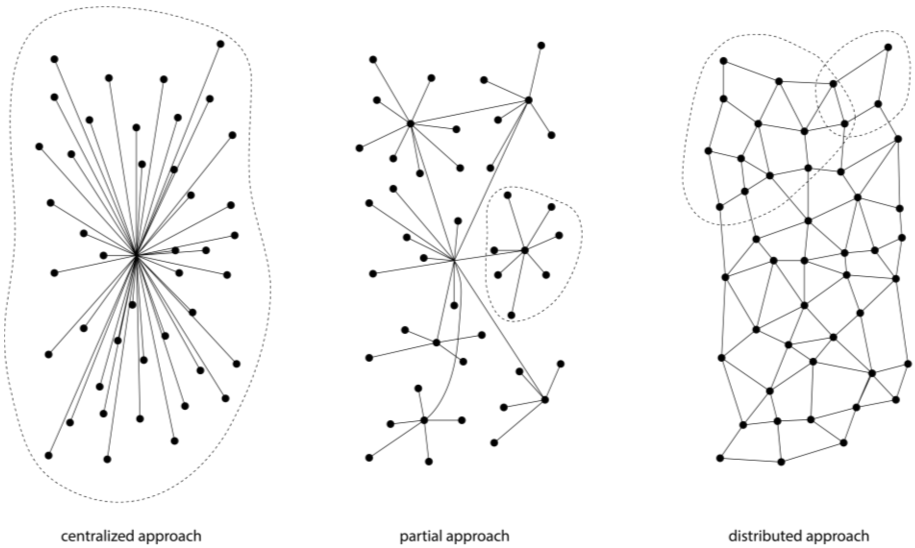

Fig. 1. Diagrammatization of the tripartite model based on the three types of network proposed by Paul Baran [8]. Redrawn by the author.

Translating these terms from network sciences to the field of computational design as *centralized*, *partial*[1] and *distributed,* constitutes a platform for a possible mapping of computational approaches, and it is instrumental to understand and assess the condition of subjectivity and intentionality, and then, reveal a possible shift from centralized to distributed approach.

3.1 Centralized Approach

The centralized approach can be described as the model where all data is sent to one central node, which then directs the data to the intended recipient [10]. This definition can be translated to the field of computational design where the central node corresponds to the main algorithm that determines and forms the whole.

In this approach, there exists an underlying idea about the formal logic rather than a pre-determinate idea of final form, and an algorithm can be designed or customized to write a specific code for form exploration [4]. According to Alejandro Zaera-Polo, such approach to computation can be interpreted as a centrally organized algorithmic system '*that tries to articulate everything at once*.' [11]. Therefore, in this model, computation is essential to formal content and generation of form, and correspondingly, this condition makes this approach more vulnerable to the changes

[1] As an *indirect* translation from Baran's diagram, I propose the term "partial" instead of "decentralized" for a better definition.

in computational methods and theory, as the structuring of the code directly affects the resultant configuration due to the organizational capacity of the algorithm [11].

The comprehension and assessment of this approach is substantially bounded to the recognition the potentials and limitations of algorithmic methods. As an example to this, work of Roland Snooks - whose approach falls into a rather experimental and innovative design field - reflects such centralized model, yet, according to Mennan, he manages to embed his design intentions and subjectivity within the quantitative logic of computation by participating actively in the automatic evaluation processes through 'strange feedback' which attempts to hybridize emergent characteristics of bottom-up algorithmic processes with the architect's top-down subjective decision mechanisms [1].

Such interference to centralized algorithmic systems is a great difficulty, but similar attempts will extend the formal and organizational capacity of computational design processes, this time enabling more of subjective domain from the architect as well.

3.2 Partial Approach

Partial computation is a method used in computer science to evaluate and optimize partial programs with the given parameter values [12]. If we borrow and apply this definition to the domain of computational architecture, it suggests the application of computational methods to evaluate and optimize partial phases of form generation with the given parameter values. In this approach, algorithmic methods are applied to certain phases or parts of design, which then cause the formal content to become partially dependent on the computational content.

Studies based on optimization and efficiency can be positioned under this approach, where the main reasoning in the use of computation is rather *explanatory* through optimization Pre-rationalization and post-rationalization can be interpreted as the two dominating uses of this approach.

The intentionality in the use of computation is similar in both processes of pre-rationalization and post-rationalization, however in pre-rationalization, the rationalization process is superior to form generation process, whereas in the post-rationalization, the subjectivity is superior and rationalization is inferior to form generation. Therefore, it is possible to state that, in the former approach, rationalistic-determinism is the dominant approach, on the contrary, for the second approach; the formal logic is subjective and intuitive, yet partially rationalized.

As a critique of this performance or optimization approach to computation of form, David Benjamin examines efficiency and creativity, the two contrasting yet complementary concepts, and their implications in the field of architectural design. He names them, *exploitation* and *exploration,* meaning in sequence, *'utilizing existing'* and *'searching for new.'* [7]. He states that:

'Designers interested in exploitation prefer a narrow, continuous design space, such as a slanted plane or a topological surface with one or two bumps. In this case, it is possible to quickly hone in on the region of best performance and to locate the single

global maximum. The simpler the design space is, the faster they can find the optimal design.
Designers interested in exploration prefer a wide, discontinuous design space, such as a jagged mountain range with multiple peaks. In this case, there are many distinct regions of good performance, and it is often possible to find multiple local maximums that are both interesting and high-performing, even if they are not the global maximum. The more complex the design space is, the more likely it is that they will make an unpredictable discovery.' [7]

Benjamin also suggests introducing '*subjective criteria'* into the optimization processes in order to integrate the seemingly separate qualities of human intuition and creativity with computational thinking. Even though such method is under-utilized, it enables to incorporate subjective criteria, such as atmosphere, aesthetics and program, with objective technical criteria, like structural performance and circulation efficiency, in the same optimization process [7]. In such a process, he argues that the subjectivity of the architect is translated into objectives and value judgment, and the creativity of the designer comes from '*designing objectives and designing experiments rather than simply designing solutions*,' which bring about the role of the architect more engaged in designing the problem and focused on potential design space, '*the complex topological surface*'. [7]. About the subjectivity in these processes, he claims, '*although they might be buried and hidden, they are there*.' [7].

It is possible to name pre-rationalization, post-rationalization and reverse engineering under this model.

Pre-rationalization

As the name clearly expresses, in this approach, the rationalization process is at the early stages of form generation, consequently the formal logic is dependent on the initial-factual data and therefore, it can be argued as highly objective. This approach can also be defined as a data-centric approach since the form is optimized from the beginning, and efficiency is the major decisive factor in form generation [13]. Thomas Fischer explains this approach by mentioning Buckminster Fuller: *'[His] approach of addressing design challenges before they become acute, which he referred to as "comprehensive anticipatory design science" is largely based on the concept of pre-rationalization*.' [13].

As a result of the dependency of form on the data, the freedom and subjectivity of the architect in form generation can be evaluated as *low*, but since the construction of design problem and the intention to use such methods belong to the architect, it still embodies some degree of subjectivity but in a highly rationalized form.

Post-rationalization

In this approach, the use of computation is partial and rationalization process is placed at the final stages of form generation. The formal logic is dependent on the intuitive and artistic decision making of the architect and therefore, it can be argued as belonging to the '*subjective world of states of consciousness, or of mental states-with intentions, feelings, thoughts, dreams, memories*.'[2]. This approach can also be referred as the intuitive approach, since intuition is the major decisive factor in form generation. Although the dominant mode of formal logic is intuitive and therefore subjective, it still requires some sort of rationalization at the final stage in order to calculate structure and to construct and fabricate the final form (Such as surface tessellations of facades, some parts of structural design etc.).

