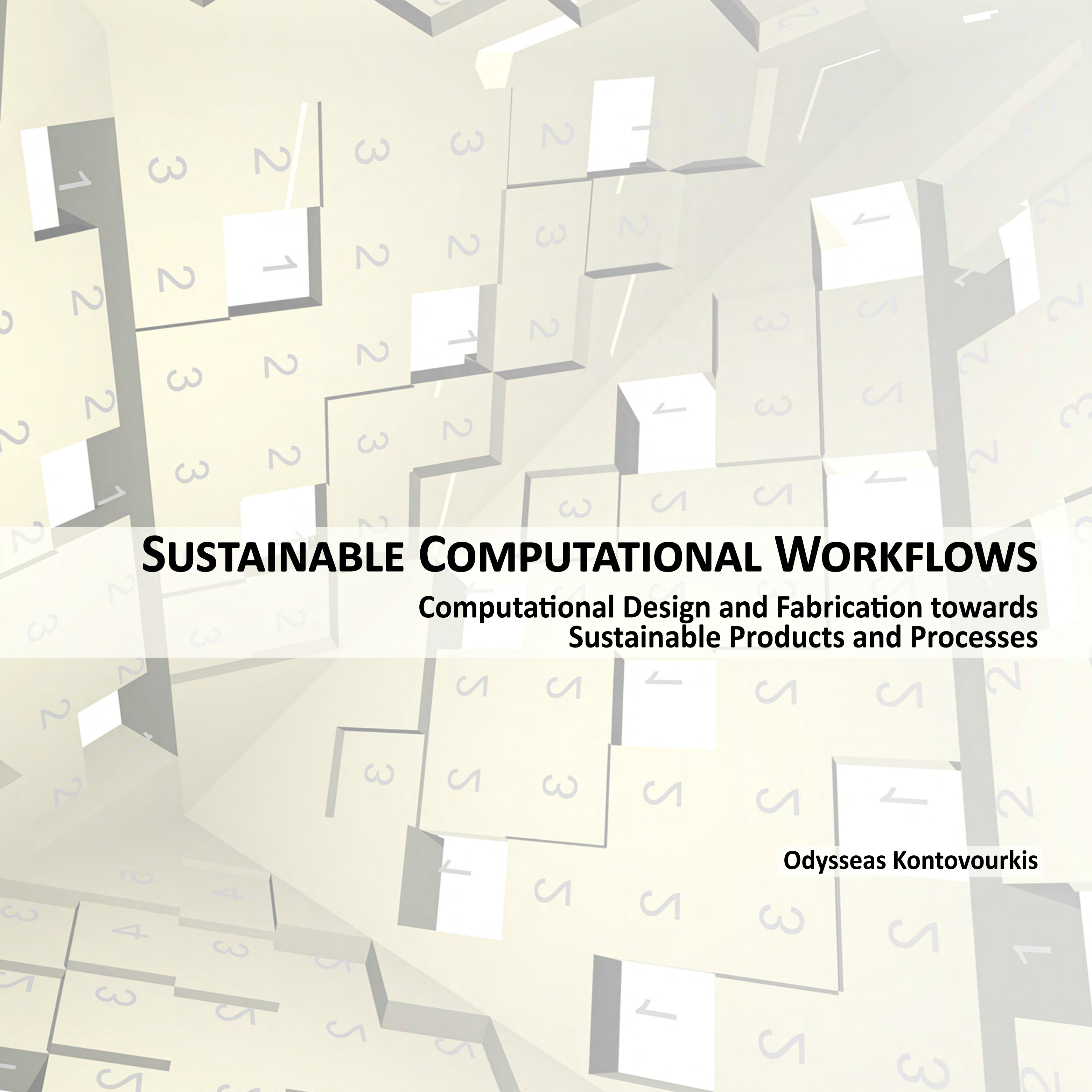

# Sustainable Computational Workflows

## Computational Design and Fabrication towards Sustainable Products and Processes

Odysseas Kontovourkis

# eCAADe RIS 2018

# Sustainable Computational Workflows

Computational Design and Fabrication towards
Sustainable Products and Processes

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# Sustainable Computational Workflows

## *Computational Design and Fabrication towards Sustainable Products and Processes*

At a time when sustainability plays a key role in the way different disciplines approach development and production, the role of digital technology is crucial, as through smart and efficient techniques, it can lead to the creative design, analysis, evaluation and fabrication of solutions that are ecologically and economically viable and socially accessible. On the other hand, recent developments in the socio-economic context have caused changes and redevelopments in Europe, particularly in the Mediterranean region, which have a direct impact and affect the overall reflection on how new technologies, currently in open source and with a widely accessible status, contribute to a better and more sustainable future, without running isolated or far beyond today's reality.

The theme of the symposium has been shaped in the light of this concern; that is how computational processes in design and production can have a direct impact on shaping the built environment in such a way that it will achieve and offer conditions of social inclusion and economic viability with less environmental impact. Within this framework, such strategies might lie within a regional context, associated with local conditions (social, economic, environmental, etc.) that influence design and fabrication decision-making, without neglecting their influence within a universal context.

The symposium aims to bring together educators, researchers and professionals under the common goal of developing and presenting computational design and production workflows and to open a debate on the potential of such techniques in delivering positive results for a more sustainable future. Through a bottom-up approach, the symposium aims to cover the range of computational processes and workflows in design, analysis, performance evaluation and in the context of physical production, using digital fabrication mechanisms. Whether design methodologies include parametric and generative design processes, performance driven or performance oriented approaches, optimization techniques, and so on or whether fabrication mechanisms include additive manufacturing, robotic fabrication, and so on. Papers and workshop proposals in similar directions, corresponding to the theme of the symposium, are presented in these proceedings.

Given the wide range of directions that such computational workflows could get, the symposium and the workshop attempt to cover, different approaches ranging from digital design to prototyping and possible workflows of methodological investigation in-between, by connecting the virtual with the physical and vice versa towards a more sustainable future, both on a theoretical and a practical level.

The work presented in the proceedings of the symposium proves in the best way that the latest developments in the fields of computational design and fabrication can contribute, through imaginative workflows that touch different investigations, to the common goal of examining and finding solutions that could respond and answer issues related to contemporary concerns regarding the design and construction of the built environment in a way that serves the sustainable needs of society. This is achieved through their integration into the wider context of computational design and fabrication processes, but also through their contribution both in conceptual, design development and physical construction levels of investigation. Briefly, through the general framework of the symposium theme that deals with Sustainable Computational Workflows, this volume presents work that approaches issues on topics like Design concepts in research and teaching, Design tools development, Digital design for sustainable development, Design and structure optimization, and Digital fabrication and robotics in construction.

*Odysseas Kontovourkis*
eCAADe RIS 2018 Symposium Chair

*All the papers of these proceedings are accessible via CuminCAD – Cumulative Index of Computer Aided Architectural Design: http://papers.cumincad.org/

Acknowledgements

We are grateful and would like to thank those who have helped and contributed to the 6th eCAADe Regional International Symposium in Nicosia. Also, those who have participated in the discussion and exchange of views on Sustainable Computational Workflows and on how this theme can be associated to and integrated within the framework of Computational Design and Fabrication.

We would like to thank the eCAADe Administrative Council for providing the opportunity to organise the Regional International Symposium 2018 in Nicosia. Especially, we are grateful for the contribution and support at scientific and practical level provided by Joachim Kieferle, Jose Manuel Pinto Duarte, Bob Martens, Henri Achten and Nele de Meyere. We would also like to thank the eCAADe Organisation for providing financial support that has enabled us to organise the symposium. Also, we would like to thank the Scientific Review Committee for their help during the peer-review process. Their remarks were significant for the selection of the work presented during the symposium.

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Last but not least, we would like to thank the Department of Architecture and the University of Cyprus for their financial support and practical assistance. Also, for the provision of premises and laboratories of the university. Their contribution and help was crucial in the successful organisation of the 6th eCAADe RIS 2018.

Nicosia, May 2018

*Odysseas Kontovourkis*
Symposium Chair

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# Keynote

## Guillaume Habert

Chair of sustainable construction, ETH Zurich, Switzerland

After studying biology and geology, Guillaume Habert graduated in 1999 from the Ecole Normale Supérieure in Paris, with a degree in earth, atmospheric and oceanic studies. In 2004 he completed his PhD in Toulouse (France) on structural geology. His research was based on the relations between internal structures in granites and the tectonic context. He focused on three case studies located in the Sierra Nevada (California, USA), the Colorado plateau (Utah, USA) and the Cyclades islands (Greece).

After his PhD Guillaume Habert used his knowledge of natural rocks mineralogy to explore how specific clays and pozzolans can be used as a cement substitute. This work, funded by the CNRS and Lafarge, was followed by a post doctorate position at the Federal University of Paraiba (Brazil). In Brazil he looked into how waste products from the ceramic industry, can be used as pozzolanic materials to improve the mechanical and water resistance of adobes. From 2007 to 2012 Guillaume Habert conducted research at the Laboratoire Central des Ponts et Chaussées in Paris. His work focused on the development of sustainable concrete. This also led him to address the environmental evaluation of building materials as well as the development of new binders such as geopolymers.

Since August 2012, Guillaume Habert holds the Chair of Sustainable Construction and is associate professor at the ETH Zürich. The objective of the chair is to identify the relevant parameters that influence the environmental impacts of buildings and infrastructures at international, national and regional levels in order to implement sustainable practices throughout the development of innovative constructive techniques adapted to the technical, economic and socio-cultural situation of specific territories. He is, since 2013 partner of a large National Competence Centre on Digital fabrication in Switzerland involving 15 Professors and more than 30 PhDs in different disciplines from computational science, robotics to architecture. His main work has been to explore the potentials of digital fabrication for a more sustainable construction and identify the key drivers, which need to be considered in the early design phase of projects.

## Keynote lecture

***CAN WE ADD SUSTAINABILITY TO DIGITAL FABRICATION?***

In the era of technological innovation and digital revolution, inadequate working conditions and high resource consumption are still common practice in the construction sector, a sector that requires a deep transformation to keep up with other industries in terms of environmental impacts and productivity. As a potential solution, the adoption of Industry 4.0 technologies such as Additive Manufacturing (AM) in construction, promise to enhance the sustainability of the sector, resulting from improved productivity, efficiency, safety, collaboration, etc. In particular, the combination of computer-aided design and automated fabrication techniques for additive construction demonstrates the ability to produce complex architecture with optimized geometries and integrated multi-functionality. However, so far, few example are convincing and research trends are not necessarily focused on a sustainable digital fabrication

The aim of this presentation is to identify the sustainability risks and opportunities associated with the implementation of digital fabrication in construction. This will lead us to identify the design parameters that influence the sustainable performance of digitally fabricated architecture and define guidelines for early design stages. Multifunctionality of digitally fabricated component is key to achieve better environmental performance as long as the life span of structure is considered. Finally Socio-economic consequences derived from the implementation of digital fabrication in the construction sector will also be discussed. While digital fabrication has the potential to improve productivity in the building industry, it will not necessarily reduce employment in the long run. It is expected that existing roles will evolve, mainly related to the human-robot interaction, and new roles requiring digital skills will be created. Moreover, the digitalization suggests an evolution of the conventional construction organization towards a platform-based integration of planning and construction phases.

# Workshops

**TreeHugger**

The workshop will be referenced to presented paper with the same name, adjusted to present location. It will offer hands on experience of prototyping and placing into public space the responsive wood insect hotel, TreeHugger. The research addresses the landscape ecologists' discussion that our agricultural land has become so toxic (i.e. use of pests) that many species, that had adapted to them hundreds years ago, are recently adapting for the life in the cities. The workshop will provide a lecture and consultancy on responsive solid wood system panelling Ray and TreeHugger prototype. The hands on will start with adjusting its Grasshopper code to the local tools and local specific parameters. For high speed visual complexity communication in this case analogue, process-based diagramming, so called 'GIGAMapping', will be used. The participants will explore the responsive solid wood digital fabrication skills, critical public space eco-systemic intervention skills and most importantly, the performing and interacting prototype's observations registrations.

**Instructors**

Marie Davidová, MArch., Ph.D. and Ing. Arch. Šimon Prokop

**Morphogenetic Fluid Dynamics**

The Morphogenetic Fluid Dynamics workshop aims to introduce a performance-driven design methodology, through exploring the ideas of shape optimization and iterative simulation feedback. The workshop will look into the morphogenetic potential of fluids, based on the use of Computational Fluid Dynamics simulations and Computational Design processes. Working with a real-world scenario and objective and through analysing the context and data of the given site, participants will be asked to use introductory level parametric geometry and simulation tools to explore the effects of their design on the airflow and ventilation of the building.

**Instructor**

Angelos Chronis, Ph.D. Candidate (Marie-Curie Fellow), IAAC, Barcelona

# Contents

# CAAD THINKING

# Aural Virtual Worlds

## *Noises, Signals, Human Brain Interface and Audio-Visual Programming*

*Karolína Kotnour[1], Miloš Florian[2]*
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*The symbiosis of architecture and sound in connection with the human mind and body. This project explores possible connections and interactions between sound, imagination and visualisation of space through experimental work with Brain-Computer Interfaces, BCI technology, EEG headsets, and visual programming in audio-visual studio MAX MSP. The architecture reflects the sensory experience of space and sound while transforming its own structures. Space is changing under the influence of sound waves and vice versa.*

**Keywords:** *Acoustic, Architecture, Arts, Brainware, Communication, Creation, Emotion, Medium, Neuropsychology, Sound, Space, Structure, Synthesis, Radio*

*"For beauty is nothing but the beginning of terror which we are barely able to endure, and it amazes us so, because it serenely disdains to destroy us. Every angle is terrible." Reiner Maria Rilke, Duino Elegies, 1923*

### SOUND SHAPE SPACE

FRAME of this work is engaged with Sound Shape Space relationship and impermanence in architectural forms, possible ways of inhabiting architecture that is reflecting a human behaviour, and perception and their interaction in-between.

How DO we perceive the space?

Project Sound Shape Space interconnects physical quality of architecture and a human body, human behaviours, where architecture is a constructed expression of mental space and imaginative empathy. SOUND is understood as a signal that we hear and is also a vibration that we feel. Sound in one of the dynamic forces that brings a motion into the image of reality, as it is developing over time and space. SHAPE is a two dimensional or a FORM three dimensional element of art that encloses space. Forms are natural or artificial, and we can describe them as visible particles mutating under influence of forces at low rates of speed. SPACE is narrative medium, psychoplastic matrix, a mutable scene that is changing over time and disappearing again. And because we are constantly under influence of these forces therefor meaningful architecture is impermanent as the basic need and desire, besides biological needs, is the possibility of communication and movement in space. We work with a physical materials, and transforming a material and implementing it in to a structure in an effective and constructive way, but the most important part of our work besides understanding the environmental qualities and possibilities is an empathy, intuition and instinct, that means understanding a human behaviours, AND integrate them in to a functional expression in architecture.

Architecture is a living organism, and human and all organisms are mutually interdependent. Human is a very fragile creature, and the purpose of architectural making since ever is to preserve LIFE, that is an expression of collaboration between individuals (Kiesler, 1946).

## AUDIBLE EXPERIENCE OF SPACE

Architectural space is closely related to a human body and its ability to perceive and create an image of its embodiment in our mind. This image of tangible space and its audible soundscapes is a creation of our mind and processed nothingness, nothing and noise that surrounds it. Recognition of repetitive patterns of noise as a sound or a structure enhanced by repetitive textures is only a result of our brains memory and ability to learn, therefore we create our reality by our struggle for existence, from our needs and their evolutionary power of learning (Kiesler, 1946).

Noise contains the whole spectrum of frequencies and theoretically an infinite number of frequencies. Same as light can be divided into the colour light spectrum by optical prism, decomposed and composed by a number of planes in a prism, noise is decomposed and composed when sound waves bend by changing the media.

The way how human mind perceives the boundary between noise and silence affects the dimension of understanding nothing, anything, and everything. White light, in contrast to the emptiness filled with darkness. White noise, swayed by silence. What we perceive and understand as reality is always based on the position from we look at, or perceive or listen to. The visual evaluation of reality seems to be decisive in comparison to the audible experience for humans, in both cases, they are equal in a process of sensory determination of the dimensions of our reality. This reality is largely shared and co-created reality. The dimension of inner reality is the ability to interfere with shared reality.

NOTHING that we change to something, as a reaction, or a thought, an idea. Nothing as a possibility of change. The human condition is based on two concepts of space, actual and virtual. What surrounds us is shared reality between us, as it has been mentioned prevailing information processing by our brain is a visual system of perception, obviously we tend to avoid our other senses, but from the chaos and noise around us we receive an information about space through all our sense organs, our brain works on several perception systems, such as orienting, haptic, tasting and smelling, visual and also auditory system. Humans sense the space, and by learning, we create our image of reality. The human body should be understood as a sensor to be involved directly into the adaptive environment and immediately participate on its architecture.

Figure 1
Energy zones mapping - body as an emitter

## MOTIVE

The ability and need for a human to move are determined by his physiological possibilities and biological and psychological needs. The same way we understand an ability of humans to shape the space, and the natural environment into a technological (developed) environment. Where human contribution on a balance between natural, human and technological character of architectural space is determined by the available technologies and creative and intellectual activities, as well as an ability to express herself or himself. Same time the character of space is also given by the ability to communicate and the need to communicate and understand (Lickinder, 1960). The resulting architecture should be able to respond to these needs and natural forces. One can feel securely and freely in an indifferent space but can be deprived without the possibility of further influencing or changing this space. This fact is mostly unconscious until there is a need for a fundamental change in the way of movement in space or changing its character. Such changes occur naturally and are significantly associated with the change of the mental map of the space and thus its internal architecture as during human life (evolution) there are changes of the psyche and the relationship between the inner/spiritual / and the external/physical / world, between virtual and actual. (see Fig.1)

## ARCHITECTURE, BODY AND MIND

Perceiving give us a comprehensive environmental information and is based on five models of perception such as basic orienting system, auditory system, haptic system, tasting and smelling system, visual system and the sixth atmospheric or environmental sense (Pallasmaa, 2012). Sound brings forth the experience of reality. This research is questioning, how sound can take a part in creating and shaping architectural space.

The human body is transmitting the received energy back to the environment, and we can learn from our body where are our energetic zones and cores, from biofeedback, by observation of our physiological performance, our brainwaves, body motion, emotional condition, heart beat or blood pressure.

Naturally, architecture has always been an answer for environmental situations and biological and physiological needs of living organisms. Building proportions were derived from proportions of a human body and very often had an intentional psychological effect on its inhabitants - so very often designed places were to be inhabited space as an only static scene. Architecture is no longer static and this proposal offers a possibility to inhabit aural space of a moving image *texture or a pattern* and transform it immediately, and interact with architecture freely. As the human body is an extension of our mind architecture is an extension of our body. We all are looking for our place in present times rather than being a future or a past.

Architecture is a living organism, and human and all organisms are mutually interdependent. Human is a very fragile creature and the purpose of architectural making since ever is to preserve LIFE. Live is an expression of collaboration between individuals (Kiesler, 1949).

## NEUROPHYSIOLOGICAL AND BIOMETRIC DATA

While we work with perception systems, specifically with an auditory system we need to employ neurophysiological and biometric analyses. In this paper, we outline how Brain-Computer Interfaces, and software for EEG data processing, allow us to involve in the design process and architectural creation, a subjective understanding of our environment, by sound signal processing through our auditory receptors.

Sound signals and noises as a resulting audio information are processed in a brain, in this project we work further with an interpretation of vision creation, so it is necessary to involve technology that records and transmits information about brain activity. Our mind is stimulated by external and internal trigger forces, our cerebral cortex reacts to them by envisioning and creating a model of reality, as an adaptation of frequented synapses between the neurones.

The impermanent interactive architecture of an aural virtual worlds responds to a subjective experience of a person moving through the sound-space, and also allows an experience of animate and inanimate matter of natural and artificial bodies. With a human-brain-computer interaction technology, architecture becomes an engine with an immediate impact on the physical and mental well-being of a man.

Sound as a mutable material provide a seamless joining of architectural structures and for this distinctly differential characteristic, it should be considered its effect on human mind the same way as we understand architectural elementary tools and typologies. In this study, we observe continuously incomplete transmuting processes that emanate from sounds, visions, creation from invisible and visible, passive or an active, spontaneous or deliberate act and vice versa.

Voice is the sonic instrument with which we begin as humans - beginning as an intricate enfolding of inner and outer, ear, lungs, throat, skull and mouth, abstract thought and physical projection, biology and consciousness, breath and listening -and which develops as the articulation of impulsion, feeling, word, speech, paralinguistic noise, even musicality, resonating in time, mind and the air of open space (Toop, 2005). (see Fig.2)

Figure 2
Model - morphing veil

The creative synthesis of sound and architecture allow us to see what we hear. The presumption is that is possible to code an architectural form as a soundtrack. This way we use sounds to manipulate architecture forms. Another question is what is the best approach to capture the entire sound and brain performance characteristics and translate their effects on such as structural forms. We all participate in the creation of shared reality and the possibility of the dynamic creative process of architectural making through sound with the direct involvement of its user whether it is an active or passive acknowledgement of someones virtual or actual presence, emitting or perceiving energy (Achten, 2013). A person entering into such a structure or space provides his measured EEG and has a possibility of the intervention in the character of the space and interactive feedback experience of architectural space (Edelstein, 2013).

## AUDIO-VISUAL PROGRAMMING AND MAX MSP

We involve available biofeedback and EEG screening technologies in a process of architectural design. The aim is to connect Brain-Computer Interfaces, BCI technologies, with a software for audiovisual programming *MAX MSP* and create a multidimensional architectural environment based on a physical and biological response, and soundscapes interconnecting an actual and virtual world, and modify them in real-time by a biofeedback of the listeners in an aural virtual worlds.

Sensory sensitive architecture approach brings a new ability of architectural shape behaviours.

Personal biofeedback carry on devices bring a possibility of an intuitive and dynamic dimension in the field of sound design, and sound and space creation. From the perspective of an auditory architectural construction, is essential to understand space as a time-varying medium. It reflects the sensory experience of space and sound while transforming its own structure.

## NEUROARCHITECTURE

With our question, how sound creates or shape space, we are not questioning only a mechanical distribution of atoms that are manipulated by sound waves, but rather how sound affects our mind and how it influences our emotion and therefore our ability of vision and imaginative process and construct of reality.

NeuroArchitecture Technologies allow us monitoring our neural, physiological and psychological responses measurable from biofeedback influenced by natural, human and artificial human built environments and our cultural behaviours and help us understand what is the impact of architectural environment on our brain and nervous systems.

We are able to observe both our conscious and sub-conscious responses on an initiation signals *sound signals*. Following this approach in the architectural making, we are able to understand better how our brain and body responses to internal and external consequences and expand architectural tree dimensional space into correlations of multidimensional experience of reality.

BCI (BBCI) or HCI allows humans to have a subjective influence on the environment and architecture, and that help them to communicate and interact with the outside world as they need it. This project works with a simulation where a software for a visual programming is preconfigured for certain emotional reactions. When we are relaxed the structure is more open and even invasive when we are excited, or more tensed, compact and enshrouding structure when we are stressed or anxious. Technologies that are available now help us to read and understand, in better detail what is happening in our mind and body and what is the immediate factor of architectural environment.

## THE BUILDING AS A COGNITIVE ENTITY

The way we experience our inhabited space is limited by our imaginative ability to transform a matrix, a matter with a relationship of evolutionary interactions and polarisation of internal and external forces, that are mutating in forms, functions and structures, aiming to fulfil human needs and purpose. The building is here understood as a dynamic architecture that is lead by the creation of a man's needs caused by the absence of instinctive adaptability (Pallasmaa, 2012). (see Fig.3)

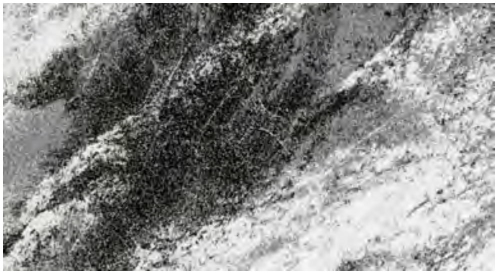


Figure 3
Seeing by learning

## BOUNDARIES AND INTERCONNECTIONS

If you try to draw in a virtual aural space, you will find yourself in an unconstrained sound environment and you get involved with your senses and the whole body. This technique can be characterised as a sound-body-space effect or brain-body-space effect. Sound signal or noise is interpreted instinctively by each listener according to his own sensitivity, noise information is ambiguous, therefore human mind enters a creative process and has to decode an information and evaluate it as a distraction or as a code to decipher and translate it. Reaction to a noise is always intensive and we experience unclear and mixed physical and emotional reactions at once. While we are exposed to noise, the reaction is very easily recordable in our brain waves performance.

## SPATIAL REPRESENTATION AND THYSELF CONFIGURATION

By continuous monitoring of our brain activity that is measurable in brain wave oscillations defined in several intervals of frequencies, so we can work with comparable data sequences of our conscious, subconscious and unconscious neural reactions to certain initiation forces. Those dynamic forces, in a concept of shaping a form, are sound signals, our body motion, our behaviour powered by our brain activity. The brain waves represent different states of mind and different emotions. Neuroscience explains how our brain activity is related to different processes such as unconscious instincts, subconscious emotions, and conscious concentration and mental activity processes, or even extreme focus and ecstatic states. The brain performs on slow and fast waves slow waves represents deep brain activity and loss of bodily awareness and fast waves represents mental and creative activity and conscious processes. Brain performance is recognised as a unique sequence of dominate waves developing over time. (see Fig.4)

### *Basic types of brain waves and observed behaviours*

*Delta - loss of bodily awareness, instincts, unconscious processes for survival that's where our sixth sense is - a sense of environmental reality, atmospheric sense*

*Theta - subconscious, state of deep meditation, emotions, trance, dreams, creativity*

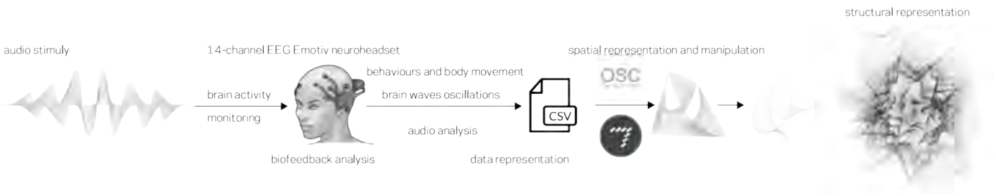



Figure 4
Data flow diagram

*Alfa - physically and mentally relaxed, awake, consciously aware of the body, integration of feeling*

*Beta - awake and normal perception and concentration, though-fullness, mental activity*

*Gamma - total conscious, heightened perceptions, will, extreme focus, extremely energetic and ecstatic states.*

For an animation, interactive observation and examination of behaviours in virtual space and aural worlds, we work with multidimensional geometries, forms and matrixes in 3/4/5D programs, that allow us to work with CSV files (playback data protocols) of recorded EEG data and compare different spatial and neural situations. Grasshopper Rhino is here as a 3D interface for rendering shapes and forms with a given geometry, by using gHowl plugin, and OSC channels stream the real-time data from EEG device Emotiv EPOC Neuroheadset so they can communicate together and process received data as a parameter for a Rhino geometry and compare it in MAX MSP with manipulated noise cloud.

Simulation of and the aural virtual world is created in MAX MSP that communicate together with Emotiv Neuroheadset through open sound control ports so the data flow works on a real-time basis.

Sound creates and transforms space structures; it becomes an immediate factor of an architectural space. MAX MSP visual programming of virtual worlds and architecture forms give us a possibility to communicate our environment, with a continual real-time transformation of a structure and free movement in space.

Impermanent architecture constantly demands a possibility of reactive change. Meaningful architecture is impermanent, in a close symbiosis with the human body and mind.

This interaction opens potential connections and interactions between sound, imagination and visualisation of a space through experimental work with BCI technology and EEG data processing and programming of various approaches.

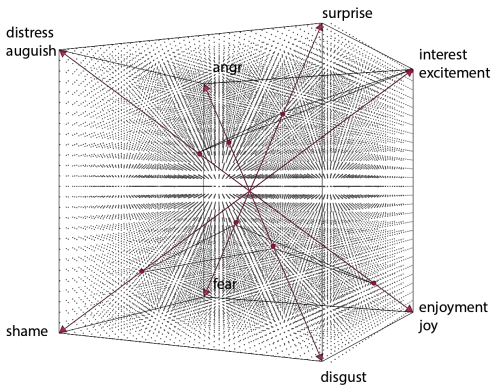



Figure 5
Matrix - correlations and illusion of the perspective

## MATRIX OF EMOTION

As we already mentioned, a human body is a sensor, and we can learn from a biofeedback about our emotions. The brain activity manifests into the whole body so we can read the actual physical location of that emotion. We can program a structure regarding an emotion, so, for example, openness and invasive structures can express for happiness or dense and closed structure for fear. We physically interact with the environment also in a form of emitting an energy. We always measured the architectural proportions by the human body but with BCI technology we have an immediate feedback how our body and mind react to the environment. Our intention is to consider in a creative process a human biofeedback. (see Fig.5)

To outline a relationship between sound signal our perceiving and its representation, the theoretical model needs to be determined, simplified to a cube of emotion or a matrix of emotion. It is a concept of a spatial representation of human body and emotion in space.

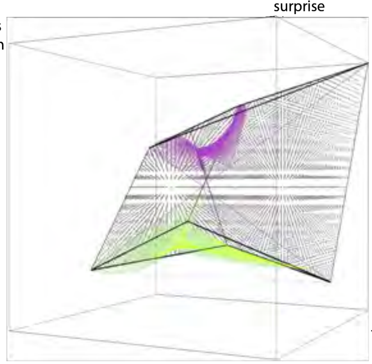



Figure 6
Matrix - emotion spatial evolution

This model is expressing a relationship between emotion and space. The centre point of a matrix of emotion represents of a state of nothing, equilibrium, the moment we feel all the emotion at once, absolute consciousness, ecstatic state, maybe we can say it is a representation of a point of life but static - inanimate or dead. This place or this moment, also the moment when the boundary between actual and virtual blend in one. These correlations give an impermanence of architectural forms.

*Emotion direction out from assimilated form of ex "out", from old French emouvior "stir up".*

The concept of the matrix of emotion is an unlimited cube filled with an infinite number of particles - matrix - a matter that can be infinitely reduced and displaced than I have a perspective and we have an actual image of this virtual space. (see Fig.6)

And by analysing data from our brain activity we put each emotion to the model so they represent the relation in-between emotion and we get an actual envelope of these relationships in a virtual space and we also get a volume of the particles in the envelope of emotion. In this moment when architectural strategy comes in, because for an effective distribution of particles -a matter - a material we have to look at biological systems, in many examples nature geometry operates with minimal and maximal surfaces with an intention of efficient transmission of an energy, and thas also our intention to allow energy flow efficiently. Effectivity of a matter distribution reflected in the geometry is a natural strategy of an energy transmission - the architecture of nature. Composition and decomposition of a form, function and structure. (see Fig.7)

## CONCLUSION AND FURTHER WORK

Developed structures and forms of mutating architecture presented here are envisioning an experience, a script of the aural world but static. We already explained that architecture is a living organism, and life is an expression of the cooperation between individuals and between species.

*Organism - "organic structure, the organisation"; "living animal or plant"*

The result of trigger forces of life is a matter and represent what we understand as a reality. But the matter is only one of the expressions of reality, and not reality itself because if the matter would be the only reality, life would be static. In shaping matter, we shape reality and narrative of space that encloses a form of life.

*Matter - materie, "subject of thought, speech, or expression," or mature "theme; substance, material; character"*

The sound has a magical power to influence our feelings and emotions, change our state of mind and brings a dynamical element in.

*Sound - "noise, what is heard, sensation produced*

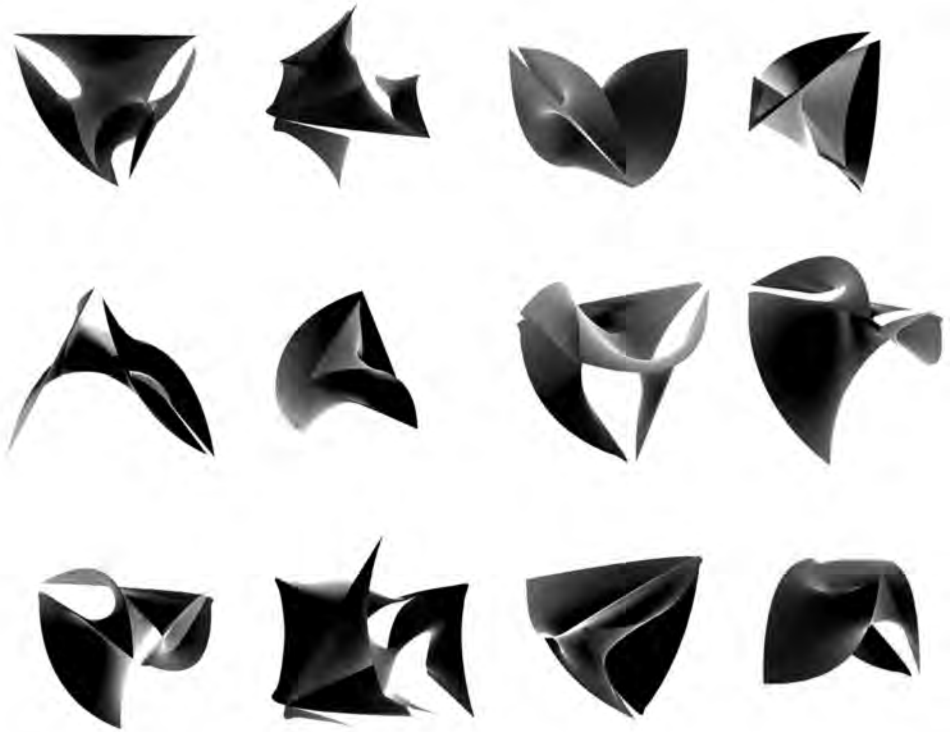


Figure 7
Matrix - emotion formulations

*by ear" or son "sound, musical note, voice"*

Light as radiant particles or waves, that makes things visible. Brings life and vibrant colours into our environment in a form of energy and human civilisation is depended on that energy received from space. The ecosystem and climate are moved by this energy.

*Light - "brightness, radiant energy, that which makes things visible"*

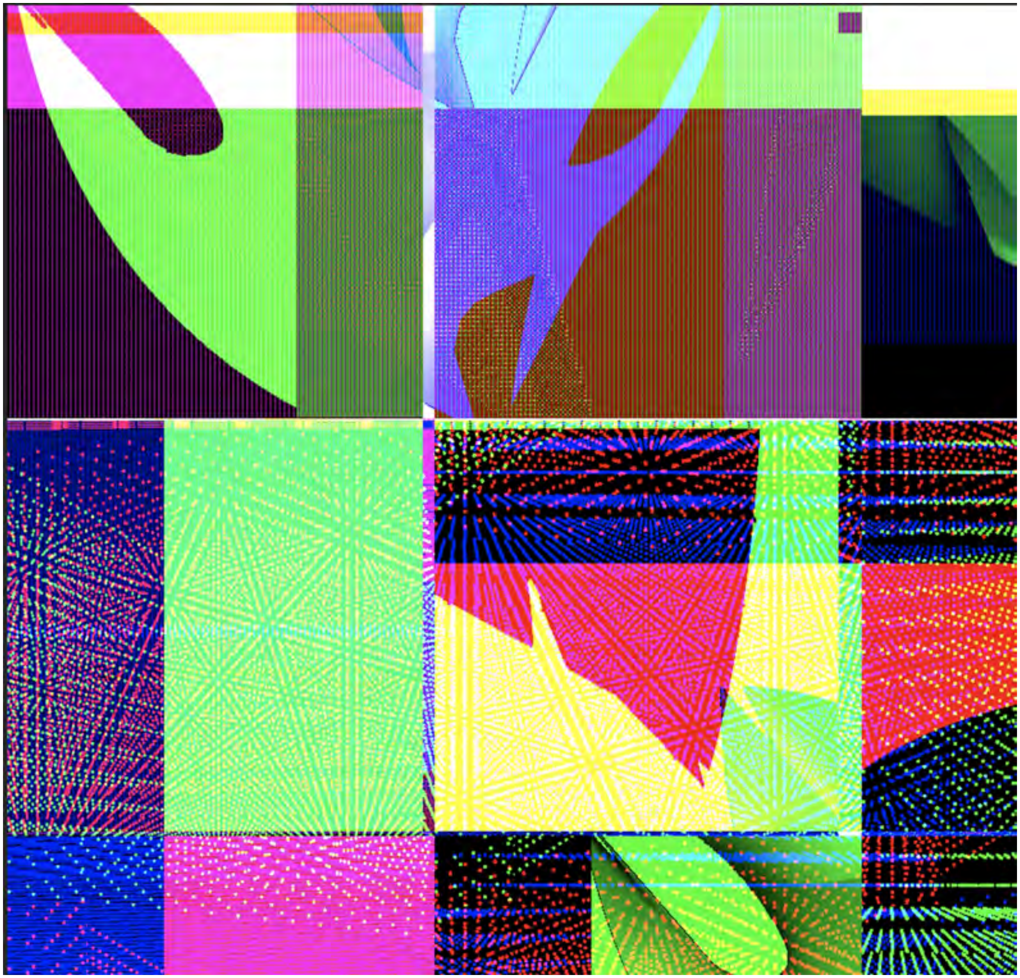
*Energy - "force of expression"; "actuality, reality, existence"*

And the same way, SOUND, brings dynamics into a creative process of architectural modelling, and we have a possibility of a close interconnection and involvement of these dynamical changes.

*Dynamic - "pertaining to force producing motion"; "active, potent, energetic" or "energetic force; motive force"*

Aural architecture is an interaction between real, the perceived, and the imagined where actual leads into virtual and vice versa. It is an architecture that blends in-between and merges and dissolve these worlds in a form of impermanent narrative struc-

Figure 8
Matrix - memory



tures. The constantly presented true of limited three-dimensional illusion and continuous deceit is defaced.

To experience the environment of reflection and shimmer, we need to employ a dynamic medium - a film - in a way of impermanent architecture experience, so we can achieve performative character of an architecture and with an intention to extend architectural environment in to aural worlds we have to work with augmented or virtual reality technologies.

*Virtual (adj.) "influencing by physical virtues or capabilities, "excellence, potency, efficacy" Virtue "force, strength, abilities" from vair "man" wi- ro- meaning "man"*

Sensory interactions between human and building, generating architectural structures, and creation of environment based on human auditory body-space experience a computer-generated landscape that can take infinite forms never seen before is a simulacrum it can take infinite forms never seen before, it is *"real without origin or reality: a hyper-real." -Jean Baudrillard*

Human Brain-Computer Interaction Symbiosis, outlines the possibilities of interactive symbiosis between humans and computer, in a way that architecture will offer to humans an equally close symbiosis, brain to brain interactions, and provide a personal comfort based on individualities within the whole architectural structure. (see Fig.8)

## ACKNOWLEDGEMENTS

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[3] https://www.etymonline.com

# Local Adaptation of Modern Architecture

## *A Grammar for Hajjar's Domestic Architecture*

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*The purpose of this study is to analyze Abraham William Hajjar's single-family houses in State College, PA, using shape grammar as a computational design methodology. Hajjar was a member of the architecture faculty at the Pennsylvania State College (now The Pennsylvania State University), a practitioner in State College and an influential figure in the history of architecture in the area. Shape grammars are used specifically to verify and describe the influences of modern architecture as defined by Hitchcock and Johnson (1932) and traditional American architecture in the area on Hajjar's domestic architecture. The underlying hypothesis is that the work of Hajjar is the result of a hybridity phenomenon that will be traced through a computational design methodology. The first step in this endeavor is to establish the single-family architectural language of Hajjar, which is briefly described in this paper. Future steps will aim at verifying and describing the hybridity between modern architecture and traditional architecture in his work by comparing Hajjar's grammar with grammars encoding modern and traditional architecture.*

**Keywords:** *Shape grammar, Modern architecture, American architecture, William Hajjar, Hybridity, Single-family houses*

## INTRODUCTION

The residential architecture of A. William Hajjar, a faculty member at Penn State and a practitioner in the mid-twentieth century incorporates many of the shapes, rules and features of both European modern architecture and traditional American architecture. On the basis of this hybridity between modern architecture and traditional American architecture in the work of Hajjar in State College, PA, in the mid-twentieth century, in this study, this architectural phenomenon is compared and contrasted with both the modern architecture of the time and the traditional American architecture of the local context. Via computational design methodology, this comparison will provide information to identify and establish the single-family architectural language of Hajjar and to verify and describe the hybridity between modern architecture and traditional architecture in his work.

The notion of hybridity between modern architecture and traditional architecture, or the duality between modern and traditional, international and local, and designed and vernacular in architectural practice has already been addressed in the literature. Terms or ideas such as "high style" versus "popular" architecture in the mid-twentieth century (Devlin & Nasar, 1989), "Brazilian popular modernism" (Lara, 2008), "critical regionalism" (Frampton, 1983), and "vernacular modernism" or the contrast between vernacular traditions and the twentieth-century built environment (King, 2016) all refer to this duality, in various geographic locations or time periods. Also, the idea of mixing elements of European modernism with traditional American elements in architectural practice happened earlier in the twentieth century, although not in domestic architecture. As scholars like Leland Roth note, most skyscrapers built in the 1920s combined selected elements of the International Style with traditional revival styles such as Renaissance and Gothic typologies (Roth, 1979). In a U.S. college town such as State College in mid twentieth century, a key question on this point pertains to whether this hybridity can be described, and if yes, whether shape grammars as a computational design method can be used to verify and describe it.

## METHODOLOGY

This paper is part of a larger scale study, in which Hajjar's domestic architecture is compared with the modern and traditional architecture of the time, in the following steps: (1) Tracing Hajjar's life and practice to identify likely influences on his work; (2) Developing a shape grammar for the houses he designed in State College; (3) Identifying or developing grammars for some of his likely influences; (4) comparing Hajjar's grammar to the grammars of these influential works to determine the nature and extent of such influences; and (5) identifying aspects of the social and technological context that may explain such an influence-i.e., trends in regard to lifestyle and available technology. This paper, focuses on describing Hajjar's single-family architecture by developing the grammar of his work. It will include rules of the grammar of single-family houses designed by Hajjar, a derivation of a house designed by him in State College and solutions generated by the grammar that were not Hajjar's designs. Future papers will focus on other methodological steps.

Shape grammars in computation are a specific class of production system based on an initial shape, or a set of finite shapes, and transformational shape rules (Stiny & Gips, 1971). Since the 1970s, as a design computation method, the concept of shape grammar has been used in architectural analysis when a pattern in design characteristics or a stylistic repetition of shapes in architecture is evident. This method has been used to analyze examples of historical architecture, such as the Palladian Villas by Stiny and Mitchell (1978), Frank Lloyd Wright's Prairie houses by Koning and Elizenberg (1981), Bungalow houses by Downing and Flemming (1981), Queen Anne houses by Flemming (1987), Alvaro Siza's houses at Malagueira by Duarte (2001), and many more. Given that the work of the proposed study's focal architect shows some evidence of shared shapes and transformation rules, the shape grammar methodology is appropriate for testing the hypothesis. For example, many of the houses designed by Hajjar can be considered in reference to shapes and rules as follows: a wing (i.e., a garage), connected through a breezeway (the connector, usually the main entrance) to the main volume. This main volume in his early work is a simple shoe box, which regardless of size (small or large) and orientation (parallel with or perpendicular to the main road), usually has a low-pitched roof. The main volume sometimes comprises two stories: the bottom story is usually the main living area (living room, dining room, and kitchen) and the top story is usually the sleeping area. Depending on the orientation and slope of the site, the bottom story may be a garage whereas the main living spaces may be located in the wing, the latter of which consists of one or two stories.

## RELATED WORK

This work is on the footsteps of previous work by other authors. In 1994 Knight showed how stylistic evolution in art and design may be explained by the evolution of the underlying grammars. Knight illustrated her argument by describing the transformation of Frank Lloyd Wright's Prairie houses into Usonian houses. In 2001 Çolakoğlu used this idea to propose a methodology to design contemporary houses from vernacular Turkish Hayat houses, while in 2005 Chase and Ahmad used grammatical transformations to understand hybridity in design. Then in 2011, Eloy and Duarte proposed the concept of transformation grammar to adapt an existing house type to contemporary living needs. In the same year, Kruger et al (2011) advocated the use of transformations to study Alberti's influence on Portuguese classical architecture. More recently Benrós (2018) used transformations in design to study the phenomenon of hybridity in architectural languages.

## WILLIAM HAJJAR

Abraham William Hajjar (1917-2000), the focus of the proposed research, was born on February 11, 1917, in Lawrence, MA, the youngest of a large immigrant Lebanese family. He received his bachelor's degree in architecture from the Carnegie Institute of Technology (now Carnegie Mellon) in 1940 and his master's degree from MIT in 1941 (Hadighi, et al., 2016). Hajjar joined the Department of Architecture at the State College of Washington in 1942, and in 1946, he moved to State College, PA, to join the architecture faculty at the Pennsylvania State College (Penn State). When Hajjar moved to State College, PA, most single-family residences in the area were in the Georgian revival, Colonial revival, Tudor, and Cape Cod styles, although ranch and split-level houses were also starting to appear. With more than thirty single-family houses that he designed and built in the area, Hajjar, significantly influenced the architectural language of the houses built in the mid-twentieth century in the area, especially in neighborhoods adjacent to the Penn State campus. In doing so, he contributed to the stability and popularity of localized/Americanized modern architecture by reshaping mid-twentieth century modernism in the area and to some extent in the United States.

While Hajjar was at Carnegie, the school's philosophy of design was dominated by the Beaux-Arts, similar to most of the other programs in the country. MIT was probably where Hajjar was introduced to modernist architecture given that proponents of modernism, such as Lawrence Anderson, who worked directly with Hajjar as his supervisor, were teaching there at the time. Lawrence Anderson not only designed the first modernist buildings on an American campus (MIT Alumni Pool-1939), but also tried to bring a modern outlook to MIT's program in the late 1930s. He advocated for Alvaro Aalto's appointment as a Research Professor in Architecture at the school in 1940. More importantly, it is likely that Hajjar was influenced by modernist ideas propagated by the German émigrés: He was at MIT during the time Gropius and Breuer were at Harvard when students from the two schools attended lectures together and when Anderson often invited Gropius, Breuer, and other outside critics to MIT to review the students' work (Anderson, 1992).

Hajjar designed and built thirty-two single-family houses in State College, PA, in two neighborhoods close to the Penn State campus. Many of these houses blend in the neighborhood with traditional houses based on their exterior building materials, volumes, and roof shapes. However, they have very unique and modern interior organizations. The broader scale study includes an analysis of the formal structure of the houses in relation to the exterior and socio-technical context in order to understand aspects that may affect Hajjar's interior spatial relationships.

## HAJJAR'S ARCHITECTURE

Hajjar's first design in State College was his own family home in the College Heights district adjacent to the university. The house consisted of a simple shoebox and a garage connected to the main house via a breezeway. With cement blocks for the base and wood cladding for the top part together with a sloped roof, Hajjar's first design in the neighborhood seems to be similar to other houses in the area. However, there is no front porch and no entrance in the front façade. In fact, the front façade seems to be a side façade in comparison to the appearance of other houses in the area. Most of the Colonial revival houses in the area have a garage at the back of the building. Hajjar rotated the organization of the house in a way that made the garage part of the front façade with the main entrances hidden in the side and through the breezeway. While at Penn State, Hajjar designed and built more than thirty single-family houses in the area, many of which designed with the same strategy as his own family house.

Hajjar took advantage of the sloped sites of the College Heights neighborhood by situating the entryway of the homes in between the two main levels of the houses. A feature that can be read as an adaptation of the mid-century split-level effect. Although in section and façade there are similarities between Hajjar's architecture and mid-century split-level houses, in terms of the interior planning, design, organization of the fenestration, and the slope of the roof, there are differences. Hajjar's interior planning leans toward a modernist idea of open plan, especially in the public part of the house (living-rom-dining room-kitchen). Specifically, typical midcentury split-level houses still had a room organization with the living room facing the street, whereas Hajjar's designs were open with the kitchen facing the street and the living room at the back of the house with large openings between the various functional areas of the house.

In the plans, the entryways to Hajjar's houses are generally in the middle open space, which could include a hall and a family/sitting room or area. Hajjar was interested in the placement of windows: his houses often featured window walls opposite the entryway (on both levels). Hajjar's typical plan can be read as a modern plan with an open space in the center, rooms organized on both sides, and the service spaces, including the bathroom, staircase, and hallway in the middle. However, it can also be read as a very traditional plan used in the Georgian period and the Georgian Revival as a developed hall-parlor organization or as a developed foursquare design (Figure 1).

Through a consideration of the spatial relationships and main features of Hajjar's single-family houses in the area, five subtypes in his plans have been identified (Figure 2): (1) tri-part organization, where inhabitable space is connected to the garage with a breezeway and consists of a lower floor serving as the living space and an upper floor serving as the sleeping area (sometimes with a basement as well); (2) split-level organization, where the sleeping area is a half floor above the living area; (3) butterfly or cross-shape plan organization; (4) compact organization, where a square-shaped plan reflects Hajjar's idea of a core area in his architecture; and (5) horizontal/linear organization.

## HAJJAR'S GRAMMAR

Grammar of Hajjar's single-family architecture in the State College area was developed based on the five subtypes of his houses. The generic vocabulary, relationship between vocabulary elements, and shape rules schemata that generate Hajjar's single-family house plans are extracted from the analysis of houses that were designed by Hajjar and built in the area, especially, spatial analysis of interior planning and relationships of exterior volumes.

To define a grammar that generates Hajjar houses, four phases or groups of rules are introduced: (1) Rules related to the way in which Hajjar situated his houses in the lots (Figure 3); (2) Rules that describe the formal relationships between mass volumes (Figure 4); (3) Rules that describe the spatial relationships of the interior planning or the way in which room were organized. These rooms, especially in the common area of the house, can be imaginary, since they were part of a larger open space (Figure 5); and(4) Rules that generate details such as placement of closets, wall thicknesses, etc.

Figures 6 to 8 show derivations of designs in the corpus used to infer the grammar. In addition to all the houses designed by Hajar included the corpus, the grammar can generate Hajjar-inspired houses-solutions generated by the grammar that were not designed by Hajjar. For facilitating the generation of designs and eliminating human input while applying rules to generate Hajjar-inspired houses, a computer program has been developed. The code was written in the Python scripting language for Rhino. Like the grammar, the codes proceeds by dividing the main inhabitable space into rooms and then joining and dividing these rooms based on both Hajjar's ideas regarding spatial relationships and user needs (Figure 9).

## DISCUSSION

As noted earlier, this paper is part of a larger study that aims to analyze Hajjar's hybrid architecture by developing a grammar of his work and comparing its shape rules with those of grammars for the work of modernist architects and traditional American architecture. The selection of modernist architects and traditional American architecture with which to compare Hajjar's work was based on a careful analysis of his personal and professional life, which suggested likely influences. Among them are the works of immigrants like Gropius-and Breuer, with whom Hajjar contacted while at MIT, and of Frank Lloyd Wright, who Hajjar's son pointed out during an interview as an important influence on his father's work. It is important to note that a shape grammar of Wright's Usonian houses has already been created (Knight, 1994) based on a transformation grammar of Wright's Prairie Style houses (Koning & Eizenberg, 1981). The grammar of Gropius and Breuer's architecture in the United States needs to be developed, though. In terms of traditional American architecture, it is necessary to identify house types or styles that might have influenced Hajjar's architecture and develop the corresponding shape grammars. Preliminary analysis suggested some possibilities in this regard but further work is needed to confirm them. In any case, a grammar for the Buffalo Bungalow houses was developed by Downing and Flemming (1981) and this will be considered in the analysis.

An important question in comparing shape grammars is how detailed the grammars need to be. This question can be answered by finding where hybridity exists, whether in the functional organization (layout), the building system, or in the decoration, following Habraken's definition of house type (1988). At this stage, Hajjar's grammar is used to describe the spatial relationships in his interior layout and the volumetric relationships in his overall design, mainly because preliminary analysis suggest that hybridity might exist particularly at this level. The next step is to determine the extent to which the rules of the respective grammars are similar or different. By comparing the rules of Hajjar's grammar to those of other grammars, we may be able to determine which rules might have been maintained, changed, deleted, or added (Figure 10). In this regard, it is important to note the grammars must be developed in a way that enables comparison, as shown by Benrós in her comparison of Palladian Villas, Wright's houses and Siza's homes (2018).

## CONTRIBUTIONS

The proposed study makes a contribution to the field of architecture not only by proposing shape grammars as a tool for verifying and describing hybridity between modern and traditional architecture, but also by describing the work of Hajjar, a local architect who contributed to the stability and popularity of modern architecture in the United States. Furthermore, it is our hope that the study will show the potential of shape grammars as a complementary tool that architectural historians may use to verify formal and functional similarities between styles in a rigorous way.

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# Revisiting ancient Greek technology with digital media

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*This paper presents design research on ancient Greek technological achievements and their reinterpretation in the contemporary world. The research involved the study of ancient greek technology and its respective digital representation and led to a semester-long design studio within the product design curriculum at the International Hellenic University. The students would study the morphology of ancient Greek technological devices through their 3D reconstruction and prototyping. The paper will present the results of the aforementioned design studio, commenting on the methodology, the learning theories adopted and the learning outcomes.*

**Keywords:** *CAD education, Ancient Greek Technology, active learning, 3D modeling, product design*

The research presented in this paper took place in 2017 at the International Hellenic University as part of Computer Aided Design (CAD) core course of the postgraduate program "Strategic Product Design". The students of this cross-disciplinary program have different backgrounds and skill sets; they would therefore need to familiarize themselves with digital representations, including 3D modelling and rendering. The aim was not to merely engage in software tutorials, but to use this opportunity for research through design. This course offered a unique set of circumstances to explore the multiple educational benefits of "bibliographic research through making" (Symeonidou, 2016) and engage in active learning ( (Bonwell and Eison, 1991; Felder and Brent, 2009). Every year CAD curriculum explores a different thematic area, which acts as motivation for design explorations. In 2017 the course brief was developed around the thematic area of Ancient Greek Technology. The course included literature review and museum visits, in order to study and understand the function and geometry of ancient technological objects, by examining photographs or replicas. This initial study would form the basis for digital design explorations, the students would collect information and extend their research across several different technological fields of the ancient world.

During the preliminary design stage the students were asked to select a case study of a technological object drawn from the thematic area of ancient Greek technology and examine its function and design characteristics. The students would need to extract the geometric data for creating a 3D model of the object using a methodology of their own, therefore some of them were based on photos from different perspectives, others would work from 2D plans found in books or museum catalogues, while few of them had access to the actual exhibit or parts of it and could 3D scan the object to obtain more precise geometric data in the form of point clouds.

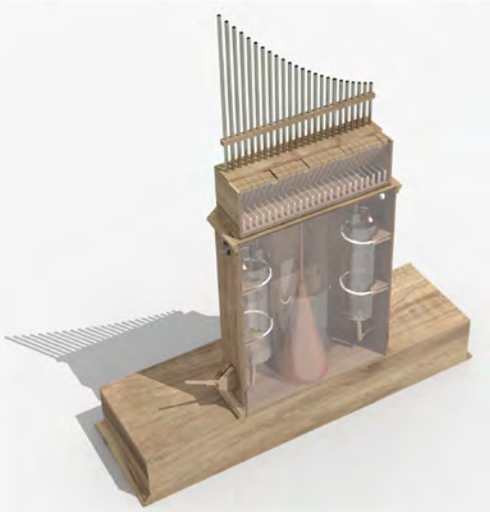

Figure 1
3D model of an ancient Greek Hydraulis by MSc student Katerina Mavromoustakaki

Figure 2
3D model of ancient Greek oil press by MSc student Evri Karamichali

In each of the cases the students had to devise their own design strategy, based on the available data, and combine methodologies to recreate a precise 3D model. The aim was to understand the underlying physical or mechanical principles through the actual modeling of the artefact. The generated objects included mechanical parts and machines, musical instruments, tools, scientific and military equipment. More specifically the students modelled the Aeolus Sphere, Heron's pump, the Catapult, Philon's Chain Pump, the astronomical Dioptra, the musical instrument Hydraulis (Figure 1), the ancient Greek oil press known as "torculum graecanicum" (Figure 2), the "Valistra" crossbow (Figure 3), the ancient Greek Crane (Figure 4), Ptolemy's astrolabe, the Antikythera Mechanism and the "Clepsydra" water clock. For several of them, the students combined data from both museum exhibits as well as books (Hodges, 1992; Jones, 2017; Kotsanas, 2011; Oleson, 2009; Sherwood et al., 1997; White, 1984).

The subsequent design stage of the aforementioned CAD brief involved the design of a contemporary object based on the knowledge gained during the previous stage where the students analyzed and 3D modeled the case studies. In parallel to their design investigations they studied precedents of similar applications such as the Lyre project (Koumartzis et al., 2015) which was reconstructed as a new music instrument based on the ancient Greek Lyre of Hermes using 3D laser scanning, advanced Computer Aided Design and audio analysis, as part of a dissertation undertaken at the International Hellenic University a few years ago. Similar to the Lyre project, the challenge was to design a new object that would be inspired in the case study but would address contemporary needs and aesthetics. In several cases the new object would also relate to the previous exercise with regards to use and function, but would off course not need to follow the same morphological vocabulary. Unlike the Lyre project which was designed in accordance to the main morphological and typological principles of the ancient Lyre, the aim of this year's brief was the design and prototyping of an innovative contemporary object inspired in ancient Greek Technology. Having overcome the initial barrier of CAD literacy, and having obtained basic skills with digital tools and methodologies for 3D modeling during the previous stage, the students were now free

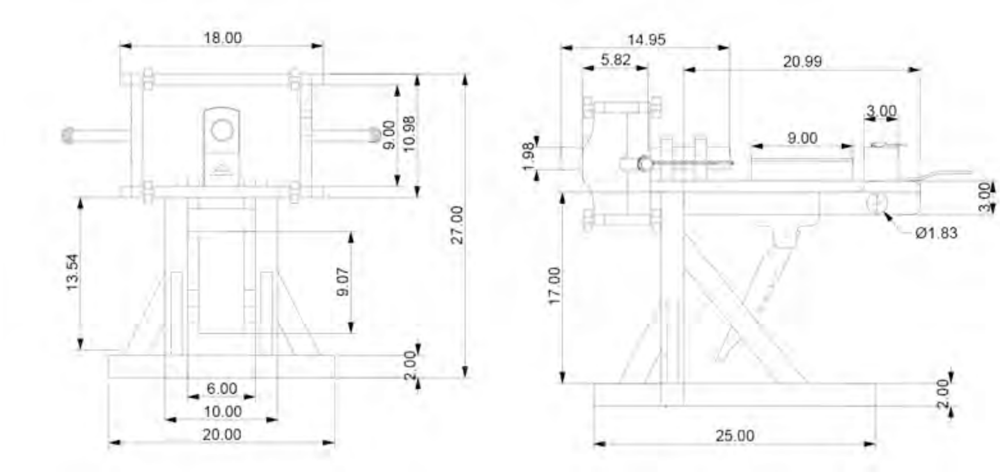


Figure 3
Technical drawings of the ancient Greek valistra. Front and side view by MSc student Lazaros Alilomis

to innovate, devise original objects and address contemporary aesthetic paradigms. In several cases they found inspiration in science fiction, video games or robotics (Figures 5 and 6).

During the last decades there is a growing interest in learning-by-making pedagogies , particularly in the field of design computation. It is broadly recognized that knowledge is a consequence of experience and that the role of technology is significant in the construction of knowledge (Stager, 2014). This school of thought was initiated in the predigital era and goes back to big historical figures like Leonardo da Vinci who is considered to be among the greatest makers of all time. Following the same lines Pestalozzi (1746-1827), inspired by Rousseau, thought that learning resulted from the learner's firsthand experiences and self-activity, favouring things and deeds over words. (Martinez and Stager, 2013). In our days digital media for design and construction offer a very fertile ground for experimentation and observation, particularly when combined with rapid prototyping, encouraging active learning through digital making.

One of the leading figures and supporters of active learning is Seymour Papert. Being a mathematician and computer scientist, Papert realised the huge power of computation as an educational tool and encouraged a creative use of computers within schools, adapting active learning strategies for teaching computation. In the majority of his writings, Papert focuses on propagating the idea of learning by actively constructing knowledge through the process of making and sharing both the artefact (analogue or digital) and the knowledge. (Papert, 1994, 1993).

While historically in architecture and engineering fields the knowledge was transferred from the master to the disciple, in a pre-technocratic notion of apprenticeship, Alberti separated between design and making (Carpo, 2011), leading to the technocratic stage (Schön, 1985) where professional education moved into academic institutions. This has been followed by the 'post-technocratic' stage, where increasing emphasis is placed on the acquisition of professional competences relating both to software as well as construction skills. Mario Carpo distinguishes among 3 technical ages with regards to the actual production and this inevitably relates to the above classification of knowledge transfer. He distinguished among hand making, mechanical making and digital making, depending on the media used

Figure 4
3D model of an ancient Greek crane by MSc student Nikolaos Papanotas

for the actual production of an artefact (Carpo, 2011). Therefore, the traditional learning by doing approach is not abandoned, but it adapts to each respective technological milieu.

Figure 5
Contemporary interpretation of the crane by MSc student Nikolaos Papanotas

Through the study of the aforementioned instruments and mechanisms, the aim was to achieve a hands-on experience enriching the collective knowledge about ancient Greek technology within the design studio. The concept of learning by doing is deeply rooted within the traditional apprenticeship, and now being revisited with the use of digital media; it is attributed to Sophocles 445 B.C. to have said that "One must learn by doing the thing; for though you think you know it, you have no certainty, until you try". The virtual 3D reconstruction of ancient Greek technology devices aimed exactly at this. To understand the form and function of the case studies through 3D modeling, an exploratory and self-initiated learning, that would lead to the development of new original technological ideas. Kolb advocates that the constructivist self-guided learning pedagogies are of a very high educational value

Figure 6
Contemporary interpretation of the ancient Greek catapult in a science fiction context by MSc student Majdy Miqdady

(Kolb, 1984), he elaborates saying that hands-on processes, followed by critical reflection and experimentation lie in the core of the learning process. Within the CAD studio students were highly encouraged to reflect upon their choices, actions and design decisions.

Future steps of this research agenda will include a more detailed prototyping of selected instruments and mechanisms, and the construction of an interactive virtual museum, where the visitor can go around each object and activate certain parts of it and explore the kinematics and its repercussion to the geometry and assemblies. The aim of the design brief was therefore manifold, to educate design students on the potentialities that arise from 3D modeling through a wide range of methodologies (3D scanned data, photographs, measured sketches, etc) and at the same time disseminate ancient Greek technological achievements to a broader public, and use the knowledge gained as inspiration for future innovation in the field of product design.

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# CAAD TOOLS

# The Geometrical Structure of new Architectural Object

## *The role of meta-mechanics of Holography in its formation*

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*In recent years there has been a gradually increasing interest in the terms on which the design and geometrical representation of the architectural object is based. The true challenge lies in the development of a methodology or mechanism which, having as its starting point the traditional object geometrical representation practices, will allow for a combination of new technologies towards creating new visual messages. In this research, the process of putting together a new architectural object, the digital hologram, will be seen as one such mechanism. The new views and strategies on space are open to treating spatial constructions, as a restructuring of the structures that could bring about changes for more favorable conditions for the representation of the architectural form. Thus, the strategies of architectural pioneering are judged by their ability to develop new procedures that are capable of reversing.*

**Keywords:** *architectural object, digital hologram, holography, syntax*

## INTRODUCTION

Holography -> Όλον (olon: Greek for "whole") + γραφή (graphe: Greek for "writing")-> Recording of all the information on the object.Holography is the process of recording optical information deriving from an object, when it is suitably illuminated by a monochromatic source of light (laser light). It is based on the phenomenon of the intersection of waves. A section of the laser beam illuminates the object (object beam), while another is directed towards the photosensitive film (reference beam). The light reflected by the object intersects on the surface of the film with the light of the reference beam, thus creating the interference fringes that contain the optical information. The hologram is the recording of this interference. The entire process is carried out in laboratories based on strict requirements concerning the stability of the system.Conventional (analogue) holography produces a singular copy of a material object of our choice: on the one hand, this copy is a physical object as it consists of light, however it is not tangible, giving the impression of a hybrid balancing between material and digital reality. The next step is the production of a hologram starting from a digital object. The object, having been designed on a computer, is projected on a screen which, in the layout of the holographic experiment, takes the place of the material object. The produced object is a hybrid of information and material whose starting point is not the material world, but the digital world. The object of holography (physical and immaterial), defined in this bidirectional way, throws doubt on the boundaries of reality as we know it, transforming the linear - up until now - relationship between the material and digital in a system of constant supply and recycling of matter and information. Thus, as opposed to the traditional methods of design of the architectural object, the mechanism in question aims at the production of an architectural object through a renewed view of the notional aspect between digital and physical space in the architectural scene.

## THE RESEARCH FRAMEWORK

Before formulating the basic issue, it is necessary to present the broader framework within which the research is being conducted, as this is the base that feeds research interests, produces the general questions and guides the research methods. The present paper is being written at a time when the centre of gravity of architectural activity is shifting from its perception as a form or (and) functional organization, which corresponds to a given architectural programme, to its perception as a combination of elements, the main concern being to define their properties and relationships. According to John Wiley (Wiley, 2009) the entire endeavour is something more than a search for a "style"; it is a deep change of paradigm, where the creative endeavour no longer lies in the personal gesture of the architect, but in the design methods that waver between accident and intention. The breakthrough for Wiley is the relationship of the architect himself with the dynamic field, where his every movement does not produce a designed object but contains a multiplicity of different results. So at the dawn of our late-capitalist era (Hays,1998) we bear witness to a change of paradigm that encourages a new relationship between design and object, which according to Michael Hays is none other than the passing from a "critical history" to a "theory" of architecture. Many researchers believe that this change in paradigm opens up the door for Architecture to completely redefine its theoretical and tool-related position. In the field of design, new concepts and tools are established, placing emphasis on change, modification and the ultimate logic. The exploration of this new relationship between design and object and the introduction of new design concepts and tools in an era in which 'the death of the monologic world of International Modernism has been pronounced' (Hays,1998), are the main elements that have given occasion to pursue this research proposal. However, if one takes away the undisputable phantasmagoria of the objects emerging as results of the new design processes, and focuses on the manner in which the processes in question are articulated so as to yield a methodological tool for the formation and depiction of the architectural object, what shapes/conclusions can result from this negotiation of the object on new terms? Within this logic, through the acknowledgment of the "architectural object" as an internal element of the cross-functional synergy of concepts such as those of information, matter, structure and the "explicit" shift of design from the creation of a "physical scene" to a practice for managing variable elements, the research focuses on ways in which these central concepts yield an architectural tool that focuses on the tool-related and performance logic of forming and depicting the architectural form. Our aim is, through such an exploration, to shift the management and depiction of the object from a juxtapositional, typological version of the structuring of elements and forms to a diagrammatic and relational typological approach. The methodology is based on the correlation of two levels. The first level concerns the theoretical overview and the "vertical reading" of theories of philosophy, mathematics, and ecology to support the shift in the architectural toolkit, from typo-morphological patterns to more diagrammatic typologies constituting the urban fabric. The second methodology level concerns the Empirical Documentation investigating the establishment of the methodology through a composite diagrammatic entity, capable of operating with feedback and shaping a wider scope than that of the active metabolic factors.

## THEORITICAL OVERVIEW

"A system, according to Ludwig Von Bertalanffy, the founder of the general theory of systems, is 'a set of elements that stand in interaction - that is, they are linked by such relations that if one is modified, the others are too, and, as a result, the entire set is modified.' A system is, then 'a set of objects and of relations between those objects and their properties." (Gausa, 2003)The experiment which takes place in the Holography Lab at the School of Architecture of the National Technical University of Athens has a specific set of elements which are connected with interactive relations, as Bertalanffy describes. Our holography arrangement consists of a LASER, precision optic sets, holography films, a special solid mask, an LCD screen and a process of design and representation of the experiment object. The change of a single attribute in one of them affects the attributes of every element in the set, resulting in the rearrangement of the set and the production of a new output. Based on Bertalanffy 's definition for open system's (Bertalanffy, 1969) we could think of the experiment's set as an open system which can change, take inputs and give outputs. This system can have an interactive relation to its environment, the lab, since every change or action in the lab has an immediate effect on both the system and the output.If we think of the process set as an open system, we can do a double but parallel reading of the process itself, dividing it into an Observer Relative part, outside the system, and a System Relative part which is about the process from inside of the system. The division between the observer and the system itself starts at the process of designing the "3d model" in a CAD program. What a computer user sees on the screen is an Observer Relative output of a complicated and fast computation within the machine; that is an output that is visually familiar and understandable and which the observer can interpret according to their own way of perception. In this case there is a representation of objects which in reality, within the computational system are just fast computations of 0 and 1. (1) For example, an architecture model which is designed in a 3D modeling program, is perceived by the observer as a 3D object when what the observer actually sees is the representation of a 3D model on a surface of two dimensions. Said representation though is the output of a set of algorithms inside the computational system which turns the pixels of the screen on and off and we can say that it operates in zero dimension.U33->U22->U00

### *Observer Relative Process*

The Observer Relative Process has the element of traveling between dimensions and we can theorize that it starts with a finite edition of the object which is represented in the three dimensions through the CAD program. Through the Observer's point of view, there is a 3D object (W33) (Kotsopoulos, 2000) with certain attributes such as shape, material and light and those attributes can change through design. Since there is a finite edition of the 3D object, the next step is the rendered caption of multiple 2D views of the objects (W22). The rendered views need to fill specific criteria which will be mentioned later in the paper. These 2D views hold all the necessary data for the synthetic process of the 3D object in the next phase of the experiment. These views could be called Sections of the object's representation. It is through the synthesis of those Sections that the object can be rebuilt, like for example, a doctor does with the digital reconstruction of a human member through

MRI.The next step is to activate the Section with the LASER beam and capture it on the holography film. The caption is done in stripes whose width is so small that the Observer cannot distinguish a second dimension (W12). These "Linear" elements that hold the data of the two dimensional Sections, are combined on the film through the holography procedure to create an edition of the three dimensional contingent object which is activated through the exposure of its representation medium, the film, to the light. From the observer's point of view the object undergoes a constant reduction of dimensions, from three to one and through the holography procedure it is reconstructed in the three dimensions with different attributes than those the object had to begin with. W33->W22->W12->W22->W33

### *System Relative Process*

The computer, as a machine, operates in zero dimensions. That means that no matter what the Observer Relative Output is, all of its procedures are done in computing of 0's and 1's, a switch between low and high voltage in its circuits. As it was mentioned before, for the computer system, the representation of a 3D architecture model in a CAD program is a series of computations in a binary arithmetic system. These calculations are translated into pixels on the screen that are either turned on or turned off in order for the right Observer Relative Output to be produced.

Studying the process from inside the system, one could say that the procedure is linear and stable in a single dimension, the W00. The data which sustain the Observer Relative Object are produced from certain computations of the software and are illustrated on a screen as pixels that are either runned through with electric current or not. There is a binary condition, 0 or 1, turned on or off. During the activation of the object that is illustrated on the screen, there is a monochromatic LASER beam which interferes with those that are emitted from the pixels that are turned on. Then the beam, whose attributes are changed after the first interference, interferes again with the reference beam of the LASER on the film's surface in order for the data to be recorded. The sum of the light data (the output) is captured on the film, synthesizing a light object which exists in U00 and has Observer Relative attributes.The description above allows us to observe that while according to an Observer's point of view, the object is traveling through dimensions, when we study the inner system and the output, the object remains in W00, zero dimensions, with different attributes in each activation.

## HOLOGRAM : ARCHITECTURAL OBJECT OF DESIRE

The current research is integrated in an attempt to open the sense of the object, where the object requires a way of thinking which does not adopt the dipoles of the representation / reality and of critics *representation but goes beyond the line of control and monitoring. Instead of answering continuously, what is the architectural object, by continuously writing its history, in the current research for the produced object, we focus on interactivity as a manifestation of time and space. So, there is an architectural object which is treated as an opening corpus of relations, as a contingent object, where its main body and its parts are not impregnable from the existing interrelations.The meaning of virtual as something contingent was approached by G. Deleuze in "Difference and repetition" (Deleuze, 1968) and was adopted by Pierre Levy. In his book, "Que' est ce que le virtuel ?", (Levy, 1999) , Levy brings up the idea of the contingent as a unique way of being but also as a process of reformation of the produced object depending on the sum of the forces that interact. To sum it up, in the current research the product, or as we call it, the contingent architectural object is not exactly an object. It is almost an object. It is an object that cannot be isolated, detached from its environment and be repeated as a unit. It does not have a single, stable shape. As a contingent form, it has forms in singular expression. It is part of a field of interactions and cannot be reassigned* reduced to an elemental unit. In contrast, it is organized around a process, acquiring an almost-intrinsic attribute rather than a single identity.The design process, which will be explained

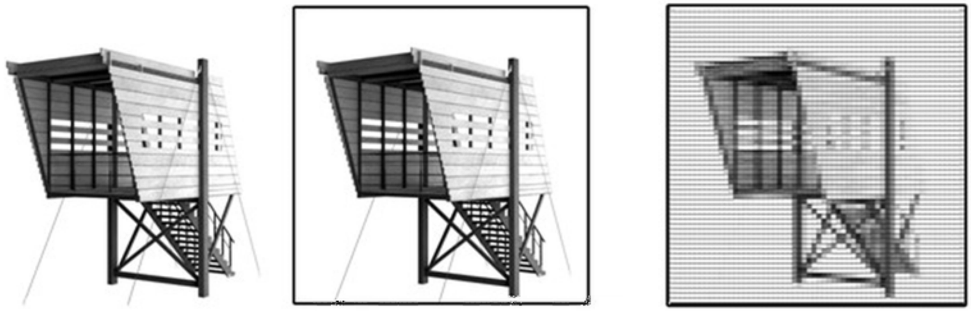


Figure 1
Observer Relative Process: the object undergoes a constant reduction of dimensions

in extent later in the paper, provides the conditions for the emergence of the object, which is the hologram. The constitution of the procedure to produce the hologram is essential for the object to preserve its attribute to achieve a certain goal in relation to its environment. The contingent object does not represent the interrelations of the procedure but the momentary conditions of each interaction. In other words, one could say that the current research resembles the nomadic war machines. They are assembled (grounded) to achieve a certain goal (to deground their context while giving feedback) and then they are reassembled attacking to the links they had created before.The procedure of producing a hologram is a strategy that turns against any emergent identity, any form of hierarchy, having as an ultimate goal the constant de-grounding through the change of the system. The contingent architectural object of the current research also requires a re-definition of the architectural practice. The need for an object with the outmost degree of freedom requires not only the adoption of technology aiming at interaction, but also the design of the technology which will be the infrastructure that will realize the contingent architectural object. In this particular point, it is worth to mention the space in which the contingent architectural object of this research, the hologram, takes shape. When considering digital space, one cannot ignore the aspect where virtual space coexists or is associated with physical space. The digital always exists in relation to physical space; it is defined within it and therefore its relationship with it somehow affects its syntax. A typicalexample is that of augmented reality, which uses a combination of VR (Virtual Reality) and characteristics of physical space, superimposing graphic information on real space. Augmented reality helps the user to work on physical space, enriching it with additional information. Lev Manovich (Manovich, 2002) talks of "augmented space", which is defined by successive levels of information on physical space. This category refers to many applications, all of which are related to the dissemination of digital information in physical space and to its management in the most direct manner by the typical feedback systems. He claims that architects have the ability to see material architecture in combination with the new immaterial architecture of the flow of information, as a unified whole. He concludes that the design of electronically augmented spaces can be approached as an architectural problem. "In other words, architects [...] can take the next logical step to consider the 'invisible' space of electronic data flows as substance rather than just as void - something that needs a structure, a politics, and a poetics". In recent years, references to the coupling of the digital and physical are increasing as technological advances mark the transition from the immaterial to the material. "We observe that the digital dimension is involved directly with the 'physical' in a series of hybrid conditions". A few years ago, virtual reality was tantamount to an artificial reality. Today, when we talk about "virtual reality", emphasis is placed on "reality". Within this logic, in digital holography the designed object ceases to be defined by three dimensions, but is activated and travels through light to infinity, constantlychanging based on its parameters. (Kourniatis, 2013) It is a hybrid of the physical and digital world, having inherited the properties of its matter, of light, and those of particle and wave nature.

## TOPOLOGICAL GEOMETRY AS A PRODUCTION TOOL OF THE HOLOGRAPHY OBJECT

Before we proceed to the second part of this research, which regards the empirical and experimental study of the procedure of the production of the holography object, it would be advisable to do a brief note to topology, since it is the science that focuses on the connections between incongruous elements, in a reshaping structure, a fact that makes her particularly useful in structures that take over the venture of multiple elements management. Topology is not interested only in metric characteristics and for the precision of the whole, but it is interested in models of abstract organization and for the type of the relation between the elements of the set. Since topology examines which attributes of the geometric formations remain constant when the formations undergo elastic deformation, it gives the current research a medium to preserve control over the process of the object production. Topologic surfaces are affected from one another but also from the field in which they are created, since that space is not static but dynamic. The result that takes shape is a uniform surface whose form is the result of the multiple forces that affect it. So, every set of such objects is a system that at the same time is singular, since it is an entity uniform and continuous, but also multiple, since it is characterized by inner complexity. Every system is less simple or more simple or complex and stable or unstable, depending on the fields that affect it and the number of the components that interact. The idea of simplicity is different than that of simple reduction and the idea stability is different from that of being static, meanings that are linked to conventional geometric structures. Complexity is not always expressed but it exists as a possibility and so the system is "potential" and it has the ability to reform itself repeatedly while keeping its continuity. That is the main reason that this research is interested in Topology, because topological entities are defined through differential calculus in the contingent space, they are able to introduce time and movement to their form. Context becomes an active space for design, where fields, forces and flow interact and the holography object takes a different form depending on the different links. Therefore, there is a transition from a linear to a non-linear thinking of space, enabling the creation of more complex forms and structures, like in this case, the holographic object.

## EMPIRICAL DOCUMENTATION - THE EXPERIMENT

The transition from analogue to digital holography requires, in theory, a simple change of the holographic subject. The physical object is replaced in the experiment's holographic bank by the digital object, which can only have a physical presence in our reality as an output datum through a computer screen.The experiment was conducted in the Holography Laboratory of the School of Architecture of the National Technical University of Athens. The process is the following: a single laser light beam is released through the movement of a shutter made of an aluminium sheet. Thereafter, it goes through the beam splitter where it is split into two separate beams, that which interacts with the holographic subject (object beam) and that which is directed towards the film (reference beam). The two beams meet again after successive reflections on the surface of the holographic film, where the waves converge.In the case of analogue holography, this interaction occurs when the beam of light falls on the physical object and is reflected in such a way that it carries information on it. The reflected light interferes with the light of the beam that shines directly on the film, thus producing the hologram. In digital holography, the light beam goes through an LCD screen and interferes with the second beam, which carries information on the two-dimensional representation of the object on the screen, viewed from a specific angle. In order to go from the two-dimensional representation of the object to the three-dimensional holographic object, it is necessary to record on successive thin strips (1 mm in width in our experiment) on the film, successive snapshots of the object from neighboring angles of observation, each one with its next angle. The snapshot angles are continuous and neighboring and calculated in order to respond to the analogy of 1:30, which is a satisfying analogy of clear artificial stereoscopic view. For this purpose, we have constructed - with the help of Vangelis Karras and Nikos Tsoukalas, graduates from the Department of Computer Systems Engineering of the Piraeus University of Applied Sciences - a mask that covers the film, leaving uncovered only a single strip with a width of one millimeter in each position. The recording of snapshots is carried out using a photorealistic rendering program (Michael, 1997).

## THE TOOLS - MEDIA

The experiment is conducted with the help of the Arduino microcontroller, using Arduino and Processing open software. With the exception of the optical instruments and reflectorsavailable in the holography laboratory, the remaining mechanical and electronic tools used in the experiment have been designed, constructed or modified by us. More specifically, the filters, lamps and diffuser have been removed from the LCD screen in order to achieve translucency (Helseth, 2001). The mask of the film has been through two phases. In the first phase the mask was made of a metal sheet and placed to close proximity to the metal film case. During that phase the masks movement was horizontal, from left to right, with a step of 1mm. After several experiments we noted that this layout was not suitable for the lab's arrangement since the mask was shadowing the slot because of the laser beam's angle of incidence on the film. After this observation we changed the mask's structure from a horizontal movement mechanism to a vertical one, in order to eliminate the shadowing. The new mask is made from a flexible but solid cover that leaves a single strip of 1mm uncovered in each position. The cover moves vertically with two axes connected to two steppers motors which are controlled via the Arduino microcontroller. The structure of the mask is made in a way so it can be moved and secured anywhere on the bank. Along with the new mask we made a new aluminium shutter which moves with the help of a servo motor and is programmed to release the laser beam in sync with the mask's reposition.

Figure 2
Metal mask and moving mechanism, Holography Lab, School of Architecture, N.T.U.A

### *Experiment Process*

The mask stays in place, in perfect alignment with the LCD screen and close to the film, in order to achieve stable lighting conditions of the slot throughout the process. At the beginning of the experiment, the film's case is in the X0 position, which is the lower end of the film, leaving a one millimeter-wide strip uncovered. At the t0 time point, the first snapshot of the holographic object is projected onto the screen. After a pause of a few seconds (t2), the computer gives an order (via Arduino) to the shutter to perform a 90-degree rotation, thus releasing the laser light beam. After a specific time period, which is determined by elements such as the intensity of the light on the surface of the film, the quality of the film, its age, etc. the shutter moves in the opposite direction, thus closing the opening of the laser (t3) and preventing the light beam from moving to the system. The system settles

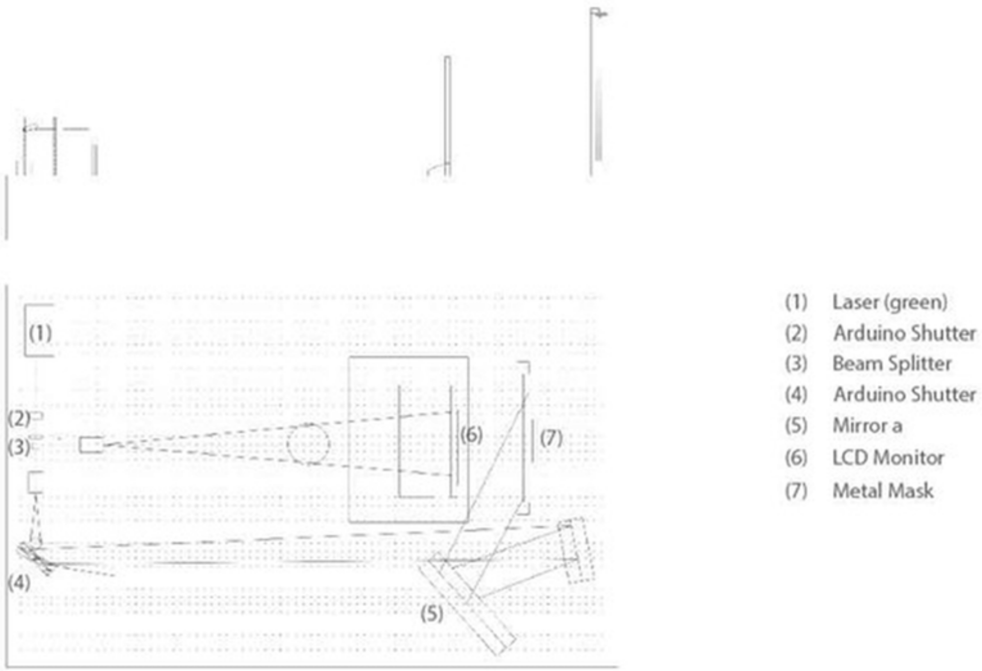



Figure 3
System set-up upon the metal table, front and ground view

down for a few seconds, and at the t4 time point, the film case shifts up by 1 millimeter, to position X1, thus leaving the strip neighboring that in position X0 uncovered. This process is repeated in position X1 after a necessary pause. At time point t5, the second snapshot of the holographic object is projected onto the screen, having been imprinted from an angle of observation following that of the first snapshot. The process continues until all snapshots of the object are recorded on the holographic film. At the end of the process and after the necessary pause in order for the system to settle down and not affect the hologram, the cover returns to position X0, ready for the next experiment.

**Parametric layout | Physical to digital and back..**
Closing the first phase of our experiments and studying the results concerning the procedure, the team moved on to digitize the layout of the system on top of the holography bank. The elements were measured and designed in a CAD program (Rhinoceros 5). Following that there was a matching of their position on the holography bank using a coordination system. The next step was to parameterize the layout by setting the laser beam and the correspondence angle as variables, so we can have the best light path for each trial. The parameterization was done with the help of the Grasshopper plug-in program of Rhinoceros 5 in order to help us in the procedure but also as a control experiment to check the physical layout in relation to the digital model. We aspire to add more variables to the parameterization, so we can have a better control of the physical part of the system.