Based on the intuitive decision-making of the architect, this approach mostly denotes a traditional top-down approach where the creator relies on her background knowledge and former experiences. As William Mitchell defines it, this '*knowledge-based*' [14] approach can be problematized, as its design mechanism is a closed system or a '*black box*' where the idea of form is in the designer's mind and is pre-determinate.

Neil Leach remarks that Frank Gehry is a seminal name and a representative of this formal approach in which architect is considered as the creator, who '*imposes form on the world in a top-down process*', while engineers are responsible for the making of form as close as possible to the architect's initial expression [15]. Although, there exists some degree of rationalization in Gehry's projects, the formal logic is purely subjective in which intuition is considered as the source of inspiration.

Reverse Engineering

There exist a more generative version of post-rationalization, which deals with reverse engineering in order to translate not just the subjectively constructed form in a computable representation, but also to extract the underlying logic and geometry of the form to an algorithm. By this way, this approach enables more than just post-rationalization but breeding new variations based on the initial form and extracted information [16].

The biggest challenge here is the involvement of a secondary designer and his/her ability to encode the subjectivity in the architect's mind and to rationalize this highly intuitive and subjective formal logic to the algorithmic logic. Mark Burry's research on Gaudi's design of Sagrada Familia can be an appropriate example of this type of an approach [17]. Here, according to Neil Leach, Burry explores 'digital techniques for understanding the logic of Gaudí's own highly sophisticated understanding of natural forces.' [15].

As a remark on the partial approach to computation, it can be stated that it is highly practical based on the design intention. However, it fails in rendering a totalitarian architectural approach, and thereby becomes a limited application within a larger content. It stays within the borders of validation by being explanatory rather than exploring the potentials brought along with computational paradigm. The

[2] In discussing the "knowledge" and "imagination" as objective and subjective oppositions, Kostas Terzidis refers to Karl R. Popper. (The Logic of Scientific Discovery, 1968) in Terzidis, K.: Expressive Form: A Conceptual Approach to Computational Design, Spon Press, (2003)

condition of this approach that doesn't fully test the limits of computing subjective design thinking, it becomes inapplicable both to rationalization of subjectivity and subjectification of computation.

3.3 Distributed Approach

In the simplest version, distributed computation can be defined as the condition where the use of algorithms and codes are multiple and distributed to the different and particular stages of design. Different from partial computation, this approach includes both design exploration and exploitation, and furthermore, it is flexible and intention-oriented [11]. As Alejandro Zaera-Polo explains, it is '*the co-evolution and optimization of relationships between multiple routines, mediated through the mainframe, which is able to produce real innovation, rather than the heaviness of a centrally organized system that tries to articulate everything at once*.' [11].

This approach can also be referred as a non-linear workflow approach in which computational methods are used and customized in a certain degree to adopt the subjectivity and intentionality of the architects. It includes employing custom and disposable codes, which are '*intentionally purpose-built for the task at hand*', to respond to specific problems or spontaneous needs at certain phases of the design process in order to encourage creative thinking rather than perfect the code itself [18].

Accordingly, this dismantling and distributing computation throughout the design process makes it more efficient and flexible to encode subjectivity and intentionality, therefore subjectivity of the architect becomes more solid due to the radical increase in his/her freedom and control over form. Furthermore, it enables instantaneous design experimentation and rationalization within the same system by integrating two seemingly contrasting worlds - that of computation and intuition - with more freedom in subjective criteria.

The challenging part of this approach is the management of the complexity created by the involvement of different parts (specialized design territories) and parties (vast amount of specialized information) distributed within the same process. However, it allows design collaboration and inclusive design practices in order to respond the increased amount of information and complex design problems. This leads a great extension in the capacity of the architect.

4 Conclusion

Along with the methodological and epistemological changes in design thinking and modes of reasoning, this ongoing research expects a shift in the condition of subjectivity and intentionality in comparison to the dominant computational design approach and its modes of reasoning. It is argued in the paper that such a change is indicated through definitions of new modes of subjectivity within computational design that are impure, distributed and embedded. The gap created by the shift towards the language of computation and its associated rationality requires reestablishing the modes of subjectivity and intentionality, since "[c]alculation leaves an incomplete space that cannot be saturated with information alone and waits to be filled with meaning and interpretation." [1]. This gap emerging from the epistemological opposition of human and computational rationality constitutes the point of departure in the search for alternative approaches restating the subjectivity and intentionality of human agency in the field of computation.

In 2009, Neil Leach points out a shift prior to the introduction and multiplication of computational methods in architectural design that *'[...]the architectural imagination has been displaced into a different arena – into the imaginative use of various processes.'* [15]. In 2012, the editor of the book *Digital Workflows in Architecture,* Scott Marble, identifies a further shift that the dominant computational approach experiences: 'from process to workflow.' [19]. Marble states that 'the identity of the architect is largely built upon her or his ability to author design solutions' and the challenge is in the *'capturing the full range of architectural design intent within digital workflows,'* and he suggests the proper formation and expanded use of these workflows, which has the potential to transform the subjectivity and intentionality with freedom and control that have been *'increasingly displaced by technologically mediated processes over a long time'*. [19].

This study proposes a further shift in tandem with these alterations in the definition of designer(s)' subjectivity and intentionality within computational design processes. The centrally posited subjectivity and intentionality is moving towards a distributed and embedded model as the use of computational methods becomes multiplex, distributed and intention-oriented.

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Design and Architecture for the Dawn of the Personal Computer

The Pioneer Vision of Adriano Olivetti

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Abstract. In 1952 the Italian Olivetti Company opened a study laboratory on electronic calculators in New Canaan, USA; in 1955 it created an electronic research laboratory in Pisa and two years later, co-founded a company to produce electronic conductors. In 1959 it presented ELEA 9003 and in 1965 the P101, respectively the first full transistorized computer and the first desktop computer. This paper aims to investigate how the Olivetti Company accomplished in such a brief period of time a pioneer vision in the field of computing. By one hand it seeks to highlight the forerunner idea of Adriano Olivetti (1901-1960) for an integrated awareness of what computing could become and on the other hand, how that wakefulness fostered an innovative agenda among architects, designers, filmmakers and scientists for the invention of the computer as an artifact expression of an epoch. This successful endeavor anticipated what would become the concept of personal computing. Moreover the paper underlines how the early commercial development of Olivetti and IBM computing flourished in the context of the Universal Exhibitions of Brussels and New York.

Keywords: Olivetti, Computing, Architecture, Mario Tchou, Ettore Sottsass, IBM

1 Introduction

History of computing and its impact in architectural thinking and production is still a recent area of inquiry. However scholarship upon these themes has grown over the last years with research focusing at particular aspects of the intellectual history of architecture computing: namely investigation exploring the relevance of the Second World War with the emergent field of computing and the inception of architectural research centers started to be documented[1]. These works give particular emphasis to

[1] See: Rocha, João. Architecture theory 1960-1980. Emergence of a Computational perspective. MIT, Ph.D Dissertation, 2004; Alise Upitis, Nature Normative: The Design Methods Movement, 1944-1967. MIT, Ph.D Dissertation, 2008; Daniel C. Llach, Buildors of the Vision. Software and the imagination of design. Routledge, 2005.

the development of computing mainly in the USA and in the UK, but there is still the lack of a broader historical account of that phenomenon in Italy. This paper attempts to bridge this gap by presenting an interpretation of what was the vision and endeavor of Adriano Olivetti's Company by the early 50s to foster a pioneer research agenda for the design, construction and commercialization of the (personal) computer. This vision included also a remarkable investment in architecture, product design, advertising and media for an industry that should be unified under an extraordinary high standard for visual communication.