Figure 4
System set-up upon the metal table, front and ground view

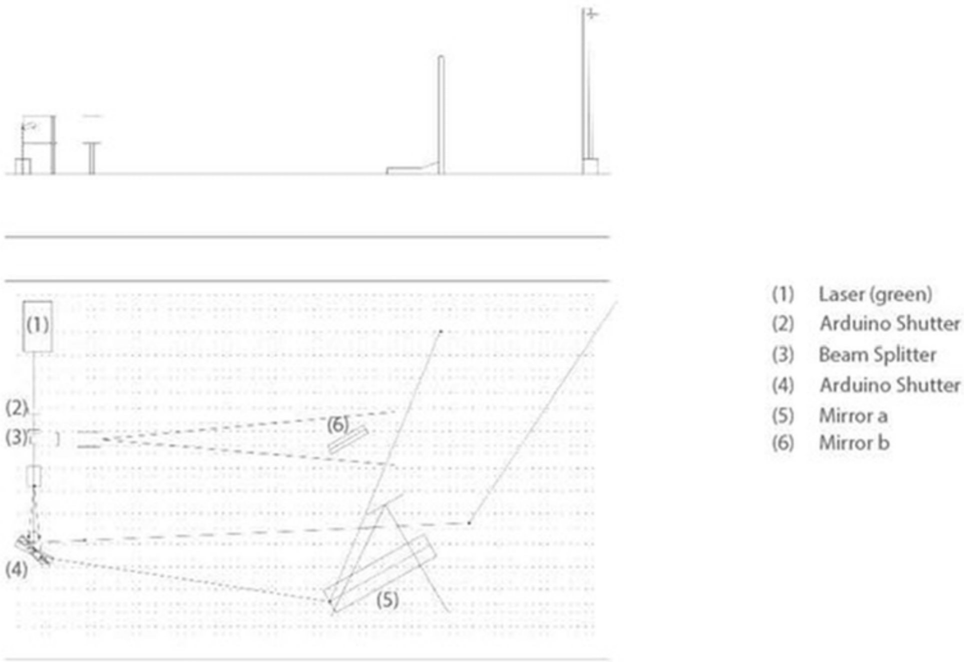
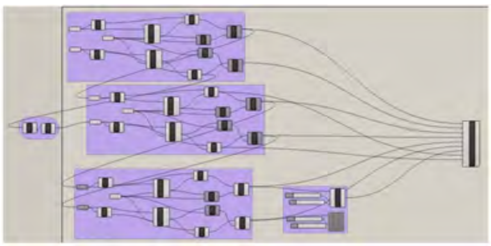



Figure 5
Parameterization of the process



## *AFTERWORD*

In The Structure of Scientific Revolutions, Thomas Kuhn hypothesizes about the process by which major changes come about in scientific fields. Briefly, Kuhn's thesis is this. When a scientific field is going to through a stable period, most of the practisioners in the discipline hold a common body of belief and assumptions; they agree on the problems that need to be solved, the rules that govern research and on the standards by which performance is to measured. They share a conceptual model that Kuhn calls a paradigm, and that paradigm governs activity in their profession. But paradigms are not necessarily immutable. When several people working in a field begin to encounter anomalies or phenomena that cannot be explained by the established model, the paradigm begins to show signs of instability. For a while, those who subscribe, to the paradigm try to ignore the contradictions and inconsistencies that they find, or they make improvised ad hoc changes to cope with immediate crises. Eventually, however, when enough anomalies accumulate to make a substantial number of scientists in the field question whether the traditional paradigm can solve many of the serious problems that face them, a few innovative thinkers will device a new model. And enough scientists become convinced that the new paradigm works better that the old one, they will accept as the new norm. Similarly, the need for a change of paradigm, that is, the need for the formulation and establishment of a new theory that includes and explains all contemporary questions posed by science, is evident in the field of digital holography. The way we treat holography today and the applications we are in a position to juxtapose, indicate the (visible) boundaries we impose on its potential and on the advancement of the research field supporting it.In summary, if today the cultural view changes in search of a new architectural object, then the design strategies will have to move from point interventions to construction techniques that manage change through evolving and developing platforms. The architectural object is now in a constant state of transformation, and therefore we must offer our knowledge, as well as our conceptual and technological tools, so that it may incorporate this change. In the shaping of a new architectural object, the production process should not constitute a scene on which the object is to be placed, but should constitute a dynamic field for studying the management of the object in question. Thus, geometry seems to play a dynamic role to the formation of such an object, giving the rules of its appearance to the physical world.It is on this basis that we have in this text attempted the first conceptual and, primarily, practical approach to a mechanism that may monitor change and be supplied with data resulting from its analysis, aiming at their composition and the redefinition of the architectural object. This is hybrid process and it could be argued that it functions as a filter that does not only receive information but also checks whether this information can be modified, while also producing geometrical connections and forms, which eventually give shape to the architectural form. The basic element of this mechanism is the production of an information substructure, which may gather information through distributed systems and networks, while always taking into account the temporariness, change, gradual evolution and adaptation of this information through time. As opposed to the traditional design methods of the architectural object, the mechanism in question aims at the production of a smarter architectural object, in the form of a digital hologram, through a renewed perception of the notional aspect between digital and physical space in the architectural scene.

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[1] https://www.youtube.com/watch?v=rHKwIYsPXLg

# Behavioural Space Configurations

## *Architectural Spatial Configuration from a Biological Standpoint*

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*The following research, depicts a theoretical model of producing architectural spatial layouts. This is based on a more Biological View of Architectural space and concerns it self with the way that organisms (and in-turn we) perceive and interact with our environments. The model presented here emanates from a range of different fields and not only architectural theory and design. This research touches upon the fields architecture, mathematics, biology, behavioural psychology and has been inspired and draws heavily on the work done by Tim Ireland, as well as some of the work of Gregg Lynn and Alessandro Zomparelli, as well as the theoretical work of Uexküll and Kwinter. The model has began from a simple coding exercise and has developed into a detailed organism that acts and interacts with its environment. The end results present a bottom-up approach to spatial architectural layouts that are defined by the way the organism design interacts with given spatial qualities and other similar organisms with other given spatial qualities. The results retrieved from the coding exercises represent a more abstract -at this point- representation of space and have been slightly manipulated in other Modelling Packages to receive a clearer image.*

**Keywords:** *behavioural space configurations, agents, behaviour, bottom-up*

## INTRODUCTION

In the 1960's there was a surge of interest in the field of Automatic Planning in Architecture. This aimed to counter the existing Top-Down layout configuration procedures and propose new and improved, functional models for design. This movement ultimately dissolved in the 1980s after architects in practice failed to adopt the new ideology into their design process.

Since then, there has been a rejuvenation of interest in *Automatic Planning* along with fresh ideologies and new computational means *[1]*. The presented Bottom-Up approach of this paper, aims to; analyse the initial principles of Automatic Planning and the reasons that eventually led to its dissolution, in an effort to "learn from mistakes made" as well as creating a new model of countering Complex Spatial Problems.

The research is drawing from various sources and is not limited only to the fields of Architecture and Design. It concerns itself with many principles and parallels drawn from the work of Architects (Tim

Ireland, François Roche, Greg Lynn, Michael Hansmeyer), Biologists (Uexküll), Behavioural Psychologists (B.F Skinner), Philosophers, Mathematicians and so on.

## THEORETICAL BACKGROUND

The initial idea is triggered by the statement made by Uexküll, that the term "space", does not necessarily signify an enclosure. On the contrary, space is a property of all living things. It is an experience of the environmental stimuli around us (Uexküll, 1926). Kwinter also supports this, by signifying that only living things can experience the stimuli in the environment (Kwinter, 1992). Our environment (Umwelt) and thus space can be experienced through complex receptors. These receptors are embedded in our organisms and they allow us to comprehend and interact with the stimuli in the environment and sequentially space (Kwinter, 1992, Uexküll, 1926). Now, all living things have a decentralised nature. That means, that all living organisms are the embodiment of the self-organisation of the individual parts of their system (Johnson, 2001, Resnick, 1997). From a biological standpoint, self- organised and emergent, embodied organisms, experience space, in a self- organised and emergent environment. This entertains the idea that space has a dynamic definition and also cannot be defined as merely an enclosure, but, as a consequence of the, by the time mentioned, existing stimuli, coupled with the stimuli imposed by the actors, an infinite loop (Uexküll, 1926). As proposed by Ireland, the whole architectural configuration can be viewed as a single individual system, comprised of multiple self-organising parts (spaces) (Ireland, 2015b).

Taking as a base the theories mentioned above, the new model proposed, takes each individual space and room and "trains" them to detect and understand their environment as well as interact with other similar and different organisms. The model is being created using the *Processing Language Environment*, creating various behaviours for the organisms (agents) that are being placed within the environment. These digital organisms are designed and used for the purpose of mirroring parallel and natural processes and that in turn would be coupled with basic architectural principles, with the ultimate goal of generating architectural spatial layouts. The created organisms have certain behaviours, that allows them to sense and interact with their environments using their distributed cognition. At the beginning, the organisms have more rigid and basic geometric shapes (circles, rectangles, etc.) and the pairing of these organisms with the environments (actual context/building site) can give an abstract representation - using these geometries- of the spatial experiences (henceforth, space) and spatial configurations.

The organisms and the algorithmic exercises can be used as tool for analysis, although the overall goal is to be developed to a point of an Automated Spatial Arrangement Design Tool. Multiple human-centric as well as behavioural psychological models have been investigated in order to settle on the basic behaviours of the organisms.

Burrhus Frederic Skinner *a Behavioural Psychologist*, stated that *'Education is what survives when what has been learned has been forgotten'.* He also established, that the behaviour of any organism is depended on the interpretation of stimulus in its environment (Skinner, 1938). This coincides with the theoretical examples set by Uexküll, which as mentioned understand the organism's perception of space as a dynamic process of interpretation (Uexküll, 1926). The result of this translation process can be understood as the behaviour of the organism. Furthermore, Skinner defines behaviour to be as a series of actions, reactions and reflexes to stimuli (Skinner, 1938). What an organism is acting towards, or reacting against- specific stimulus - can essentially define Behaviour (Myers, 2004).

On another front, the ancient Greek Philosopher, Empedocles, suggested that all the movements of the Elements, along with all the changes taking place in the universe could be attributed to Attractions and Repulsions. These changes can either be of creation or destruction and are depended on the two great fundamentals *[2]*. Evidently, any forms that arise or perish solely depend on the self-organisation of the constituent parts along with, the "Holding Together" (Aggregation) or the "Falling Apart" (Individuality), respectively (Wade, 2007).

Self-organised systems such as the one introduced, are always depended (organised and modified) upon the local interactions that occur among the component parts of them. Those interactions are the behavioural traits of every living organism. The feedback loop created between organism and environment, along with the self-organisation of the parts, begets emergent patterns at a global level ("global" is defined; as the extended limits of the environment, sites, universe or world) (Johnson, 2001, Kwinter, 1992, Uexküll, 1926, Mallgrave, 2013).

## TOP-DOWN SPATIAL CONFIGURATION

The configuration of a functional layout is a very important and vital stage in any design project. It has always been signified as a major stepping-stone in a project, since; it essentially defines how the entire building proposal would be organised and how it would function through the years and of course, how the people within it use it, experience it, etc. *Architectural Layout Configurations* are always the product of a methodical analysis and arrangement of the activities, functions and rooms of any architectural proposal. This will be providing an understanding of the entire building program and the needs of the building along with the needs of the inhabitants (Ireland, 2015a).

The traditional Top-Down approaches, to spatial configurations, need to rely on biases and references of existing architectural proposals of a similar typology. This happens so that the organisations can be justified and it essentially revolves around the antiquated idea, "if it isn't broken don't fix it". These established ideas and biases have provided a template for Architects to fall upon, as a safety net, allowing them to add or remove from the template as much or as little is needed to satisfy the given scenario *[3]*. Furthermore, Top-Down approaches have a tendency, to essentially counter the problem of space configuration by viewing it as something flat and static (Ireland, 2015a). The Architect divides equally his attention and skill on each individual room. This proves to be a significant strain when the problems and proposals become bigger and more complex. By flattening the configuration, the traditional (top-down) approach allows the designer to manage and organise the functions of the building in a more straightforward manner. This saves time for the designer, since there is no consideration for, the dynamic relationships and the behaviour and interactions between spaces, or even interactions between parts (rooms and functions) and the whole (building proposal). The functionality of a building is thus being flattened out and eventually takes second place rather than being the dominant element. It becomes a linear process of stages that one must pass through with no concern of the shift in relationships with every deterministic step in design that is taken.*[1]*

Naturally, spatial solutions respond to problems existing in the world. These solutions are organised wholes within geometrical boundaries. Taken for granted that geometry can be expressed as a set of rules. This set of rules is applied on specific scenarios by giving variables and parameters the correct values. In the same manner, the designer can achieve spatial configurations to certain problems, by manipulating these rules and parameters to fit the given scenario (Ireland, 2015a).

Traditional Top-Down Approaches to layout configurations, tend to focus on the outcome, the organisation or the phenomenological aspects of a proposal, but in most cases, not at the same time, or sometimes, not in the same case. The dynamic relationships between rooms and other rooms, rooms and the building, and building to context, are what I personally believe to be the definitions of a building proposal. By coupling the ideas of Uexküll and Kwinter, who argue that, space is empirical and thus it is a dynamic entity full of stimuli, and Ireland's and Lynn's suggestion that geometry itself is simply a set of rules, it can be viewed as a new paradigm for layout configurations. In essence, the aforementioned rules, when followed, can help replicate the experience of space. Thus space should be viewed as a multidimensional entity and then, so do layout configurations in architectural proposals. It should not be flattened and countered as a static and linear procedure, since spatial configurations are by nature dynamic (Ireland, 2015a, Kwinter, 1992, Uexküll, 1926, *[1]*).

Figure 1
Initial Spatial Configurations Using Primitive Shapes

## SPATIAL CHARACTERISTICS

Hillier states that space, is a very specific trait with vast significance for the human behaviour. He suggests that any form of interaction such as; attracting, repelling, congregating and so on, are not merely activities that take place in space, but rather, these activities can establish patterns of spatiality (Hillier, 1999).

As part of a whole, each room and function expresses its own character's qualities, as mentioned before. This is understood as the way that it interacts with other functions according to the parameters that are set up by the system's designer. The entire layout configuration is always depended upon a wide range of factors and parameters and the end result defines a very unique 'mode of habitation' and this mode of habitation can be used to define form (Ireland, 2006).

Hillier suggests that the relationship between space and the act of living is implied by the relationships between configurations of people and spatial configurations, a mode of habitation (Hillier, 1999). Thus, this way of viewing spatial configurations will provide a spatial morphology. This will be depended on the configurations carried out from the interactions and the relationships between the functions of the spaces. The functionality of the whole will define the form of the building proposal. Form follows Function (Hillier, 1999, Ireland, 2006).

In any approach (top-down, bottom-up), the planning is emphasising on the connectivity of rooms and their adjacency. The designer is always inclined to allocate rooms depending upon functional necessities, along with a tendency towards the conversation and connectivity of the rooms by prime importance. The rooms that have a higher exchange of information and stimuli are established with a shorter distance than those that do not (Ireland, 2015a).

The way this was approached by Hsu and Krawczyk (Hsu and Krawczyk, 2003, Hsu and Krawczyk, 2004) and Ireland (Ireland, 2015a), provides a new and interesting inside on how spatial configurations can emerge as self-organised wholes. Their research suggests that the way rooms and functions are viewed, could be radically changed and by doing so, append identities and characters to each individual area. Thus each function has its own behavioural traits and experiences space through it's own individual receptors, and then again space is emergent from the self-organisation of all the characters/rooms. The characters (whatever they may be called; rooms, functions, areas, spaces, etc.) have specific likes and dislikes, urges and needs, that they need to satisfy in order to reach their order and calmness (Chalmers, 2008, Ireland, 2015a).

Hsu and Krawczyk have suggested a term, for the identities of each room, *'Space Character'* (Hsu and Krawczyk, 2003). It is easier to understand the analogy, that if we view these spaces as individual persons, and then these individuals gather around as a group, these groups of individuals are aggregating amongst similar individuals with similar interests or *"requirements"*. Having said that, each person has individuality and his/her own character. Thus each space can be viewed as an individual person that has a specific character. These characters, when placed within a specific environment full of stimuli, will self-organise, according to the relationships of the individuals amongst them and the individuals to the whole. These newly formed self-organised patterns provide the template upon which the program of the building will be based (Ireland, 2015a, *[4]*). Therefore, it could be argued that space adjacency could be *behavioural*.

Figure 2
Spatial Configurations Using Primitive Shapes engulfed by swarms

## BEHAVIOURAL SPACE CONFIGURATIONS - PERSONAL EXPLORATIONS

An Architect's duty is to synthesise a collection of activities and spaces, and find solutions to contextual and spatial problems in order to complete a unified whole. This Algorithm can be used to provide a single solution (for optimisation) -the best possible arrangement - or provide multiple solutions for the Architect to use as a stepping stone, which could be developed further or to be disregarded.

For the resolution of *Automatic Planning* and *Automatic Spatial Configurations*, I have looked at all the aforementioned theories and examples and my work draws heavily from them. My configurations are built around personal models I have developed in the Processing Language Environment. I view space as an experience and as a biological trait and in the same way I orientate my models and *"bio-digital" organisms* and view them as dynamic entities with their own traits and their own behaviours and characters . My personal organisms are set free within the developed models/universes and they counter and interpret basic spatial configurations by perceiving stimuli in the environment, either left, or created by themselves or by the other organisms in the system.

I personally find that a better way of countering spatial configuration problems, is to carry out several building typology analyses and identify the rooms and functions that are needed ,depended on the activities that will occur under the mantle of the building and from that point forward to readjust the model so that it can better beneficial for a specific given case study. Furthermore there could be an identification as to the behaviours of each of the functions, either that is by most used space, function requirements and essentially everything that could affect the spatial layout.

My initial models are revolving around the depiction of building areas and functions as primitive shapes to make it easier to understand how the relationships work between them. In essence, how they congregate and how they aggregate. Beforehand, there were certain parameters established so that the agents (functions) would have some predefined restrictions and an inert sense to achieve equilibrium. These restrictions will be developed even further in the models when the proposals need to be implemented at specific sites. Those sites will have their own restrictions and their own parameters, such as sun and wind exposure, rainfall, noise levels etc. By adjusting and shifting those parameters to accommodate any given site, we can reach an automatic planning and spatial configuration that is always depended upon the behaviour of the organisms (functions) within the environment (plot). (see Fig.1)

These primitive shapes (circles) are sensing changes in their environment and thus move around and shift their positions to a place where their existential needs are met. These basic models and organisms draw heavily on the worldview of Empedocles; that every form that exists in the universe is depended on the two basic forces, attractions and repulsions. Also, by the fact, that the final forms are depended by the ability of the elements (or organisms in this case) of holding together or falling apart. *[2]* Henceforth and following the aforementioned theoretical background, the initial behavioural traits that are being *"learnt"* by the organisms are *Attraction and Repulsion* (Simply put, Like and Dislike). Additionally to the two basic behaviours, two more behaviours are being introduced, those of *Indifference* and *Compromise*. The latest behaviours serve to add more complexity to the model as they are triggered and settled according to the system's stimuli. The before-mentioned organisms have been inspired by coral reefs and how they react to their environmental stimuli and how they aggregate and create their own colonies etc. The digital organisms act as self-organising parts of a whole system and are at the end of the day, depicting rooms of a specific architectural proposal that have a *"Spatial Character and Behaviour"* (Ireland, 2015a).

In essence the circles are being attracted by others or repelled by others until every organism in the system is satisfied and settled at its position. My initial models have been focusing on the way corals aggregate and create a composite structure that can house activities and also help the seabed -They are defined by their environment and redefining their environment. I have taken the way that corals form and how they aggregate and also how they proceed to a compromise according to their environmental surroundings. These environmental stimuli shift, due to underwater currents, to schools of fish, carcasses and even man-made objects that sink into the ocean. Corals adapt and change their behaviour to accommodate this new stimulus that appeared within their environment.

In this manner coupled with one of the most significant debates in architecture, along with papers by Tim Ireland (Ireland, 2006), I have looked at how forms can arise from organised parts, and how form follows function. In my attempt to provide an organic spatial configuration I have added the 'Swarms' parameter within my models. This basically represents environmental factors, whichever they should be, that adjust their course by the obstacles in their environment. These swarms engulf the aggregation of the functions and define the form as an organic flow of curves. These new curves have been taken into consideration and have formed a more smooth transition between the basic circular layouts and the site chosen for the exercise. (see Fig.2 and Fig.3)

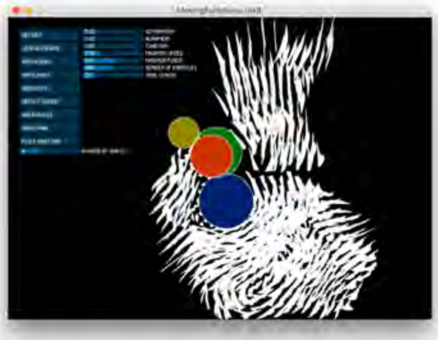

Figure 3
Spatial Configurations Using Primitive Shapes engulfed by swarms

Although with these spatial configurations, I do get some interesting and dynamic forms, some of the spatiality of the building is lost. This happens due to the fact that the rooms are aggregating as circles and then the swarms elongate those circles in a direction. This goes back to what Christian Derix has said about organic architects in the past, that they were representing areas and spatial configurations as loose fits and thus having multiple identities (Derix, 2014). Although these models have spatial qualities and relationships, the swarm might take some of that away, since the elongations do not necessarily benefit the spatial configurations in the correct ways -in any given situation (sometimes they benefit the spatial configurations but others not so much).

Furthermore to the established behaviours of the organisms, the basic geometric shapes have been developed further by their conversion into swarming bodies with their own individual *Spatial Character*. Every room now, instead of being represented by basic geometries, becomes a more malleable network of spaces, not bound by the limitations of simple geometries as before (Circles, Rectangles etc.) Consequently, the change from basic geometrical shapes to this more flexible geometry, further transcends the traditional Top-Down configurational approaches which tend to be more rigid. (see Fig.4 and Fig.5)

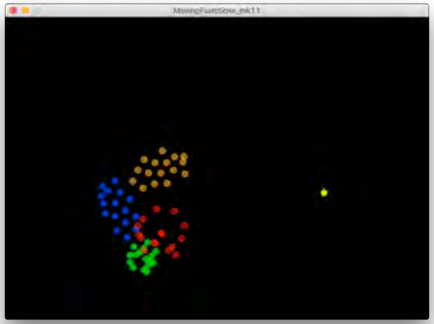

Figure 4
Spatial Configurations by turning the circular bodies in swarming bodies to give a more malleable approach. The behaviours have been adjusted for a swarming body but still remain extremely similar

It should be stressed at this point that all the arrangements seen so far have been taken out of the *Processing Language Environment* and imported into Rhinoceros to be used as the basis for further explorations, modeling etc. The following results have been extrapolated into 3D forms as well and have been physically build with 3D Printers in order to provide a more physical understanding of this conceptual exercise, it essentially provides a more realistic feel to the configurations.

As the end result, also resulting from nearing to the end of my *Thesis*, I have further developed the organisms to move and interact in a 3D Environment - at the end of the day, Architecture is a 3D Phenomenon. The resulting configurations now span multiple levels and have various behaviours that result in a very malleable but still organised wholes. The new configurations in three-dimensional space now, have no given site and are just positioned for the sake of the argument in a randomised site, since the import and consideration for real-world applications takes longer to incorporate in such a young algorithm. (see Fig.6 and Fig.7)

The geometries extracted from the swarming 3D bodies, have been imported into Rhinoceros, culled using Grasshopper and then engulfed into various shells to provide some possible solutions one generic site. The three dimensional geometries have been quickly rendered to show a possible appearance of what the proposal could develop into (at this point in time).

## CONCLUDING REMARKS

It can be understood, that space is a dynamic entity. We perceive space by all the stimuli and interactions that we dwell in, by moving around in our environment, through our receptors. It can be observed that some organisms have developed the ability to create artefacts, to house all their activities, and those artefacts are the result of their behavioural interaction with their environment. Humans on the other hand, are the only organisms that have a variety of structures (artefacts) and every one accommodates a different set of activities.

These activities that the organisms dwell in (for separate typologies) can be defined as a series of stimuli that can affect the behaviour of the organisms and their behaviour can in turn affect them. This happens by a nonverbal communication between stimuli and organisms and the resulting behavioural patterns of habitation - lived spaces- can represent the artefacts that are created as part of the organism's spatial intelligence.

There are multiple models to understand these stimuli and behavioural patterns and transform them into habitable buildings. The transformations will take place after functionality in the system has been defined and structured, by the self-organisation of the organisms within it. Functionality can be determined by the observation, simulation and fabrication of dynamic systems and buildings that take into consideration human behaviours. Thus aesthetics are second in nature after functionality.

By personal explorations, I find that the idea of an organic form or organism representing a room or a function, that moves within the environment and is seeking to satisfy its existential needs by interacting with other functions, is fundamental to automatic planning and automatic spatial configurations. By trying to understand and mimic nature and its relationships between its parts, it is apparent that although there is self-similarity within its inner workings, there are multiple dynamic self-organisations within cells. These organisations are paralleled with their neighbour relationships that they usually co-exist. Furthermore, organisations coupled with the neighbour relationships and behaviours of each individual cell; provide relatively simple configurations but, with a high degree of content.

The models presented in this paper, although they can propose spatial qualities and can produce various structures that can be inhabited, are still far from completion. There are various aspects that could be implemented in order for the models to have more spatial relationships and relevance to even more typologies and even a more *in-tune* relationship with their environments. The algorithm itself is still in an early stage of development and there is still work to be done -out of personal curiosity and drive- on the models, to be developed to a finalised and intuitive program that recognises building typologies and allocates functions accordingly in a human-centric behavioural model of functionality that could also provide some aesthetical reconfigurations to meet specific demands.

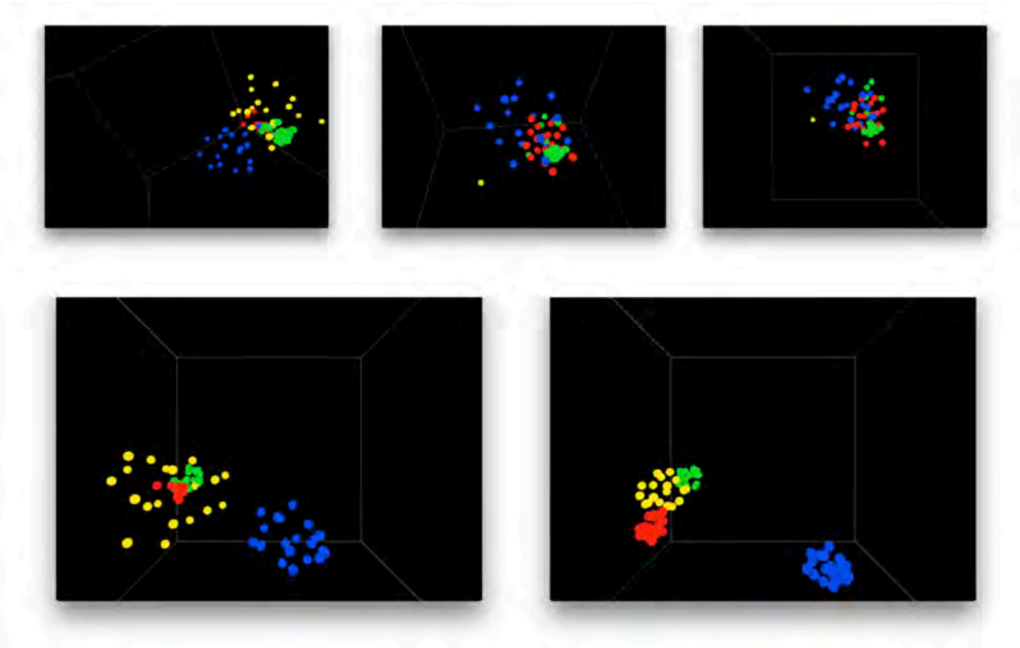

Figure 5
Various Results from the 3D Movement Model

Figure 6
Initial Configuration Variation from 3D Swarming Bodies

Figure 7
Final Configuration Variation from 3D Swarming Bodies


## ACKNOWLEDGEMENTS

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# ZEBRA | COMPUTING MOIRE ANIMATIONS

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*This paper documents the development and application of a set of computational tools under the name ZEBRA to support and facilitate the design, simulation and realization of two and three-dimensional moiré animation installation. Additionally to traditional two-dimensional moiré animations, the authors implemented the above tools to examine a novel approach which combines the depth of field and motion of the spectator to achieve a large-scale, analogue animation effect in three dimensions. The tools were established to aid the design of an interactive sculptural installation for a memorial in Cyprus which was completed in March 2017. ZEBRA is currently in beta testing and will be launched as a plugin for Grasshopper 3D in the near future.*

**Keywords:** *Moire, Animation, Raytracing*

## INTRODUCTION

This paper documents the development and application of a set of computational tools under the name ZEBRA to support and facilitate the design, simulation and realization of two and three-dimensional moiré animation installation (Figure 1). The tools aim at automating the processes and verifying the legibly of the results of analog animation produced by the interaction of two superimposed layers; a grating (a transparent screen with evenly spaced strips) and a composite image formed by parts of the frames in the animation. The technique is based on masking all, but one, frames of the animation at a time, using the grating layer. The successive registration of frames generates an ″apparent motion″ effect, an illusory phenomenon of movement that occurs when ″two or more adjacent stimuli are briefly presented, one after the other (Sperling, 1966). The method is encountered in literature as Moire Animation, Barrier Grid Animation, Picket-fence Animation, Kinegram, Magic Moving Images, or Scanimation.

Since the above technique is proposed to be utilized in a built environment context, the 2d Moiré Animation method is therefore modified to meet new constraints and parameters imposed by the suggested 3d Moiré Animation technique. The computational tools presented in this paper were developed as part of the design workflow to address the difficulties of assessing the legibility of the animation effect implemented in the case study project. Since the technique is based on the utilization of a limited amount of low resolution frames (usually 4-6), a frequent visual evaluation of a large number of iterations was necessary to ensure the legibility and flow of the animation. The actual slicing and recomposing of frames presents a laborious and time consuming process that would otherwise hinder the exploration of a large number of design options or the optimization of the selected designs. Furthermore, variations of the width of the grating slit can affect the animation results in terms of speed and legibility. The investigation becomes even more complex when 3D

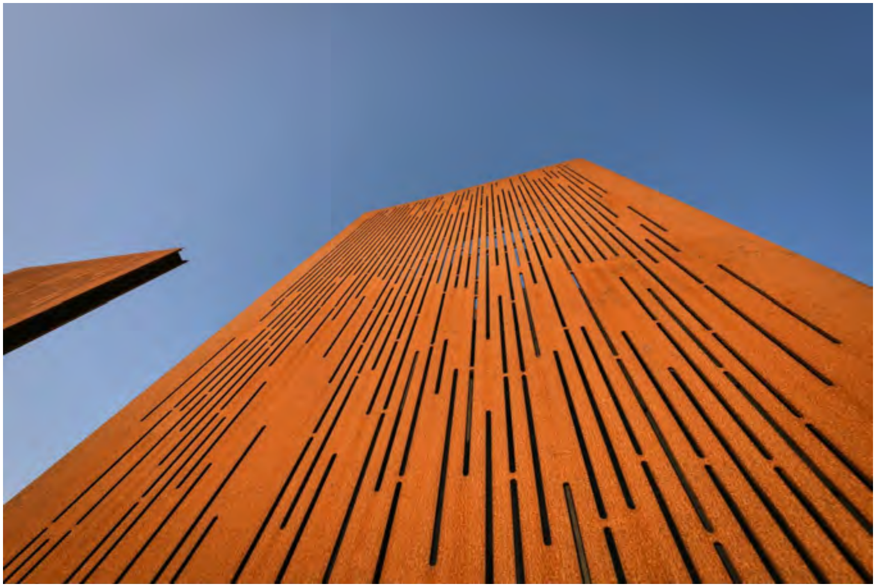


Figure 1
Memorial Stele Grating Close Up View
(Photographer, C. Solomou)

moire animation parameters are added as the material thickness and spacing of the two layers can both affect the outcome. As a result, the research team opted for developing a set of tools to facilitate the design process and asses the design results.

## LITERATURE REVIEW - EXISTING WORK AND HISTORICAL BACKGROUND

In this part the framework within which the study is carried out is presented. The collection of precedents discussed is limited only to those exhibiting animation characteristics. Projects involving the utilization of Moiré Patterns and Effects are deemed relevant, but are purposely excluded as they are considered by the authors as a separate study set.

Variations and adaptations of the Moiré Animation technique can be traced throughout history as early as the end of the 18th century when the 'artificial fireworks' devices presented the illusion of movement by employing a dynamic patterning produced by moving a lined screen in juxtaposition to a perforated picture. Moiré Animation is also present in the 1898 Motograph Moving Picture Book which featured engravings of objects brought to life when an acetate transparency with a fine line pattern was moved slowly over the pictures (Herbert, n.d.). The technique is also evident in a series of postcards marketed under Alexander S. Spiegel's patent as Magic moving pictures by G. Felsenthal & Co and as Magic moving picture card by the Franklin Postcard Company. Similar cards have been published in Japan around 1920 as Cinematograph by SK and in France around 1940 as Mon cinema chez moi (Barrier grid animation and stereography, 2017). The Ombro Cinema toys, popular in 1920s France, also present a very relevant example. Operated by an analogue clockwork mechanism, the interlaced image (a paper roll) is moved behind a grating to produce an animation. According to Rufus Butler Seder after the 1920s it appears, that the progress of Moiré Animation technology comes to a recession, supplanted by the advent of conventional motion pictures, lenticular plastic imaging, holography and video (Herbert, n.d.).

Moiré Animation attracts new attention, over

Figure 2
Memorial Steles View during Night (Photographer . C. Solomou)

the last decade through a series of children books mainly by Colin Ord and Rufus Butler Seder (Shan and Chung, 2016) which according to Christine Chiou offer predominantly visual stimulation for aesthetic purposes, showing animations of running animals or rotating gears (Chiou, 2016). In addition, the quite recent example of The "Magic Carp-pet", designed by Johnii (John Leung) for ClarkeHopkinsClarke Architects in 2010, presents a unique 3D Moiré Animation instance which shares common characteristics with the project under study (Leung, 2010).

Figure 3
Dancing man scanimation illustrations by Rufus Batler Seder. (Heeza L'Univers du Cartoon, 2017)

The above examples can be categorized in three groups based on the apparatus-viewer interaction. The first and most populated category is the translation of the grating to produce the animation. Artificial Fireworks, Motograph, Magic Moving Pictures and recent Scanimation books, toys and gifts belong to this category. In the second group, the grating is kept static and the motion is transferred to the interlaced image. The most notable example of this category is the Ombro Cinema Toy. The third category involves no movement in any of the two layers but relies on the spectator to produce the animation. Such an apparatus requires the two layers to be spaced apart to enable interaction with the viewer. The "Magic Carp-pet", as well as the memorial presented in this paper belong to this category which is defined in this paper as 3D Moiré Animation. This last category seems to be facilitating scaling-up of the Moiré Animation due to the absence of moving parts on the apparatus. The notion is also supported by a few existing examples that utilize this third type of interaction with Moire Patterns in architecture (Brzezicki, 2011). In addition and based on the findings of this paper, 3D Moiré Animation operates on additional and more complex parameters than 2D Moiré Animation. The above, could partly explain why just a single example ("Magic Carp-pet") escaped the 2D

Animation technique and the scale of handheld objects.

As such the project presented, differentiates from previous examples as it attempts to apply the technique at a much larger scale and in a fundamentally different context and viewing conditions than any of its predecessors.

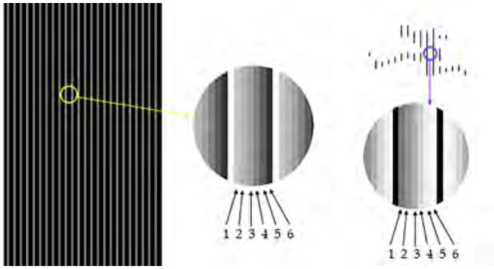



Figure 4
Relationship between frame vertical slits and transparent mask, Illustrations by David Phillips, Barrier-Grid (Or Picket-Fence) Animation, 2012

Further to that, it is suggested that 3D Moiré Animations could potentially have additional applications. Animated Signage for wayfinding or commercial purposes for example could be a domain where the method and proposed tools could be applied offering low maintenance and affordable alternatives to current technologies enabling large scale animation effects.

Figure 5
Moire Animation Frames

Figure 6
Moire Animation sequence

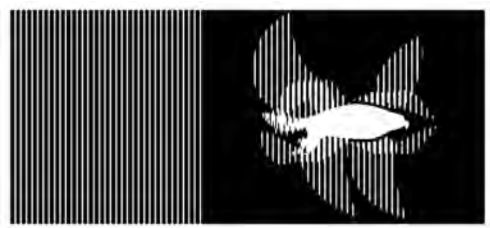


Figure 7
Composite image with Transparent Mask layer (Grating)

## METHODOLOGY AND COMPUTATIONAL TOOLS DEVELOPMENT

This paper defines and investigates 3D Moiré Animation as the generation of a legible, large scale analogue animation on physical structures, having the grating and the composite image spaced apart and static (Figure 2). The animation effect is consequently generated by the motion of the spectator. As already mentioned, the technique, encompasses the parameters used in classic 2D Moiré Animations but also proposes a series of new ones that outline the perception of the animation. ZEBRA has been developed to assist the above workflow by automating the majority of the operations involved in the process. The design team was therefore able to examine a large number of alternatives and verify their performance/legibility before moving to construction. This chapter presents the stages of the process along with the ZEBRA tools developed along each phase.

### *2D MOIRE ANIMATION PARAMETERS*

According to Shan and Chung (2016) there are four key parameters affecting legibility in 2D Moire Animation (Scanimation), the number of frames used, the image physical dimensions, width of the transparent slit and the width of the grating strips. The animation is achieved by reducing each frame of the original compilation into vertical strips (slits), later combined together into a composite scattered looking image. The dimensions of the slits depend on the desired resolution of the animation and number of frames. A striped mask layer is then imposed on top of the scattered composition which reveals a frame at a time, and thus when translated horizontally enables the animation effect.

The composition of the vertical strips containing the frames needs to occur sequentially, in order for the animation to be legible. As shown in figure 4 below, an animation consisting of n frames, would have distance between the slits comprising the same frame. The masking layer, would also have the same gap for the animation to work. Each frame is shifted by a horizontal unit in order not have an overlay.

Figure 8
The 3DMoire
parameter space

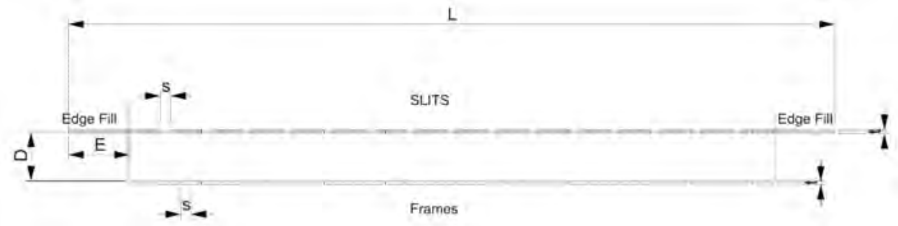
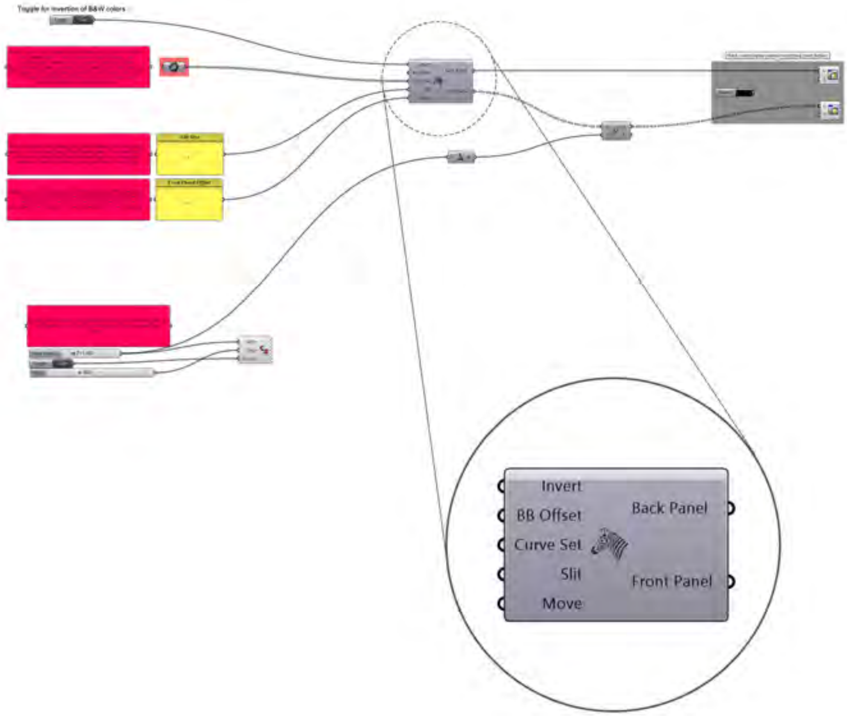



Figure 9
The frameworks
grasshopper
Definition



As illustrated in figure 5 below, the frames need to be abstracted to a solid silhouette, reinforcing Rufus notion that legibility of the animation depends on the meaning and technical interpretation of the images utilised. In addition, keeping parts of the frames intact, allows for improved perception of the illusion (Phillips, 2012).

## X = (N-1)SLITWIDTH (1)

ZEBRA is developed as a user cluster in Grasshopper 3D and consists of a number of components that automatically produce the two constituent parts of a 2D moire animation (the grating and the interlaced image), by importing a set of predefined frames. Additional utilities enable the visualization of the animation. The plugin operates by reducing each imported frame of the original animation into vertical strips (slits), and later combines them together into a composite scattered looking image. The grating, a striped mask layer is then produced based on the number of imported animation frames and the user desired resolution/speed. Finally the user is able to visually examine the results of the animation using the 2D Animator component which translates the grating horizontally over the interlaced image, revealing a frame at a time, and therefore enabling the animation effect.

The tools are set to accept Closed Curves as input, following the animation frames' sequence. Any number of frames is accepted and their bounding boxes are automatically divided into slits based on the desirable resolution set by the user.

Differentiating from the typical black-on-white-background layout of the technique, ZEBRA has the option to invert the Black & White colours, which work in a contrasting manner in relation to the transparent grid. The contrast between the two would improve legibility at large distances. When figure 3 is compared with figures 6 and 7, it is evident that the solid illustration revealed on the first image is substituted with a stripped one on the latter case. The stripped result is clearly generated by the inversion of the frame colours.

The 2D animation slider component was assembled using an addon compiled by David Rutten which allows for a controlled viewing motion at desired speeds.

## *3D MOIRE ANIMATION PARAMETERS*

A three-dimensional perception of the problem would mainly depend on the perspective view through the grating onto the frames layer. The animation setup becomes more complex at this stage, and involves examining the influence of the distance between the two layers, the thickness of the layers, the path (distance) and moving speed of the spectator (Figure 8).

3D Moiré capabilities are incorporated into ZEBRA by the creation of a set of components which combined the grating and the interlaced image into a 3D Apparatus based on two parameters defined by the user; material thickness and layers spacing (Figure 9). Visually examining the results of the animation at this stage pre-supposes additional user input to define the spectator's path (distance) and moving speed. These parts are analysed and explained in the raytracing investigation presented in Figure 10.