The society Ing. Camillo Olivetti & C. was best known for its early success with the manufacturing of typewriters and was founded in October 1908 in Ivrea, a small city 50 miles north of Turin, at the foot of the mountains around the Valle d´Aosta, Italy, by Camillo Olivetti (1868-1943) an industrial engineer who studied at the Politecnico di Torino. His son, Adriano Olivetti (1901-1960) was a chemical engineer and industrialist whose personality compelled him to become a leading entrepreneur and patron of the arts. When Adriano took over the company succeding to his father, all Olivetti products were based on mechanical technologies and it was Adriano who gradually started to transformed the company into a modern factory. Looking ahead he predicted that sooner or later, mechanical products would reach its limits and that the future of the company would be to move into electronics.

At the end of World War II, Italy was a devastated country with a ruthless memory of twenty years of a fascist dictatorship, a defeat against the allies and within a turmoil of an internal political crisis. Alcide de Gasperi (1881-1954) the last president of the ministerial council of the Kingdom of Italy and the first prime minister of the Italian Republic was who initiated the reconstruction of the country making use of the “Marshall Plan” thanks to an unconditional political and financial support from the United States of America. During this period, Olivetti launches its first electromechanic calculating machine, the *Divisumma 24,* which constituted a major commercial success that paved the way for Olivetti´s further technological experimentation with automatic and electronic devices. The development of electronics at the Olivetti Company emerged in this context and could be divided in four phases encompassing sixteen years of pure and applied research. The first phase is firmly associated with the foundation of the *Olivetti Bull Spa* in 1949, a commercial agreement with the French company *Machines Bull*, the principal opponent of IBM in Europe, for the distribution of mechanographic punchedcards equipment in Italy. *Olivetti Bull* has provided a fundamental contribution to the understanding of the market requirements in terms of information processing, and for a sucessuful evolution towards the adoption of electronic data processing systems consistent with the Olivetti vision.

The second phase encompasses the early years of 1950s when Dino Olivetti (1912-1976) the youngest brother of Adriano, becomes the Director of the *Olivetti Corporation of America* (OCA) in New York city and responsible for the initiation of an Electronic Research Laboratory[2] in New Canaan, Connecticut in 1952, with the technical supervision of the mathematician Michele Canepa. During that period a group of distinguished Italian mathematicians did a study trip in the USA to visit the

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[2] Centro di Ricerche Elettroniche.

main scientific laboratories where computers were being developed and tested. The idea was from Mauro Picone (1885-1977) a notable Italian scientist who created in 1927 one of the first institutes dedicated to develop applied research in mathematics, the *Istituto Nazionale per le Applicazioni del Calcolo*, (INAC). Therefore under the guidance of Picone, Angelo Guerraggio, Gaetano Fichera, Giulio Rodinó, Bruno de Finneti, and Michel Canepa (an engineer already working for Olivetti) a joint effort for studying the possibility of designing and constructing an Italian computer was devised. This corresponded to state of the art technology that needed to be acknowledged in first hand by the Italian mathematicians who also participated at important scientific Conferences and Seminars, as we will describe ahead. The result of this enthusiastic and pioneer journey constituted an early and solid contribution for the definitive decision that Adriano Olivetti would do in order to expand his business in electronics.

The third phase, may be characterized by the agreement signed in October 1954 between the University of Pisa, Italy and *Olivetti* for an initial partnership with the aim to design and build, the "Calcolatore Elettronico Pisano-CEP". To accomplish this goal Olivetti establishes the Electronic Laboratory at Barbaricina, near Pisa, in a nineteenth century Villa. To lead the scientific participation of *Olivetti* at the development of the CEP, Mario Tchou, son of a Chinese diplomat in the Vatican and professor in Electrical Engineering at Columbia University, New York, where he taught from 1952 to 1955, is invited. Olivetti was introduced to Tchou in New York in the spring of 1954 and at the age of 31, Mario Tchou become the head of the "Divisione Elettronica Olivetti" responsible to conceive, design and construct the first electronic products for the Ivrea company. This represents the birth of the ELEA (Elaboratore Elettronico Automatico) project, which constituted a major technological and commercial breakthrough being presented at *Fiera Campionaria di Milano* in 1959.

The fourth phase comprehends the full development of the computers series ELEA 9003 and P101 and the relocation of the Electronic Division to Borgolombardo in the periphery of Milan. This was an extremely exciting period with *Olivetti* designing and producing two groundbreaking computers, with the participation of architects Mario Bellini, Ettore Sottsass and Tomas Maldonado whose involvement in the full design process was fundamental for the inception of an innovative design praxis.

2 Mathematics Computing and Olivetti in America

The need of sophisticated computing machines for the practical use of advanced mathematics was initially claimed by Picone who became overwhelmed with the first news about the appearance of automatic computers in the USA. Since then he started to envision the possibility to raise funds and partnerships to design and build an Italian computer. To achieve this it was important to do study missions in the USA and to the UK, in order to gain first hand insight into the emergent field of computing and electronics. Indeed and at request of Mauro Picone, Gaetano Fichera, (Picone´s student), the mathematician Bruno de Finetti (a consultant at the INAC) and Michele

Canepa, visited some of the most advanced research centres in computing, during the Spring of 1950. This coincides with the 1st International Congress of Mathematics, held at Harvard University and at the Massachusetts Institute of Technology[3] (FIG.1), where world mathematicians gathered for their first post-war congress. Picone with Fichera and Guerraggio left from the city of Naples to New York in August 1950 in a ten-day ocean trip on board of the *Conte Bicamano* cruise ship.[4] The group visited several Institutions in the West and East Coast of the USA, but was at the Harvard Computer Lab that better acquaintances were established. Here, Howard Aiken (1900-1973) was building an electromechanic machine that could perform mathematical operations quickly and efficiently. He succeeded in convincing IBM to fund his project becoming thus co-inventor of MARK I, the first IBM electromechanical automatic computer that started to be used in the war effort during the last period of the conflict.

Canepa, Picone, Finetti remained the summer in the USA and all joined the Harvard Congress of Mathematics which had the chairmanship of John von Neumann. The meeting run for a week with several thematic sessions, many of which given by leading scientists whose work become relevant for the field of computing. Namely, Claude Shannon and Stanislav Ulam presented a communication entitled, *Random processes in physics and communications;* John von Neumann and Sydney Goldstein presented, *Partial differential equations;* Norbert Wiener, *Statistical Mechanics*.[5]

Fig. 1. First International Congress of Mathematicians, ICM, Harvard University and MIT, September 1950.

From the Italian group both Bruno de Finetti and Gaetano Fichera spoke at the congress, which illustrates their knowledge within the addressed topics.[6] The meeting

[3] August 30-September 6, 1950. The American Academy of Arts and Sciences, Boston College, Boston University, The Massachusetts Institute of Technology and Tufts College.

[4] See for this subject: Guerraggio, A.,Mattaliano, M and Nastasi, P.: Alla fine fu FINAC. In, SAPERE, 42-55, Aprile (2005).

[5] The program also included: Szolem Mandelbrojt, Rice Institute and College de France, "Théorems d unicite de la théorie des fonctions", Saturday, September 2. Section II Analysis; Norbert Wiener, MIT, "The statistical mechanics in communication", conference in applied Mathematics Statistical Mechanics", Wednesday, September 6; Howard Aiken, Harvard University, "Computing Machines", August 31 evening lecture; Claude Shannon, Bell Telephone Laboratories, "Some topics in information theory".