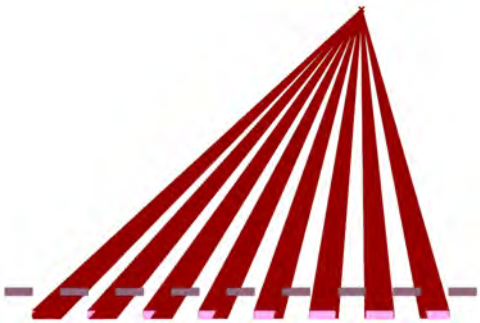


Figure 10
Raytracing visualisation (Grasshopper 3D)

### *Raytracing Investigation and Legibility Rating*

Since the legibility of the 3D animation depended on perspective aspects rather than pure translation between the two layers, the impact of the combination of all 2D and 3D Moire parameters had to be investigated. The difficulties of assessing all possible iterations with realistic visual outputs lead to establishing a parametric raytracing framework able to produce analytic results. The framework was formulated using Grasshopper 3D plugin in Rhino 3D with iterative loops using the Anemone plugin and Microsoft Excel integration using GHowl plugin. Custom coded C Sharp components were also used in conjunction to the above.

The frames of the animation were illustrated with distinctive colours repeated with the desired pattern. A ray producing source would be placed along the spectator path, casting rays towards the grating, having a layer structure shown above. At each given step increment along the path the algorithm traced the rays which passed through the grating and were projected onto the frames (Figure 8 & 10). Those rays would signify the visible portions of each frame at any given instance on the path.

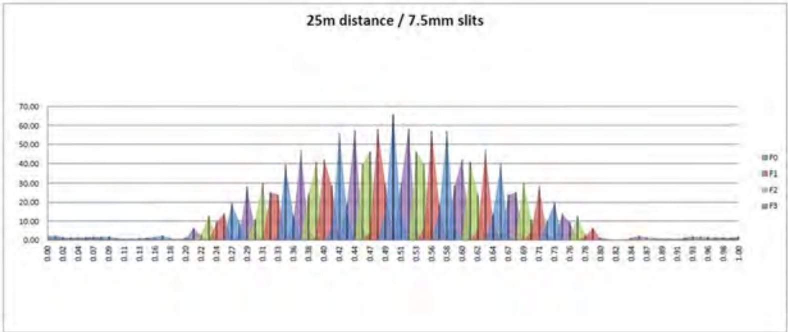



Figure 11
Raytracing visualisation with a 4 frame animation

Figure 12
Overall Memorial View (Photographer, C.Solomou)

Recording and plotting the generated data in graphs (Figure 11) would yield important findings on the relation on the frame visibility and frame transition overlap of the animation. Comparing Graphs and their characteristics enabled the designing team to rate the animation legibility for each design option assuming a constant spectator speed and distance from each grating.

Even though the raytracing investigation was carried out for the purposes of the case study, such functionality is not currently included in the ZEBRA tool set. Future work aims at incorporating a legibility rating component for different 3D Moire apparatus setups.

## CONCLUSION

The paper proposes a sub-categorisation of Moire Animations into 2D Moire Animations and 3D Moire Animations. It is suggested that the latter facilitates scaling-up and thus enabling built-environment applications offering low maintenance and affordable alternatives to current technologies enabling large-scale animation effects. (Figures 12)

In parallel, ZEBRA computational toolset is introduced. The plugin aims to facilitate the design, simulation and evaluation of 2D and 3D moiré Animations for the built environment. The framework is assembled in Grasshopper 3d with the use of custom scripts written in C Sharp programming language and most of its clusters are currently available as parts of ZEBRA. The plugin was set-up to interactively generate the constituent parts of 2D and 3D Moire Animations while enabling the visualisation of the animation results.

Work currently under development involves the compilation of the raytracing components into modules and their incorporation into ZEBRA. This will enable a legibility rating for 3D Moire Animation Setups generated through an analytical process.

## ACKNOWLEDGEMENT

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# PERFORMANCE COMPUTATION

# Predicting the effect of bio-luminescent plants for reducing energy consumption in urban environments

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*The present paper is part of an ongoing research that deals with the inclusion of the effect of bio-luminescence as a substitute or complimentary light source in urban environments, with the main scope of reducing energy consumption for lighting in exterior areas. The paper discusses the selection of genetically modified transgenic plants for use in the climate of Greece and through bibliographic reference and preliminary experiments the modeling of a simulated light source that has the bio-luminescent properties of a specific plant. The modeled light source can then be used in lighting simulation software. Results, through the lighting simulation of the modeled transgenic plant in a case study scenario, support the fact that bio-luminescent plants can be used as supporting lighting agents in a suburban setting and eventually reduce energy consumption for lighting.*

**Keywords:** *bio-luminescence, lighting design, energy saving*

## INTRODUCTION

Current discourse in architecture and urban design is mostly based in the search for new dynamic and evolutionary forms that correspond to the fluidity of contemporary urban living. To this end multi-disciplinary teams have developed several new concepts that try to mold new ideas that envelop the notion of sustainability, mostly in the sense of reducing energy consumption. Architects, urban planners, biologists, botanists, IT engineers, physicists, chemists, bio-technology engineers have collaborated with each other to produce several technologies that can be incorporated into architectural skins or spaces, or become digital tools that can predict and eventually reduce energy consumption (Armstrong, 2012). Bio-digital architecture is the merger of biological and digital technologies for the application of genetic processes in architecture and urban areas (Estevez, 2009). Through mathematical functions, biological systems' simulation and the development of new adaptive technologies, the relationship between building functions and human made environments is explored (Hensel, 2010, p. 5).

This research takes into account the phenomenon of bio-luminescence and with the help of digital tools and simulations tries to represent and exploit its uses by integrating it into contemporary urban design, as a means of complementing or even - in specific cases - replacing artificial lighting. In this particular study, an attempt is made to exploit the ability to create transgenic plants through genetic modifications using bacterial bio-luminescence and simulate the possibility of their utilization for the lighting of outdoor suburban spaces in Greece.

The main novelty of this research is the attempt for the estimation of the light performance of the transgenic bioluminescent plants, so that they can be used as substitute sources of outdoor urban lighting in Greece.

The extraction of measurement results on the lighting performance of bioluminescent plants, can be used to calculate the amount of them required to illuminate outdoor spaces, by limiting the required artificial lighting fixtures, or substitute artificial light in new installations, protected areas etc, achieving energy savings and environmental sustainability.

## EXPLOITATION OF THE PHENOMENON OF BIO-LUMINESCENCE TO CREATE LUMINESCENT PLANTS

Studying bio-chemical phenomena, such as light emission by living organisms in nature (Bioluminescence), with the help of other sciences, such as genetics, biology, chemistry and digital media technology, we can "reconstruct" these phenomena and employ them in contemporary design in various ways.

In recent years, the use of bio-luminescent plants in specific applications has been a challenge for researchers. In 1984, researcher Marlene De Luca (Ow, DW, DE Wet, JR, DE Wet, JR, Helinski, DR, Howell, SH, Wood, KV, DeLuca, M ,1986), succeeded in reproducing the bio-luminescence property of the firefly in transgenic plants (see figure 1). Thus, a series of plant combining processes with desired properties for "breeding" began, but at the same time - with the development of molecular biology - the "production" of desired properties was sought, intervening in their genetic material (Vamling, 2007) and proceeding to a genetic mutation, so that they could develop (express) the desired properties. (Branchini, Magyar, Murtiashaw, & Anderson, 1999, pp. Biochemistry 38:13223-13230).

Extensive research and the achievements of new specialized light measurement and imaging instruments as well as molecular biology tools, have led to the rapid development of bio-luminescence, indicative of the discovery and development of GFP (Green Fluorescence Protein, which consists of 238 amino acids, emitting light -fluorescence- when exposed to light of the blue or ultraviolet), for which researchers Osamu Shimomura, Martin Chalfie and Roger Y. Tsien were honored with the 2008 Nobel Chemistry Award (Roda, 2011, p. V).

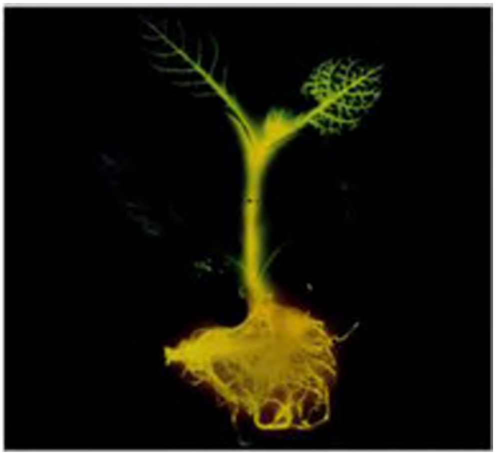

Figure 1
Luminescent tobacco plant produced (Origin (Lonsdale, Moisan, & Harvey, 1998) and (Barnes, 1990)

Studying the results of experiments carried out for the production of transgenic plants and simulations implemented in the last decade by research teams, we explore the possibility of producing plants with the capacity of bio-luminescence, through a group of plants, genetically modified that are also suitable to grow in the climatic conditions of Greek urban space and meet variable lighting requirements.

## THE DEVELOPMENT OF A METHODOLOGY SUITABLE TO SIMULATE PHOTOMETRIC DATA FROM LUMINESCENT ORGANISMS

Simulating a bio-luminescent plant is not something covered by international standards on light measurements (DIN 5032-2, DIN 5032-4 and EN13032-4:2015). Therefore, a methodology has to be developed that takes into account current standards and proposes ways to deal with the issues of foliage shape and plant growth. The proposed methodology is divided into four stages as follows:

### *Stage 1: Selection of plants that can be genetically mutated to acquire luminescent properties*

This stage concerns the selection and categorization of plants that are appropriate to the environmental conditions of the site in question (Mediterranean climate) and among them identify the species, in which "stable genetic transformation" has already been achieved (Loukas, 2000) [1]. On this theoretical basis, a protocol of desirable photogenic properties can be created, as well as an enhancement of the plant's resistance against pathogens and other diseases [1, p.113].

In the selected plants, their average growth time can be parameterized by calculating their expected foliage percentage per volume in the timeframe in question and taking into account their horizontal growth at the expected height.

### *Defining the light output of the selected transgenic plant*

In order to approximate the amount of luminescence emitted from the selected transgenic plants, it is initially assumed that for this effect bacterial bioluminescence is used. The calculations take into account both the existing literature data (Hastings, 1978, pp. 125-130) and the results of experimental measurements of emitted luminescent cultures of bio-luminescent bacteria. By converting the light energy, produced by microorganisms or bacteria, into luminous intensity per foliar surface of the bioluminescent plant, the latter can be perceived and modeled as a light source. Furthermore, the reduction of the expected bioluminescent leaf rate per average plant growth area provides a measurable light intensity to be used for lighting calculations [2].

### *Creating a simulation model of the selected transgenic plant*

Simulating the light output from each leaf and using it to accurately simulate the photometric data of the whole plant is an impossible calculating process, which can be simplified if we assume that the effect of the luminous plant can be simulated using an isotopic light source. To this end the photometric data from experiments and the calculations from bibliographical references on the luminous energy emitted by transgenic plants is used to create the model light source.

## CASE STUDY

The next phase of the research concerns the inclusion of the simulation model light source in a case study, so that early simulation results of light calculations can verify the assumption that bio-luminescent plants can be used as outdoor light sources either on their own or complimentary to conventional lighting fixtures and as such can reduce energy consumption. The case study presented in this paper used a representative suburban outdoor space, with low ambient luminance levels, in Athens, Greece. The study was conducted in the following steps:

1. A detailed mapping of the existing outdoor space, including the existing lighting equipment and plants, was carried out. Then, the area under study was categorized in terms of ambient lighting and necessary levels of illumination according to the standard CEN/TR 13201 - 1 2014 και EN 13201 -2 2015.
2. Potential bio-luminescent plants that could be inserted in the immediate area were selected from existing, genetically modifiable plants.
3. The study continues with the modeling of a bio-luminescent light source. In order to simulate the illumination of the bio-luminescent plants, it is assumed that any leaf of the plant emits light as an isotropic light source. A photometric file (Eulumdat file [3]) was created using light measurements and the corresponding calculations of the photometric properties (luminous flux, luminous intensities etc.). The derived Eulumdat file was used in Relux (Relux, 2018, lighting simulation tool) and the plant was then simulated by accumulating an assortment of representative plant leaves as a three dimensional light and then calculation

of the produced lighting intensity on the horizontal by it.
4. The next step includes the lighting calculations of the bio-luminescent light source on a pedestrian path. The path is modelled and simulated in Relux and illuminance values are calculated on the horizontal plane of the path according to EN13201 (Figs. 2 and 3).
5. Depending on the desired level of illumination in the horizontal plane of the modeled site, (determined according to lighting standard EN13201 for the individual use of each subarea) the necessary number of bioluminescent plants is determined to achieve the desired lighting levels.
6. Depending on the design of the site and the existing plant density, the appropriate plants (from the recommended list) are selected and the quantity required to adequately illuminate the area under study is determined.
7. The final step concerns the evaluation of the lighting calculation results that show the percentage of energy saved by the limitation of artificial light sources by using bio-luminescent plants. The existing light posts and luminaires are re-evaluated and a new scheme is proposed based on the results.

## RESULTS AND EVALUATION

Preliminary results show that the use of bio-luminescent plants cannot fully replace the lighting output of conventional urban lighting. However, taking into account the standards (EN13201, 2015), they could provide complementary lighting to pedestrian pathways in suburban settings, or in protected areas, dark sky parks etc, with no ambient luminance (due to eye adaptation the orientation should be possible in these conditions). According to our calculations the bio-luminescent plants achieve the illuminance set by the international standards at a maximum distance of 1.00m from the light source. Furthermore, in non-urban areas, bio-luminescent plants could provide the sole means of lighting for pedestrian pathways, open sitting areas, small buildings, kindergartens etc.

Figure 2
Rendering the optical characteristics of the bio-luminescent plant layout

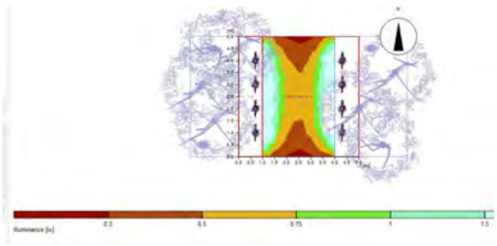

Figure 3
Lighting calculation of the proposed bio-luminescent plant layout on a 3m wide pedestrian pathway. For the above evaluation area (3x5) an illuminance variation between 0,42-1,91 lx was recorded

## EMERGING ISSUES RAISED BY THE USE OF BIOLUMINESCENT PLANTS IN THE ENVIRONMENT TO REPLACE ARTIFICIAL LIGHTING

It is unquestionable that all processes of genetic transformation in natural organisms are interventions in nature and it seems paradoxical that these interventions aim at creating a sustainable environment. But it is also undeniable that continuous man-made interventions in nature and the intensive over-exploitation of natural resources have led to the irreversible failure of many of them, as well as to the destruction of the environment.

Mankind has to choose the least harmful version. We are obliged to use every possible source of energy to create the environment of our habitats, without consuming natural resources, employing every op-

Figure 4
Effect of radiation field on animals [4]

| | UV | Violet | Blue | Green | Yellow | Orange | Red | IR |
|---|---|---|---|---|---|---|---|---|
| wavelength (nm) | <400 | 400-420 | 420-500 | 500-575 | 575-585 | 585-605 | 605-700 | >700 |
| freshwater fish | x | x | x | x | x | x | x | |
| marine fish | x | x | x | x | | | | |
| shellfish (zooplankton) | x | (x) | (x) | | | | | |
| amphibia&reptiles | x | x | x | >550 | x | x | x | x |
| birds | x | x | x | x | | x | x | x |
| mammals (excluding bats) | x | x | x | x | | | x | |
| bats | x | x | x | x | | | | |
| insects | x | x | x | x | | | | |

note: (x) = assumed possible but not identified in literature

portunity of state of the art technology.

On the other hand, molecular biologists claim that new transgenic species do not exchange their properties with their environment (Hanneman , USDA, 1995). They are simply organizations that are "gifted" with a new property, that of luminescence. In their words, it will not be possible to reproduce between different plant species in order to overcome the potential danger of the propagation or prevalence of the luminescent plants within the ecosystem! In each case, an investigation into the effect of this plant's property on other organisms, such as insects, or perhaps birds, should be explored (likely to be attracted by the lit foliage, etc.) see figure 4.

This is also stipulated by the European Directive (EFSA-European Food Safety Authority) [5], which introduces the idea that GM (genetically modified) plants and their "metabolites" as potentially hazardous to the environment should be subject to an environmental risk assessment (ERA) before being placed on the market. The test is carried out in several stages, while the test plants are in an experimental protocol (Arpaia, 2017). However, it should be noted that the regulations concern transgenic plants intended for use as food, but the remote risk of the impact of plants on the food chain cannot be ruled out (d).

Regarding the side energy costs for this transgenic transformation of the plants, it is not possible to be evaluated accurately in the present work.

This particular attempt seems to adopt Kaoru Mende's (LPA founder, distinguished and awardwinning lighting designer) insightful words in his book «Lighting Design for Urban and Environments and Architecture»: «In the coming years, lighting design will be expanded by the use of light to illuminate objects, to use self-illuminated objects and materials that move freely within the space. Even more, with the evolution of technology that will lift the limitations that the use of electricity causes, the design of lighting will be called upon to play a role in producing a quality value and to influence and affect people hearts and spirit. As in a painting, it will remove us from our sorrow; it will revive us and even help us to expel the diseases of our body and spirit» (Mende, 2003).

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# Environmental design

## *Lessons learned from teaching LCA*

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*Architects largely define the environmental impact a building will cause throughout its life cycle. Especially decisions taken in early design stages have a great influence on the environmental performance. The integration of environmental assessment into the design process requires adequate tools and basic knowledge of the architects using them. This paper discusses both aspects by means of two case studies with students. In both case studies, the goal was to use Life Cycle Assessment (LCA) to optimize the environmental performance of the building in the design process. The results of the first case study proved the benefits of using LCA-based information for decision-making, but some issues of using the tool during the design process became evident. In the second case study an improved LCA-tool was employed that proved to be applicable by all students. Nevertheless, only one group used the feedback to optimize the building design in an iterative process as intended by the supervisors. This leads to the conclusion that the difficulty of environmental design shifted from a lack of adequate assessment tools to the question of the design approach.*

**Keywords:** *LCA, environmental design, parametric design, teaching*

## INTRO

### *The need for environmental design*

The built environment is responsible for one third of the global greenhouse gas emissions and more than 40% of the world's primary energy demand (UNEP SBCI 2009). Additionally, approximately 50% of the world's processed raw materials are used for construction (Hegger et al. 2007). Architects largely define the resource demand and environmental impact a building will cause within the next 50 to 100 years. While the energy to operate the building is influenced by user behaviour, the embodied energy and emissions are predefined by the building geometry, the type of construction, and material choices. To assess the energy embodied in the material and the emissions released during production and disposal, waste processing or recycling, the internationally standardized method of Life Cycle Assessment

(LCA) is commonly used. LCA involves the evaluation of the environmental aspects of a product or service throughout all stages of its life cycle (König et al. 2009). It has originally been developed in the 1970s to evaluate consumer products such as beverage packaging (Klöpffer and Grahl 2014). Since then LCA has become a widespread method for environmental impact assessment of consumer products and services. In the last ten years, it has also increasingly been applied for the assessment of buildings, especially in an academic context (Weißenberger, Jensch, and Lang 2014). However, evaluating the building design through LCA is not sufficient on its own, as it does not improve the design (Wittstock et al. 2009). To minimize environmental impacts, an integration of LCA into the architectural design process is needed (Hollberg and Ruth 2016).

In general, decisions made in the early stages of the design process, have the greatest influence, as they set general conditions for the subsequent design process (Paulson Jr. 1976). As such, the concept and developed design phase do not only have the largest impact on costs, but also on environmental impacts (Bogenstätter 2000). Especially in small-scale offices, architects largely rely on their own knowledge and expertise to make design decisions in early stages (Weytjens and Verbeeck 2010). Many decisions with consequences for the environmental performance of the building are taken in interplay with the client, before advising experts are involved in the planning process (Meex, Knapen, and Verbeeck 2016). Energy consultants are usually involved for issuing energy performance certificates needed for the building permit application, however, it is then late for major design changes. This highlights the important role architects and designers play in climate change mitigation and resource efficiency even if they might not always be aware of it (Meex et al. 2018). Clearly, there is the demand for integrating environmental aspects in the design process. To allow architects to analyse the environmental impact of a building while designing it, two prerequisites are necessary: LCA tools must be adapted to the architects' needs and architects need to acquire basic knowledge to be able to interpret the obtained results. Both aspects are discussed in this paper.

## *State of the art of teaching environmental design*

Architectural education has a long tradition of teaching in design studios. The students develop solutions, receive feedback from professors and other students and refine their solutions based on the feedback (Kvan and Yunyan 2005). Professors teaching design studios are often successful architects that base their feedback on their own practical experiences. In the last two decades, design studios have increasingly focussed on environmental aspects in a qualitative way, for example energy efficiency (Heidenreich and Schütz 2010), eco-design (Suau 2013) and reuse/recycling projects (Colabella et al. 2017).

In contrast, scientific environmental assessment tools are based on quantitative results. Usually, environmental assessment methods are taught in independent seminars using simplified case studies. Nault et al. (2017), for example, use a simple pavilion as a case. Reinhart et al. (2015) developed a sophisticated game to teach various aspects of environmental design, including energy simulation, lighting and ventilation. Charles and Thomas (2010) employed an interdisciplinary approach of forming teams of architecture and engineering students focussing on teaching collaboration. Many further studies teaching building performance simulation to architectural students using different have been published, e.g. Rajagopalan, Wong, and Andamon (2016), Beausoleil-Morrison and Hopfe (2016), Beausoleil-Morrison and Hopfe (2015), Hensen and Radosevic (2004). However, none of these studies include LCA. Simonen, Moore, and Cooper (2011) describe seven courses focussing on teaching the LCA methodology and LCA tools with limited implications on the building design. Finnegan et al. (2013) describe a four-year curriculum of teaching LCA for the built environment, but integration into the design process is lacking.

This separation between the "core" design studios and the "supplementary" lecture classes in technology can be observed in most schools of architecture (Oakley and Smith 2007). Nevertheless, the ultimate goal of environmental assessment methods from an architect's point of view is to apply them during the design process to improve the building. When integrating these methods into the design process, additional difficulties arise, mainly because some choices might improve functional or aesthetical design aspects, but decrease the environmental performance. According to Rittel (1992), a vast design space has to be explored to find the optimum solution. Therefore, variants need to be generated, analysed and compared. Lawson (1994) observed that many designers express a need to generate and assess alternative design ideas. While some designers deliberately generate a series of alternative solutions early on, others prefer to work on a single idea, but accept that it may undergo revolution as well as evolution (Lawson 2006).

In both cases, the design approach requires generating and comparing design variants, which is the only approach towards optimizing buildings during design. With a parametric design approach it is easy to generate many variants (Davis 2013). Once a parametric model has been developed, the generation of further design alternatives is nearly effortless. Hence, the parametric approach is ideal for environmental design optimization (Hollberg 2016).

## METHOD

This paper analyses and discusses the application of a method named *Parametric life cycle assessment* (PLCA) (Hollberg 2016) during the architectural design process using digital tools. Two case studies of student design projects are compared with focus on the design results and the design process. During both case studies the aim was to teach students environmental design by generating design variants, analysing them using LCA and comparing them to finally optimize the design solutions in an iterative way. The task was to optimize the building design towards minimum environmental impact while providing a high architectural quality. While environmental aspects of the project can be quantified by the LCA tools, the architectural dimension is difficult to quantify. The evaluation of architectural quality is a complex part of any design assignment in architecture studies. For this paper, the grades given at the end of the design studio are used as an indicator for the architectural quality.

One of the main points of the teaching approach was to consider the operational energy demand and the embodied energy at the same time to optimize the design in a holistic way and to consider trade-offs from the beginning of the design process. Therefore, the assessment in the case studies includes the production phase of the materials, the replacement of building components at the end of their service life, the operational energy use during the use phase, the waste treatment and disposal of materials at the end of life and the recycling potential. According to EN 15978 the following life cycle modules are considered: A1-A3, B4, B6, C3, C4, D. The primary energy demand non-renewable total (PENRT) and Global Warming Potential (GWP) based on 100 years according to IPCC 2007 are used as indicators.

## CASE STUDIES

### Semester project

The first case study is based on the design studio called *Link-in-Energy* held at Bauhaus University Weimar and University of Mersin in 2015 (Hollberg et al. 2016). The 36 participating students were all in the master programme of architecture.

**Teaching approach.** The design task consisted in developing a use scenario and designing an environment-friendly building for the historic city of Tarsus, south Turkey. The environmental aspect was one of the main criteria from the beginning of the project and all students received introductory lectures on sustainability, energy concepts, LCA and the importance of embodied energy in building materials.

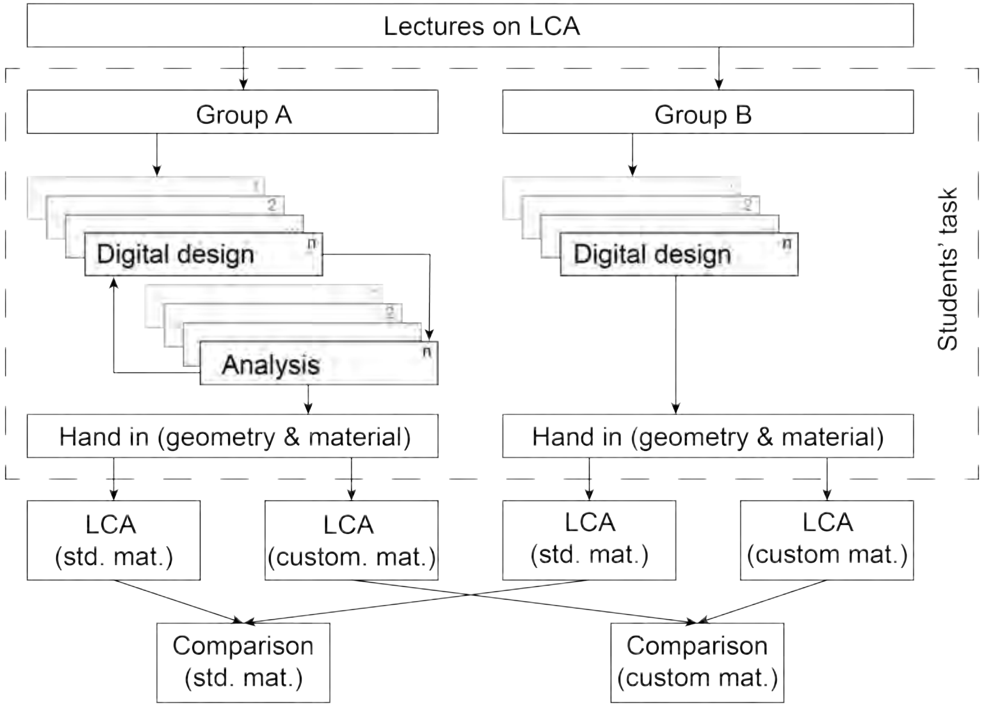


Figure 1
Schematic workflow of the semester project

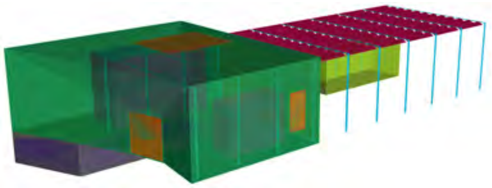

Figure 2
Geometry model in Rhino

Nine students (Group A) took part in a seminar for design-integrated LCA. The students were asked to improve the environmental performance of their building by generating and comparing different design variants using an LCA tool. The goal was to lower the environmental impact as far as possible while providing a high architectural quality. The first part of the semester focused on the improvement of the geometry. A default material configuration had been provided for the students, which served as a baseline scenario. For the second part of the semester, the students should model their custom materials to improve the environmental performance further. Each week the results should be presented to the supervisors of the seminar.

The 27 students that did not take part in the LCA seminar (Group B) had the same design task and were asked to base their environmental concept based on the qualitative information they received in the lectures. Both groups had to hand in a 3D model of the geometry and a list of materials at the end of the project. The supervisors used the same LCA tool to calculate the final LCA results. The workflow during the semester is visualized in Figure 1.


Figure 3
Parametric material definition in GH


Figure 4
Visualization of results in Rhino

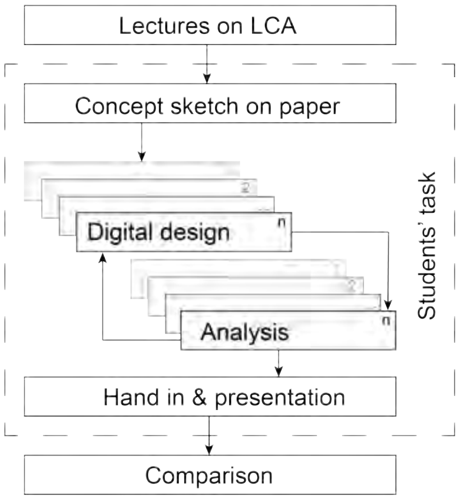


Figure 5
Schematic workflow of the summer school course

**LCA tool.** A prototype tool to apply the PLCA method was developed in Grasshopper, a parametric plug-in for the 3D CAD software Rhinoceros (Hollberg and Ruth 2016). The main difference to other LCA or building energy performance assessment tools is the combined calculation of operational and embodied energy (and other environmental indicators). A 3D model is drawn in Rhinoceros (see Figure 2). The materials and HVAC systems are input in Grasshopper using drop down lists and sliders (see Figure 3). The simulation of the operational energy demand is based on the EnergyPlus (DOE 2015) engine. A self-developed script calculates the embodied impact using the German Ökobau.dat database 2013 (PE International and BBSR 2013). The results are visualized in a Rhinoceros viewport showing the Non-Renewable Primary Energy (PENRT) and Global Warming Potential (GWP) (see Figure 4).

## Summer school

The course *Environmental Design Strategies* took place in Weimar as part of the Bauhaus Summer School in August 2017. During two weeks, an international group of 11 students worked in interdisciplinary pairs of two.

**Teaching approach.** The task was to develop an environment-friendly design for a student apartment house for 45 students in Weimar. The course focused on the environmental aspects of the building design, including an energy and a material concept. The students received an introductory lecture and then started developing a concept on the first day. This concept was refined on day two after a visit to the building site. On the third day, all students were introduced to an LCA tool called CAALA (CAALA GmbH 2016). Their task was to analyse the concept they had developed using qualitative information. Based on the first concept they should generate different variants, compare them and finally optimize their design. They presented their projects every second day and could acquire feedback from the supervisors at any time.

**LCA tool.** *CAALA*, a cloud-based plug-in for SketchUp, was developed based on findings from using the parametric prototype tool. The software automatically collects the areas of different building components from SketchUp and calculates both, oper-

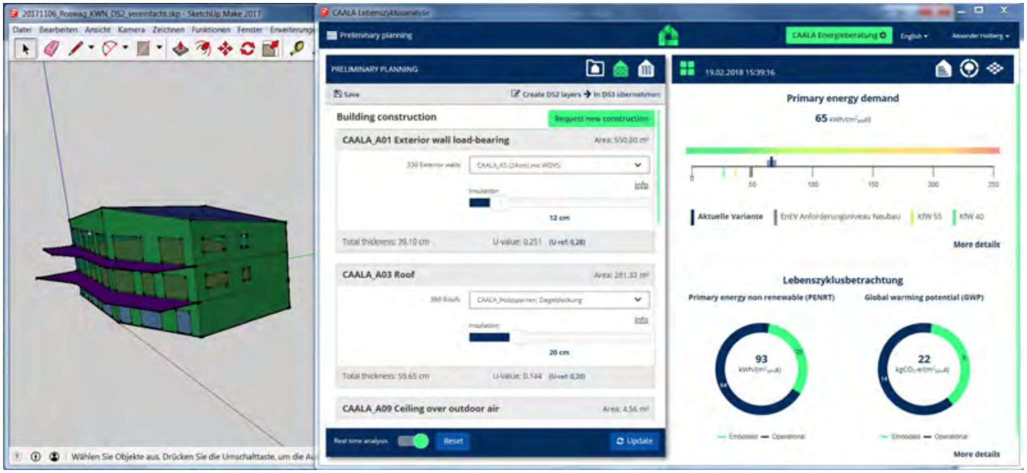


Figure 6
User interface of CAALA (left: SketchUp modelling environment, right: input of materials and visualization of results in browser window)

ational and embodied environmental impacts. For the operational energy demand calculation, a simplified monthly quasi-steady approach based on DIN V 18599 is employed (Hollberg et al. 2017). The embodied impact is calculated using the database Ökobau.dat 2016 (BBSR 2016) and the simplification rules of the DGNB system (German Sustainable Building Council 2015). The results are visualized in real-time in a browser window. As such, each change to geometry, material or technical equipment can be quickly assessed while designing.

## RESULTS

### *Semester project*

In the first phase of the semester, the students of Group A, who took part in the seminar, used the predefined standard materials to develop their designs. These results were compared to the designs of Group B. The average of the results of both groups did not diverge. In the second phase, the students of Group A chose their custom materials and were able to save an average of 8.2% of PENRT and 16.2% of GWP compared to the baseline scenario. However, with the custom of custom material the designs of Group B performed worse than using the standard material. In consequence, the designs of Group A performed more than 40 % better when using the custom material (Hollberg et al. 2016).

At the beginning, the students taking part in the seminar (Group A) had some difficulties in modelling the geometry. First, it was difficult for some students to draw abstract 3D massing models. Around half of the students had 2D floorplans of their design including wall thicknesses when they started modelling in 3D. It seemed difficult for them to reduce the complexity of their model for an energy "shoebox" model. Second, many issues arrived from the requirement of a watertight volume for the EnergyPlus calculation. Almost all students needed help in the beginning to fulfil the specific model requirements for thermal simulation. Throughout the semester they learned to find the errors themselves, however, it was a frustrating process for them. Finally, the simulation time of one to five minutes seemed to be a problem, because they felt like they had to wait for the results and felt interrupted in their work. In consequence, they seemed to have simulated less variants than they desired, because they wondered whether it was worth investing the time. As such, the idea of an intuitive, playful, iterative optimization process did not work out. As a result, the tool was not applied in early design stages and the geometry was not optimized using the tool. This can be seen in the results, because for the standard material the design of Groups A and B perform equally well on average (see Figure 7).

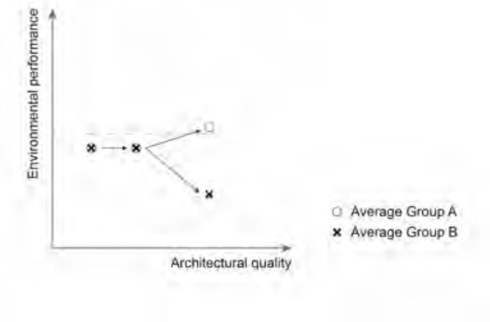


Figure 7
Development of environmental performance and architectural elaboration of the different designs from initial concept to detailed design with defined materials (Group A with tool, Group B without tool)

However, the tool helped to take informed material decisions. Although both groups had the same task and attended the same lectures of sustainable construction and materials, the designs of Group A performed 40% better on average. Apparently, the environmentally friendly choice of material within the complex interactions between building equipment, insulation thickness, operational energy demand and embodied impact is not evident. Figure 7 summarizes the results for the start and end of the project.

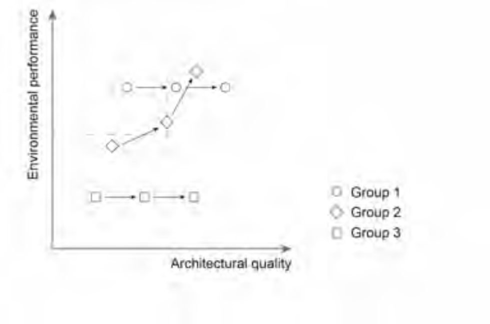


Figure 8
Development of environmental performance and architectural elaboration of the different designs from initial concept to developed design with defined materials

### *Summer school*

The students had only minor difficulties in modelling and the application of CAALA in the concept design phase worked well. Nevertheless, only one group (Group 2) did a variant-based improvement process as intended by the teachers. Some groups started with an initial design with low environmental impact, based on their general knowledge or intuition. Group 1 for example, chose a compact geometry, well-oriented windows and a combination of timber and earth construction material. Clearly, in this case the optimization potential using an LCA tool is smaller than for other groups that chose conventional materials, such as Group 3. Figure 8 summarizes this aspect. Group 2 evaluated many design variants and reduced their impact compared to their initial variant. They even achieved slightly better environmental results than Group 1 that did not improve their initial variant based on the results of the tool. However, the design of Group 1 showed the highest architectural quality. Both designs fulfilled the goals of the assignment. Group 3 started with an initial design with high environmental impact and were not able to increase the environmental performance during the course. In this case, the goal of the assignment was not fulfilled.

## DISCUSSION

During the students' work for the first case study, many tool-related issues could be observed and the idea of intuitive, playful, iterative optimization did not work out. As a result, the tool was not applied in early design stages and the geometry was not optimized using the tool. For the second case study, the tool could be much improved based on the learnings from the first application. There were only minor difficulties in modelling and the application of CAALA in very early design worked well. Nevertheless, only one group did a variant-based improvement process as intended by the teachers (see Figure 9). While during the first study, the main issues resulted from the tool, the main question during the second case study was the design philosophy. Most students were interested in analysis results to use them as an argument for the supposed benefits of their design solution, but they did not seem interested in using the results to improve their solution. Only one group questioned their initial solution and used the tool to improve their design.

While during the semester project *Link-in-Energy*, the main issues resulted from the tool, the main question during the summer school *Environmental Design Strategies* was the design approach. One reason might be that the assignment was to abstract. The supervisors asked to environmentally optimize the designs as far as possible. The results might have been different, if a limit on the GWP would have been fixed the same way a client fixes a financial budget for any design project. Furthermore, benchmarks showing how many kg of CO2-eq/m2 is "good" or "bad" might have helped to question solutions with low environmental performance.

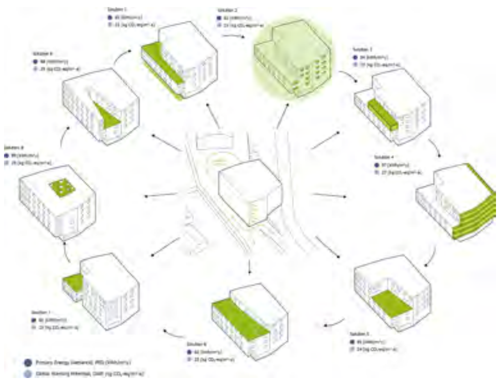

Figure 9
Comparison of the environmental performance of different geometries

the tool. Nevertheless, only one group used the LCA tool to compare different design variants and optimize the building towards minimum environmental impact. As such, only one group fulfilled the project task as intended by the supervisors.

This leads to the conclusion that the issue of environmental design now shifted from a lack of useable LCA tools to the question of the design philosophy. The two weeks for case study two were too short to introduce an approach of generating variants, analysing, comparing, and improving. This variant-based design approach is the only way to optimize the environmental performance of a building systematically. However, it requires an additional design effort. Through parametric approaches and real-time analysis tools, this additional effort is reduced to a minimum. Nevertheless, the variant-based optimization approach requires the willingness and openness to question and revise design decisions already taken. Although, Lawson (2006) describes this approach as commonly employed in architecture offices, the students in the case studies did not seem willing to apply it. The case studies show that the success of teaching environmental design in separate seminars is limited. Teaching such a variant-based design approach can only be done by fundamental work in a design studio. Therefore, a closer collaboration between teachers of the "core" design studios and the "supplementary" technology-focused seminars are necessary to successfully implement environmental performance optimization into the design process.

## CONCLUSION

The results of the two case studies highlight the potentials and limitations of teaching environmental design to architecture students using digital LCA tools. For most students in the first case study, the tool was to complex and its application too time-consuming. In case study two an improved LCA tool with real-time feedback was used, which proved to be intuitive enough to be applied by the students in early design decisions. All students were able to use


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# TreeHugger

## *The Eco-Systemic Prototypical Urban Intervention*

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*The paper discusses co-design, development, production, application of TreeHugger (see Figure 1). The co-design among community and trans-disciplinary participants with different expertise required scope of media mix, switching between analogue, digital and back again. This involves different degrees of physical and digital `GIGA-Mapping' (Sevaldson, 2011, 2015), `Grasshopper3d' (Davidson, 2017) scripting and mix of digital and analogue fabrication to address the real life world. The critical participation of this `Time-Based Design' (Sevaldson, 2004, 2005) process is the interaction of the prototype with eco-systemic agency of the adjacent environment - the eco-systemic performance. The TreeHugger is a responsive solid wood insect hotel, generating habitats and edible landscaping (Creasy, 2004) on bio-tope in city centre of Prague. To extend the impact, the code was uploaded for communities to download, local-specifically edit and apply worldwide. Thus, the fusion of discussed processes is multi-scaled and multi-layered, utilised in emerging design field: Systemic Approach to Architectural Performance.*

**Keywords:** *eco-systemic urban prototypical interventions, systemic approach to architectural performance, eco-systemic agency, giga-mapping, responsive wood, full-scale prototyping*

### INTRODUCTION

The project COLridor, where the TreeHugger (see Figure 1) is a first prototype, engaged cooperation of Collaborative Collective NGO, CooLAND NGO, Faculty of Art and Architecture at the TU of Liberec, Faculty of Forestry and Wood Sciences at the Czech University of Life Sciences in Prague and the local community biotic and abiotic agency, including humans. The paper covers a fusion of several process based fields, namely 'Systems Oriented Design', 'Performance Oriented Architecture', 'Time-Based Design' and in this sense 'Prototypical Urban Interventions', while performing as 'Service Design' and co-design and co-creation. We have to, at least shortly, address all of these because within this work these fields have been fused from eco-systemic, process-based perspective into one new emerging design field ratified in 2017 by the first author in her PhD thesis as 'Systemic Approach to Architectural Performance' (Davidová, 2017c). SAAP develops method-

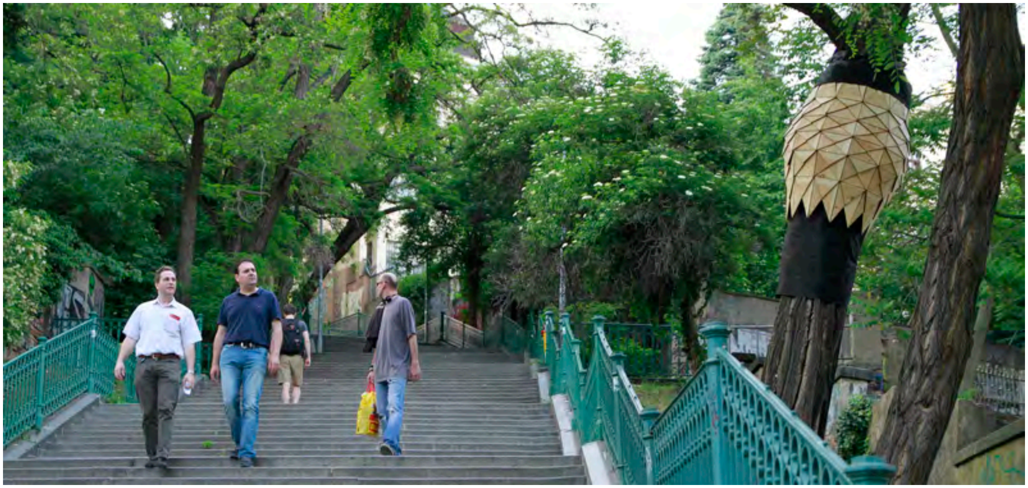

Figure 1
TreeHugger Insect Hotel Eco-Systemic Prototypical Urban Intervention Attracting the Public Attention (photo: Carrithers 2017)

ology and generates theory through experimental practice. It involves Time-Based Eco-Systemic Co-Design performed by both biotic and abiotic agency. It belongs to a broader field of Systemic Design, while considering the overall eco-system in action. It is reached through engagement of eco-systemic 'prototypical urban interventions' (Doherty, 2005), thus interaction with- and integration in- the (eco)system. Therefore, we cannot really differentiate the methodology from so-called 'result' as the result is an over-evolving performative design process. For this reason, the section 2 and section 3 as well as a concluding part are in the process of feedback looping.