[6] Finetti presented the communication: "La nozioni di beni independenti in basi ai nuovi concetti per la misura della utilità", In, Proceedings of the International Congress of

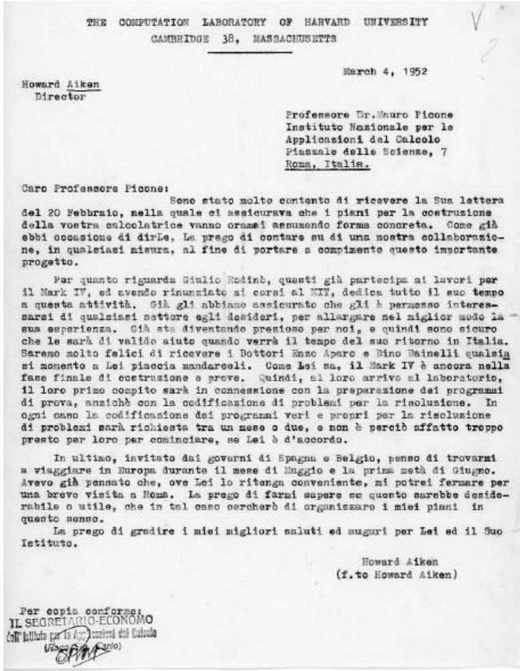
revealed state of the art technology on the application of digital calculating machinery, Picone felt that he was on the right place and the contacts made with Howard Aiken´s Laboratory favoured a research stay of eighteenth months for Michele Canepa. Here Canepa and Giulio Rodinò received training in circuit and component design for electronic digital computers, while working at the Mark IV project. In a letter to Picone dated March 4, 1952, Aiken mentions the work of the Italian mathematicians at his Lab, he says: "... as you know the Mark IV is at its final stage of construction and tests (…) and Giulio Rodinò who decided to not enrol courses at MIT is dedicating is entire time at the this project (…)"[7] (Fig. 2).

Finetti already in 1949 had written an initial article about the working principles of electronic machines, "*Como funzionano le calcolatrici elettroniche*" (Fig. 4) takes this opportunity to travel in the USA to attended other important scientific meetings, such as the Symposium on probability at the University of California at Berkeley[8], and the Industrial Computation Seminar, held in New York and sponsored by the International Business Machines Corporation (Fig. 5). The ninety researchers who participated, met to discuss the fundamental computational methods applicable in a variety of research problems and this meeting drew upon the success of IBM's Selective Sequence Electronic Calculator (SSEC), built under the direction of Wallace Eckert, distinguished astronomer and founder of the Thomas J. Watson Astronomical Computing Bureau at Columbia University. Eckert's paper read at the IBM seminar, "*The Role of the Punched Card in Scientific Computation*" caught Finetti attention since he had been working in this filed in Italy at major insurance companies.

Mathematicians, Cambridge MA. Published by the American Mathematical Society, 1952.pp: 588-589. Fichera presented a paper entitled: "Methods for solving linear functional equations, developed by the Italian Institute for the applications of calculus". The success of this meeting followed the Symposium of Large Scale Digital Calculating Machinery, which took place precisely one year earlier also at Harvard University and sponsored by the Navy Department Bureau of Ordnance and the Computation Laboratory.

[7] Finetti and Rodinò also attend the International Symposium on Automatic Digital Computing in Teddington, London, March 1953. See: Symposium on automatic digital computation (in collaboration with N. Kitz, and G. Rodinò). In: *La Ricerca Scientifica,* n.7 (1953), 1248-1259.

[8] Finetti presented a paper entitled: "Recent Suggestions for the Reconciliation of Theories of Probability". In, Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, 217-225, University of California Press, Berkeley, 1951.



THE COMPUTATION LABORATORY OF HARVARD UNIVERSITY
CAMBRIDGE 38, MASSACHUSETTS

March 4, 1952

Howard Aiken
Director

Professore Dr. Mauro Picone
Instituto Nazionale per le
Applicazioni del Calcolo
Piazzale delle Scienze, 7
Roma, Italia.

Caro Professore Picone:

Sono stato molto contento di ricevere la Sua lettera del 20 Febbraio, nella quale ci assicurava che i piani per la costruzione della vostra calcolatrice vanno oramai assumendo forma concreta. Come già ebbi occasione di dirLe, La prego di contare su di una nostra collaborazione, in qualsiasi misura, al fine di portare a compimento questo importante progetto.

Per quanto riguarda Giulio Rodinò, questi già partecipa ai lavori per il Mark IV, ed avendo rinunziato ai corsi al MIT, dedica tutto il suo tempo a questa attività. Già gli abbiamo assicurato che gli è permesso interessarsi di qualsiasi settore egli desideri, per allargare nel miglior modo la sua esperienza. Già sta diventando prezioso per noi, e quindi sono sicuro che le sarà di valido aiuto quando verrà il tempo del suo ritorno in Italia. Saremo molto felici di ricevere i Dottori Enzo Aparo e Dino Dainelli qualsiasi momento a Lei piaccia mandarceli. Come Lei sa, il Mark IV è ancora nella fase finale di costruzione e prove. Quindi, al loro arrivo al laboratorio, il loro primo compito sarà in connessione con la preparazione dei programmi di prova, anzichè con la codificazione di problemi per la risoluzione. In ogni caso la codificazione dei programmi veri e propri per la risoluzione di problemi sarà richiesta tra un mese o due, e non è perciò affatto troppo presto per loro per cominciare, se Lei è d'accordo.

In ultimo, invitato dai governi di Spagna e Belgio, penso di trovarmi a viaggiare in Europa durante il mese di Maggio e la prima metà di Giugno. Avevo già pensato che, ove Lei lo ritenga conveniente, mi potrei fermare per una breve visita a Roma. La prego di farmi sapere se questo sarebbe desiderabile o utile, che in tal caso cercherò di organizzare i miei piani in questo senso.

La prego di gradire i miei migliori saluti ed auguri per Lei ed il Suo Istituto.

Howard Aiken
(f.to Howard Aiken)

Per copia conforme:
IL SEGRETARIO-ECONOMO
dell'Istituto per le Applicazioni del Calcolo

Fig. 2. Letter from Howard Aiken to Mauro Picone, March, 1952.

Once Finetti concluded his trip, he wrote a major review about the state of the art computing. Initially published by the University of Trieste, Finetti´s article entitled: "*machines that think and that make you think,"* [9] (Fig. 3) was full of first hand analysis gathered during his journey, presenting technical descriptions about the several computing machines he observed and studied. His article, the first in itialan language, presented an apendix with detailled illustrations and photos of the main computers ("machine calcolatrici") he saw: SIMON, 1950, conceived by Edmund Berkeley; the SSEC, 1947, (Selective Sequence Electronic Calculator) designed and built by IBM; the UNIVAC, 1951 (Universal Automatic Computer) designed by Ecert-Mauchly Computer Corperation; the SEAC (Standards Eastern Automatic Computer) built at the National Bureau of Standers, Washingon, D.C, 1950.

Wallace Eckert in the meantime, become director of the Thomas J. Watson Astronomical Computing Bureau at Columbia University, writing an important article, "*Electrons and Computation*"[10], in which he describes the advantages of the

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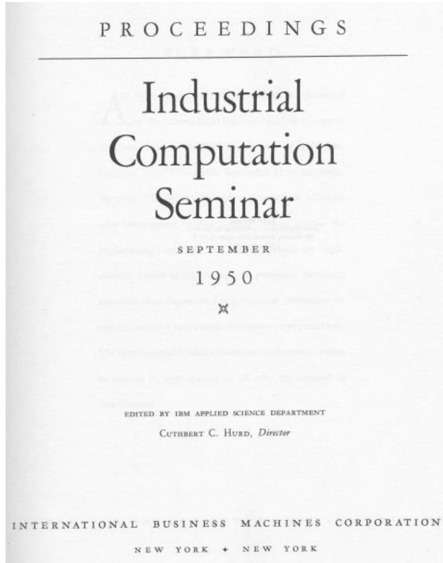
[9] "Macchine «che pensano» (e che fanno pensare)", In, Pubblicazioni delle Facoltà di Scienze e di Ingegneria della Università di Trieste. Serie A. Trieste,1952, 40pp.