## *Systems Oriented Design*

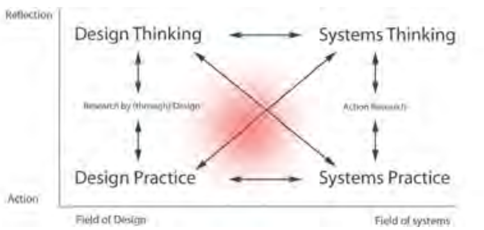


Figure 2
Field of Possibilities in Systemic Design. Systems Oriented Design is Located at the Red Dot. (Sevaldson, 2013) – publishing with the courtesy of Sevaldson

The methodology discussed here originates from Systems Oriented Design founded around 2006 by Birger Sevaldson. SOD is the most designerly and practice oriented way to deal with systemic relations (Sevaldson, 2017a) (see Figure 2). SOD namely bases in the trans-disciplinary design process tool called GIGA-Mapping which we discuss in more detail in the Methodology: Analogue and Digital Co-Creation section 2, namely in the GIGA-Mapping Co-Design subsection 2.1. It is an unbounded visual diagramming of complexity of different scales and layers. As we see in following text, it can perform well as a co-design (- subsection 1.6 and 2.1) tool among community, digital designers (- subsection 2.2) and other professions. SOD is used and developed in many design fields, namely in a very process based field of Service Design. (- subsection 1.5). Therefore, there is very short and beneficial connection to relate to our process based design of co-designing co-performances and co-living for SOD references.

## *Performance Oriented Architecture*

Performance in architecture (therefore Performance Oriented Architecture) was reformulated by Hensel in 2010 as a reconsolidation of form and function into synergy of dynamics of natural, cultural and social environments (Hensel, 2010). Crucial for this field is full-scale prototyping of material performance and the non-anthropocentric architecture or design (Hensel, 2012, 2013). Our approach is to see these synergetic performative processes as the processes of co-design (see Co-Design and Co-Creation 1.6 subsection) with the overall eco-system, including humans. The eco-systemic co-design, co-creation and co-habitation in architecture has been, by now, mainly discussed as 'weathering' (Mostafavi & Leatherbarrow, 1993). However, this has been done mostly from anthropocentric perspective.

### *Time-Based Design*

The above discussed is happening in- and needs to deal with- time. Sevaldson explains Time-Based Design as an approach that leads towards understanding action, performance and life cycles (Sevaldson, 2005). Through GIGA-Mapping (- subsection 1.1 and 2.1), full-scale prototyping (- subsection 1.2 and 2.3 and section 3) and the placement of these as performative prototypes into public space as Prototypical Urban Interventions (- subsection 1.4 and 3.2), we believe to rise this understanding while co-designing, co-creating (- subsection 1.6 and section 3) and co-living actions, performance and life cycles with the overall eco-system.

### *Prototypical Urban Interventions*

Prototypical Urban Interventions were established by CHORA at the start of millennium. These perform the agency as landscape design interventions that trigger other processes and events, through a planning and design methodology. It is questioning the master planning in favour of an indeterminate approach (see 1.3 Time-Based Design). Therefore, it is calling for urban adaptation. The answer is in the level of contextual networking in a project. It is tapping into the rhizomatic and networked landscape and designing with it (Doherty, 2005). We add to this performance oriented time-based approach the view that we are not intervening the urban environment only from anthropocentric perspective. Through the nature of our prototypes (see subsections 1.2 and 2.3 and section 3), we claim to interact with the overall (eco)system. While doing so, we claim it to co-create and co-design, therefore to re-design it.

### *Service Design*

Stickdorn and Schneider explain the field as a cross-disciplinary practice that works with systems and processes and is aimed at providing holistic service to user. They point out that variety of services have been performed and organised since time immemorial. However, they claim that the field today offers consciously designed services that incorporate new business models that are empathetic to user needs and attempt to create new socio-economic value in society (Copenhagen Institute of Interaction Design, 2008; Stickdorn & Schneider, 2011). We do not feet very comfortable with this discussed conciseness in designing. As we discuss in 2.1 GIGA-Mapping Co-Design, we believe a lot of intuition and subconsciousness needs to be employed when dealing with systemic design. This comes especially when co-designing with eco-system. However, the field is very advanced in SOD application, cross-disciplinarily, systems and processes development and holistic orientation from which our work benefit when designing systemic interventions and offering DIY services for local specific co-design (- subsection 3.2).

### *Co-Design and Co-Creation*

The division between 'participatory design' and 'co-design' was explained by Sanders and Stappers, where participation means that the related stakeholders are invited to the discussion board, while co-design means 'co-creation' (Sanders & Stappers, 2008) where the stakeholders play a creative active role within the design process as co-authors. However, in present text, both terms are used in the means of co-creation, discussing the participation in co-design. In presented methodology, the participants have their roles, expertise, cycles and privileges in different events of the time-based (- subsection 1.3) co-creation of eco-systemic performance (see all parts of the paper).

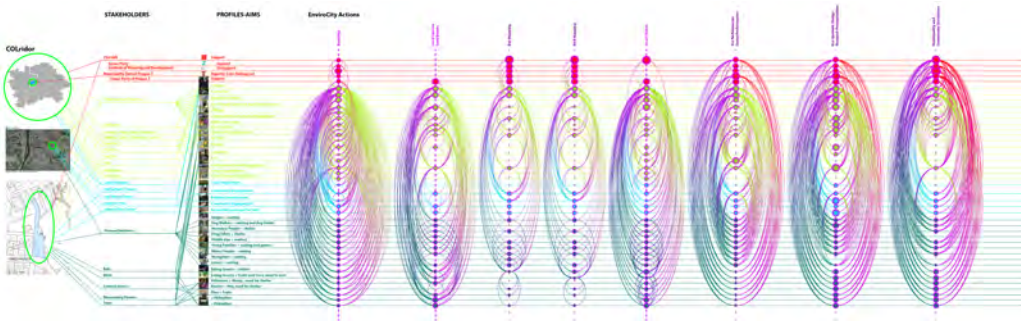


Figure 3
The Exhibition and Public Communication GIGA-Map (Davidová 2017)

## METHODOLOGY: ANALOGUE AND DIGITAL CO-CREATION

The methodology covers creative media mix of analogue and digital. This needs to be adapted to trans-disciplinary and community participation when designing. This methodology has been examined by the first author in an article 'Systemic Approach to Architectural Performance: The Media Mix in the Creative Design Process' (Davidová, 2017b), focusing namely on GIGA-Mapping and full scale prototyping, while opening the discussion towards participation. This project aimed to take several steps forward in this discussion, proving that GIGA-Map (see Figure 3) might be a crucial tool to utilize these processes. The most important point to mention here is, that the 'design result', the section three (Methodology: The Responsive Wood Insect Hotel), is considered as a design process of the eco-systemic performance, therefore the crucial methodology as well. All of these layers of processes are therefore endlessly feedback looping.

### *GIGA-Mapping Co-Design*

The community and trans-disciplinary design processes need to cover complex, yet not organized information, relevant to vide range of participants. All these participants have different communication and design tool preferences and skills. Therefore, visual information that communicates various individuals' tools outputs needs to be cross-referenced and based on that evolved. Therefore, we developed a special case of GIGA-Mapping. While, GIGA-Mapping is defined as a most designerly way to deal with complexity, using visual diagramming (Sevaldson, 2011) and use of generated images and photography has been introduced by the authors some time ago (Davidová, 2007, 2014, 2016b, 2017b), this project introduced the mapping of such across the community together with the trans-disciplinary team. This approach proved that such visual communication performs well across the disciplines, stakeholders and engaged community, as people often easier understand image than words, however they might not master drawing and drawing reading skills. This is because the image is engaging both, the experience and the imagination on tacit and intuitive level while it enables to map such collective relations. Please, see Figure 4 with an early stage of second community co-design GIGA-Mapping workshop, when all the participants were asked for printing out their stakeholder's or professional interests references to be cross-Referenced and drawn upon. The media mixed GIGA-Maps were feedback loopingly reworked and updated from workshop to workshop and by other processed methodologies to digital versions for receiving new and new analogue layers (see Figure 5).

Sevaldson discussed the need of ethics for the situation when certain stakeholders cannot be represented in GIGA-Mapping process (Sevaldson, 2017b). In this case, this was resolved by trans-disciplinary team acting on behalf of such stakeholders (i.e. ecologist on behalf of endangered species). Therefore, the GIGA-Mapping was utilising and relating all the other performed design processes with its specialists' design tools and expertise across the mapping and represented integrated stakeholders' and disciplines' interests. These processes, plans and speculations were afterwards digitally GIGA-Mapped for exhibition and public communication purposes (see Figure 3).

Figure 4
The Early Stage of Second Community Co-Design GIGA-Mapping Workshop (Photo: Davidová 2017)

Figure 5
Detail of GIGA-Map That Was Based on Digital Preprint Resulting from Previous Session (Photo: Davidová 2017)

## *Grasshopper Script Development*

The Grasshopper coding of the TreeHugger prototype (see Figure 1) was investigating several tools such as LunchBox script and the inbuilt Grasshopper component called Box Slids to solve the modelling issues. However, custom made scripts had to be used at the end as any of the released solutions was not suitable. For their development, GIGA-mapping was used to communicate and resolve the intricacies of the three-plane panelling and other problems across the expert team. In some cases, only an analogue model or prototyping was able to display the nature of the problematique. The final structure was changed several times within the design process based on the prototyping even in prototype's finalizing state (see Figure 6).

In the beginning, the LunchBox plugin was used to generate the diamond-like divisions of the reference surface. However, due to the behaviour of LunchBox's script near the seam of the surface a custom script had to be written for the sake of simplifying the top and bottom parts. Such panelling was leveraging the fact that whole bearing construction was also fabricated digitally on a laser cutter. This approach allowed for lowering every next layer of panels so that the overlay was kept by tilting the panels slightly in a vertical manner. The relationship between the loadbearing structure and infilling panels is reciprocal, not hierarchical like architects used to think before digital fabrication.

The structure itself was a simple waffle script which again tested the inbuilt Grasshopper component called Box Slids. Intersecting first the boxes and then try to cut them into proper shape revealed as not such successful approach. Therefore, first the exact shapes were created and extruded and a custom intersecting script was used. The final shape of the structure was changed just 5 days before the construction date due to unrealistic estimation of wood bending during the design process.

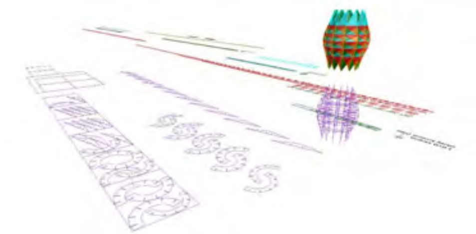

Figure 6
TreeHugger Final Production Drawings Organised with Nesting Tools (image: Prokop 2017)

The most critical coding and geometrical challenge of the TreeHugger design was to provide triangular panels facing all four UV directions on a double curved surface and to keep overlaying of their parts to keep rainwater out, the strength of the Ray design (Davidová, 2013, 2016a) (see Figure 10). This was also exemplified on an example of planarization task, where representing a given reference shape is done by a mesh with planar quadrilateral faces (Jiang, Tang, Tomiči�c, Wallner, & Pottmann, 2015). However, Ray panelling system operates at three different planes due to panel overlaps. This complicated the whole task of planarization. Finally, for each planar face of the reference surface, three planes were established and panels were distributed accordingly to the flow of rainwater. However, the final state of this code was resolved during the final prototyping after the waffle script structural base was produced and physically investigated.

### *Analogue and Digital Fabrication Combination*

The process of designing the TreeHugger (see Figure 1) involved a few structural and conceptual shifts that had to be implemented by the digital model almost immediately. Without the parametric approach provided by use of Grasshopper, such changes would take weeks to remodel in the full scope of the project. First ideas leaned towards a very light bent structure made from thin strips of solid wood, which should had been covered by the performative panels. To apply proper bending, a formwork was developed from ply-wood boards using a simple waffle script. The wooden strips were wrapped around it and fixed by screws (see Figure 8). Although this approach was considered to be feasible by the wood engineering experts, the designers were very suspicious through their intuition and this proved to be correct as the screws were leaping out and we registered several cracks in wooden strips.

The team decided to redesign structure using ply-wood board waffle as the main structure instead of the bent solid wood strips. The script had to be rewritten in one 4-hour session and the rest of the more or less critical design changes were creatively handled through analogue improvisation in the workshop (see Figure 9) as there was no way to obtain new material and to extend the deadline. I.e. the 0.5 cm thin large ply-wood boards were bending in laser cutting machine when the design was cut. Therefore, some parts had to be resolved by hand-saw.

Figure 7
The Final Adjustments of the Prototype (Photo: Davidová 2017)

Figure 8
The Prototype Trial that Structurally Failed to Perform (Photo: Davidová 2017)

Figure 9
The Waffle Structure with on Place Improvised Wooden Slats to Fix the Panels (Photo: Prokop 2017)

An example of a critical point was the locking of the two halves of the prototype that had to fit with the tree trunk. The to the prototype central trunk was modelled in simplified manner as a cylinder with two different approximate perimeters and the prototype was adjusted manually on place to fit the real nature of the tree (see Figure 7). The digital solution would include 3D scanning of a large portion of the trunk and restoring the resulting mesh. However, this would have to be afterwards anyway optimised to a manageable vertex count with similar result as the first solution. Instead, the approximation along with a simple physical measurement was less time and technology consuming and more efficient when customising in real life situation the analogue way.

## METHODOLOGY: THE RESPONSIVE WOOD INSECT HOTEL

This prototype is to real life co-design the eco-systemic performance with biotic and abiotic agency of its environment. This covers cross-species habitation, nutrients and social and cultural performance in variety of scales. With the today decrease of biodiversity and biomass in agricultural land due to pests, herbicides, etc., we fight to adapt our cities for the species that started to inhabit them, leaving mentioned toxified land. This certainly cannot happen without human inhabitants accepting and adapting to these settings of co-living situation. Therefore, we no longer design for- but we aim to design with- the overall eco-system (including humans) as an ever-evolving design process.

### *The Responsive Wood Prototype TreeHugger*

The prototype has benefited from- and has developed the- concept of 'responsive wood' (Hensel & Menges, 2006), in this case applying solid wood concept of tangential section observed on Norwegian traditional architectural panelling (Larsen & Marstein, 2000). It is applying first author's research in this field on a screen that airs in dry and hot while enclosing itself in humid and cold climate, Ray (see Figure 10). TreeHugger is a first contemporary built dwelling using this feature. As the performance of the solid wood panels cut from the centre of the trunk have larger warping than those from the edge (Hoadley, 1980), the prototype not only allows their overlapping, but also enables the design of variety of climatic chambers for variety of insect species. This diversity is also supported by overall world axis orientation, as the species have different preferences to i.e. sun and wind exposure. The inner structure of the chambers towards the tree trunk is open to secure escape in all kinds of situations without climatic exchange (see Figure 11). The wood itself allows future algae and lichen habitat to support its responsive feature while the pine wood material does not attract decaying species.

Figure 10
Ray 2 Responsive Wood Envelope Prototype

Figure 11
The Inner Structure of TreeHugger (Photo: Davidová 2017)

I.e. the Ray 2 responsive wood envelope prototype is in semi-dry April weather partly open for boundary exchange between exterior and semi-Interior (see Figure 10 left). After April light rain the system immediately closes, not allowing the humid and cold air to pass through the boundary (see Figure 10 right). Both photographs in the figure are taken in the same day after four years that the prototype has been exposed to weather and biotic conditions. The prototype is inhabited by blue stein fungi, algae and lichen. These, namely the algae, are regulating the moisture content of wood, thus co-causing its warping. Notice also the organisation of algae habitation caused by the material's fibre direction and position within the design that is affected by material performance and form. Thus it is organised through its moisture and the organism's abundance and distribution interaction (Davidová, 2017a).

This 'non-anthropocentric architecture' (Hensel, 2013) is to support co-living and co-creation across the species and abiotic agents within urban environment. However, the first author claims that her evaluation of such crossed interaction is in the end also the most beneficial to humans (Davidová, 2016b). Anderson at al. points out the necessity of human public engagement in-, experience of- and participation in- such to appreciate it (Andersson, Tengö, McPhearson, & Kremer, 2015). We would be more specific and add that this cannot happen without its co-design, co-creation and co-living. While the, later on digitalized, analogue GIGA-mapping allowed for transdisciplinarity and human public engagement, the Grasshopper parametric modelling allowed fast responses in design changes and environmental diversity of designed spaces. This is due its customisation of spatial organisation that have been co-generated through material performance life, in real life.

To avoid future design restrictions a new prototype of Ray panelling research lead by the first author was needed due to possible surface curvature. Ray 1, 2 and 3 (Davidová, 2013, 2016a) were designed to operate only on a flat surface. The use of parametric modelling tool Grasshopper enabled working on the structure of panelling even without knowing the exact shape. This way Ray 4 was developed.

### *The Eco-Systemic Prototypical Urban Intervention TreeHugger*

The discussed prototype TreeHugger (see Figure 1) is an insect hotel prototype and application in public space in the same time. It serves both, as dwelling for insects and algae as well as, while following the concept of 'edible landscape' (Creasy, 2004), providing urban farming of food for local bats and birds. Therefore, it is interacting with a local specific eco-systemic chain. While interacting with the system, it co-designs and re-designs the ecosystem. Therefore, the eco-systemic prototypical urban intervention can better the overall eco-systemic environment within the location. Flying insects in general by their biomass and birds from agricultural land decreased by 80% since 80ties/90ties in the Central European region (Czech Ornithologists Association, 2016; Vogel, 2017). Many of these have been observed to adapt to the urban environment, being safer than agricultural land full of herbicides, pests, etc. This project is to re-design the urban environment to adapt to the new coming neighbours for the co-living situation with humans. It took part in larger eco-socio interventionist project COLridor that culminated through multi-genre EnviroCity festival, organized for the reason of human community engagement. One of the critical part of attracting it is also aesthetics (see Figure 1). This also proved to perform against vandalism from variety of social-groups in this and our previous public space interventions (Davidová, Šichman, & Gsandtner, 2013). The larger scale context of COLridor and EnviroCity is discussed in separate paper 'COLridor: Co-Design and Co-Living for Sustainable Futures' (Davidová & Zímová, 2017).

With local specific adjustments options, we intervened globally, publishing the production code and information for non-commercial Creative Commons usage. The crucial part is that the reproductors will correctly differentiate on left and right side of the panels in reference to the position in the tree trunk, therefore the fibre density, for the direction of warping. With the common accessibility to the laser cutting machines and basic workshop tools in the cities, the communities can adopt and adapt such interventions in their public spaces. Therefore, the eco-systemic urban intervention can also be performed as DIY 'Service Design' (Stickdorn & Schneider, 2011), possibly with larger impact after the first prototype was born and observed.

## CONCLUSIONS AND SPECULATIONS

The project has developed the concept of responsive wood into its first dwelling and urban farming application with the advanced use of its material features and the prototype has welcomed its first inhabitants at the end of the season. Its larger eco-systemic impact is subject to larger observations. However, even its current eco-systemic engagement is observable and unquestionable. Though we are not claiming any 'butterfly effect' (Stewart, 2002), we claim the re-design of the system through interacting with it. We therefore claim that its crucial co-design process is the process of its performance within its real life physical environment, interacting with overall adjacent biotic and abiotic eco-systemic agency. The work on the prototype and the prototype itself also managed to generate public curiosity, interest and engagement in local bio-top support. There also its attractive outfit design plays crucial role. Please, see Figure 1 where it is catching the eyes of passers-by.

However, we cannot neglect the role of media and agency mix also in GIGA-Mapping within its design process with which the Grasshopper coding worked well in feedback looping in co-designing the public and transdisciplinary communication and co-design itself. The parametric features of the model allow for adjustments to specific variations for any other future applications. However, from our experience, we have never digitally fabricated anything, that would fully fit into real life physical environment. It is therefore wise, to keep several aspects open for real time improvisation and real life problematique adaptation when prototyping the 'result'. Therefore, we claim, that analogue and digital processes need to be combined and benefit from each other in all kinds of designing, analysing and design goals.

With basic understanding of wood material science and coding, the prototype can be rebuild by other communities, when digitally, materially, structurally and, first of all, nature-culture-socio-geography specific adjusted to co-create itself on place in real time. Though the code for the TreeHugger was given under Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) Licence to tinkering public before X-Mass for free at project's Facebook site. We urge, that all the prescript fabrication always require on site creative designers' and the environments' themselves analogue real life environmental adaptation.

Therefore, the project that is inspired by concept of 'ecological urbanism' (Mostafavi & Doherty, 2016a, 2016b) is twofold. It is in one-way physically prototyping and testing our work through overall eco-systemic engagement. On the other hand, it is giving the tool to communities to spread the work through using the parametric code for local specific prototyping. These multi-layered and multi-scaled local specific eco-systemic co-design real time processes are therefore building the ground of the very open newly emerging design field of **Systemic Approach to Architectural Performance**.

## CREDITS

The project is co-organized by Collaborative Collective, z.s., CooLAND, z.s. with support of the Technical University of Liberec, Faculty of Art and Architecture and the Faculty of Forestry and Wood Sciences at the Czech University of Life Sciences in Prague and co-designed with them respectively, together with the local community and local environment. It has been, by now, co-funded by VIA Foundation and through EEA Grant program for Biodiversity and Climate Change Adaptation lead in cooperation of the Technical University of Liberec, Faculty of Art and Architecture and the Oslo School of Architecture and Design. The sponsorship involved the Forests of The Czech Republic, Stora Enso, Rothoblaas, Škuta Design and the Faculty of Forestry and Wood Sciences at the Czech University of Life Sciences in Prague.

The festival events were listed as a part of European Sustainable Development Week and European Cultural Heritage Days.

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# STRUCTURE OPTIMISATION

# Tall Tensegrities

## *A Parametric Deformation Control Analysis*

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*The design of tall structures with high slenderness, i.e. width/height ratio, and minimum self-weight, considers in addition to aspects of modularity, constructability and connectivity of the primary members, the static and dynamic behavior of the systems. Assuming constant mass and damping ratio over the height of the building, the structure necessitates respective definition of its stiffness properties, resulting from its configuration, i.e. geometrical stiffness, and the section properties of the members applied, for achieving controlled deformations under horizontal loading. In particular, structural deformation control is traced in the current paper in simplified means through a Finite-Element Analysis of a tall tensegrity structure with overall system dimensions of 12.12/96 m, i.e. 1/7.92 slenderness, developed in three different configurations. Furthermore, a differentiated pretension of the tension-only members of one of the systems has been applied for control of its response behavior. The parametric structural analysis of the tensegrity systems verifies the significant role of the tension-only elements in the system stabilization and horizontal response.*

**Keywords:** *Tall tensegrity structures, Cable pretension, Structural deformation control*

## INTRODUCTION

The design of tall structures with high slenderness, i.e. width to height ratio, and minimum self-weight, considers in addition to aspects of modularity, constructability and connectivity of the structural members, the static and dynamic behavior of the systems. While the materials and the structural typology applied are decisive for the load-deformation behavior of the system, adaptive characteristics are required, when considering the influencing time-varying horizontal loading. In parallel, advances in embedded computation, material design and kinetics on the technological side, provide a background for emerging kinetic architectural solutions. The necessity for an architecture that is not static, instead it has the ability to adapt in time changes through systems with embedded kinetic mechanisms was initially proposed in (Zuk and Clark, 1970), whereas active control concepts envisioned, were directly influenced by respective advances in aerospace and mechanical engineering (Yao, 1972). In particular, concepts for structural deformation control were proposed, such as the 'variable controlled deformation' method, through application of stressing tendons within the structure. The control members should be capable of being variably and automatically tensioned to counteract excessive deformations. Such a control mechanism was conceptually applied in five classes: axial, flexural, torsional, instability and vibration and seismic control. Kronenburg argues that for a building to be 'flexible', it must be capable of adaptation, as a way to better respond to transformation, defined as alterations of the shape, volume, form, or appearance, movability and interaction, which applies to both the inside and the outside of a building (Kronenburg, 2007). Along these lines the human body may be considered as the most representative example of dynamically interactive living organisms. The engineer Guy Nordenson describes the phenomenon in active kinetic systems as creating a building like a body: A system of bones and muscles and tendons and a brain that knows how to respond (Davidson, 1995). Thus, the structural mechanism, responsible for different geometrical configurations of the lightweight components through among others, transforming in size and shape, and the control system, which directs the structure towards specified transformations, are significant for the kinetic operability of the system (Schumacher, Schaeffer and Vogt, 2010).

Engineering precedents for the development of adaptive structures include meanwhile commonly known systems, such as deployable tensegrity and scissor-like systems (Pellegrino, 2001). These precedents form an important part of the practical knowledge currently available for the development of adaptive structures within architecture. Tensegrity structures essentially comprise self-stressed systems composed of tension and compression members (Pugh, 1976), whereas certain advantages in terms of their constructability, load-bearing behavior and control efficiency may be obtained, when the compression elements are interconnected (Djouadi et al., 1998; Wang, 2004). Deployable tensegrity structures may be transformed from a closed configuration to a predetermined expanded form, in which they are stable and effectively transfer loads (Gantes, 2001), through alteration of the compression or tension members' length, with only small quantities of energy needed due to their kinematic indeterminacy (Hanaor, 1998). Relevant studies on the analysis of the deployment mechanisms and shape control are included in (Gantes et al., 1989).

In principle, a great advantage of tensegrity structures is that the cables are not stressed in compression that causes buckling and therefore can utilize the use of materials strong in tension. This fact results in material efficiencies and low structural self-weight. By extent, tensegrities self-stressing characteristic means that they can easily adjust their shape. These properties are particularly interesting with regard to the development of adaptive tensegrity systems.

A representative example following a tensegrity structure morphology is the Warnow Tower conceived by the architects Gerkan, Marg and Partners in cooperation with the engineers Schlaich, Bergermann and Partners. The Tower was built in 2003 and it constitutes one of the most recent tensegrity structures, whereas the continuous compression members connections are semi rigid. The structure consists of six 3-strut t-prisms with a height of 8.30 m each, assembled vertically. Each prism consists of three compression members of about 10 m length and 273 mm diameter, three diagonal cables of 50 to 75 mm fully locked coil ropes and three horizontal cables of 30 to 50 mm. The horizontal cables form a triangle at the bottom and top planes of each prism, which are rotated against each other by approximately 30°. The overall structure measures 62.30 m in height and 5 m in diameter. The first natural frequency of the structure amounts f=

0.6 Hz, whereas the stiffness of the system depends mainly on the pretension of the cables, set at 30 % of the tensile strength of the members (Klimke and Stephan, 2004). A further design example of a proposed tensegrity structure with continuous compression members is the Filamentosa high-rise by Orambra (Orambra, 2018).

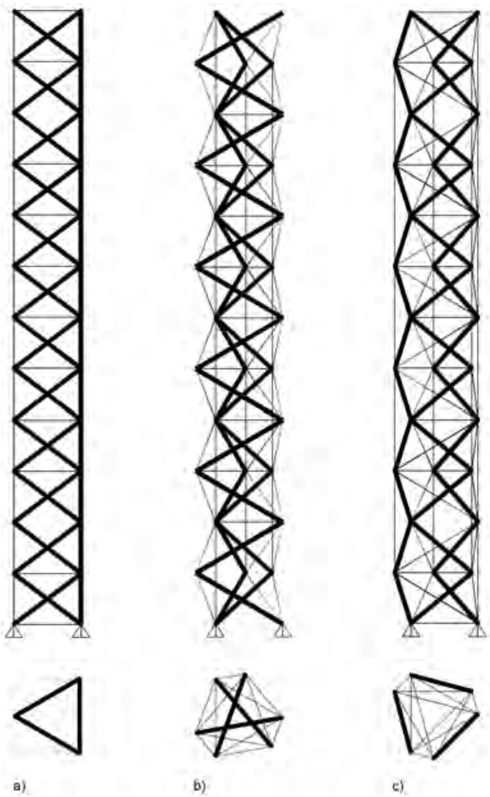



Figure 1
Tensegrity structural system configurations. a) S1, b) S2, c) S3

In tensegrity structures, the structural members and active elements can be combined for active deformation control, provided that the tension members carry both the sensing and actuating functions. The structure may be controlled through alteration of the pretension of the cable members, in order for the system to adapt to the respective loading conditions. A different adaptive mechanism may be provided by systems with the ability to manipulate their internal force distribution or influence their external loads over time (Sobek and Teuffel, 2002) that is not further pursued in the current paper.

The control approach is traced in the current paper in simplified means through a static nonlinear Finite-Element Analysis of a tall structure developed in three different configurations. The systems are initially analyzed without pretension in the actual cable elements. In a selected system configuration, a uniform as well as differentiated pretension of the cables has been applied. The differentiated activation of the tension-only members against horizontal loads, proves to influence the dynamic behavior of the system. Furthermore, moment resisting connections of the continuous compression members provide improved stabilization and deformation behavior of the system under horizontal loading. In the next section, the geometrical design principles of the tensegrity structure configurations and the analysis procedure explained. Subsequently, the preliminary comparative numerical results are presented. The final section refers to the pretension scenarios applied and the respective numerical results obtained.

## TENSEGRITY STRUCTURE CONFIGURATIONS AND ANALYSIS MODELS

The configurability aspect of tall structures and their deformation behavior are investigated on the basis of three tensegrity systems, e.g. self-stressed systems composed of tension and continuous compression members, with overall system dimensions of 12.12/96 m, i.e. 1/7.92 slenderness. The primary structure consists of twelve units placed successively on vertical axis. Each unit consists of three compression members of steel hollow sections with 17 cm diameter ((S450, E= 2.1x104 kN/CM2, ρ= 78.5 kN/M3), three horizontal and six diagonal cables of 12 cm diameter (E= 1.6x104 kN/CM2, fe= 140 kN/CM2). In addition, the units are interconnected through vertical cables of 12 cm diameter. Each alternative unit plane is rotated by 120, 200 and 270 degrees to provide the respective system configuration, while the length of the diagonal members varies to keep in all cases the units height constant, Fig. 1. The first system, S1, has a triangular shape on the horizontal plane with all the members positioned at the perimeter. The second system, S2, has a polygonal shape on the horizontal plane with the diagonal members crossing opposite sides. The third system, S3, also has a polygonal shape on the horizontal plane with the compression members positioned at the perimeter and the tension-only members, crossing opposite sides.

The tensegrity configurations have been investigated with the Finite-Element Analysis, FEA, software program SAP2000. In a preliminary stage, the three systems have been investigated based on a linear FEA. The cables were modeled as frame objects with zero compression limit representing the actual behavior of flexible tension-only members, without been assigned any pretension. The selection of appropriate sections of all members for the specific vertical and horizontal loads of 2.5 and 1 kN/M2 respectively, was based on achieving reduced natural period of the systems and horizontal displacements.

Subsequently, the cables of a selected system have been modelled as cable elements and assigned with certain constant and differentiated pretension over the height for achieving a system response improvement. In this stage, the systems have been investigated based on a nonlinear FEA. The pretension of the cables, has been applied as an initial respective target force in the elements, followed by respective application of the vertical and horizontal loads to the system. In System 2.1, S2.1, a uniform cables pretension of 150 kN target force has been applied. In System 2.2.1, S2.2.1, the pretension of all diagonal cables has been increased to 300 kN. In the optimization stage of the selected system, the diagonal cables of only the three lower, middle and upper units over the height, S2.2.2, S2.2.3 and S2.2.4 respectively, have been assigned with increased pretension values of 300 kN, whereas in all other cables of the system the pretension has been kept constant at 150 kN. The differentiation of the pretension of the units diagonal cables over the height proved to improve the dynamic behavior of the system. Finally, in System 2.2.1 with a diagonal and vertical cables' pretension of 300 and 150 kN respectively, the connections of the compression members have been set to moment resisting, S2.2.3, in increasing further the horizontal stiffness of the system.

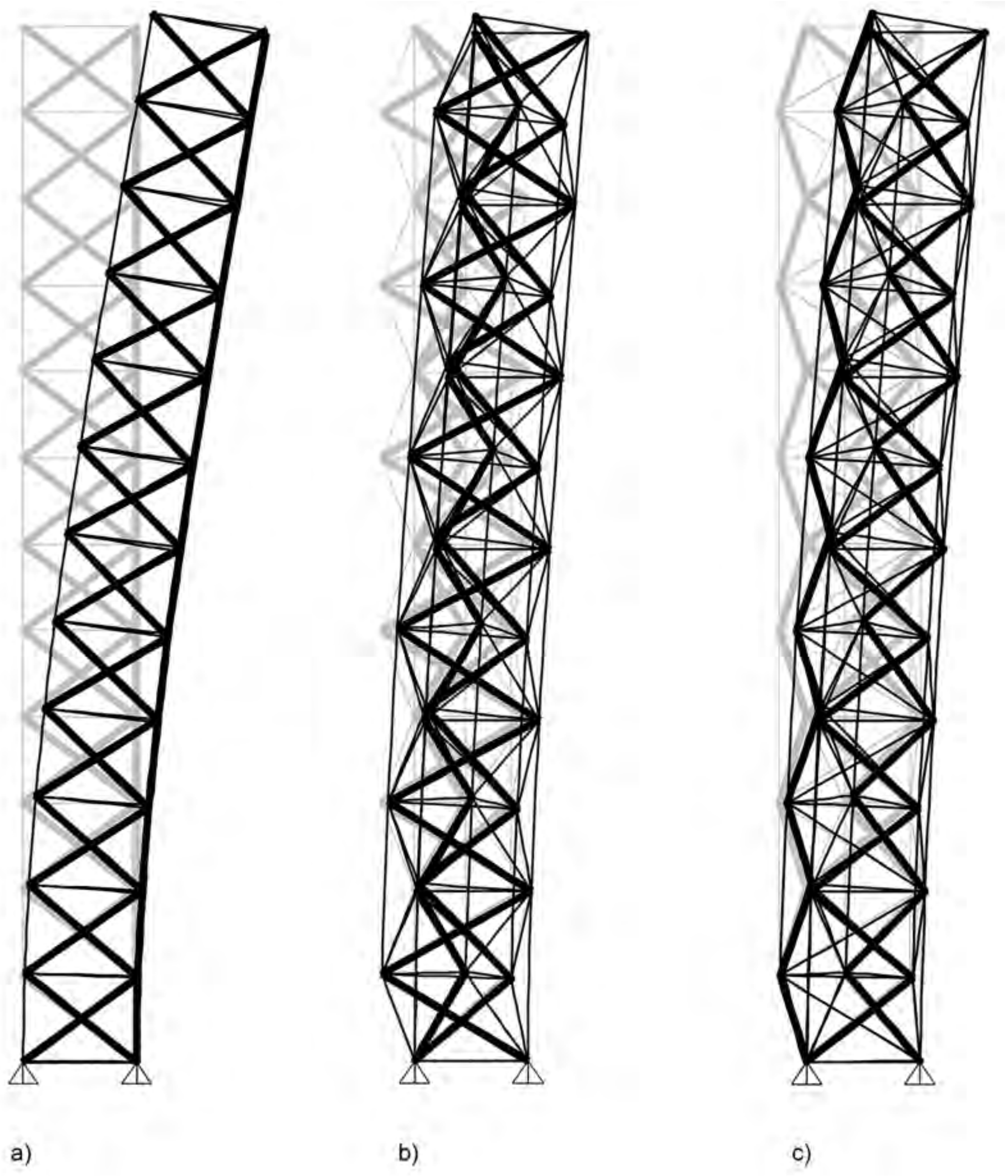
Table 1
Systems response under wind loading and 1st eigenperiod

| SYSTEM | COMPRESSION MEMBERS | | | CABLES | $U_{max}$ [m] | $T_1$ [s] |
|---|---|---|---|---|---|---|
| | $N_{max}$ [KN] | $Q_{max}$ [kN] | $M_{max}$ [kNm] | $N_{c,max}$ [KN] | | |
| S1 | 399 | 47.64 | 0.45 | 2403 | 79.00 | 4.06 |
| S2 | 1052 | 54.17 | 0.60 | 2001 | 65.00 | 3.13 |
| S3 | 1177 | 61.90 | 0.53 | 1729 | 71.00 | 3.51 |

## PRELIMINARY ANALYSIS

The three tensegrity structural systems have a similar dynamic behavior with prevailing bending deformations and a rather high fundamental eigenperiod, Fig. 2. System S2 has the lowest eigenperiod of 3.13 s, indicating also the highest stiffness among the ones investigated. The system's eigenperiod is by 28 % lower than the highest one, of S1. The systems maximum responses under wind loading are included in Table 1. While the bending moments of the compression members due to the members' self-weight are negligible, the maximum axial forces in the members result from the synergy of the compression and tension members. The highest maximum axial force of 2403 kN is developed in the cables of S1, whereas the lowest maximum value of 1729 kN is developed in S3. The maximum horizontal displacement of the systems amounts approximately to h/150 up to h/120. The lowest respective value of 65 cm is registered by S2. Based on the results obtained in the preliminary investigation, S2 was selected for a further nonlinear analysis, as described in the following section.

Figure 2
1st eigenform of the tensegrity structural systems. a) S1, b) S2, c) S3



## NUMERICAL ANALYSIS AND CABLES ACTIVATION

System S2, modeled with cable elements and assigned with different respective values of pretension, exhibits an improved dynamic behavior with prevailing bending deformations as shown in Fig. 3. In all systems investigated with hinge connection of the compression members, i.e. S2.1 to S2.2.4, the first eigenmode refers to respective bending deformations, followed by the second and third eigenmode of torsional deformations of the systems. Principally, a high pretension of the diagonal cables, uniformly applied over the system height, and moment resisting connections of the compression members, as in S2.3, succeeds in reducing the first eigenperiod and especially the torsional flexibility of the system. The results of the model analysis of the systems are included in Table 2. While the highest system stiffness is obtained in S2.2.1 with an increased pretension of 300 kN in the diagonal cables, and in S2.3 with additional moment resisting connections of the compression members, the lowest system stiffness is obtained by S2.1 with a relatively low uniform pretension of 150 kN in all cables, followed by S2.2.4 with an increased pretension in the diagonal cables in the three upper units of the system only.

The systems maximum responses under wind loading are included in Table 3. While the maximum bending moment values in the compression members remain at a practically low range between 624.54 and 786,32 kN, the axial forces in the compression members increase considerably compared to the previous linear analysis investigation. As anticipated, a highest maximum value of 6244.77 kN is developed in the compression members of the lowest tensegrity units in S2.2.2 with an increased pretension of the diagonal cables in the respective units. A lowest compression force of 6032.45 kN is developed in S2.3 with moment resisting connections of the compression members. The respective value corresponds to a respective reduction of only 3 % of the highest value in S2.2.2. The maximum axial forces development in the cables of the system follow a similar

Figure 3
1st eigenform of tensegrity structural system S2.1 to S2.3

Table 2
System 1st, 2nd and 3rd eigenperiod

| SYSTEM | $T_1$ [s] | $T_2$ [s] | $T_3$ [s] |
|---|---|---|---|
| S2.1 | 2.27 | 1.93 | 0.60 |
| S2.2.1 | 2.09 | 0.54 | 0.36 |
| S2.2.2 | 2.13 | 1.35 | 0.42 |
| S2.2.3 | 2.25 | 1.48 | 0.52 |
| S2.2.4 | 2.27 | 1.79 | 0.51 |
| S2.3 | 2.09 | 0.54 | 0.36 |

Table 3
System response under wind loading

| SYSTEM | COMPRESSION MEMBERS | | | CABLES |
|---|---|---|---|---|
| | $N_{max}$ [KN] | $Q_{max}$ [kN] | $M_{max}$ [kNm] | $N_{c,max}$ [KN] |
| S2.1 | 6211.58 | 181.49 | 781.99 | 1810.59 |
| S2.2.1 | 6334.84 | 181.49 | 738.49 | 1848.52 |
| S2.2.2 | 6366.68 | 181.49 | 781.43 | 1871.53 |
| S2.2.3 | 6257.82 | 181.49 | 784.42 | 1808.39 |
| S2.2.4 | 6244.77 | 181.49 | 786.32 | 1799.41 |
| S2.3 | 6032.45 | 181.49 | 624.54 | 1769.05 |

tendency. The highest maximum value of 1871.53 kN is developed in S2.2.2 with an increased pretension of the diagonal cables in the middle units, while the lowest maximum value of 1769.05 kN is developed in S2.3. The respective decrease amounts to 5.5 %.

Figure 4
Typical deformation of tensegrity structural system S2.1 to S2.3 under wind loading

Table 4
System load-deformation behavior under cables pretension and wind load case

| SYSTEM | PRETENSION | | WIND | |
|---|---|---|---|---|
| | $U_X$ [cm] | $U_Z$ [cm] | $U_X$ [cm] | $U_Z$ [cm] |
| S2.1 | 0 | 54.48 | 13.59 | 53.12 |
| S2.2.1 | 0 | 50.07 | 13.26 | 48.76 |
| S2.2.2 | 0 | 53.14 | 13.54 | 51.79 |
| S2.2.3 | 0 | 53.23 | 13.52 | 51.88 |
| S2.2.4 | 0 | 53.96 | 13.44 | 52.63 |
| S2.3 | 0 | 44.37 | 13.18 | 43.06 |

The nonlinear analysis of the systems proves that their load-deformation behavior is strongly influenced by their torsional flexibility that leads to respective vertical deformations. Figure 4 shows the typical deformation of a pretensioned system under wind loading. This is mainly governed by the vertical deformation component, which is induced by the torsional motion of the compression members under the imposed loading.

In gaining further insight in the load-deformation behavior of the system, Table 4 includes the respective deformation values obtained in the horizontal and vertical direction, under both load cases, pretension and wind. As shown in the pretension load case, unless the compression members connections are set to rigid, the pretension of the cables yields already at this initial loading stage, a torsional deformation of the system that results in overall maximum values of h/190 to h/175. Under wind loading the system with hinge connected compression members obtains maximum horizontal deformations in the range of h/725 to h/705 and a minimum amount of vertical deformations. Note that the respective values indicated in Table 4 are the result of the respective vertical deformation of the system due to the initial pretension of the cables and the horizontal loading. In improving the load-deformation behavior of the system, the compression members connections are set to moment resisting. This system alternative enables a maximum vertical deformation reduction of 19 % in the pretension stage and a maximum horizontal deformation reduction of 3 % under wind loading compared to system S2.1 with uniform cable pretension of only 150 kN.