[10] W.J. Eckert. "Electrons and Computation". In, The Scientific Monthly, November 1948.

SSEC calculator, in terms of computation speed and easy use by "any reader of this article." Finetti´s text "*Macchine che pensano e che fanno pensare*", which can also be seen as an inspiration from Edmund Berkeley´s book, "*Giant Brains and machines that think"*, represents fundamentally the earliest source of reliable and detailed material ever made available to the Italian scientific community.

All this insightful information along with the research internship at the Harvard Computation Lab of Picone and Olivetti´s mathematicians strengthened the belief of a possible partnership for the inception of a collaborative electronic venture in Italy.

Fig. 3. Front page of Bruno di Finetti article, "Macchine che pensano", with an illustration and description of the UNIVAC Computer, 1952.


PROCEEDINGS

Industrial Computation Seminar

SEPTEMBER 1950

EDITED BY IBM APPLIED SCIENCE DEPARTMENT

CUTHBERT C. HURD, *Director*

INTERNATIONAL BUSINESS MACHINES CORPORATION

NEW YORK ✦ NEW YORK

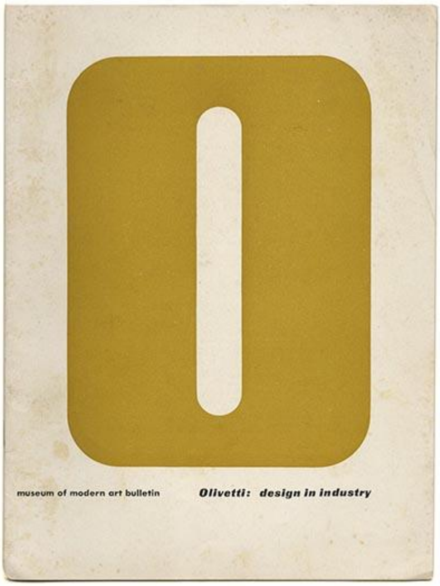
Fig. 4. Bruno di Finetti article: "Come funzionano le calcolatrici elettroniche", February 1949.
Fig. 5. Proceedings of the Industrial Computation Seminar, IBM, New York, September 1950.

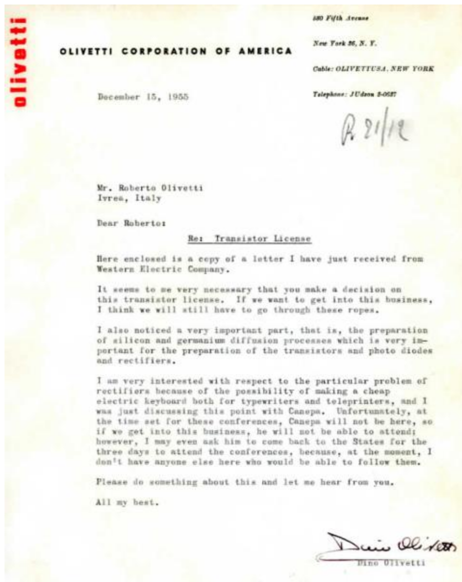
3 Olivetti Corporation of America

Was this affinity with the American academia and industry mainstream just a happy coincidence or was rather the consequence of a former familiar empathy with the USA scientific milieu? Certainly that we can acknowledge that the Olivetti family had a previous contact with the American University and with its entrepreneur and research environment. Camillo Olivetti visited the USA in the fall of 1894 and for six months become assistant of electrical engineering at Stanford University in California. Later his son Adriano at the age of twenty-five does his first trip in America departing from Liverpool and arriving to New York in August 1925. But probably more important was that Dino Olivetti came to Cambridge, USA, by the end of the 30s, after having participated at the Italian fascist military campaign in Ethiopia that culminated with the conquest of the city of Addis Abeba by in May 1937. In Cambridge, Dino enrolls as a student at the Mechanical Engineer Department of the Massachusetts Institute of Technology where he submitted a dissertation entitled, "*Performance test on a Sterling Diesel Engine*" as a requirement to obtain the Bachelor of Science Degree in General Engineering (1940).[11] Here he also gets an appointment at the Automotive Laboratory, being this stay fundamental for Dino´s new connections with young scientists working in mechanics and electronics both at MIT but also in New York and at Columbia University, something that proved decisive when Olivetti started to recruit for their new Electronic Laboratory in New

[11] Dissertation co-authored with John Vanderpoel under the supervision of Prof. C. Fayette Taylor, MIT.

Canaan. On the other hand, Roberto Olivetti (1928-1985) a strong supporter of the development of *Olivetti's* electronic department, after graduating from economics at the Bocconi University in Milan, does in 1954 a Business Administration course at Harvard University.





olivetti

OLIVETTI CORPORATION OF AMERICA

580 Fifth Avenue
New York 36, N. Y.
Cable: OLIVETTUSA, NEW YORK
Telephone: JUdson 2-0627

December 15, 1955

R. 21/12

Mr. Roberto Olivetti
Ivrea, Italy

Dear Roberto:

Re: Transistor License

Here enclosed is a copy of a letter I have just received from Western Electric Company.

It seems to me very necessary that you make a decision on this transistor license. If we want to get into this business, I think we will still have to go through these ropes.

I also noticed a very important part, that is, the preparation of silicon and germanium diffusion processes which is very important for the preparation of the transistors and photo diodes and rectifiers.

I am very interested with respect to the particular problem of rectifiers because of the possibility of making a cheap electric keyboard both for typewriters and teleprinters, and I was just discussing this point with Canepa. Unfortunately, at the time set for these conferences, Canepa will not be here, so if we get into this business, he will not be able to attend; however, I may even ask him to come back to the States for the three days to attend the conferences, because, at the moment, I don't have anyone else here who would be able to follow them.

Please do something about this and let me hear from you.

All my best.

Dino Olivetti

Fig. 6. Front cover of MOMA Catalogue exhibition, *Olivetti: design in industry*, 1952.
Fig. 7. Letter from Dino Olivetti to Roberto Olivetti, December 1955.

The foundation of the *Olivetti Corporation of America* (OCA) in New York takes place in 1950 with Dino Olivetti becoming its president. The American market was a challenge for *Olivetti* and now with the establishment of a branch in New York, started to be possible to expand *Olivetti´s* commercial boundaries. Moreover with the creation of the *OCA*, the company invested in new and better production facilities, but design excellence was what really set it apart from competitors. Under Dino Olivetti´s leadership in New York an exhibition of the work of the Olivetti Company at the Museum of Modern Art, MOMA is organized in 1952. *Olivetti: Design in Industry* (Fig.6) was at display from October 22 to November 30, showing architecture and industrial design products by the architects Luigi Figini and Gino Pollini, Ugo Sissa, and Marcello Nizzoli, constituting a main surprise to the American public and a major success proving that an industrial company could also be a leading corporation in the design field both within its products as well as within its buildings. *Olivetti* demonstrated to be a model of intelligent and imaginative management, and a cornerstone of Italy's post-war economic revival. Central to its success was its enlightened patronage of contemporary design and art, and the elegance with which they were integrated into its commercial interests. Dino Olivetti was also responsible to open a showroom in New York fifth Avenue, entrusting the design of their store to the Milanese architectural firm of Banfi, Belgioioso, Peressutti and Rogers (BBPR).