## CONCLUSIONS

A number of tall tensegrity structure configurations has been investigated in the present paper. The systems have been initially morphologically differentiated and their load-deformation behavior has been investigated based on a linear FEA. At this stage, the cables have been modelled as frame elements with zero compression limit and were assigned with no pretension. Following selection of a system configuration with favorable load-deformation behavior, the nonlinear FEA conducted has been based on a uniform pretension of the cables of the system, increased pretension of all diagonal ones and of differentiated three units ones over the height. Finally, a system alternative investigated is based on moment resisting connections of the compression members in limiting the vertical torsional deformations of the system under the initial pretension of the cables.

In principle, the parametric structural analysis of the systems clarifies configurational aspects in tensegrity structures and gives an insight into their structural behavior. The development and differentiation of the pretension applied in the cables of the selected tensegrity system verifies the significant role of the tension-only elements in the system stabilization and horizontal response. Nevertheless, pretensioning of the cables in tall tensegrity structures has proven to induce considerable vertical torsional deformations of the system, which acts negatively on its horizontal load-deformation behavior. This indicates that in achieving a favorable system response behavior, the initial self-stress condition through appropriate pretensioning of the cables should be sought after as part of further developing the system into an active control mechanism.

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[1] http://www.orambra.com/˜filamentosa.html

# Qualitative Study on two Kinetic System Simulations

## *Experiments Based on Shape Memory Material and Stepper Motors*

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*This investigation intends to compare two computational design experiments operating on two kinetic architecture (Zuk and Clark 1970) design application domains: Shape-memory material (SMM) activated grids and stepper-actuated (SA) responsive skins. In the first one, the goal was to build a standard way of simulating SMM, which can be used as actuators in the construction of kinetic structures and in the second, to simulate and construct a responsive skin according to human interaction using kinect and stepper motors. In both experiments, a similar generative workflow was employed, combining insights from materials and mechanical systems. The objective is to investigate kinetic performance, kinetic design methodology, simulation implementation and applications within the two separate design domains. The general hypothesis is that both experiments become design workflows in themselves as real-time, dynamic modeling systems. A qualitatively study of both sets of cases, is taking in count general, simulation and application aspects, using evaluation criteria including workflow, material quantity, data capture and mechanical properties.*

**Keywords:** *Kinetic Design Methods and Information Processing, Simulation, Fabrication, Hybrid practices*

## INTRODUCTION

Simulation processes are creatively fit to be used as part of design methods, encourage innovation in the architectural field and challenge how the discipline approaches design to production. Inside the field of kinetic architecture, this article highlights the commonalities and differences between two experiments inside two domains: an individual design process that uses SMM embedded actuation and a second group project, which develops and controls SA responsive systems. In both cases, parametric simulation tools were utilized as means of exploration and design development, having the same parametric workflow employed.

In the SMM domain (SMMD), a research prototype published by Raviv et al.(2014) was taken as guideline to be replicated using different computational methods and tools than those used in the original experiment. This was achieved by building a parametric simulation model using commercially available Nickel-Titanium (Ni-Ti) alloy material data. The material itself is programmed to respond to external environmental heat induction, remembering its shape when cooled (Otsuka and Wayman 1988). In the SA domain (SAD) the experiment was a real scale self-supporting kinetic structure. Simulation strategies were used to make before-the-fact visualization of stepper actuated, thereby informing the decision-making process, merging design and digital manufacturing in a single workflow. The emphasis is given on the behavior of the system and its interaction with human movement.

The objective of this article is to qualitatively compare the two kinetic performance frameworks of material and stepper motors responsive behavior before and after prototyping. The hypothesis is that these experiments become design workflows in themselves as real-time, dynamic, visual simulation models that, when confronted to a particular application, determine among themselves their common denominators and differences, and in turn, optimize the design process and its results from concept design to digital fabrication.

## PROGRAMMABLE MATTER BASED SIMULATIONS (SMMD)

Dynamics is the part of physics that studies movement. It is divided in kinetics and kinematics, where kinematic means geometric controlled models (angle, distance, position) and kinetic subscribes to vector controlled ones, like force, direction and sense (Beer and Johnston 1999). Inside the context of performance software approaches for kinetic architecture, programmable matter - based simulations experiments are classified as kinetic or kinematic applications (Montas 2016) and are exploring how to build digital simulation models to aid kinetic architectural decision-making. Specifically, the goal is to build a standard way of simulating SMM, which can be used as actuator in the construction of kinetic structures. SMM can undergo through shape shifting changes by being programmed to "remember" a previously cast shape and to return to its original morphological condition by means of heat differential activation.

The experiment hypothesis is that, by collecting, simulating, and re-using data from already tested physical models, kinetic architecture design methodological framework would organically evolve from a Design-Fabrication-Simulation workflow (Raviv et al. 2014) into a Design-Simulation-Fabrication one, where:

1. "Design": Propose a computational approach for designing self-evolving structures that vary over time due to environmental interaction.
2. "Fabrication": Provide an implementable framework by specifying readily printable self-evolving elements that pair with computational models.
3. "Simulation": Realistically imitate the deformation of the materials for enhancing design capabilities.

### *Methodology*

The Design-Simulation-Fabrication design methodology is described as observation and design/research by doing, hereby testing solutions on a dataflow model using live physics engine for interactive simulation, optimization, and form-finding. This way it was easier to visualize the algorithms working on demand and apply them to specific circumstances without having to go through the "imperative" programming Edit, Compile, Run loop cycle, therefore bypassing time-consuming processes that hinder intuitive design decisions mostly happen on the fly. Following this methodology the research tackles some of programmable matter's fundamental exercises, attempting to replicate them through a different computational method than that of Raviv et al.(2014), using data from commercially available Ni-Ti, branded Flexinol, provided by a California (USA) based materials company named Dynalloy

(Table 1). The data-flow diagram (figure 1) outlines the general algorithm which uses analytical geometry and vector-matrices to build parametric models (Montas 2015) which approximately replicate the work of Raviv et al. (2014). Vector fields are a useful and straight-forward way to implement kinetic actuation. Furthermore, force-vector analysis is viable, as a general method, for simulating programmable matter based kinetic systems, at least when it comes to mesh and surface model ones.

Table 1
Flexinol® Actuator Wire Technical and Design Data [1]

| Diameter Size inches(mm) | Resistance ohms/inch (meter) | Pull Force pounds/ (grams) |
|---|---|---|
| 0.001 (0.025) | 36.2 (1425) | 0.02 (8.9) |
| 0.0015 (0.038) | 22.6 (890) | 0.04 (8.9) |
| 0.002 (0.050) | 12.7 (500) | 0.08 (8.9) |
| 0.003 (0.076) | 5.9 (232) | 0.18 (80) |
| 0.004 (0.10) | 3.2 (126) | 0.31 (143) |
| 0.005 (0.13) | 1.9 (75) | 0.49 (223) |
| 0.006 (0.15) | 1.4 (55) | 0.71 (321) |
| 0.008 (0.20) | 0.74 (29) | 1.26 (570) |
| 0.010 (0.25) | 0.47 (18.5) | 1.96 (891) |
| 0.012 (0.31) | 0.31 (12.2) | 2.83 (1280) |
| 0.015 (0.38) | 0.21 (8.3) | 4.42 (2004) |
| 0.020 (0.51) | 0.11 (4.3) | 7.85 (3560) |

### *Kinetic Experiment. Deformation of a 2D Grid into a Double Curvature Surface (Synclastic and Anticlastic)*

Under a conventional geometry based approach for constructing a parametrically modeled double curvature surface, the basis for the modeling is usually derived from a hyperboloid equation: $x^2/a^2-y^2/b^2+z^2/c^2=1$ (Davis 2013). Whereas, under the suggested approach, it was possible to achieve a double curvature surface without having to use this specific mathematical equation, but to use vector matrices instead. Raviv et al., while publishing detailed formulas that define their computational design approach, disclosed few details concerning their simulation methods. Instead of calculating point positions as in Davis (2013) case or angle rotations, as any other matrix set, the original grid is defined as a vector field lattice, where every point in space has a force value, normal to the original flat grid. The deformation patterns is driven by applying the proper values to the specific points in space to produce the desired result. The generated model, qualitatively speaking (meaning that their forms are visually similar and of the same nature-equation, hyperboloid type), closely approximates the original experiment. For visualization, chronophotography was used to capture the object's movement (figure 2).

## RESPONSIVE SKIN SIMULATION (SAD)

The "Interactive Bodies" workshop series focused on developing 1:1 scale, real-time, interactive architecture prototypes with a specific focus on physical computing. This implied building physical systems by means of software and hardware that sense and respond to the analog world, to us humans, to environmental conditions, to dynamic activity patterns and to other physical objects. Specifically aimed to demonstrate bidirectional information exchange between human beings and the digital world, the nature of systems in the built environment and their capacity for adaptation. As a result, generated architectonic skins, which were programmed to react to external movement according to specific computer programming applications of stepper mechanisms. Morphodynamic techniques and fabrication strategies were embedded as a set of local interactions of geometrical systems. Elements, structure, skin, and performance of this networked kinetic system were designed as integrated layers that made up a construct capable of accommodating the dynamic nature of human occupation.

### *Methodology*

A two-pronged strategy was implemented: A design driven methodological framework for underlining an interaction concept and a physically interactive prototype with embedded sensing, actu-

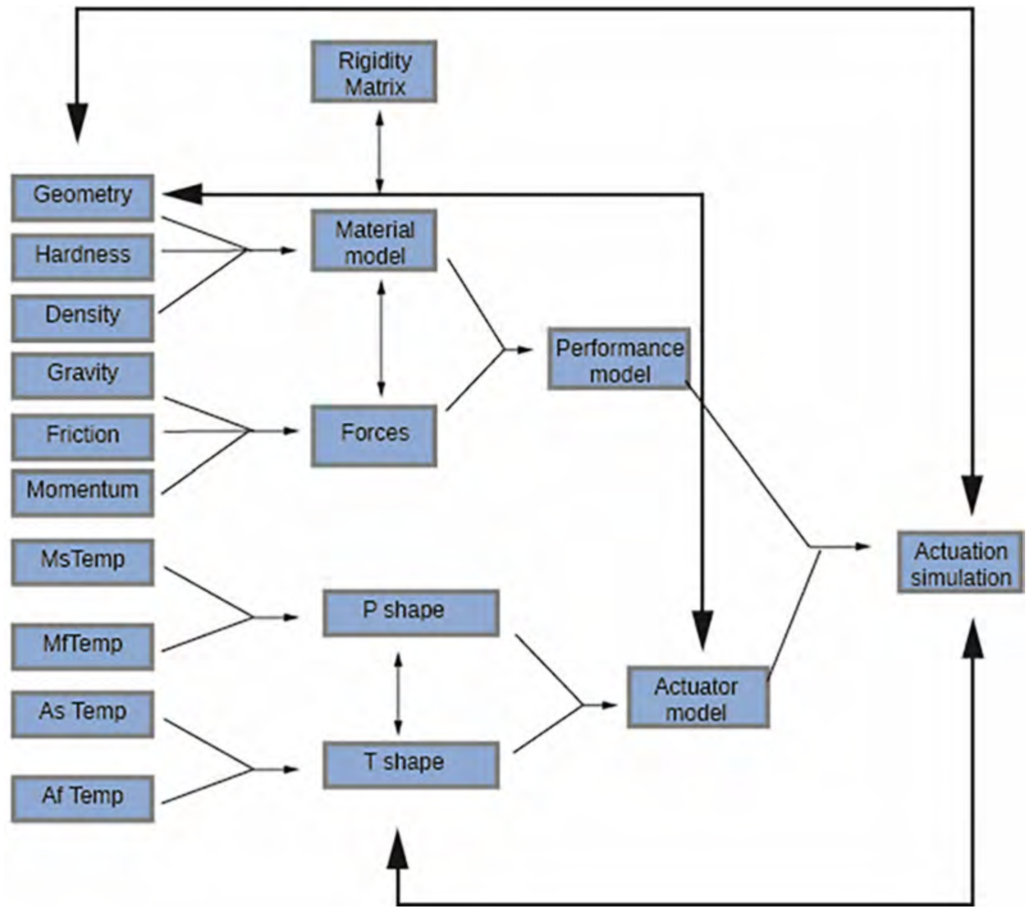
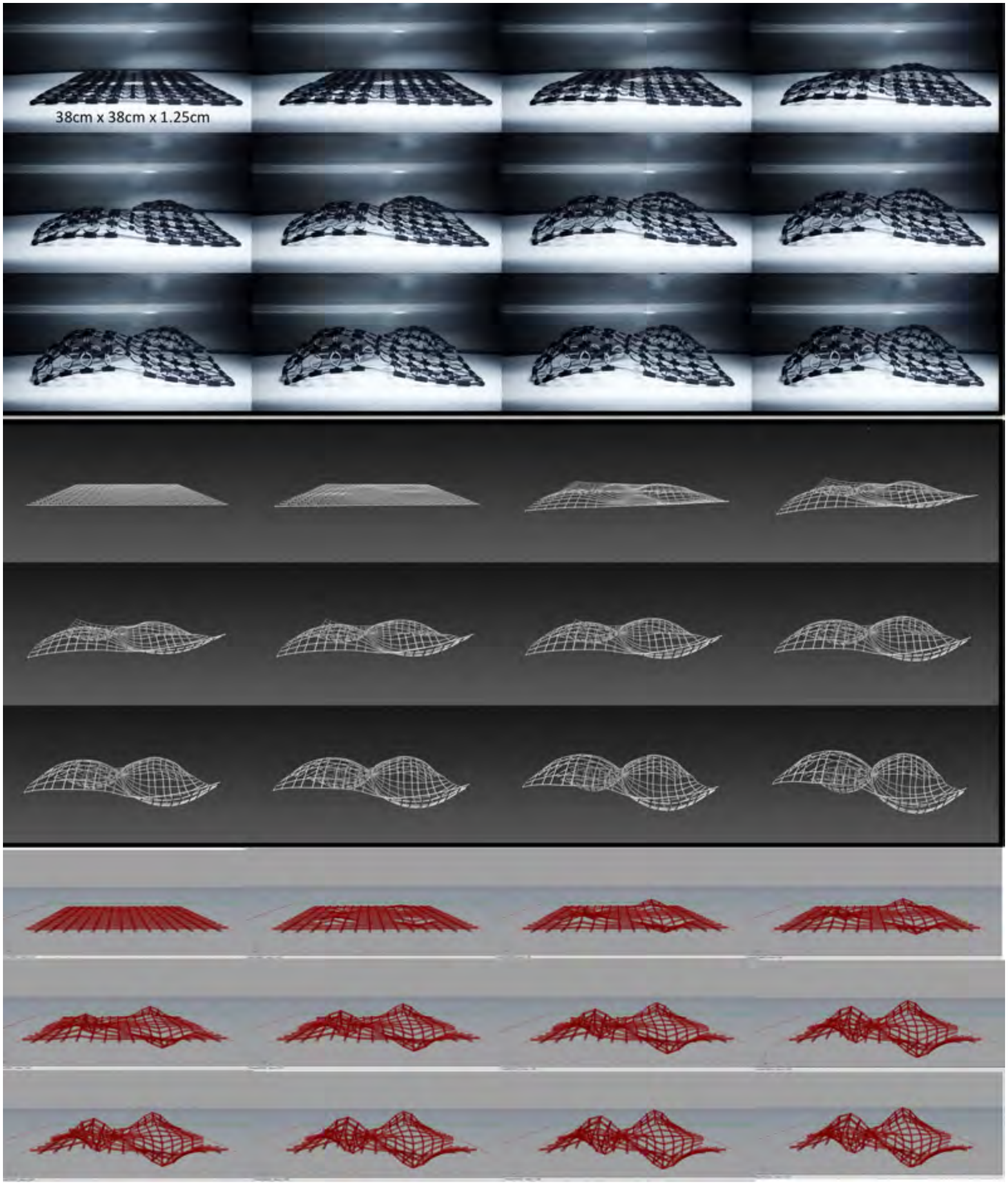



Figure 1
Theoretical algorithmic data-flow diagram for case study simulations. P shape: permanent shape, T shape: temporary shape, Ms Temp: martensite start, Mf Temp: martensite finish, As Temp: austenite start, Af Temp: austenite finish temperatures

ation, and control systems as a proof of concept. The methodological framework was constantly shifting from a design-fabrication-simulation to a design-simulation-fabrication workflow in order to understand firstly the structure and skin system's behavior and secondly to redesign it, adding more complexity and optimizing the geometry. Force-vector analysis was required for the kinetic structure. The physics engine was used for the simulation of the movement of the structure, based on the specific behavioral design intentions and principles. A series of 3D/4D parametric models served as design previsualization tools for the concept, schematic, development, and construction design phases. On the technical front, the tools mainly used were: Arduino, Grasshopper, Firefly, and electronics (kinect, sensors,

Figure 2
Case study, left side, one-point perspective, to be read from left to right, top to bottom. Comparison between the physical model (top), Raviv et al. (2014) original simulation (middle), replicated one (bottom) (Montas, 2015)



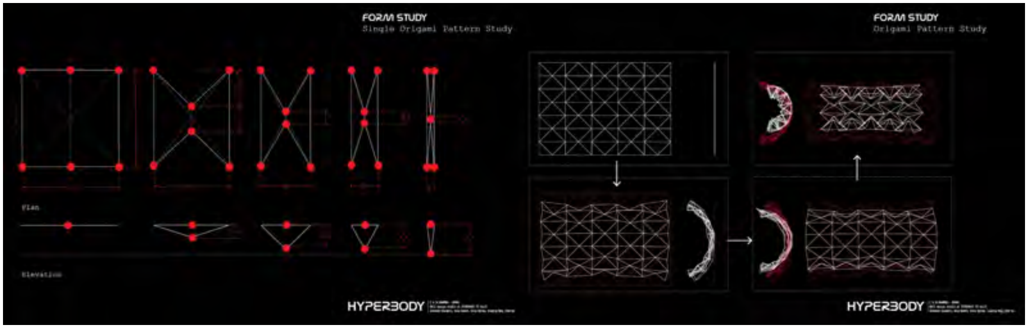



Figure 3
(left) Origami pattern study I with overall behavior. Plan and elevation. (right) Origami pattern study II. Plan and elevation. This study helped to understand the behavior and how to implement mechanical elements [2]

stepper-actuators and microcontrollers). Materialization and testing was realized using CNC, laser cutting, 3D printing and integrated electronics.

### *Project*

From an origami pattern and mathematical rotation degree studies, geometrical data was extracted as a form finding technique (figure 3). The design pattern was adapted according to the closest behavior to the simulation, and by testing with different materials. After the material was chosen, the pattern for laser cutting was revised to meet fabrication criteria and the behavior to be tested again. Interactivity was studied calibrating the Kinect system to capture body behavior at a 37.5 degrees field of view and communicate with the stepper-actuators, sending data through the microcontroller. Distance, speed, sound, and skeleton parameters worked as inputs. Driven by five stepper motors, the dynamic configurations were generated as real-time calculations transforming the overall behavior of the system (figure 4).

## QUALITATIVE STUDY BETWEEN SMM DOMAIN (SMMD) & SA DOMAIN (SAD)

Hypothesis, SMMD: By collecting, simulating, and re-using data from already tested physical prototypes, the methodological framework would organically evolve from a design-fabrication-simulation workflow into a design-simulation-fabrication one. This has been confirmed to be an accurate suggestion. After a successful replication of Raviv et al.'s model, it was possible to expand the model's parametric functionality towards a design-simulation-fabrication workflow building a SMM modeled data library, as predicted.

Hypothesis, SAD: Besides parametric and computational tools for finding joint typologies and assemblages; material and behavior simulations were applied in the beginning of the design process for optimizing the workflow, minimizing fabrication time and enhancing production according to interactivity design intentions. This hypothesis has not been found to be exactly true. A priori, interactive, behavioral simulations could not accurately foresee critical impromptu aspects concerning geometry and structural considerations. Prototyping and a posteriori simulation was the only reliable method to extract accurate data necessary to build more realistic simulation models.

### *General aspects*

In terms of material quantity, in the SMMD, simulations were means to establish reliable approximations at the microscale level to replicate already built and tested structures in order to build an actuation data library which could used to construct reusable actuation simulation models. In the SAD, some of the simulations were meant to establish reliable ap-

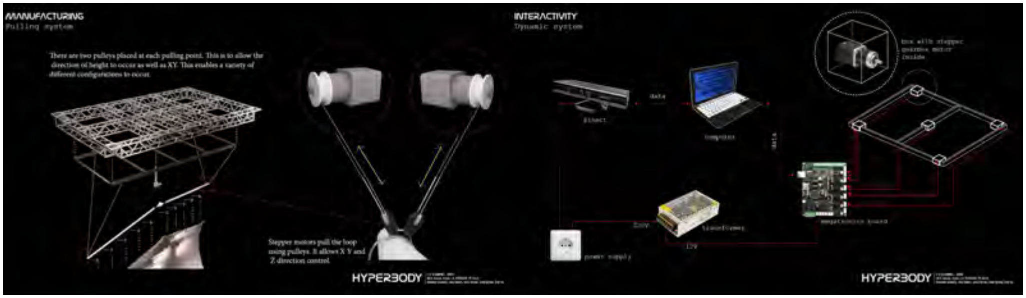



Figure 4
(left) Pulley system with stepper motors, coiling strings to maneuver the origami structure and allowing to control it on x,y,z directions. (right) Dynamic system [2]

proximations at the macroscale level to avoid having to build whole structures and to observe realistic results, thus saving time and prototyping material, in order to arrive at actual actuation, thus addressing the scalability problem from a pre-visualization standpoint.

In terms of data capture and analysis, in the SMMD, data capture and shape shifting output is intrinsically carried out by the material itself, arising from inherent material properties and their resultant behavior. In the SAD, gathered sensor data from the kinect camera were used as an input for the geometry and stepper control. In both cases it was difficult to accurately calculate the amount of data.

### *Application aspects*

Concerning mechanical properties, in the SMMD, heat activated shape memory reaction was based on information from Dynalloy's mechanical data, Grasshopper, and Raviv et al.'s physical and simulation models. A shifting logic was used to program and remember shapes by means of the shape memory effect. Achieving approximated, reliable replication of mechanical (physical) actuation.

In the SAD, simulations were used to design a system which responds to human interaction. The pull & expand stepper logic was programmed using arduino circuit boards and computer software, to pull certain movable parts in the structures and, in certain cases, make the whole structure move and adapt to specific interactive relations.

Both experiments suggest that, at least with current data and tools, it is not possible to approach kinetic (whole) structures through design-simulation-fabrication workflows. This can only be achieved after prototyping first -and only if correct behavioral data is gathered and adequately controlled. The SMMD experiment was used to investigate material behavior responding to external stimuli to achieve a programmed shape, which required one type of simulation, however, more than at least one iteration. The SAD simulations were used to design a system which responds to human interaction which required two types of simulations; one for mechanical behavior and another for human interaction.

## CONCLUSIONS

Computational tools have given architects a high variety of possibilities in design and education, meanwhile material property investigations have a lot of potential for development, especially in transitions of scale, patterns, structure, curvature, and porosity variations. It has been difficult to construct complex geometries from smaller towards bigger scales, particularly with current digital fabrication machines, contrary to simulation, in which a wider range of complexity is possible to model. This gap needs to be shortened to successfully address the "scalability problem" within kinetic architecture, suggesting that these relatively new methods should be continuously re-appraised. The conception of architectural space as a closed system is seen as a complete contrast, which perceives architecture as a subject for real-time calculation, possessing a continuous state of activation, representative of contemporary socio cultural dynamism (Biloria 2014).

After a close evaluation of both cases, we hereby conclude that design-simulation-fabrication workflow processes are possible and invaluable tools for designing programmable matter and interactivity powered kinetic architecture structures, using physical simulation models replicated in CAD/CAM software. Yet, it is noticed that its learning curve, while achievable, is substantially high; taking large amounts of time to understand the mechanical phenomena at hand, requiring at least one prototype to fully grasp the phenomena to model. Nonetheless, once the parametric models are built, they seem to be easily modifiable, expandible, and reusable, if structured correctly and orderly. However, this method seems to have a handicap: it can become increasingly more difficult as complexity increases, therefore it is established empirically that form, complexity, and difficulty are directly proportional.

The kinetic approach (vector control in SMMD), while intuitive and didactic, requires the user to "learn" or "be taught" the physics behind the phenomenon by the Kangaroo physics engine itself. Thereby, it was possible, in the SMMD experiment, to achieve a double curvature surface without the use of the conventional mathematical equation. To achieve more accurate and precise simulation outputs, special attention has to be given to molecular, numerical, and multiscalar modeling, as current attempts remain at relatively low success. Also, it could be interesting to take into account both domains at the same time: from SMM's shape changing performance at the microscale to SA's responsive mechanical macro scale applications.

More research and development in the field of simulating SMM and SA based kinetic architecture could generate a kinetic design methodology which combine processes, insights and data from material and mechanical systems and could arrive to building a digital parametric data archive to use as basis for future before-the-fact material simulation modeling and/or to the development of a generalized theory about simulation implementation and application for pedagogical purposes.

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# Topology design of form-active gridshell structures

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*Nowadays form-active structures have a growing significance in contemporary architecture due to their good characteristics such as light weight and/or low fabrication cost. Form-active form gridshell topology design is developing and constantly seeking for new approaches. In this paper several different methods for form-active structure topology design are presented, they are evaluated and given as guideline for designers. Fabrication of these structures is shown in the example of physical test model.*

**Keywords:** *Form-active structures, Gridshell structures, Topology design, Topology optimization*

## INTRODUCTION

Form-active structures (FAS) are structures generated out of two or more elements with low stiffness which, when combined, create a structure with high stiffness (Deleuran et al. 2015). The shape of such a structure is derived from elements, which restrain each other in a reciprocal manner and take the shape of elastica curves (Deleuran et al. 2016). Elements can be linear or shaped as surfaces, which affects both the aesthetical appeal and static behavior Paoli 2007). FAS are lightweight structures with small static dimensions. They are usually self-supported structures, meaning that it does not require any additional construction. Shape of the self-supportive FAS and the lattice topology additionally improve the strength due to its double curvature (Nicholas et al. 2013). Given all these benefits, FAS have a lot of potential for implementation in the contemporary architectural practice. Until the second half of the 20th century, the main obstacle for building FAS were elastic materials which were not permanent enough and a lack of methods to design complex shapes with (Lienhard 2014). Nowadays, more persistent materials with much better properties that can be utilized for FAS fabrication are available (Quinn et al. 2016). In addition, a wide range of design methods are developed, such as physical form finding, spring-based simulations, finite element analysis etc., which are used for FAS modeling, analysis and construction (Ahlquist and Menges 2013). These novel materials and methods are implemented in an experimental and research projects such as ICD/ITKE pavilion created in the period 2012-17 or Hybrid Tower and Lace Wall designed by CITA (Thomsen et al. 2017). In the design approach of CITA projects, the designer defines the topology and the simulator generates the final shape of the structure. However, there is no possibility to predict the final shape in advance. The workflow is iterative, and requires a high level of experience in order to obtain the desired shape of the structure.Throughout history, FAS were shaped as lattice structures, sometimes as a spatial truss, but more often as shell structures in order to span larger distances. Light shell structures have a very important role in the contemporary architectural practice which can be seen in many projects (Tepavcevic et al. 2017); (Jordan et al. 2015); (Menges et al. 2015); [1]; (Thönnissen 2014). Since FAS were made of linear elements, connected and set in a grid, they are named gridshell structures. Gridshells have many advantages compared to other shell structures such as lighter weight, low construction cost and ease of assembly and disassembly. Grid arrangement topology presents a big challenge to the architects and designers, since many architectural values like functionality, aesthetics, social, environmental and economic values can be affected by the topology design.The aim of this paper is to present novel topology design methods for form-active gridshell structures. The advantage of these methods is that the designer is able to use a desired shape in advance and have more control over the topology as it will appear in the final design. This approach allows deriving various patterns of the elements arrangement in order to achieve different aesthetic, architectural and structural criteria. Design results are tested through a physical prototype.

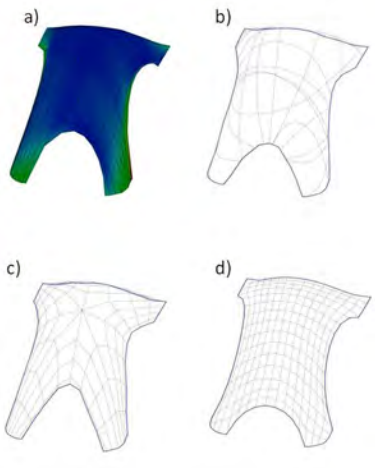


Figure 1
Types of arrangement patterns a) initial form, b) irregular pattern derived before shape generating, c) regular pattern and d) regular pattern derived after shape generating

## FAS TOPOLOGY DESIGN METHODS

Two different types of methods for deriving FAS' shape during the design process are presented. In both methods the aim is to create the topology while having the control over the desired shape.

### *Top-down method*

In the top-down method, the desired 3D shape is generated first and then the topology is created on it. The structure is self-supported, generated utilizing the physics simulation on a simple regular topology. There are many applications that can be used to obtain the final shape out of a simple quad geometry like kangaroo (Piker 2013), rhinoVault [2] or karamba (Preisinger and Heimrath 2014) (Fig 1a). All of the listed applications provide proper results and have a similar workflow. After the shape is determined, there are several ways to define the topology:

- manual modeling of the elements,
- slicing geometry (Fig 1b) and
- subdivision and rebuilding geometry as basis for extracting edges (Fig 1c).

**Manual modeling of the elements.** Manual modeling is a method which implies drawing 3D polylines on the initial form. CITA presented their algorithm for interactive manual modeling method where the final elastica shape of linear elements is derived in real time as the designer draws the polyline. An approach like this may be interesting for designers who do not have a final shape which they want to follow and if that is a given task, then this approach can have some drawbacks. In the process of drawing polylines, the designers have to consider lengths of elements, element's intersection points and overlapping segments, since all of these topology parameters are very important for the process of deriving the final model. For example, in order to connect two linear elements, vertices of the polylines' segments have to be overlapping which is very tedious due to the process of drawing a polyline on a form with a restricted number of control points. This approach is tested on the physical model of FlexiSpot pavilion which required a lot of failed attempts to derive the final form and a lot of time for exploring the ways to avoid these topology flaws.It can be stated that manual modeling is a time-consuming process which requires a lot of manual labor. It can be effective in the manner of obtaining a topology that appears to be satisfying for a designer at the moment of modeling, but that requires high level of experience.

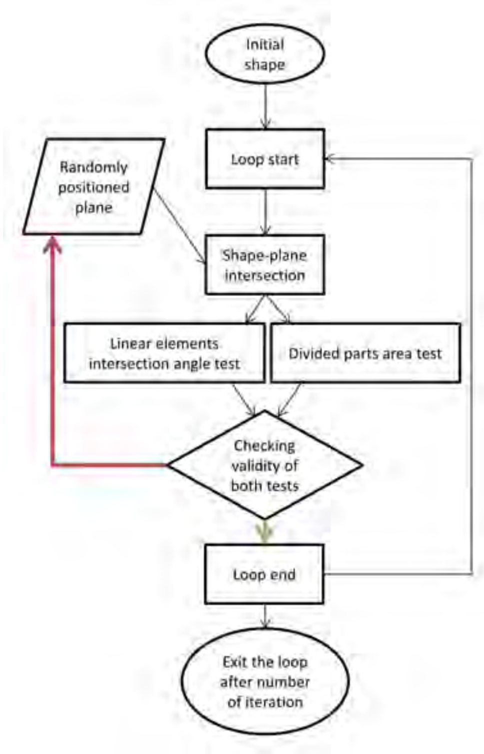


Figure 2
Algorithm for Slicing method

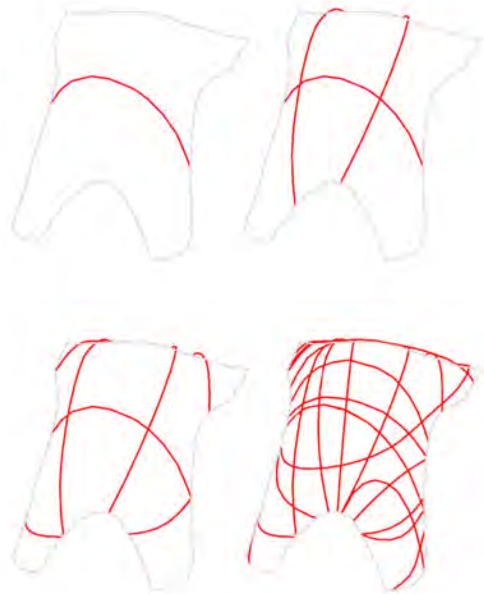

Figure 3
Slicing geometry method, step by step

**Slicing geometry.** Slicing geometry is a process in which the form is sliced by a set of randomly positioned planes, creating the segments for the next design phase (Fig 2). Linear elements are generated as a result of the intersection between the form and the planes (Fig 3). The set of planes is generated in a way to avoid unfavorable situations. Unfavorable situations appear if the angles between the polylines generated after the slicing are smaller than a certain threshold value (which depends on the size and material of elements, scale of the model etc.) or if the area between those polylines is too small which can disable the connection of the elements. On the other hand, in this approach the designer does not have to worry about elements' connection since the slicing method allows creating elements strictly on the surface of the initial form and the elements are intersecting perfectly.

**Subdivision and rebuilding geometry.** This approach includes creating geometry which is appropriate for edge extracting. With subdivision and/or rebuilding mesh geometry, the possibilities for generating various topologies are large. In this approach the initial geometry is used as a reference form, while other joined meshes are "stretched" over it. The shape of these joined meshes can also be diverse, leaving the designer free to choose the most appropriate solution. After choosing the right shape, various subdivision schemes such as Catmull-Clark, Doo-Sabin, Loop, Midedge, Kobbelt, etc. can be applied to investigate the proper edge topology. Furthermore, these mesh edges are extracted and joined to create linear elements of gridshell. At this point, proper joining of the edges is crucial.In order to outgo this potential issue, an algorithm for proper edge recognition is created (Fig 4). Proper edges in this case are the ones that form an angle as closest to 180° with the initial edge. Since the connection of n linear elements in the gridshell creates a set of 2*n prongs it can also be recognized in the mesh topology with vertices of even number valence. In the set with an even number of prongs, symmetry can be found, and hence every edge has its pair. That pair is an edge(s) connected with the randomly selected initial one, and closes the angle closest to 180° with it (Fig 5). These edges are then joined, and further on are defined as a single edge (polyline). An algorithm for recognizing proper pairs of edges is basically a loop where this step is repeated until the polyline remains with no proper pairs and after that, some other randomly selected edge becomes the initial one and the process repeats while all edges are extracted as polylines. Depending on how the topology of the mesh is defined, it can have singular vertices with odd valence. On the physical model of gridshell structure this phenomenon is not an issue since one linear element, which does not have its pair, can be ended in that singular point. In this case, that end is extended and connected with another element by an overlapping connection, i.e. one prong is duplicated (creating an even number of prongs) and is associated to the prong that does not have its pair.

The subdivision and rebuilding mesh geometry as basis for extracting the edges provides a large variety of topologies based on the regular or semi-regular patterns and one of the most suitable is quad subdivision.

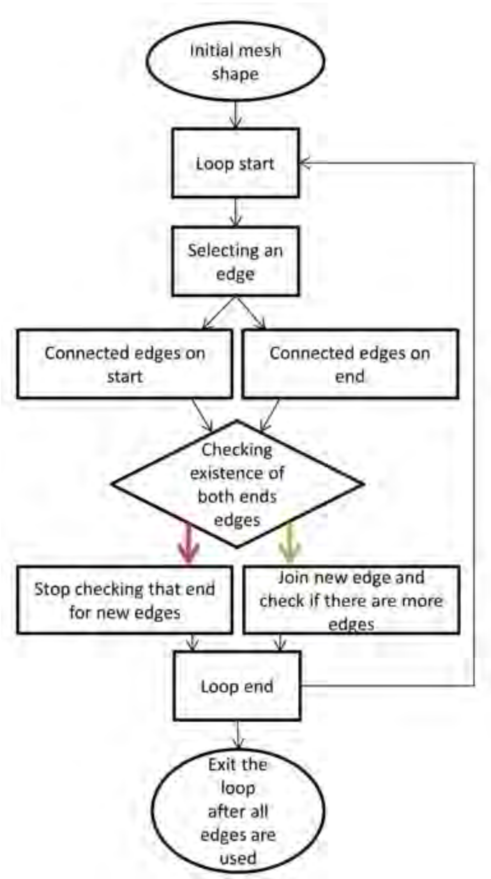


Figure 4
Algorithm for edge recognizing in subdivision approach

## ***Bottom-up method***

The bottom-up method presents a workflow where the design of the topology (manual modeling of elements, slicing geometry or subdivision rebuilding mesh geometry) comes before generating the desired 3D shape. The topology design phase is related to the planar modeling. Hence manual modeling is more appropriate in this method then in the top-down method. Since the generated shape is projection-based, slicing the shape before it is generated is not recommended. Angles between the generated and the optimized polylines may be corrupted, and affect the shape generation. Other topology defining ways, subdivision and rebuilding geometry, give similar results if applied before or after the shape construction. If it is applied before, the arrangement of polylines can be simpler which affects aesthetic, architectural and structural criteria (Figure 1d).

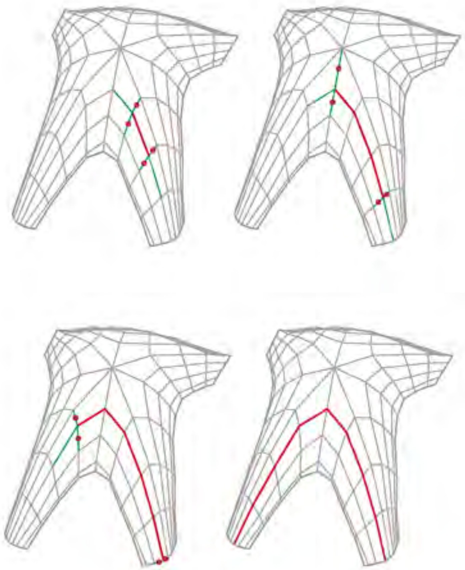

Figure 5
Finding edges in subdivision geometry method, step by step

## EVALUATION OF GIVEN METHODS

The evaluation of given methods can be divided in several aspects such as pattern regularity, impact on the final 3D gridshell shape, time and labor consumption and connection topology criterion. When speaking of pattern regularity, we mainly mean the geometrical properties of fields between linear elements and their arrangement. The connection topology refers to point connection (where a tangent of curvilinear element is not constrained at all) or linear connection (where a tangent of curvilinear element is constrained with a tangent of the connected element). Time and labor consumption (including designer's experience) is more subjective evaluation based on an empirical research.Manual modeling is an approach where the designer has the most design freedom in the manner of elements' size and arrangement and their mutual connections. The pattern can be both regular and irregular. According to this, manual modeling demands more time and labor consumption and more importantly, high level of designer experience.The geometry slicing approach gives irregular patterns related to the randomly positioned slicing planes involved in the process. The whole process is almost fully automated which implicates less time and labor consumption and experience required. In this approach there are only point connections provided.Subdivision/rebuilding approach is between the two previously mentioned approaches in many aspects. The geometry of the pattern is regular or semi-regular, consisting of rectangular, rhomboid, triangular, hexagonal or mix of two or more shapes. Based on this regularity of the pattern, the connections are usually points, but in special cases, in the singular points, linear connections may appear. This method demands medium time/labor consumption and some experience with mesh topology.The impact on a 3D gridshell shape is related to basic approaches - top-down and bottom-up. As mentioned before, top-down approaches give 3D shape in the first steps, while in bottom-up methods final shape is established at the final stage of the process. These criteria are shown in Table 1 and can be used as guidelines for further gridshell design and its topology exploration.

Table 1
Evaluation of given methods

| | | Geometry criterion | Impact on final 3D shape | Time/labor consumption | Connection topology |
|---|---|---|---|---|---|
| Top-down | Manual modeling | Regular and irregular | big | big | Point and linear |
| Top-down | Slicing geometry | Irregular | big | small | Point |
| Top-down | Rebuilding/ Subdivision | Regular | big | medium | Point (linear) |
| Bottom-up | Manual modeling | Regular and irregular | small | big | Point and linear |
| Bottom-up | Slicing geometry | Irregular | small | small | Point |
| Bottom-up | Rebuilding/ Subdivision | Regular | small | medium | Point (linear) |

## FABRICATION AND ASSEMBLY OF THE PHYSICAL MODEL

In order to test the methods presented in this paper, a physical model was created. In this case, manual modeling method is used because of its large freedom for design, simultaneously related to specific functional demands of the exhibition where the physical model in form of a pavilion is presented. Important process in this phase was careful extraction of polyline curves from the generated model and their labeling for fabrication and assembly. Elements are made out of glass fiber reinforced polymer rods and steel cables which are cut to a specified length and marked on the spots where the connection with other elements is expected (Fig 6-8). The result is a physical model which represents a self-supported structure and it can be utilized as a skeleton for further enveloping or as an armature for molding and sculpting complex forms (Fig 9-10).

Figure 6
Connections of linear elements

Figure 7
Connections of linear elements

Figure 8
Finished skeleton of the structure

Figure 9
Physical test model of FAS with irregular pattern

Figure 10
Physical test model of FAS with irregular pattern

## CONCLUSION

In this paper we presented methods for generating different topologies for the design of gridshell FAS in which the designer has the control over the desired final shape and the topology. It is shown how the topology can be created in different ways in order to affect many architectural values like functionality, aesthetics, social, environmental and economic values. Based on different design patterns, the presented methods increase the capacity for the cost-efficient design of gridshell structures. Considering the rapid progress in the field of FAS, this research may provide solutions for the further improvement of the process of FAS design. The evaluation of presented methods gives a guideline for future design of FAS. This research is conducted by exploring various forms and their topologies, but the variety and the number of different examples, especially more complex ones, can be extended in future work.

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# An integrated robotically-driven workflow for the development of elastic tensile structures in various scales

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*This paper presents an ongoing work towards the development of an integrated robotically-driven workflow that can be used for the design, development and subsequent fabrication of small-to large-scale elastic tensile mesh structures. This approach involves digital form-finding and optimization, driven by robotic manufacturing principles and it aims to overcome the limitations of currently available tools, to work either in the design or the fabrication phase of the process. At the same time, it involves the fabrication of systems in several scales followed by respective analyses of results according to the specific type and diameter of the material used. Specifically, form-finding and optimization are responsible for controlling the pretension of the elastic threads, aiming to determine the final tensile mesh and to generate the additive robotic tool-path. In parallel, the type and diameter of the material involved, define the necessary changes of the end-effector tool, which is responsible to implement the process. Despite that design results can be in any scale, for study purposes an experimentation into a small-scale is conducted, to evaluate the suggested automated construction process in general and the end-effector mechanism in particular.*

**Keywords:** *Tensile structure, elastic material, optimization, robotically-driven workflow, robotic fabrication*

## INTRODUCTION

The knowledge in regard to the design and fabrication of tensile mesh systems requires an in-depth investigation of their geometric, static and construction complexity. Similar information can be derived from natural mechanisms such as silk, spider weave and soap films. The study of such mechanisms through physical experimentation and digital simulation enables a deeper understanding of their form and structural behaviour. Nevertheless, a comprehensive integration of these results within a design and fabrication workflow requires the development of innovative design tools and digital fabrication mechanisms (Duro-Royo et al, 2015). In order to achieve structural efficiency as well as accuracy and precision regarding the physical results obtained, new directions of research require a more interactive relationship between design and fabrication.

Initial ideas trace back to the work of Frei Otto in the Stuttgart Institute of Lightweight Structures, where soap films or other materials were used for physical form-finding (Otto et al, 2006). The gradual introduction of digital tools for form-finding and, in parallel, the ability to simulate the behaviour of any material (Gramazion and Kohler, 2008) allow progressive integration of manufacturing processes within this area of research. A principal factor in this procedure is the material deformation behaviour, which varies according to the changes occurring during fabrication. Another issue that is taken into account is the scale of production that varies and depends on the ability of the mechanisms provided.

As regards the digital design and static analysis part of the process, techniques might range from form-finding to spring-based simulation, sometimes integrated with optimization techniques, for instance by applying Genetic Algorithms (GA). As regards the fabrication workflow, the continued development of automated construction techniques open new directions that move beyond a conventional physical form-finding method towards an automated procedure that might include and/or combine design and construction experimentation (Keating and Oxman, 2013). The use of industrial robots, aerial robots or gantries improves the control of the process, allowing, in parallel, an easy scale up or scale down of the structural systems under production. In addition, the advanced kinematic flexibility of mechanisms leads to a number of advantages as compared to conventional approaches, such as the safety of workers and the control accuracy of materials.

All the above lead to the development of integrated digital design to fabrication techniques that might include user-friendly interfaces for design exploration, which combine real-time form-finding methods, structural optimization control and robotic simulation (Braumanm and Brell-Cokcan, 2012), together with techniques that enable the construction of innovative materials in a wide range of scales. Related works in this direction can be found, for instance in the experimental investigation undertaken in (Wendy and Antoine, 2016), where semi-autonomous wall-based robots are developed for the weaving of a small installation with carbon threads. The main advantage of this example is that it enables the materialization of new structures that would be impossible to build by employing normal fabrication strategies. Based on similar material principles, in the example of (Knippers et al, 2012), a custom-made tool is developed and mounted on the robotic arm for controlling and feeding with thread material. By applying robotic simulation, form-finding and structural performance analysis, the construction of the overall structure can be effectively achieved. The simulation of robotic movement behaviour, the tool-path generation and the structural performance allow the adjustment of robotically-driven workflows in real scale structures.

## SUGGESTED METHODOLOGY

The integration of form-finding, structural optimization and robotic fabrication principles is in the forefront of the current research study, which aims to investigate the ability of the proposed workflow to achieve robust results in terms of their shape, static behaviour as well as constructability. Within this framework, this work focuses on the development of a parametrically controlled algorithm that can be used for the manufacturing of elastic tensile structures in various scales. The aim is to optimize the elastic tensile behaviour and hence the robotic tool-path in order to achieve an automated fabrication process that can respond to different needs. This is achieved through the involvement of several parameters and criteria that include material characteristics such as elasticity and diameter, additive weaving techniques as well as design decisions, affecting the end results of mesh structures.

The suggested algorithm is developed in the parametric design environment of Grasshopper [1], a plug-in for Rhino software [2], aiming to formulate the three-dimensional input surface and to control the initial curvature, the surface division and the scale, which influence the mesh configuration. The process of form-finding is achieved using the physics-based software Kangaroo (Piker, 2013), a plug-in for Grasshopper. The static equation aims to simulate the non-linear mesh behaviour (Figure 1). An important aspect of elastic mesh system development is the balance occurring between the material pretension and tensile strength that prevents the establishment of high sag threads geometry. The relaxation process of threads is achieved in digital environment using spring behaviour. The springs strength is described by the mathematical equation $K = \frac{A \cdot E}{L}$ ,where K is the spring stiffness, A is the cross-sectional area, E is the (tensile) elastic modulus of the rubber (Polyurethane Elastomer) thread (0.02 GPa) and L is the length of the thread. Thus, during the simulation process, pretension forces are applied on threads that cause overall deformation and stabilisation of grid structure. In parallel, using the general-purpose civil-engineering software SAP2000 [3] the form-finding results are evaluated and correlations with the parametric ones are derived.

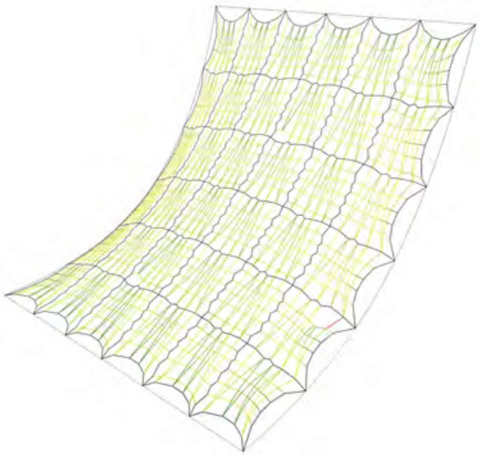


Figure 1
Final weaving pattern applied in real scale case-study B.8

The complexity of parameters and material limitations lead to the introduction and development of a multi-objective optimization analysis process based on MOGA (Deb, 2002). The optimization process controls the material section and the pre-stress behaviour as well as the construction parameters such as dimension of nodes and positioning (Kilian and Ochsendorf, 2005). The results are based on the material tensile strength (5MPa) and the parameters of end-effector tool that enable the handling of the additive process using an industrial robotic arm (Kontovourkis and Tryfonos, 2016). Through the simulation, a population of best solutions is generated. The Pareto front suggests a series of best solutions followed by the selection of desirable ones based on their ease of robotic fabrication, on their static behaviour under external load and on their initial morphology.

The suggested automated fabrication workflow (Figure 2) aims to generate a weaving tool-path that is responsible for the progressive addition of material, leading to the deformation of the overall mesh. In order to evaluate the results of digital optimization workflow and to observe the effect of robotic fabrication within the framework of an actual construction procedure, the proposed scenario is implemented using small-scale physical prototypes.In this paper, the aim is to investigate different surface categories of the best tensile mesh solutions through the design of eight case-studies with different Gaussian curvatures. Within this framework, studies regarding the pre-stress of elastic threads and the topology of the nodes are also undertaken. The purpose of this investigation is to evaluate and correlate the solutions in each category as well as their case studies, based on structural performance criteria and fabrication constrains, allowing an automated mesh weaving process through the industrial robotic arm ABB IRB2600. Some important aspects for the typological development of the elastic threads are the limitations of the custom-made end-effector tool to effectively handle the rubber (Polyurethane Elastomer) thread of ⌀0.8mm. As the continuous motion of the robotic arm determines the initial morphology of the nodes and threads, the simulation, the analysis and the multi-objective optimization of the morphology control the pre-tension that influence robotic fabrication.

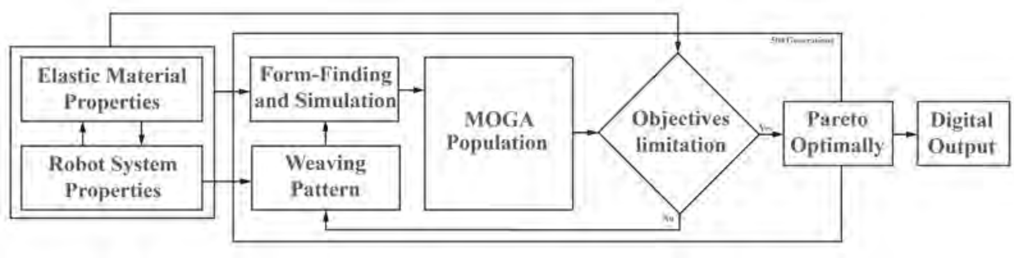



Figure 2
Diagram of the robotically-driven optimization workflow

## GEOMETRICAL CONFIGURATION AND FORM-FINDING

In detail, the research explores eight different input categories with different Gaussian curvatures in the weaving algorithm. The geometric development of the categories for each elastic mesh is determined by the gradual change of two basic lines A and B at a distance (y). In parallel, changes of tree control points in lines (start, middle and end) in z-axis for each category results in eight surface variations with the two combined curves. The categories are developed base on 1x1 YZ coordinate system, allowing the easy scale down or scale up in any direction. Aim is to investigate the behaviour of the elastic mesh weaving algorithm by correlating the initial Gaussian curvature (Ks) and the final mesh Gaussian curvature (Kf) values. The Figure 3 shows the nine interior points of which the initial and final Gaussian curvature are measured.

### *Categories of weaving patterns*

The category A shows the same transformation of A and B curves in the midpoint with value 0-0.7m. Each change occurs by increasing the position of midpoints by 0.1 meter and this creates the surface cases (A.1) to (A.8). Similarly, in category B, the changes occur simultaneously in both curve mid and end points. The midpoints are moved with the sequence (B.1) = 0, (B.2) = 0.05m and (B. 3) - (B.8) = 0.1m by changing the parameter at the end points of the curves with an increase of 0.1m per case from (B.1) = 0 to (B.8) = 0.8m. Through those changes, it is observed that in all eight cases in categories A and B, the surface Gaussian curvature (Ks) is zero. Thus, this is the result of the equation $K_s = \frac{1}{R1} \cdot \frac{1}{R2}$ where R2 = ∞ (Block et al, 2014).

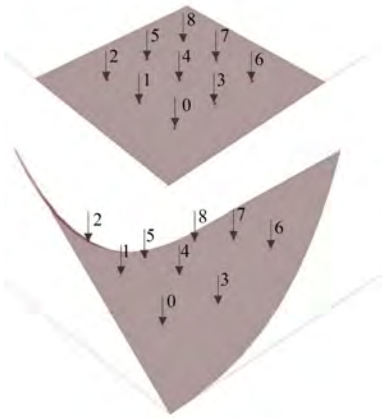



Figure 3
Gaussian curvature measuring points

In categories C the change occurs in the curve B, where the midpoint moves to 0.1m in case (C.2) and remains constant in cases (C.2 to C.8) = 0.1m. Alongside, the endpoint changes 0.1m per case with maximum value 0.8m in case C.8. The changes in each case causes a gradual increase of surface Gaussian curvature with a maximum Ks = -1.24 unit at case C.8 point 8. Similarly, in category D the changes occur only in curve B, with the midpoint varied 0.1m per case from (D.1) to (D.8) with a maximum value 0.7m. Those transformations cause symmetrical changes in

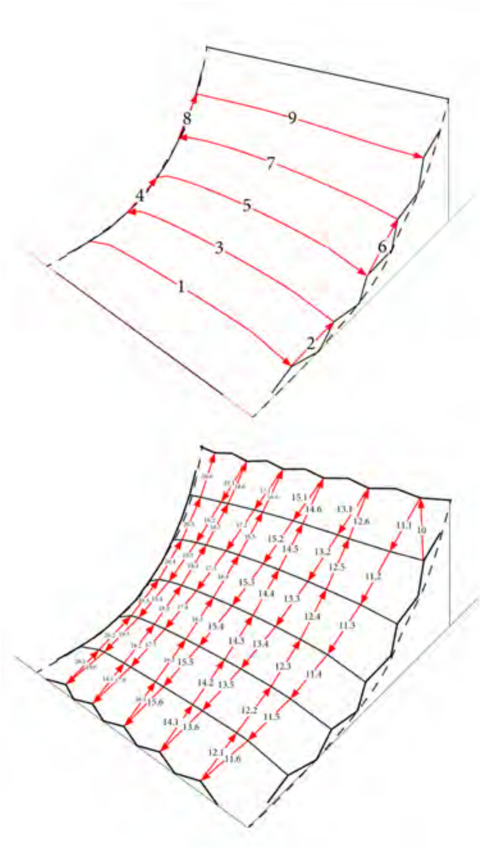


Figure 4
Wave sequence of the elastic thread

surface curvature, with points 0 and 6, 1 and 7 to have the same value, point 3,4,5 to have zero value and point 2 and 8 maximum value in case (D.8) with Ks = -1,77 units. The typology E has similar parameters with categories C and D to affect only curve B. The transformation occurs at the mid and end points of the curve B. In case (E.2) the mid and the end point have initial values 0.1m and 0.2m and this is increased at 0.1 per case (E.3) to (E.8) with maximum value 0.7m and 0.8m respectively. The movement of the points causes a maximum change of surface curvature Ks = -1.46 units at point 2 and the minimum change at points 6,7,8 with Ks value -0.3 to -0.5 units. The category F shows changes at both curves. In this case, the change occurs simultaneously at start and end point of curve A and at the midpoint of curve B. In case (F.2) the value sets at 0.2m and from (F.3) to (F.8) is increased by 0.1m per case with the maximum value of 0.8m. Consequently, surface Gaussian curvature changes in points 0,2,6,8 and 1,7 record the same value. Maximum value can be found at points 0,2,6,8 with Ks = -2,79 units, at points 1,7 with Ks = -12,68 units and at points 3,4,5 with fixed Ka = 0.

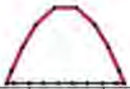
Category G applies same transformation principals with categories C at both curves A and B. In curves A and B midpoint is moved with the sequence (G.1) = 0, (G.2) = 0.05m and (G. 3) - (B.8) = 0.1m. The curve A start point and curve B end point are increased by 0.1m per case from (G.1) = 0 to (G.8) = 0.8m. Therefore, the same value of Gaussian curvature is observed at points 0 and 8, 2 and 6, 1 and 7, 3 and 5, with a maximum curvature value Ks = -1,32, Ks = -1,46, Ks = 2.01, Ks = -1.92 units respectively and with maximum value at point 4 to be Ks = -3.02 units. Based on the results of case (G.8), in category H, curve's B midpoint from 0.1 value at (H.1) to 0.8 at (H.8) are increased. In result of the transformation, the surface Gaussian curvature maximum value shifts from point 4 to point 1 and 2, where at (H.8) is observe a maximum value of Ka = -7.92 and Ka = -6.35 units respectively. The table 1 shows the Z-axis movement of point in the curve A and B and the initial surface Gaussian curvature values.

### *Weaving development process*

The simulation of the weaving algorithm aims to investigate the physical behaviour of the rubber elastic mesh for every surface variation of each category, testing in parallel the ability of the workflow to define the nodes sequence for the robotic toolpath generation. Furthermore, the parameters controlling the initial geometry can define the size of the surface and the weaving pattern density, the (div) that is the surface division in x and y direction, influencing the pattern density, the space (y) that is the distance between curves defining the surface and the value (x) that is the distance of start to end point of each curve. This, in the small scale models for the robot working area, is (div) = 1 of total of 1 pattern unit, y = x = 0.7 m and for a full scale model (div) = 6 of total 36 unit patterns, y = x = 4 m. In detail, the 2 lines are divided by the parameter (N) in 9 or 11 or 13 equal nodes that are connected in one direction with the weaving sequence A3, B3, B5, A5, A7, B7, B9, A9, A11 and B11 creating springs 1-9. Then, B11 is connected with D1 with an additional spring. The weaving sequence continues in the other direction from D1 to C2 and intersects and divides any existing spring into two segments. Then, the process is repeated with the sequence C2, D3, C4, D5, C6, D7, C8, D9, C10 and D11, leading to the creation of spring between two nodes. In addition, the notes can be moved separately in the curve by 25-75% of the neighboring unconnected points. The remaining unconnected points on A, B, C and D curve are the connecting nodes to the adjacent units and/or to the anchor points leading to the results that represents the initial geometry of the tensile mesh system in Kangaroo plug-in (Figure 4).

### *Physics-based simulation for form-finding*

Initial investigation on the material deformation and the tensile forces, which are applied in the elastic thread have been determined in previews research (Kontovourkis and Tryfonos, 2016). The prestress is calculated based on the robot end-effector capability to apply accurately holding force in the thread during the prestress and the node creation process. This parameter is described by the thread length and the initial point distance (L/D) and is set at lower value of 70% for maximum deformation and at maximum value of 100% without deformation. Therefore, the change of (L/D) factor intends to set the prestress in the overall elastic mesh structure in order to avoid thread sags. Thus, based on the surface Gaussian curvature (Ks) results, where the anchorages-nodes can be moved from 25-75% affecting the mesh typology and curvature, the aim of this investigation is to further control tensile stress behaviour.

<table>
<tr><td colspan="2">Categories</td><td colspan="6">A</td><td colspan="6">B</td><td colspan="6">C</td><td colspan="6">D</td></tr>
<tr><td colspan="2">Curves</td><td colspan="3">A</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td></tr>
<tr><td rowspan="3">C (m)</td><td>Start</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td>Mid.</td><td colspan="3">0-0.7</td><td colspan="3">0-0.7</td><td colspan="3">0-0.1</td><td colspan="3">0-0.1</td><td colspan="3">0</td><td colspan="3">0-0.1</td><td colspan="3">0</td><td colspan="3">0-0.7</td></tr>
<tr><td>End</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td colspan="2">Black = A curve<br>Red = B curve</td><td colspan="6"></td><td colspan="6"></td><td colspan="6"></td><td colspan="6"></td></tr>
<tr><td colspan="2" rowspan="3">(-)Ks</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0.15</td><td colspan="2">0.85</td><td colspan="2">1.24</td><td colspan="2">1.77</td><td colspan="2">0</td><td colspan="2">1.77</td></tr>
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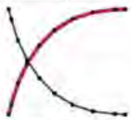
<tr><td colspan="2">Categories</td><td colspan="6">E</td><td colspan="6">F</td><td colspan="6">G</td><td colspan="6">H</td></tr>
<tr><td colspan="2">Curves</td><td colspan="3">Curves</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td><td colspan="3">A</td><td colspan="3">B</td></tr>
<tr><td rowspan="3">C (m)</td><td>C (m)</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0.8</td></tr>
<tr><td>Μέσο</td><td colspan="3">0</td><td colspan="3">0-0.7</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0-0.1</td><td colspan="3">0-0.1</td><td colspan="3">0.1</td><td colspan="3">0.1-0.8</td></tr>
<tr><td>Τέλος</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0-0.8</td><td colspan="3">0</td><td colspan="3">0.8</td><td colspan="3">0</td></tr>
<tr><td colspan="2">Black = A curve<br>Red = B curve</td><td colspan="6"></td><td colspan="6"></td><td colspan="6"></td><td colspan="6"></td></tr>
<tr><td colspan="2" rowspan="3">(-)Ks</td><td colspan="2">1.46</td><td colspan="2">0.44</td><td colspan="2">0.05</td><td colspan="2">2.79</td><td colspan="2">0</td><td colspan="2">2.79</td><td colspan="2">1.46</td><td colspan="2">1.92</td><td colspan="2">1.32</td><td colspan="2">7.92</td><td colspan="2">1.18</td><td colspan="2">0.07</td></tr>
<tr><td colspan="2">0.81</td><td colspan="2">0.24</td><td colspan="2">0.03</td><td colspan="2">12.68</td><td colspan="2">0</td><td colspan="2">12.68</td><td colspan="2">2.01</td><td colspan="2">3.02</td><td colspan="2">2.01</td><td colspan="2">6.38</td><td colspan="2">1.18</td><td colspan="2">0.07</td></tr>
<tr><td colspan="2">0.44</td><td colspan="2">0.14</td><td colspan="2">0.02</td><td colspan="2">2.79</td><td colspan="2">0</td><td colspan="2">2.79</td><td colspan="2">1.32</td><td colspan="2">1.92</td><td colspan="2">1.46</td><td colspan="2">1.56</td><td colspan="2">0.82</td><td colspan="2">0.07</td></tr>
</table>

Table 1
The initial surface Gaussian curvature for the 8 categories

The simulation is accomplished using the particle-spring behaviour modelling in Kangaroo plug-in for Grasshopper. To verify the process for the deformation results, the SAP2000 software is used. The material has high tensile strength (Fts = 5Mpa) and yield stress (Fy = 3MPa) compared to the elastic module (E= 2Mpa) and its Poisson's ratio is set to 0.5. All material characteristics are used as tendons inputs in the software. Therefore, the threads are simulated as cables with diameter 0.8mm with deformation prestress and self-weight of ρ = 0.93 Mg/m3 (Ashby, 2011). Also, the node mass in calculated as point load with value -0.012985N. The SAP2000 nonlinear analysis shows that the Kangaroo form finding have 0.1mm - 0.6mm deviations that can be used for the elastic mesh simulation. Subsequently, in case of scale changes, the algorithm allows input thread diameter range from 0.8mm to 20mm and this enables setting of external loads.

## OPTIMIZATION PROCESS AND RESULTS

The use of multi-objective optimization process via genetic algorithms (MOGA) allows handling of several multiple criteria and parameters leading to a range of acceptable and close to the optimum results. For optimization purposes, the Octopus optimization engine (Vierlinger and Bollinger, 2014) (plug-in for Grasshopper) is applied. The continuous alternation of the anchorages from 25%-75%, thread diameter 0.8 - 20mm and the length factor L/D 70-100% of mesh are simulated in Kangaroo plug-in, developing a population of acceptable solutions associated with the tensile stress, the amount of material used, the total deformation material and the allowed material tensile strength (Fa). This is based in the mathematical equation $F_a = \frac{F_{st} \cdot A}{S.F}$ (A= section area, S.F = safety factor = 1.35) (Stranghöner et al, 2016). Also, simulation is associated with the material external load (1kN/m2) and the capabilities of the custom-made end-effector tool. The selection of best solutions based on their tensile performance behaviour, the material deformation under external load and the length of threads are achieved using the Pareto front (Pareto optimality). In case of the small scales experiments, the external load is set to zero and consequently the deformation under load is always zero. Therefore, the small-scale case studies locked the thread diameter parameters for the optimization process, since the diameter of available material is 0.8Ø.

The best results formulate the population of 100 solutions in each generation for 500 generations and are evaluated based on the reduction of the average tensile force, the reduction of material deformation under external load (small-scale case studies = 0) and the total length of the deformed threads. The deformation of threads, the length amount of threads required, the tensile forces and the curvature are the criteria to evaluate the static performance and constructability of structure in each case through 500 generations. By the application of multi-objective optimization process a range of possible results are produced. These are distinguished in two categories of optimum results based on their: a. Static behaviour by prioritizing tension and thread deformation changes, b. Geometrical configuration by prioritizing curvature changes.

Figure 5 shows the best trade-offs for generation 0,50,100,250 and 500 in the case (F.8). The graph describes the relationship between the average of the tensile stress and the length of the deformed thread, where in the 500th generation the best Pareto curve appears. The results shown that the solution (a) with the minimum tensile stress average 0.2649KN has the higher L/D factor = 73.22%, lower section diameter 0.9mm and deformation length material with value 415.8378m, with material length 282.2888m. In this case, the thread deformation under external load is maximum at 7.5106m, showing that this solution is the less statically acceptable with high node displacements and the most geometrically preferable with the lower final curvature (Kf) = -0.3098. Alternatively, the solution (d) with the maximum tensile stress average 110.9773KN has the lowest L/D factor = 70%. higher section diameter 16.96mm and

| Solutions | a | b | c | d |
|---|---|---|---|---|
| L/D(%) | 73.22% | 71.01% | 70.23% | 70% |
| Diameter (mm) | 0.9 | 1.33 | 2.3 | 16.96 |
| Average Tension(N) | 0.2906 | 0.6961 | 2.0484 | 110.9773 |
| Total Material Used (m) | 282.2888 | 269.5728 | 269.5709 | 269.5726 |
| Total material loaded deformation (m) | 7.5106 | 1.3724 | 0.1905 | 0.0010 |
| Average final curvature –($K_f$) | 0.3098 | 0.3177 | 0.3208 | 0.3216 |
| $K = (-K_s) – (-K_f)$ | -0.1064 | -0.1143 | -0.1174 | -0.1182 |

Table 2
Results of case study F.8

the lowers deformation length material with value 409.9157m, with material length 269.5726m. In this solution, the thread deformation under external load is the minimum at 0.0010m. The static systems with the highest average tensile stress compared to systems with less average tensile stress can be considered optimum (Bechthold, 2008) for their static behavior, showing that this solutions are the most statically preferable with the less material length used. However, the maximum average final curvature and the higher section diameter makes this solution the less geometrical acceptable and this will require high pretension from the robotic system.

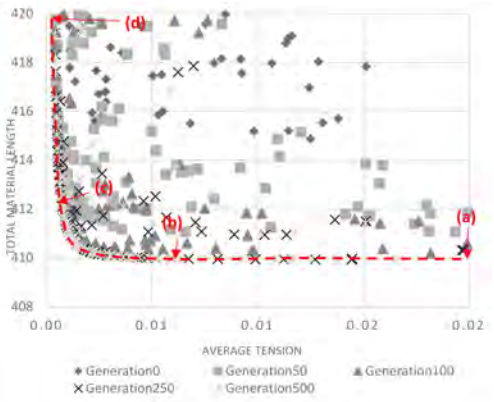



Figure 5
Results of population of solutions through the optimization process for case study F.8

Since all cases are characterized as statically balanced and are retaining the construction parameters of the custom-made end-effector tool and the robotic setup, is decided to select and fabricate solutions that are away from the boundaries and near the center. Thus, acceptable solutions with less material length and better static behaviour are those that approach the maximum allowable (L/D) factor and show a higher average tensile stress and less material deformation under external load (Table 2, solution c). On the contrary, a system with a lower average tensile stress (Table 2, solution b) and a higher (L/D) factor shows less thread deformation, increasing the length of material need and displays more thread deformation under external load. Therefore, the solution (b) considered geometrically acceptable by showing less curvature changes than the original surface.

Through the comparison of case studies in regard to the best geometrical configuration solutions, it is observed that case study A.7 hat the highest average tension with value 7.3471N and C.8 the lowest tension at value 0.375N. Proportionally, the material section diameter is higheest at case A.7 with 5.59mm and lowest at case study C.8 = 0.87mm. Subsequently, case study A.8 has the highest section diameter and the deformation that is caused by external load is the lowest at 0.2650m. Also, case study C.8 has the highest deformation thread under external load with value 6.7018m. Because of the proportional relation, case study A.8 has the highest material in use 316.7124m and the highest Caucasian curvature change K=-0.1722. In opposite, case study C.8 has the lowest material in use 233.5152m and lowest curvature change K=0.0019. Since category G applies same transformation principals such as categories C, archives to decrease the curvature change at K=0.0009 by having the lowers initial prestress L/D=85.98%. Due to this, category G has the optimum geometrically configuration category.

By comparing the best static behaviour solutions, it is observed that case A.7 has highest average tension 20.7863N and case study D.8 the lowest average tension at 0.5155N. Correspondingly, the material section diameter and material used is the highest at case study A.7 with 9.5m and at value 319.6323m respectively. In the other hand, the most economic material categories can be found in case study E.8 that has the lowest section diameter with value 1.3m and in case study C.8 that has the lowest material used with value 233.6752. Comparing the lowest thread deformation under external load, case study A.7 is the optimum static behaviour category.

In conclusion, solutions with high section diameter and high average tension have low deformation material under load and high curvature change and are considered to have better static behaviour. In opposite, solution with higher material deformation, lower average tension and section diameter have lower curvature change and are considered better in terms of their geometrical configuration.

### *Physical prototyping*

The use of multi-objective optimization process via genetic algorithms (MOGA), the continues simulation of the custom-made end-effector tool and the robotic setup (ABB IRB 2600) with the structural behaviour of the elastic mesh allow the selection of the best form-finding solutions. In parallel, continuous refinement of tool path is required due to the deformation of the whole system in each new addition of thread and nodes. The redefinition of the tool path and hence the robotic manufacturing of the final elastic mesh is achieved through the thread by thread progressive simulation of tensile's nodes addition. Preliminary experiments (Figure 6) show that the weaving algorithm and the simulation of the form-finding process can generate a robotic toolpath. In order to achieve high precision of physical models, calibration of the anchor points in the physical and digital model is required. Furthermore, future experiments will aim at the construction of small-scale structures that will fully represent the digital form-finding elastic mesh.

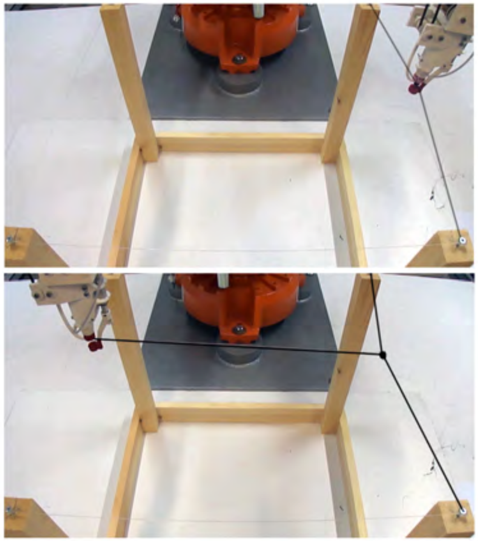


Figure 6
Preliminary experiment on the robotic construction of an elastic mesh structure (Kontovourkis and Tryfonos, 2016)

## CONCLUSION

This paper aims to demonstrate an integrated robotically-driven workflow from small- to large-scale development of elastic tensile mesh structures. Through an analytical investigation, the proposed robotically-driven optimization and fabrication workflow intents to examine the effectiveness of the process to be implemented in various scales using a specific automated construction procedure. The workflow is evaluated against its ability to control the initial design and the suggested form-finding process in an integrated manner, allowing at the same time, an automated weaving technique of manufacturing to occur. Further work will continue towards the physical realization of the results derived from form-finding, simulation and analysis workflow. Also, comparative studies that examine models in digital and physical environment will be developed.


## ACKNOWLEDGMENT

This ongoing research has been conducted within the framework of the research program Optimization Driven Architectural Design of Structures (OptArch) that is funded by the European Commission under the framework of Marie Skłodowska-Curie Actions, Research and Innovation Staff Exchange (RISE), Call: H2020-MSCA-RISE-2015.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# COMPUTATIONAL FABRICATION

# "Lucid" Foam

## *Multi-Axis Robotic Hot-Wire Cutting for Translucency*

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*Hotwire cutting of Styrofoam or Polystyrene has been a popular tool for developing fast prototypes by the architectural community. The introduction of multi-axis industrial robots in the architectural curriculum, and the enhancement of the design to fabrication process by software bridging the gap, provided an alternative meaning to the traditional mostly representational process of hotwire cutting.This paper sets out to document and assess the procedural methodology and the results of a series of integrated design to fabrication experiments that took place in the Institut für Experimentelle Architektur-Hochbau. By channelling design intention towards a component assembly for a translucent effect, students were asked to utilise industrial robots to fabricate and prototype via hotwire cutting, designs that refer to architectural elements. These elements, mainly due to their scale and the commercial availability of bulk Styrofoam panels, can lead to functional or ornamental representations of discrete elements, which can be assembled together as part of a greater design.*

**Keywords:** *Robotic Fabrication, Design Research, Hotwire-Cutting, Polystyrene, CAD-curriculum, translucency*

## INTRODUCTION

Numerically controlled prototyping methodologies, not only affect the way we fabricate things, but in several cases they extend the design process itself and become the cohesive medium for design. Hotwire cutting of Styrofoam or Polystyrene, either extruded(XPS) or expanded(EPS), has been a popular tool for developing fast prototypes by the architectural community. The introduction of multi-axis industrial robots in the architectural curriculum, and the enhancement of the design to fabrication process by software bridging the gap, between the commercially available CAD packages and the numerically controlled programming language of the machine apparatus, (Braumann; Brell-Cokcan 2011), have provided an alternative meaning to the traditional, mostly representational process of hotwire cutting.

This paper sets out to document and assess the procedural methodology and the results of a series of integrated design to fabrication experiments. These took place at the Institut für Experimentelle Architektur-Hochbau at Universität Innsbruck during the period of the Vertiefung Hochbau course. By channelling the design intention towards a component assembly for a either a translucent effect or an

Figure 1
One of the design projects as a suspended light element

ornamental / texturized result, whilst pre-defining the material (Polystyrene foam), students were asked to utilise the ABB industrial robots of REXLab to fabricate and prototype designs that refer to architectural elements (Fig. 1). A Hot-Wire cutter operating as an extension to the robotic arm was also a pre-requisite. The architectural elements produced, mainly due to their scale and the commercial availability of bulk Styrofoam panels, was speculated whether they can lead to functional or ornamental representations of discrete elements, which can be assembled as part of a greater design.

The research intention, is to comprehend whether a non-conventional fabrication process and in extend design methodology can be developed through these experiments, by targeting the material properties of Polystyrene Foam and its inherent capacity of enabling light penetrating its composite

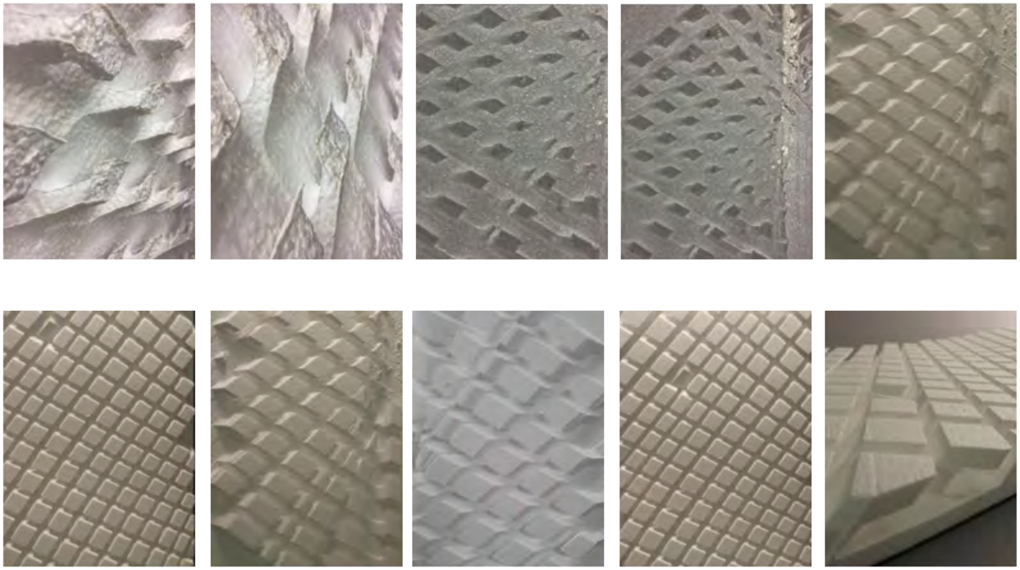
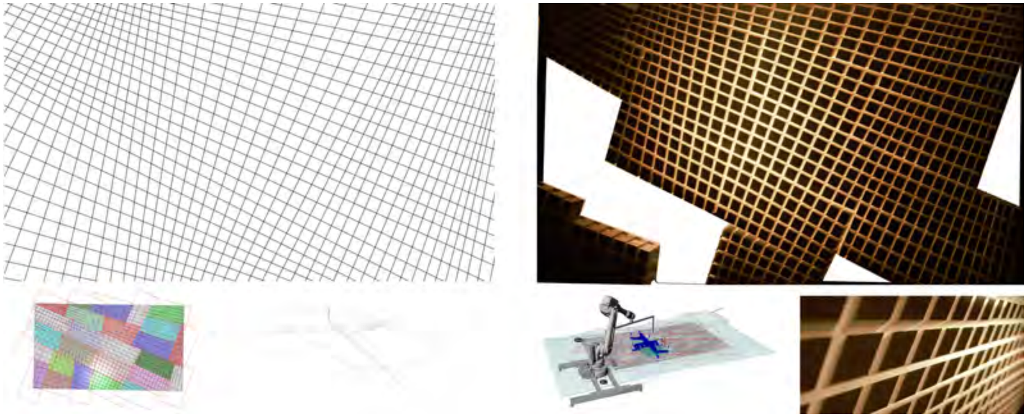


Figure 2
Difficulties with 'perlin noise' effect required lots of test-cuts to evaluate speed, temperature and object placing

Figure 3
Design to Fabrication process for Wall System and back-lit photo

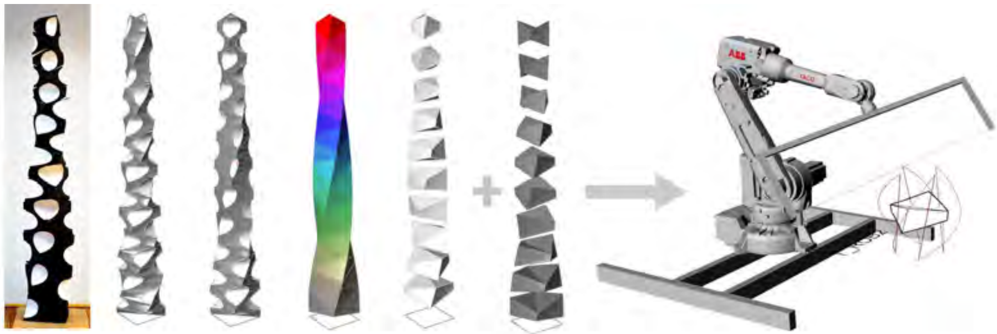


mass. An assessment of the results both on aesthetic and practical criteria (i.e. economy of material, structural integrity, prototyping time, mass customisation) may potentially render the process as universal, since the fabrication constraints are incorporated directly into the form-finding process and the data transfer from the CAD medium to the robots is automated.

## BACKGROUND

Polystyrene due to its inherent characteristics has been used extensively as the formwork for generating moulds for casting construction materials. In the instances where the design is morphologically complex, polystyrene has provided accurate formwork process, but at the same time generated the necessity for equally rapid mass production of these moulds. Constraints as economy of time and material were established, which lead to a transition from the traditional CNC milling to a faster process, that of the numerically controlled hotwire cutting utilising multi-axis industrial robots as the mass customisation medium (Feringa; Søndergaard, 2012, p. 495). In the latter, the designer is called to disengage from "visualising design through an abstract medium" (Evans, 1997), hence moving towards to an integrated approach where design, material and fabrication constraints have to work together as a seam-

Figure 4
Rationalising a twisted geometry and generating the toolpaths for mass customisation.



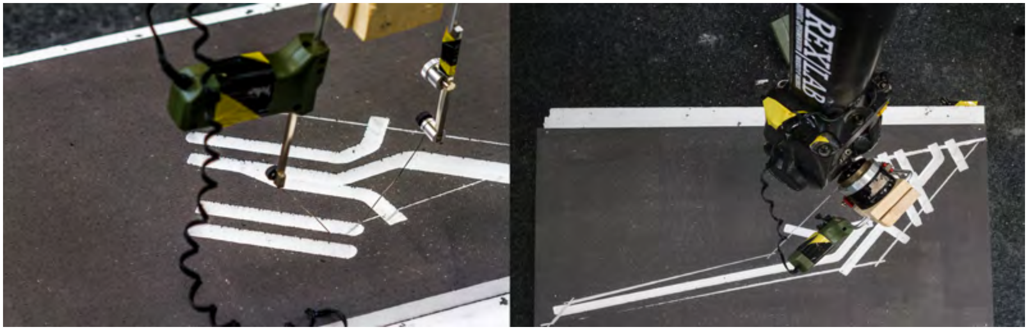



Figure 5
Custom tool subtracting Styrofoam and performing cuts

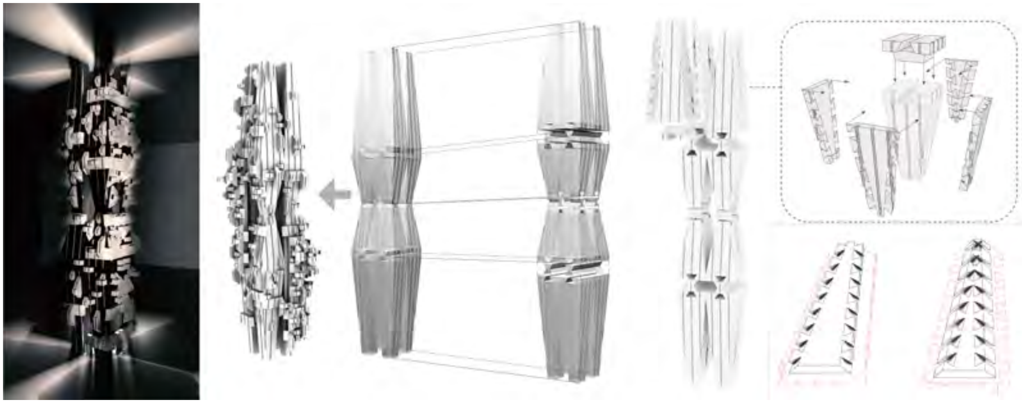
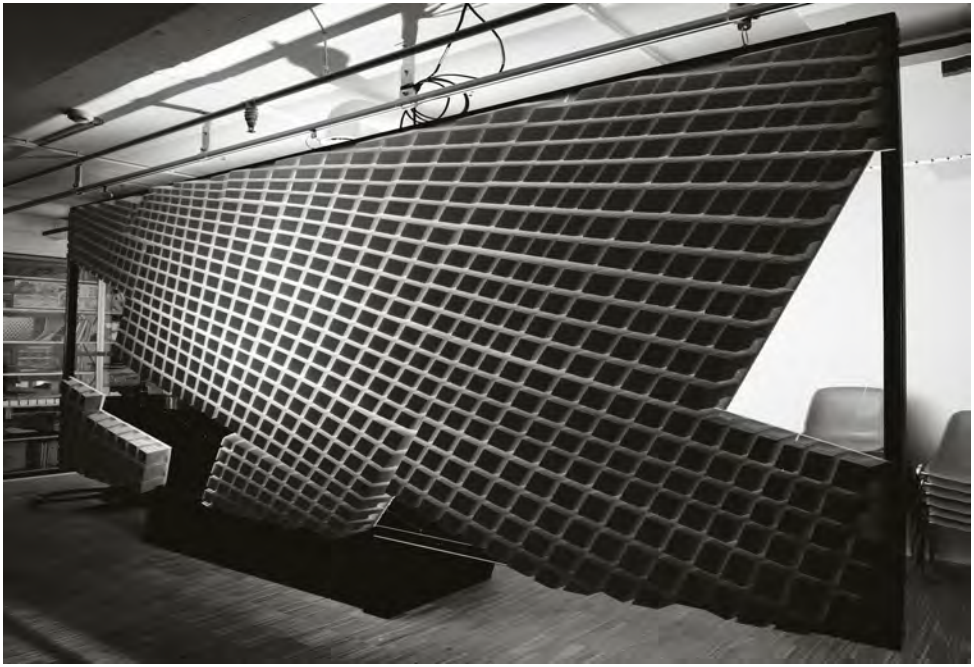


Figure 6
Finger-joint connections and minimising material waste for one of the designs

less non-linear creative process.