It is acknowledged that when Thomas J. Watson Jr. was preparing to succeed his father as chief executive of I.B.M stopped at the Olivetti shop, being so impressed, that he travelled to Italy to meet with Adriano Olivetti to discuss with him a new design policy for IBM. Olivetti machines had sleek designs and a variety of colors and the architectural space of its showroom was modern, full of light, almost as a theatre stage. In contrast, the commercial areas in IBM's offices where still very conventional and not so glamorous. The brand communication strategy competition between IBM and Olivetti has thus its roots in this store of New York with IBM hiring as the company design consultant, Eliot Noyes a well-respected architect and former curator of industrial design at New York´s Moma Museum. Noye´s goal was to create a corporate design program that would encompass everything for IBM´s products. Noyes brought in a wide variety of artists, designers and architects including Charles and Ray Eames, Eero Saarinen and Paul Rand, all working for a new company design philosophy.

While the success of the Olivetti brand in America and particular in New York was rising, their previous partnership with Pisa University and with Mauro Picone regarding the design and construction of an electronic calculator come to and end. Despite the theoretical expertise that *Olivetti* group had recently acquired in the USA, the lack of financial support from the Italian government prevented the project to be realized even if *Olivetti* collaborators were ready to do so. Michele Canepa who was working with the team of Howard Aiken, mentions to Picone in a letter from December 1951, that he was disposed to cooperate whatever decision would be made, he says: "i 18 mesi trascorsi negli Stati Uniti d´America con i solo scopo di studiare il problema mi permettono ora di vedere in modo chiaro quale la strada deve essere seguita verso la realizzazione della ricordata Macchina (...) nel frattempo avrò pure interpellato la Direzione di Ivrea circa il detto progetto e potrò quindi riferire sulla possibilità della mia collaborazione".[12] At this moment Dino convinces his brother Adriano to open an Electronic Research Laboratory in the USA so that the gained expertise would not be lost, but rather focused at the possibility of *Olivetti* moving into the electronics field. Like this Canepa will soon start to work at the newly founded laboratory created by Dino Olivetti in New Canaan, now the residency area of Dino Olivetti´s family.

The city of New Canaan, located 25 miles west of Manhattan and southeast from Boston is considered part of Connecticut's gold coast, where since the mid 1800s, many of New York wealthy citizens lived. After the World War II this quiet and beautiful area, full of colonial and farmhouses houses, become the realm for contemporary architecture and prosperous business. To this setting, contributed very much the establishment of Walter Gropius as professor at the GSD at Harvard University, and modernist architects like Marcel Breuer, Philip Johnson and Eliot Noyes, (known as the Harvard Five) initiated to design houses for their clients and

[12] Translation by the author: the 18 months spent in the United States of America with the sole purpose of studying the problem allow me now to see clearly where the road must be followed towards the realization of the mentioned machine (...) in the meantime I have also asked the Department of Ivrea about the project and I will then report on the possibility of my collaboration. Source: Archivio Storico Olivetti.

themselves in this location, transforming it, in a glamorous and prestigious residential destination.

The role of the electronic research laboratory was pivotal to *Olivetti's* new strategy and Dino´s and Canepa´s leadership is not yet full recognised within the success that Olivetti achieved in its new business. The primary goal of the Laboratory was to do R&D and to stay close to the technological advances in electronics and information technology that were been developed in the USA. The change of correspondence between the *Olivetti Corporation of America* with the Ivrea headquarters, mainly amongst Dino and Adriano, shows a enduring interest of Dino in participating at the last developments of the field, but also inquiring about the viability of incorporating these new technologies in *Olivetti´s* new electronic products. Their communication focused issues such as, the technology that *Philco* used for its electronic brain machine, and consideration about its design. In one letter Dino writes:" the machine is very neatly designed, very advanced in design especially for production"; or in another he speaks about the importance of using and producing electronic transistors, he says: "Here enclosed is a copy of a letter I have just received from Western Electric Company. It seems to me very necessary that you make a decision on this transistor license. If we want to get into this business, I think we will still have to go through these ropes."[13] (Fig.7). Moreover the *OCA* also sponsored Italian graduate students at American Universities with the subsequent possibility of being hired to collaborate with the New Canaan Laboratory, where at its peak, almost seventy researchers and staff worked.

4. Olivetti Computers and the International Exhibitions

In 1937 Pablo Picasso painted for the Spanish pavilion at the Universal Exhibition of Paris his masterpiece, *Guernica*, which displayed the agony and suffering of the Spanish people during the country civil war. Sadly this conflict constituted the offspring of World War II, the *Age of Extremes* as Eric Hobsbawm critically described. WWII forced the development of new technologies and at the early 1950s, major institutions and companies tried to bring to profit their investments and technological breakthroughs. As the Cold War grew out of the devastation of World War II, International World's fairs became staging grounds for displays of the U.S.-Soviet rivalry but also for the exhibit of new technological apparatus. In 1958, *Sputnik* satellite was launched, consumer society was emerging and the population wished to believe that the dawn of a period of peace and progress had arrived. The Brussels International Fair, inaugurated in April of that year, become the setting for this new European will.

The presentation of the two *Olivetti* computer projects coincides with the period of the inauguration of the Brussels International Fair in 1958 and the New York World Fair in 1964. In Brussels IBM participated with an exhibit with the company´s 305 RAMAC, one of the last vacuum tube computers and a modern pavilion designed by Eliot Noyes. For the event, Noyes also commissioned for screening at the IBM

[13] Letters from Dino Olivetti to Roberto Olivetti, December 1955 and December 1956. Source: Archivio Storico Olivetti.

pavilion, *The Information Machine: Creative Man and the Data Processor*, the first film of the Eames Office, bringing to a wide audience the brave new world of computing. If this projection created a great impact by its novelty, Le Corbusier´s pavilion for *Phillips* constituted also a major technological and architectural breakthrough. In that period Le Corbusier was in Chandigarh, the new city he began building in 1951, when we wrote a letter to the French born composer, Edgar Varese inviting him to collaborate at the project. Other important member of the team was Iánnis Xenaquis who was working as an advisory engineer on the structure of the Supreme Court and the hyperbolic tower of the Assembly that houses the Chandigarh Parliament. Xenaquis was collaborating with Corbusier since mid 40s and his mathematical and architectural skills constituted a strong asset for the design of the pavilion that should pay tribute to light, sound and color, since *Philips* was a leading world company in that sector. Within this context, the eighth minute *Le Poéme Electronique*, (Fig.12) was a multimedia project with electronic music, which wasn't written to sound pleasing, but rather to expand the conception of what music could be. It was laboratory created and projected with images in the inner space of the pavilion, transporting the general public, to a new atmosphere of novelty and modernity. Probably influenced by the success of these multimedia projects, the Olivetti Film Office, created for the presentation of its ELEA Computer a striking film documentary, entitled, *Elea class 9000,* with original music by Italian composer Luciano Berio, with movie direction by Nelo Risi and Nuzio Mazzolli, transforming the film into a contemporary advertising masterpiece (Fig.13). Here as well, the music score was at the forefront of electronic technology and Berio one of the most important contemporary Italian musicians used the recently inaugurated "Studio di Fonologia Musicale di Radio Milano" to compose the music for *ELEA class 9000*.

The ELEA 9003 (Fig.8; Fig.9), acronym referring to the ancient city of Elea, known for being the home of the philosophers Parmenides and Zeno, was the first full transtorized computer which mainframe and console design was entrusted to the architect Ettore Sottsass, who aware of the anxiety-inducing image of computing, gave to this apparatus a colorful visual interface (Fig.11). How one would design and give visible form to objects and buildings in a fully industrialized world dominated by the new media? Not surprisingly the work that Tomas Maldonado developed at the Ulm School of Design, Hochschule für Gestaltung, was crucial and very calling for the new electronic project at Olivetti, by creating a new sign system for the computer console interface (Fig.11). This magnificent machine presented a different concept, it had a human scale, its cables were floating in the air, and not under the ground, had a modular system and the console keyboard was designed accordingly to the last semiotic theories. The influence of the Ulm school, had an enormous impact on design thinking of the late 50s, where the role of the designer emerged as a coordinator of various experts.

Construction of the ELEA 9003 began by the early 1958 and one year later, Ettore Sottsass received the Compasso d´Oro design award. By the occasion of the official presentation of the ELEA 9003 computer at the *Fiera Campionara di Milan* in November 1959, Adriano Olivetti says: "L´elettronica non solo ha reso possibile l´impiego della energia atomica e linizio dell era spaziale, ma, attraverso la moltiplicazone di sempre piu complessi ed esatti apparati di automazione, sta avviando l´uomo verso una nuova condizione di liberta e di conquiste”.[14] Unfortunately even within the presence of his Excellency the President of the Italian Republic, Olivetti never received any governmental financial support, contrasting with the huge financial aid that American research laboratories had from their agencies.

Fig. 8. ELEAComputer 9003, 1959.

Fig. 9. ELEA Computer 9003, 1959.

[14] See: Il mondo che nasce, Edizioni di Comunità, Roma-Ivrea 2013.pp.122-123.

Fig. 10. ELEA Computer 9003, for the Monte dei Paschi bank, Siena, presentation brochure, 1959.

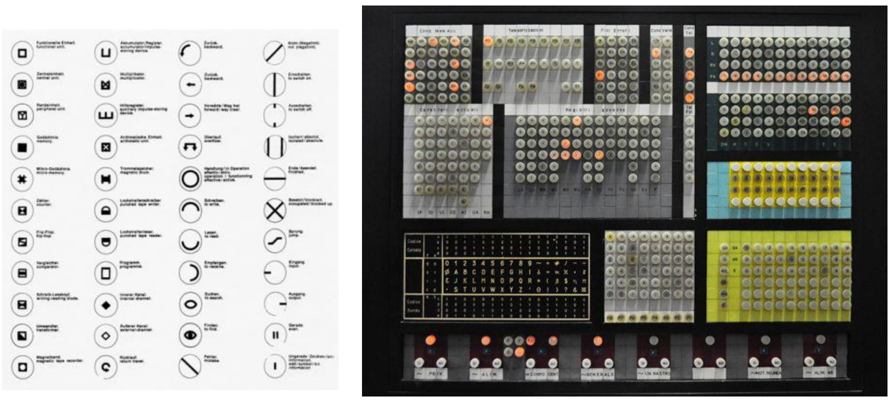
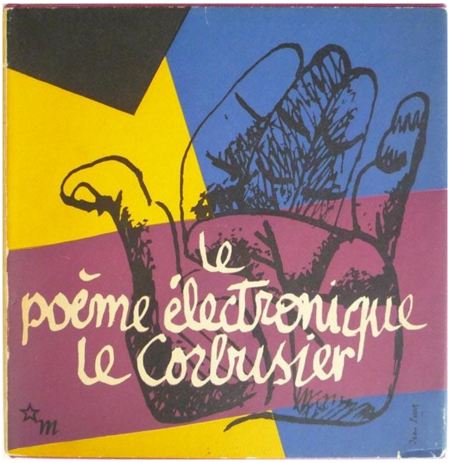


Fig.11. Sign system design, for the ELEA 9003 computer console. Tómas Maldonado with Ettore Sottsass, 1960.

However, upon the optimistic social milieu of the mid 50s there was still a suspended atmosphere of peril and the two major powers agreed to host national exhibitions from the other nation, displaying their “science, technology, and culture”. The Soviet show opened in the Coliseum at Columbus Circle in New York City in June 1959 while the American installment opened in Sokolniki Park in Moscow in July of the same year. For this exhibition Eliot Noyes did the master plan and invited Buckminster Fuller, who designed a geodesic dome for the USA pavilion and where the film of Charles and Ray Eames, *Glimpses of the USA* was projected in several suspended screens.

During the early sixties, the ELEA series represented for Olivetti, almost 30% of the Italian market share, a result that could appear satisfactory since the lack of financial support for such a robust and innovative project. However a far more reaching machine would soon be released due to research, in the meantime, carried out by a few members of the Olivetti Electronic Division, namely, Pier Giorgio Perotto, an engineer who was with Mario Tchou´s team since 1957, Giovanni de Sandre and Gastone Garziera. Together in agreement with Roberto Olivetti they worked on the development of a small, programmable ”desktop computer,” the P101, presented at the World’s Fair in New York in October 1965 (Fig. 15), competing successfully with IBM electronic products at display at the company ovoid pavilion (Fig. 14) designed by Eero Saarinen and where the Eames film *Think* was at display. Designed long before the spread of the integrated circuit, the Programma 101, as it was called, was completely built with discrete components such as transistors, diodes, resistors and capacitors and an innovative memory drum. Computing appeared as a friendly device and no longer as a ghost (war) machine. The design was by Mario Bellini, a young architect of the Sottsass' team, who soon become one of the main industrial designers of the following years. In an era when people largely regarded computers with suspicion, it had an impact few could have anticipated. The P101 was considered the first personal computer, and was a major commercial success (Fig. 17, Fig.18), with companies such NASA acquiring it for the calculations for the 1969 Apollo 11 moon landing, or the Oceanographic Institute at Marseille, which used the P101 for calculations for its ocean research program (Fig. 16).



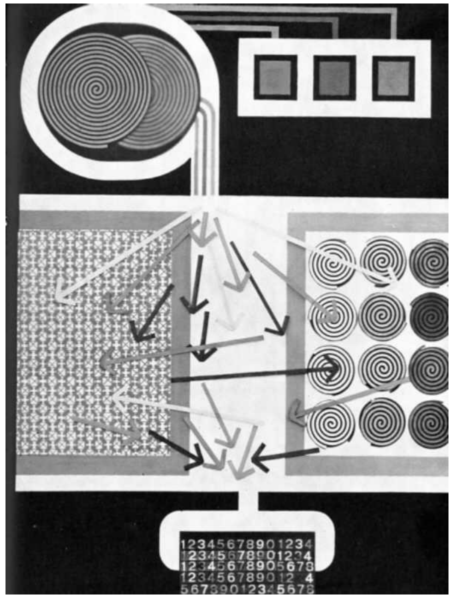


Fig.12. *Le Poème Electronique* by Le Corbusier, 1958

Fig.13. Giovanni Pintori, ELEA 9000, 1957

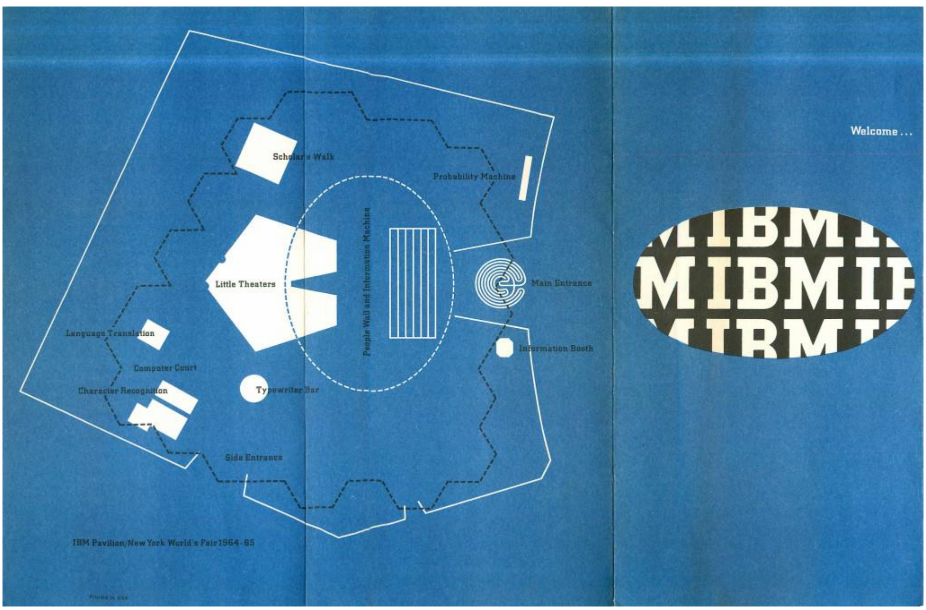


Fig. 14. Paul Rand´s brochure for the IBM Pavilion, New York World´s Fair, 1964/65.

Fig. 15. Presentation of Computer P101 at the New York, 1965.
Fig. 16. Computer P101in use at oceanographic research, Marseille, 1966.

Fig. 17. P101 Computer production line at the Olivetti-Underwood factory, designed by Louis Khan, Pennsylvania, USA, 1970.

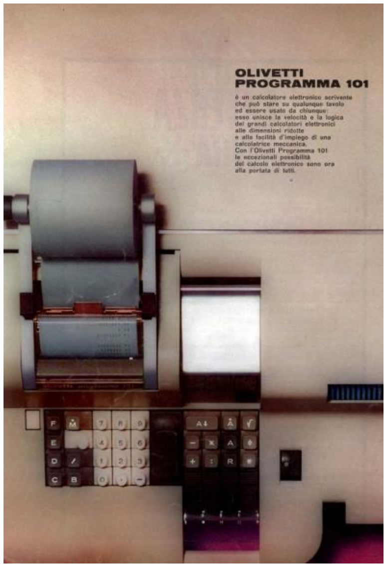


Fig. 18. Olivetti Programma 101 advertising Poster, 1966.

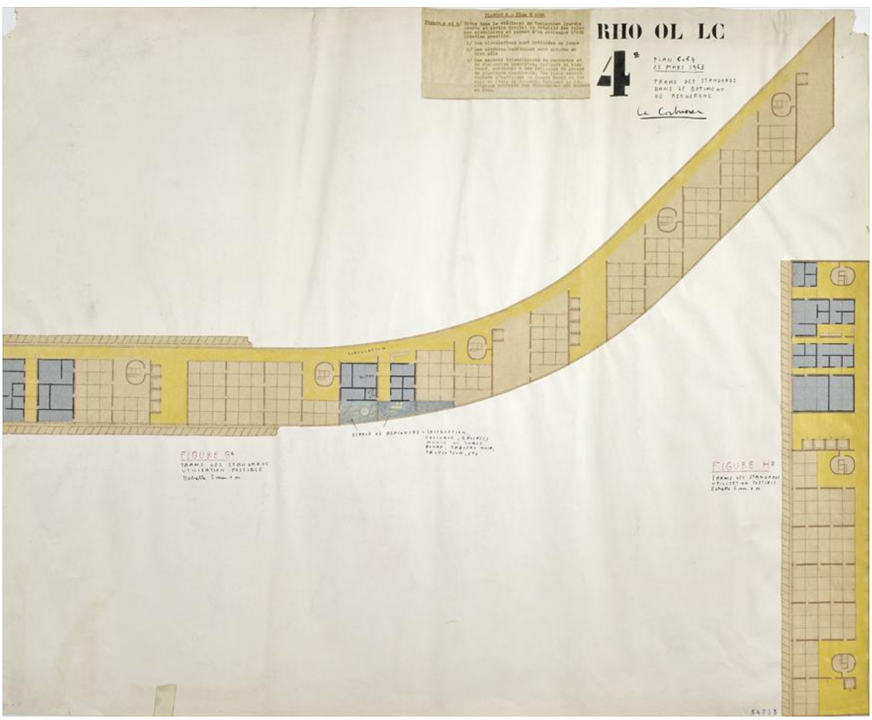


Fig. 19. Le Corbusier drawing for the *Centro di Calcolo Elettronico Olivetti*, 1963.

The initial success of the digital enterprise of *Olivetti's* company, made Adriano think of new industrial facilities to produce his state of the art computers and Le Corbusier was the chosen architect to develop a master plan and project, for this new "industrial city". The first contacts between Olivetti and Le Corbusier had taken place by the mid 30s when Olivetti decided to promote an international competition for a new social housing complex for the company. With the suddenly death of Adriano Olivetti in February1960, this endeavor would be carried out by his son Roberto, who was also the responsible for all R&D activities of the electronic department. The site for the new electronic factory was located near the city of Rho in the Milan area district, and between 1962 and 1964, Le Corbusier develops three different versions for the project, which regrettably will never come to light (Fig.18). Silvia Bodei in her book, *Le Corbusier e Olivetti*, describes in detail this project, and mentioning that Corbusier in 1965 publishes a full version of the project for the *Centro di Calcolo Elettronico Olivetti* (Oeuvre complète 1955-1965).

5 Conclusion

The numerous technological achievements of *Olivetti* in the field of computing were conducted with a vivid passion and firm belief that electronics would be the leading industry of the future and for its success, a high standard of design was mandatory for all levels of the production chain. Between 1959 and 1966 *Olivetti* developed a different range of products and projects working with architects such as: Marcello Nizzoli, Ettore Sotssas, Mario Belinni, Giovanni Pitori, Le Corbusier, Louis Khan, and earlier with the Ernesto Rogers firm, creating an exiting new culture of design excellence and influencing greatly the design and marketing strategies of its main competitor, IBM. Moreover the P101 computer remained in production at the Olivetti-Underwood factory in Pennsylvania until the late 1971, just five years before the market appearance of Apple I. The design and technology idea associated to Steve Wozniak and Steve Jobs Computer Company, benefited greatly of the several patents and design thinking that Olivetti, Mario Tchou and his electronic group so persistently pursued during their lifetime. No other corporation acted in such an integrated view, and which products, consolidated an inspirational and technological form, for years to come.

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Fig. 8. Archivio Storico Olivetti: Tratto da: "Olivetti Elea 9003. Nazionale Cogne S.p.A."/ Fondo Biblioteca Sala-F/ Fabbrica e Famiglia. Faldone 5, fascicolo 8.
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Fig.16. Archivio Storico Olivetti: "L'Olivetti Programma 101 usato per le ricerche oceanografiche a Marsiglia". Fondo Fototeca / Foto Storiche (ex DCUS) / Applicazioni di Macchine. Faldone 1, fascicolo 20.
Fig. 17. Archivio Storico Olivetti. Fondo Fototeca. Foto Ezra Stoller.
Fig. 18. Archivio Storico Olivetti. Fondo Fototeca.
Fig. 19. RHO OL. FLC 14733, © FLC/ADAGP.

OUTLINING TERRAGNI:

Calculating the Danteum's and Mambretti Tomb's Form and Meaning

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Abstract. Despite his controversial political background, the leading architect of the Italian Rationalist Movement, Giuseppe Terragni, has attracted the attention of a large group of architectural scholars. He has often been acknowledged as an enigmatic figure whose architecture oscillated between classicism and modernism. This work offers formal generative analyses of the Mambretti Tomb and the Danteum, which are seen as the 'quintessence' of Terragni's architecture. It provides a formal generation of these two projects in the form of parametric shape grammar. In doing so, this paper aims at unfolding the generative process of both projects in order to gain a deeper understanding into the ways that formal construction of Terragni's architecture expresses meaning.

Keywords: Shape grammars • Generative design • Architectural language • Type and style • Italian rationalism

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