Out of the many precedents of Robotic Hotwire Cutting, the methodology used in the conducted experiments follows a similar approach "Linking Robotic Hotwire-cutting and Assembly" (Brell-Cokcan; Braumann 2013) and the "Large Scale Hotwire and Diamond-wire Cutting" workshop (McGee; Feringa 2012) both in the context of the "Robots in Architecture" Conferences. In the latter, as well as in the case of "Robotically Fabricated Thin-shell Vaulting" (Kaczynski et al 2011, p 115) more robust, tectonic materials such as sandstone are employed, hence the original hotwire concept transforms into diamond water-jet cutting. The examined approach differs from these three precedents in terms of the design context. All of the above refer to a discretised assembly of complex geometrically building elements, whereas in the presented research the properties of the material and the fine-tuning of the robotic medium, are put into action, for designs that might not necessarily be complex morphologically, but are focusing on the attribute of translucency or ornament, both in the way they are produced and in the way they are conglomerated. Translucency in robotic fabrication has been addressed in other occasions such as in the "Graded Light in Aggregate Structures" study (Angelova et al 2015, p. 400) where robotically assemble discrete standardised elements

Figure 7
Overall view of the wall-panelling installation with the gradient translucent effect



are articulated in favour of sensing of light as a design initiative. Yet again this approach is different from the research presented, where the material is mostly subtracted to permit light emission.

## INTEGRATED ASSOCIATIVE MODELING FOR ROBOTIC FABRICATION

Four separate design experiments were conducted, each exploring a distinct design scenario based on the given material's properties and the constraints of hotwire cutting as a fabrication methodology. Fig. 2, fig.3 and fig.4 display a panelling system design where dark and light colours are produced solely by material thickness providing different levels of translucency. A gradient translucent effect was the project's requirement, with cross-direction cuts and under-cuts being of varying height or depth from the centre towards the edges of the design, producing the required effect.

Each project dealt with a different geometrical challenge, whether working on flat foam panels or blocks of foam, produced through linear cutting paths varying in height, ruled surfaces or custom-shaped wire for subtraction (fig. 5). Most difficult tasks, demanding high robotic accuracy. were required by the projects with shared edges by two or more components which where also cut by the hotwire cutter (e.g. fig. 4), compared to the ones that the cuts were merely on the surface of a pre-cut foam panel (fig. 3)

The procedural steps followed in the research sequence rely heavily on quick decision making as a reciprocal system between the designer and the machine. These steps can be comprised to the following:

1. Design research
2. Rationalisation and parametric modelling
3. Generating the procedural machine language

from the CAD software
4. Iterative testing with mock-ups using the robots, evaluating the material properties
5. Design rationalisation according to feedback from the mock-ups
6. Fabrication Process and proof of concept
7. Assembly and introduction of light fixings

The software used for associative modelling was Grasshopper3d for McNeel's Rhinoceros3d. Custom written routines in Python enabled both an iterative control over the design process and the generation of tool paths, primarily handled by Taco in Grasshopper3d(Frank et al 2016).

The fabrication methodology constraints were integrated in the parametric workflow of the designs, as they had to adhere with the size limitations of the Styrofoam block, the dimensions of the hotwire and custom tool tip and the kinematic limitations of the robot, in addition to the geometry rationalisation of the hotwire cuts into ruled surfaces. Ruled are the parametrised surfaces that can be swept out by moving a line in space (Gray et al 1993, p. 431). The hotwire end effector of the industrial ABB robots has inherently to abide to this restriction, as the wire at the end of the tool is a line that follows the kinematic movement of the arm, into space, as displayed in Fig. 4.

There are numerous possibilities for complex geometries generated just by ruled surfaces, however for the purpose of this exercise a supplementary custom tool, Fig. 5, was designed specifically to assist the subtraction of material, one level further than the hotwire end tool one. The need for micro-control and more accurate positioning and cutting has emerged from the nature of the designs, thus a significant amount of mock-ups of different forms and more importantly machine settings, like speed, torsional movement and heating temperature for the custom tool was vital for the success of the final fabrication (McGee; Pigram 2011, p 129).

The design experiments consisted of, two column designs, one wall / panelling infill module and a floating ornamental lighting element. In all of these cases there were a few principles that were rendered as the drives for an integral system of performance design to fabrication:

1. Adaptability and the dynamic associative character of the designs - necessity to evaluate many different results both on the digital and on the physical level
2. Direct connection of parametric design from the CAD software to the tool path of the multi-axis robot, which signifies economy of time
3. Economy of material - the discrete elements were tightly packed within the commercially available blocks of Styrofoam. A standardisation of elements and clustering of self similar elements also contributed significantly towards rapid mass customisation.
4. Implementing smart connections between the discrete cut parts, hence reducing the assembly time and saving material waste. For instance, a finger joint connection was integrated in a few of the designs (Krieg et al 2011, p. 576), diminishing the use of adhesive whilst enabling fewer cuts for the robot, as displayed in Fig. 6.

## CONCLUSIONS AND FURTHER DEVELOPMENT

Numerous potential can arise from the utilisation of integrated multi-axis robotic fabrication. Especially when this is enhanced by fully parametric control of the design scenario and seamless connection of the design genotype which gets then translated to phenotype by the machine grammar. From the assessment of the prototypes, the aesthetic effect of the design intention was communicated in a quite successful manner. Regarding the "by the text book" methodology, this has yet to be perfect, as lot of manual intervention was essential to tackle issues mostly appearing during the fabrication process, such as recalibration of the robot, unstable fixings which resulted to destroyed elements, even in some cases bugs in the code that made the fabrication process

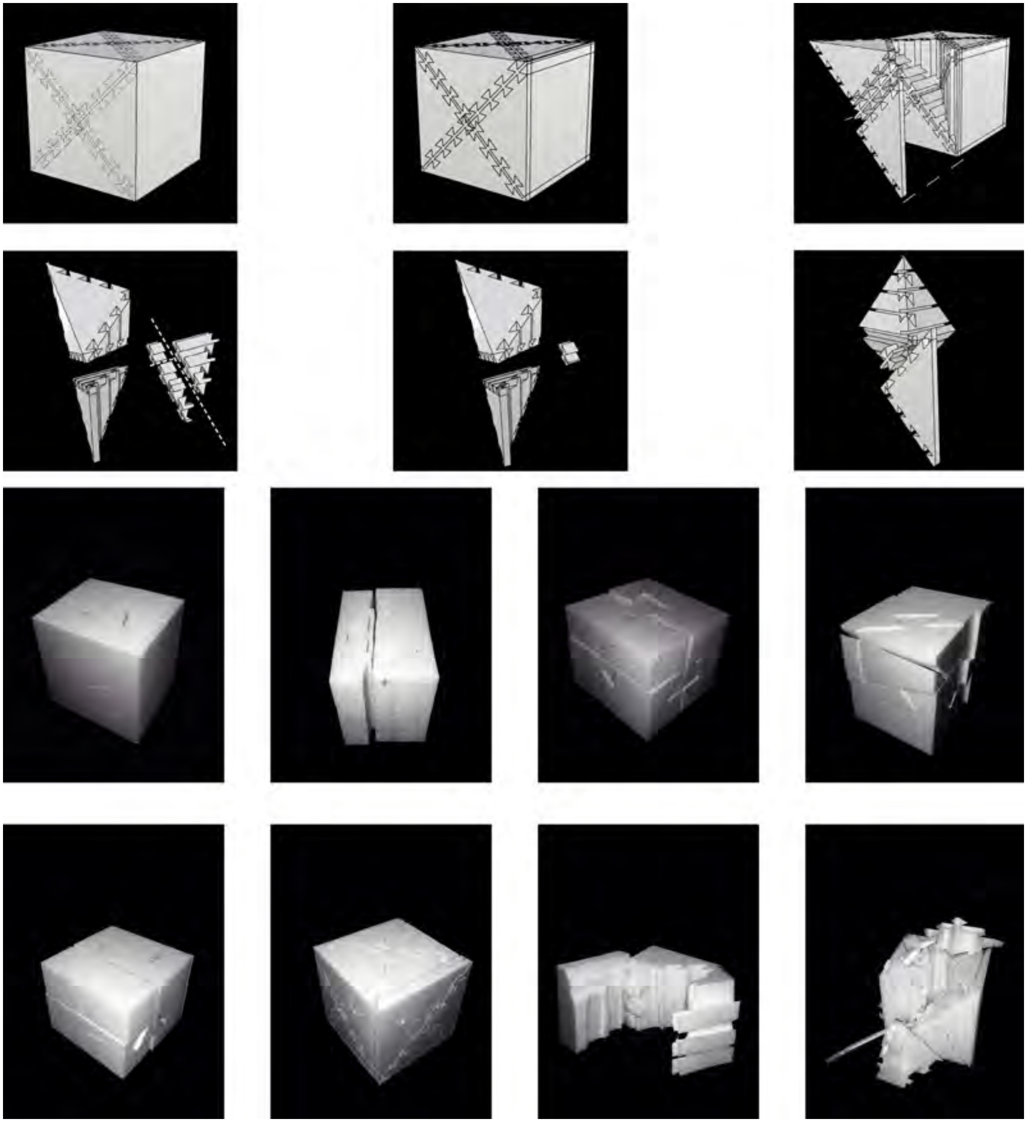


Figure 8
Hot-wire cutting documentation (digital and physical) of process aiming to produce ornamental complexity via single cube cuts and minimum material loss

erroneous. However, at least 80% of the process was fully automated. This research should be critically evaluated as an integrated design to fabrication methodology which focuses on the light permeability of the fabrication material. This distinct characteristic of light translucency, lead to non-mainstream thinking and to the development of case specific bespoke tools, both digital and physical. As further development a feedback loop in-between the robotic end effectors and the CAD software would be extremely valuable, as it would be an error recognition system, most probably based on a computer vision routine, which would enable the system to run uninterrupted without being under constant human supervision.


## ACKNOWLEDGEMENTS

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# Design-static analysis and environmental assessment investigation based on a kinetic formwork-driven by digital fabrication principles

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*This research focuses on design-static analysis and environmental assessment procedures that are based on the idea of a flexible kinetic formwork used as the automated mechanism for the production of bricks for porous wall structures. A key aspect of this investigation is the Life Cycle Assessment (LCA) analysis study that is applied in order to achieve, in parallel with the automated procedure, the sustainable potential of the products. For this purpose, the design and construction flexibility of the product is taken into account from the early design decision making stage by examining different sizes of bricks under fabrication including massive or porous ones in order to test their design and static performance, aiming to adapt their shape in multiple functional and environmental scenarios. In parallel, the LCA impact of the given design scenarios are taken into consideration, again from the early design phase, and include, among other objectives, material minimization, less environmental impact of building materials and less energy consumption based on the proposed digital fabrication technology. This is examined by comparing digital design and robotic automated results using three types of ecological materials.*

**Keywords:** *Sustainable design, LCA analysis, custom-made end-effector tool, kinetic formwork, brick wall, robotic manufacturing*

## INTRODUCTION

Currently, the rapid development of digital design and fabrication tools allow a more thorough and comprehensive control over design intentions and later on over the construction of any building part in actual scale. This prevents possible failures and misfits that are the result of direct design implementation of ideas by workers during the construction stage and after the design is completed (Kontovourkis and Konatzii, 2016). This is done on a case to case base depending on each construction scenario under implementation. For instance, in case of brickworks, a conventional design and construction procedure, this new paradigm shift and especially the dislocating aids as well as the robotic and automated processes are in a continues development (Bock, 2008). Moreover, the need for similar mechanisms is increased due to their accuracy, flexibility and fully programmable nature that make them to be superior to conventional construction approaches. In most of the cases, indicated tasks of robotic construction are executed by custom-made end-effector tools. Within this frame, apart from brick manufacturing, cases where kinetic formworks or customized formworks for casting free-form geometries are applied (Stavric and Kaftan, 2012), aiming to achieve minimum time of fabrication (Kristensen et al, 2013).

In an example of robotic implementation for wall construction, a custom-made end-effector tool fabricates the rebars and the formwork before concrete pouring occurred and this achieves to minimize wall thickness and to improve the environmental performance of a conventional wall (Hack et al, 2017). Moreover, in an attempt to mitigate material waste and to minimize environmental impact, researchers at ETH Zurich (Oesterle, 2012) have developed a flexible mould where hot wax is cast onto and then is solidified to serve as temporary concrete formwork. Later on, the wax is melted down and re-used based on the same procedure.

Nowadays, possibilities to incorporate environmental impact assessment criteria within digital design, fabrication and construction procedures have an increased trend. This becomes more significant due to the fact that the manufacturing of building materials represents 5-10% of the global $CO_2$ emissions (Habert et al, 2012). In order to overcome this, digital design and fabrication are introduced, aiming at material usage minimization (Agustí-Juan and Habert, 2017; Agustí -Juan et al, 2017) and selection of construction materials with low carbon emissions. An example of such material is the adobe that is used for the production of bricks. Adobe is widely considered, both in Cyprus (Illampas et al, 2011) and world-

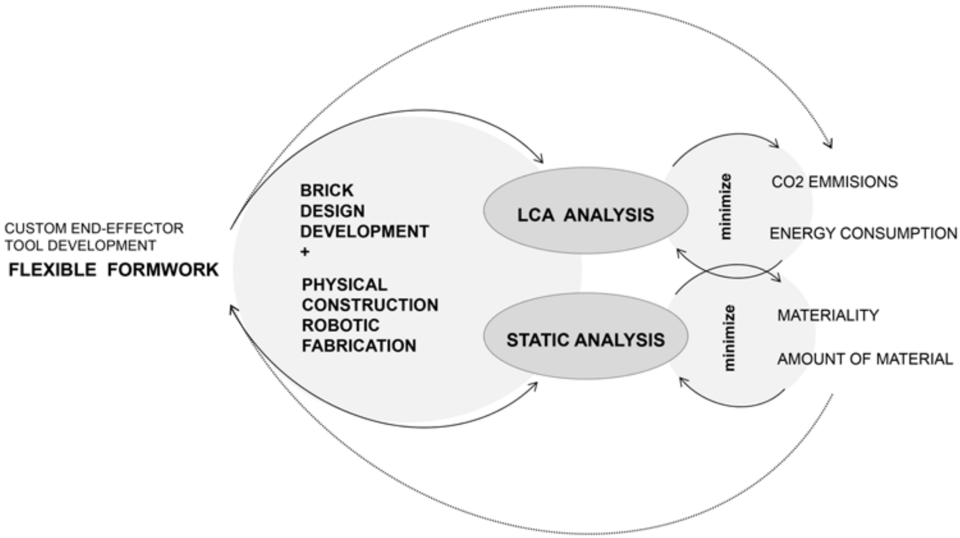


Figure 1
Diagram of suggested methodology

wide, as an eco-friendly, reusable, energy and cost-efficient construction material (Pacheco-Torgal and Jalali, 2012).

This research examines further the environmental impact of customized bricks design and production using a robotic construction procedure. More specifically, a flexible custom-made end-effector tool is applied to fabricate the custom bricks according to predefined parameters that lay within two equality important pillars, on the one hand design-static analysis aiming at the minimization of material, which is connected with material waste, and on the other hand LCA analysis that include materiality, CO2 emission and energy consumption during the fabrication procedure (Figure 1).

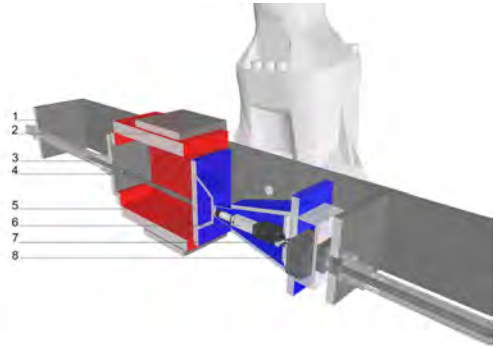


Figure 2
Section of the
end-effector model

## CUSTOM-MADE END-EFFECTOR TOOL DESIGN AND DEVELOPMENT

In this part of the paper, a thorough explanation in regard to the design and production of the custom-made end-effector tool is demonstrated. This is done in accordance with the design and static analysis results of customized brick elements that are compared with each other. Also, is done in accordance with the process of LCA assessment, which depends on the building material, the brick size and the fabrication method.

The custom-made end-effector tool is developed in order to allow automated production of custom bricks using pressed mechanism. A formwork consisting of two parts is developed, which press and formulates the material towards brick production. According to the scenario, for the automatic production of bricks, a flexible mechanism is developed, which is mounted on an aluminium base (1,2) at the edge of the robotic arm. The end-effector tool consists of a pressure system and a formwork that is capable of adapting to multiple brick shapes, producing bricks based on different desired morphologies. The final result is the production of a porous or non-porous masonry system based on the design scenario.

Specifically, the investigated procedure includes three steps: pressure, demolding, and positioning. At this point it should be noted that the process is carried out in the workshop whereas bricks and parts of masonry system are produced, and then are transferred to the site for assembling. During the production scenario, bricks are laid on a flat surface to complete the maturing stage of the building material. In the production scenario of masonry parts, the bricks could be demolded and stacked simultaneously on top of each other, in a way that bricks and parts of masonry can be produced in parallel.

The kinetic formwork system consists of two automated mechanisms. The first mechanism is responsible for the compression of the material using two pneumatic pistons (3). At the ends of the pistons, the two members consisting the formwork are adjusted on each side as shown in (Figure 2). One part of the formwork is static (5) and one is flexible. Both shapes are determined and adapted according to different hole sizes and thickness of the bricks under production. The flexible part (7) of the formwork consists of three extruded pieces that can be expanded and rotated to produce different results. The shape of each brick is defined in the design exploration stage, where number of criteria like shading area, orientation of masonry system and minimum use of construction material in each scenario are taken into account.

The typologies of structural elements are defined

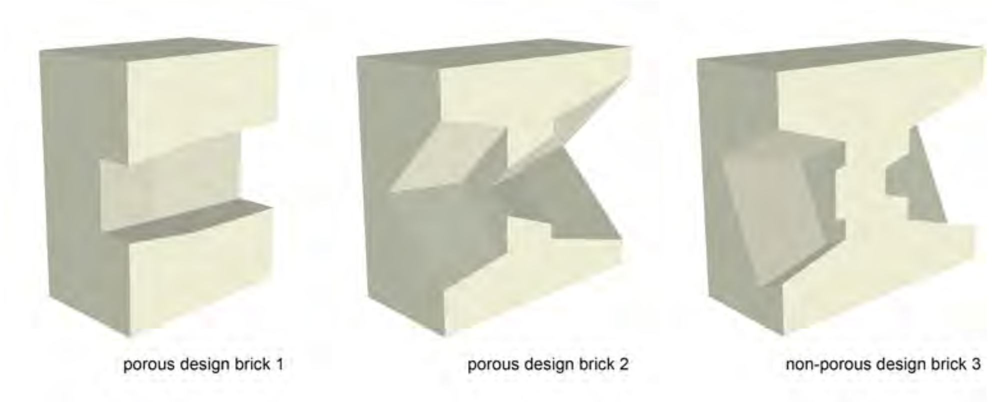


Figure 3
Sections of three representative brick geometries

as porous and non-porous. The final results of porous structural elements vary in their thickness, the morphology and the rotation angle of their openings. In terms of non-porous structural elements, these vary only in their thickness dimension (Figure 3).

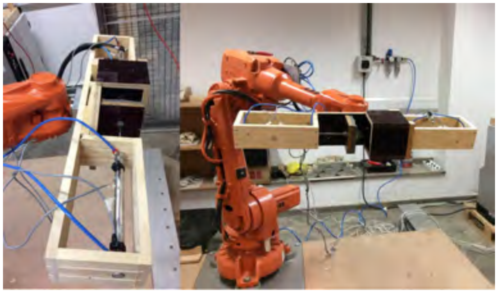

Figure 4
Physical model of the custom-made end-effector tool mounted on the robotic arm

An individual brick is produced each time and placed on working-site according to a motion planning process that is executed by the robotic arm. The robotic procedure is simulated on HAL [1] (plug-in for Grasshopper) [2] and the robotic motion is executed through Robot Studio 6.0 [3]. The task programming consists of the robotic motion control, defining the target points for bricks positioning, the actuation of the formwork mechanism and the calculated time duration for pressure. The whole procedure is repeated according to the necessary number of bricks under production. A physical model is developed in order to execute the whole procedure in real time (Figure 4).

The automated control of the kinetic formwork tool is determined by an algorithm responsible for activating the pneumatic pistons, the linear actuator (6) and the rotary motor (8). Through a series of algorithmic rules, the function of tool is determined as follows: after the robot reaches a specific position, and after the construction material is poured into the square tube, the linear actuator reaches its desired length and then the pneumatic piston is activated to move the flexible part of the kinetic formwork. If a rotated opening is required as end result, after the linear actuator is activated, the appropriate rotation is performed by the rotary motor.

In the next step, by moving the static part of the formwork, the pneumatic piston is activated to compress the material, accelerating in parallel specific formatting task. The two pistons are pressed for 30 seconds. Then, the piston 1 is deactivated at a smooth speed to transfer the produced component out of the square tube. Finally, for demolding, the piston 2 is also deactivated. Finally, each brick is placed at the desired target point by the robotic arm (Figure 5).

The pneumatic pistons, the linear actuator and the rotary motor are controlled by an algorithm developed in Robot Studio 6.0 [3] software in conjunction with the Arduino digital platform [4] for analogue control. The pneumatic pistons are activated and deactivated by sensors. In each piston, two electronic sensors at both edges, provide information to the code in order to advance the procedure as this is pre-defined. The sensor operates binary, where at its right part, informs whether the piston is actuated and hence the formwork. Respectively, at its left part indicates any deactivation of the piston-formwork.

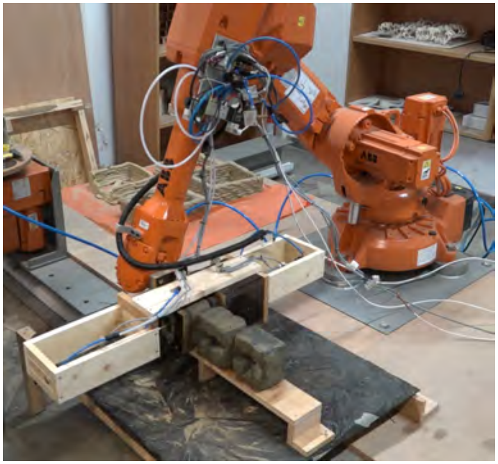

Figure 5
Produced bricks in series

## DESIGN-STATIC ANALYSIS AND LCA ASSESSMENT OF BRICK ELEMENTS

As it has been stated, the brick design is based on a flexible custom-made extrusion mechanism that is digitally activated to produce the desired result. Based on a number of actuator, the activation scenarios produce several types of bricks with maximum or minimum size of openings from 2x2cm to 7x7cm, respectively. Also, there is a massive type of brick that is produced by the extrusion mechanism through a partial subtraction of material. In all cases, a rotation of subtracted volume can be activated in selected degrees. The size of formwork and the flexible morphology allow material minimization and further investigation of static behavior as well as response to environmental criteria.

For structural reasons and optimal static behaviour of the entire masonry system under production, a cross-sectional arrangement logic of the vertical joints of the bricks is followed. At the further stage of research, for the compressive strength of the entire masonry, the possible use of mortar for the connection of the bricks and their waterproofing will be taken into account.

The numerical static analysis of three different types of building materials: adobe, concrete and a hybrid mixture of clay and cement, are performed using ABAQUS CAE [5]. The selected materials have different static behaviour and this, in turn, influences their environmental characteristics.

### *Numerical static analysis*

In the linear analysis stage of investigation, the load applied is calculated by the equation $P = F / A$, where P is the result of the total load (N) that exert force F on the structural elements on the mounting base of typical masonry with 3m height divided by surface area A of the loads being carried. The calculated pressure load for adobe brick masonry is 42,241.13 Pa, for concrete brick masonry 84,482.7 Pa and for clay with cement addition brick masonry 63,361.695 Pa. Based on the experiments made in the laboratory, the concrete is the heaviest of the three materials under investigation, and for this reason the pressure exerted is the highest.

### *Results of linear static analysis of brick typologies*

The results of the linear static analysis focus on Von Mises, U22 and S22 maximum values. More specifically, the Von Mises criterion suggests that the performance of a ductile material starts when the force reaches a critical value. U22 is the displacement value that is caused on z-axis, perpendicular to the brick opening, after the uniformly distributed load is applied to the top surface area of the brick. It is measured in millimeters (mm) and it determines a maximum permissible value according to the brick strength. S22 is the compressive stress caused on the z-axis and perpendicularly to the opening of the brick, after the evenly distributed load is applied to the top surface area of the brick. It is measured in Pa and is differentiated on the basis of the materiality and the type as well as the maximum permissible value of the percentage of the brick's openings. The displacement and the stress on the z-axis are considered to be the most critical values because they act parallel to the load pressure and define the elastic-tension limits of the brick geometry.

For adobe, concrete and clay materials a number of graphs have been developed based on the results extracted from the linear static behaviour analysis. The values for Von Mises, displacement and compressive stress are presented in relation to the bricks' opening size and its degree of rotation.

For the adobe material, through the graphical representation of Von Mises (Pa) in accordance with the typology of each scenario, it is observed that there is difference in values for bricks with small openings relative to the bricks with large openings. In scenario 1, the difference in values is almost double, in scenario 2 this difference is smaller and in scenario 2 is decreased further. For brick with small and large openings, while the rotation degree of the opening is increased, the Von Mises value is also increased.

According to the results of analysis, between adobe and concrete materials, higher values occur in the concrete due to its static behavior. In both cases, maximum values for compressive stress in z-axis and rotation angle 15 degrees are shown. In addition, geometries with minimum opening have lowest displacement values. The largest displacement is found in cases where highest values of rotation angle occurs. With regard to compressive stress, the maximum value in most of the cases for each scenario, is observed in 15 degrees of rotation angle of the opening.

The static behaviour of the mixture consists of soil and cement is between the behaviour of adobe and concrete materials. The values extracted from the linear static analysis of the clay approximate more to the concrete values. Also, the Von Mises, U22, and S22 maximum values in all scenarios are observed in same morphological typologies as the ones of adobe material. This concludes that they have the same static behaviour with adobe material but with more resistance.

Specifically, in the first phase, the static analysis of bricks shows that displacement and compressive stress values are below permissible. Between the cases of small and large openings, the pressure values are larger almost twice as well as the values in the z-axis. In all types of bricks that have been tested, Von Mises and displacement values are increased depending on the degree of rotation angle. Additionally, in scenario 1 and 2 for adobe bricks the compressive stress values in 15 degrees of rotation is increased, and then is decreased in 25 and 45 degrees of rotation. In scenario 3, the maximum compressive stress value is observed in the case of 25 degrees of

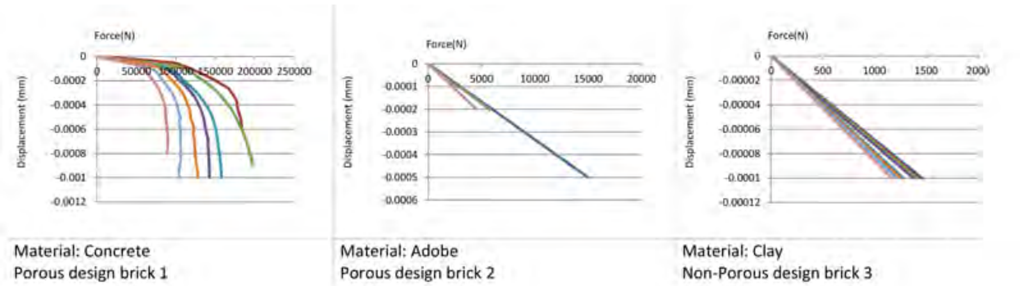


Figure 6
Force – displacement graphs for the three materials

rotation. Finally, in the maximum openings with 25 degree of rotation, the compressive stress in z-axis is also strongly increased.

### *Results of non-linear static analysis of brick - force compression*

In order to investigate the bricks' strength, a displacement force is uniformly distributed over the upper surface area of the brick. This allows measurement of the maximum value that can be applied to each brick until is cracked and crushed.

The force-displacement diagrams are derived as the sum of the reaction force that are uniformly applied to the nodes of the mesh geometry on the bottom surface area of the brick, divided by the displacement value occurs at a central node of the top surface. After the analysis of the models, these values are used to produce the graphs shown in Figure 6. Graphs show the force-displacement values for each scenario incorporating all cases, for large and small openings and for 0, 15, 25, 45 degrees of rotation angle of openings.

From each graph, the maximum force that can be applied to the computer model under compression is derived. By dividing this with the surface area where the force is exercised, the compressive strength is calculated. Practically, at the point where the maximum force is applied, it is considered that the brick is crushed and its plastic behavior ceases.

For the concrete material, a curve graph from the center of the axes is observed, while for adobe and clay the shape of graphs are straight lines from the center of the axes. It is concluded that materials have different static behaviour, where the concrete has larger compressive strength and therefore plastic behavior compared to the other two materials.

For concrete bricks, the minimum characteristic crush strength is 10.241 MPa and the maximum is 34.537 MPa. Values up to 30 MPa are permissible, so those models above the threshold are under investigation, in terms of their morphology and the percentage of their opening relative to their total volume. The maximum value has been recorded in case of non-porous brick, combined with 15 degrees rotation of extruded volume).

For the adobe material case, the minimum value of compressive strength is 0.274 MPa and the maximum value is 1.7 MPa. Any case exceeding 1 MPa based on the Eurocode 6, do not fall within the permissible limits. The maximum value is observed in case of small opening without any rotation).

In case of clay with the addition of cement, the range of compressive strength values is from 0.15 MPa to 1.30 MPa. The rules of Eurocode 6 for adobe materials are applied in this case as well, where the permissible compressive strength value is up to 1

Table 1
Results of LCA analysis for CO2 emissions and energy consumption throughout the life-cycle of masonry for the three different construction materials

| Sector on investigation | | Global warming (kg CO2e) | | | Primary energy (MJ) | | |
|---|---|---|---|---|---|---|---|
| | | Adobe | Concrete C20/25 | Clay (soil, cement) | Adobe | Concrete C20/25 | Clay (soil, cement) |
| **A1-A3** | **Construction Materials** | 3,71E1 | 4,89E1 | 3,23E1 | 3,83E2 | 2,72E2 | 9,86E1 |
| A4 | Transportation to site | 1,34E0 | 2,41E0 | 1,46E0 | 1,97E1 | 3,55E1 | 2,23E1 |
| **A5** | **Construction/installation process** | 2,65E1 | 2,64E1 | 2,64E1 | 4,87E2 | 4,86E2 | 4,86E2 |
| C1-C4 | Deconstruction | 7,86E-1 | 1,5E0 | 2,65E0 | 1,63E1 | 3,13E1 | 7,8E1 |
| D | External impacts (not included in totals) | -3,15E-3 | -6,31E-3 | -3,25E-1 | -5,29E-2 | -3,23E-2 | -4,29E0 |
| | **Total** | **6,56E1** | **7,92E1** | **6,27E1** | **9,07E2** | **8,25E2** | **6,85E2** |

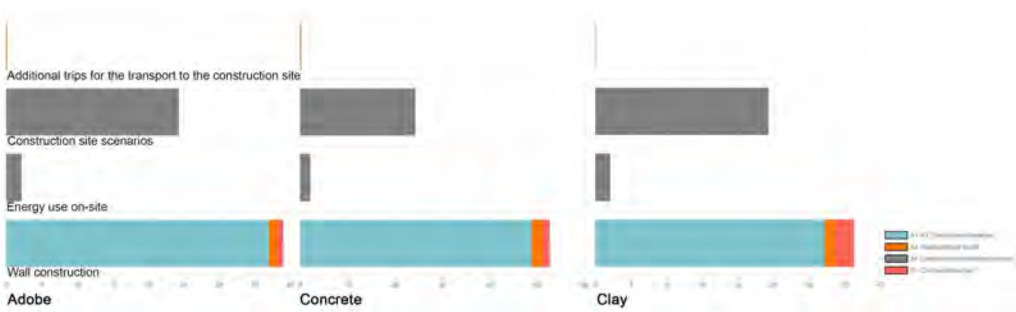


Figure 7
LCA charts for the three construction materials at the construction and life-cycle stages of the structure

MPa. The maximum value is observed in the case 2a0 (small opening, no opening) and the minimum value in the case of large opening and 15 degrees rotation of opening.

In a next step, the investigation focuses on the analysis of the design results according to the above mentioned materials, their environmental impact, as well as the energy consumption during the digital fabrication process. Within this frame, a comprehensive comparison of results derived from the selected construction materials is conducted in One click LCA [6] software for LCA analysis. Metrical results from LCA and LCI databases as well as several calculations show material cases with the best performance in accordance with CO2 emission percentage, the minimum amount of material waste and also the amount of energy that is used by the industrial robot, the custom-made end-effector mechanism and the assisted technology, in order to execute a wall section in actual scale. In the overall process, the flexible kinetic formwork and the type of material used, play a significant role for well performed results in terms of their design-static and environmental assessment performance.

### *Results of LCA analysis*

Quantitative results regarding the environmental impact on the life span of a section of 3m x 1m x 0.08m masonry wall are derived from the One click LCA software [6] that contains a large EPD database. The building life-cycle assessment is based on the European Standard EN 15978. The above mentioned LCA software covers life cycle stages from cradle to grave and can be separated into product stage, construction process, use stage, operational energy, and end of life. In the construction process, the calculated electrical energy required for the investigated masonry for one hour of work using the robotic arm can be introduced. Specifically, this is the sum of the electricity consumed by the robotic arm, the computer involved in the process and the energy consumed by the mechanisms incorporated in the end-effector tool, which are the pneumatic pistons, the linear actuators and the rotary motor. The total energy consumed in 2.39 kWh. In addition, apart from the data related to the electricity required as mentioned above, data related to the climate of the country where this is carried out are introduced, as well as data related to the energy consumed to transport the finished masonry to the construction site by truck.

The amount of carbon emitted into the atmosphere through the life-cycle of the masonry is a result of software analysis, taking into account the different values for each material due to their different material composition. The various stages in which the results of global warming effects (kg CO2) are reported, are the results of construction material selection, its transportation from the factory to the construction laboratory, its construction process and transportation to the site (See Table 1 of results).

The $CO_2$ emission values for all processes in case of adobe material is 6.56e1 kg $CO_2$, for concrete C20/25 is 7.82e1 kg $CO_2$ and for clay composed by soil and cement is 6.27 e1 kg $CO_2$ (Table 1).

The highest values are observed in the case of concrete, where the material used for its constitution have the most emissions, as well as for its demolition at the end of life of masonry (Figure 7). The values shown in the table for adobe and clay are smaller than the ones for concrete material and therefore, are more environmental friendly options. The reduced emissions of these two materials are mainly due to the way the structural components are maturing by the drying method and not by the use of thermal hob. The method of drying is a natural maturing approach of materials, and on top of this allows and facilitates the demolition process of masonry, as well as the reuse of the brick raw material. In addition, with the proposed method of masonry construction, the material waste is zero and the quantity of mixture required to produce the bricks is accurately calculated.

## DISCUSSION

The proposed manufacturing process has the potential to produce individual bricks or brick masonry systems with different morphologies due to the ability of kinetic flexible formwork to adapt its shape according to the design under investigation. Time and material are saved during the production process of bricks with or without openings, and in parallel their static performance is taken into account. The aim is to use the minimum material for construction, according to the required final design results based on various parameters. This offers the opportunity for an ecological and environmental friendly construction approach in architecture. The exploration stage of $CO_2$ emissions in the atmosphere and the selection stage of low-energy manufacturing are necessary parts towards such direction of architectural and construction studies.

In this investigation, the construction approach promotes the minimal use of construction material aiming at zero material waste during the process. The static exploration of the three materials aims to examine their strength limits, where the concrete C20/25 proves to be more durable than the adobe and clay material. On the contrary, adobe and clay are more environmental friendly, with lower $CO_2$ emissions. Regarding the accuracy of the static analysis of different brick morphologies and materials, real stress tests of physical prototypes that are produced using the suggested end-effector tool can be performed in a further stage of experimentation in order to evaluate the results of computer analysis.

## CONCLUSION

In conclusion, by examining the design and construction development procedure of custom adobe bricks in accordance with their static analysis and LCA assessment, an in depth knowledge in regard to the potential for introducing architectural strategies that take into account environmental criteria throughout the process will be acquired. More specifically, by using ecological materials, by minimizing material volume, material waste and energy consumption as well as by minimizing $CO_2$ emissions, a low environmental impact and improvement of life-cycle of brick structures can be achieved. The results of suggested process can show the potential of innovative fabrication methods to be promoted in cases were actual scale construction objectives and complex design scenarios are examined. At the same time, this can improve industrial evolution towards more ecological friendly materials and processes.

Further work towards the refinement of the end-effector mechanisms and the physical production of bricks using the suggested materials will demonstrate the effectiveness of the suggested flexible kinetic formwork to achieve accurate results using data derived from static and LCA analysis investigation.

## ACKNOWLEDGEMENT

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# The Oval - a complex geometry BIM case study

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*This paper documents the steps followed to design and construct an oval shaped, high rise structure in Limassol Cyprus. The author presents the developed computational framework which was purposely built to support multiple levels and disciplines of design, construction and digital fabrication leading to a successful delivery of a complex geometry project within time and budget. A fully informed model involving multi-disciplinary data ranging from its conception to its completion establishes a sustainable paradigm for the construction industry, mainly because of its single source of control as opposed to other precedents involving multiple models and information.*

**Keywords:** *Parametric Model, Setting out management, digital fabrication, BIM*

## INTRODUCTION

This paper attempts to illustrate the use of advanced computational tools through their application on large scale built project. The authors undertook a holistic approach on the design development and fabrication through a centrally built and controlled information model with parametric capabilities. The case study presented in this Paper, the Oval, was designed by Atkins Global and WKK Architects and planned to be built on the coastal area of Limassol, in Cyprus. The Oval was proposed to stand facing the southern coast of Limassol at a height of approximately 100m consisting of 16 stories of commercial space bound by a of a doubly curved aluminium shell. The Oval posted an early challenge both for the design team and the contracting team as it was the first large scale building of non-rational geometry to be built on the island. Furthermore, it's completion on time and within budget was of great importance as this was amongst the first ones to be constructed following the Cyprus economic recession. The Oval would be presented as the clients' flagship project marking the construction markets' recovery.

The authors were committed as geometry consultants to initially assist on the design development and the coordination of the complex shaped structure in relation to the architectural skin. As the project developed however, the authors engaged on managing a parametric Bulding Information Model that informed most parties involved in its construction. The computational design workflow therefore, as opposed to standard practice, was not predetermined but was constantly fed with additional capabilities as the project progressed. This proved to be the largest challenge for the authors, assembling a framework that was able to expand and incorporate information and capabilities (Aish et al, 2005). The basic geometric principles of the building were incorporated into the model in order to initially describe the shape and the structure to aid the design development at consultants level. Then the model was upgraded to manage the setting out and extract data for the sub-contractors and monitor the construction tolerances.

Figure 1
Completed project

At its final level of development, the model provided the basis for the panelisation and the panels fabrication and the coordination of the whole cladding build-up system.

## METHODOLOGY

### *GEOMETRIC PRINCIPLES*

The shell is described by two elliptic surfaces which intersect at the X-axis of symmetry. These surfaces are produced by sweeping two circular sections with an elliptical rail. The circular sections are sliced with two slanted (XZ planes with rotation along X axis) planes at north and south elevations, in a disproportionate manner in relation to the axis of symmetry, producing an open shell towards the North and the South. Even though the surfaces are produced with circular sections producing a rational surface of revolution, the structure is handled with sections parallel to the XY Plane, causing geometric non-linearities which weren't easily identified at first (Figure 3). Each horizontal floor plate is tangent to the shell thus creating varying concrete structure geometry with interconnected curved in space columns.

The shell cantilevers from the primary structure both at north and South sides depending on the offset of the vertical planes from the origin. The primary structure was proposed to be constructed using cast in situ reinforced concrete combining single curvature elements with faceted members. The secondary structure, comprising the skin would be composed out of curved tubular steelwork anchored on the concrete from the ground to the 15 floor. The dome area

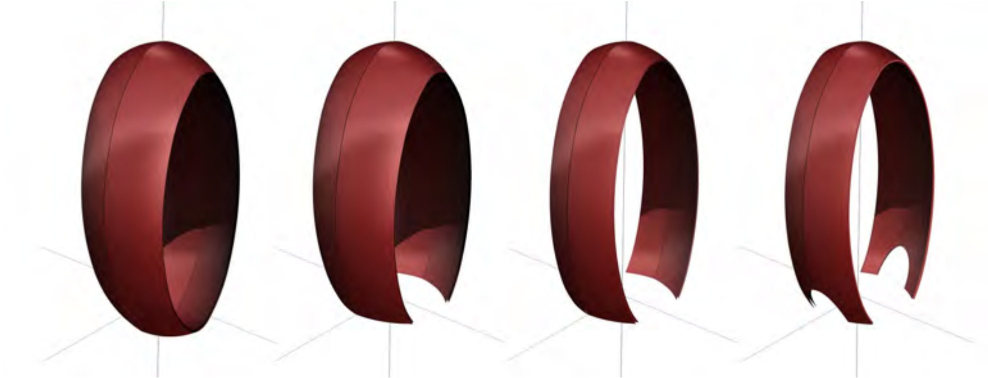


Figure 2
Geometry evolution

was constructed using variable curvature steel arches braced together with linear members. The latter area was geometrically optimised to form flat quadrilaterals in order to be easily clad with rigid structural decking.

## *THE PARAMETRIC INFORMATION MODEL*

The authors developed the custom build framework in Grasshopper 3D [1], a plugin within Rhino 3D[2], a commercial CAD software, in order to initially control the doubly curved geometry and produce 2D information for the consultants. The aforementioned geometric principles were incorporated into the parametric model, along with the geometrically varying elements of the Project. Parametric rules were set for the curved columns of the building, the doubly curved slabs, the steel structure (supporting the skin) and the front and back facades. The model was able to automatically produce layer structured 2d sections and export in CAD formats for all the variations of the project along the design development (Figure 4). The model was also used as an interactive clash detection tool for all the interfering elements bound within the skin of the building.

The parametric model was developed incrementally to incorporate information needed by consultants and sub-contractors in-volved with the project. The steelwork comprising the structural skin was incorporated into the model in order to fully understand the complexities arising and provide better insights on its cost.

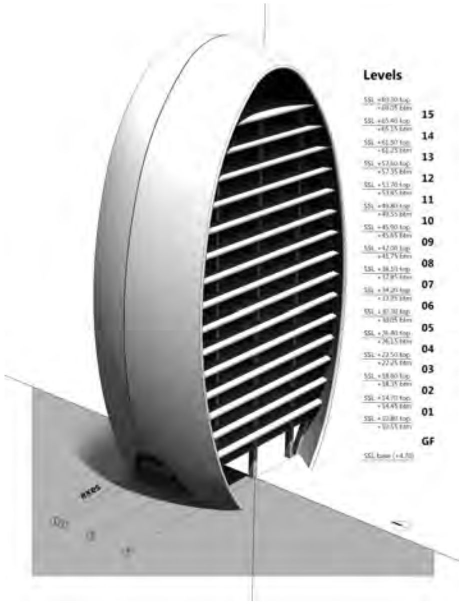



Figure 3
Shell including the horizontal elements

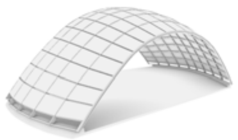


Figure 4
Proposed Dome structure with flat panels

Figure 5
2D information generation from 3D model

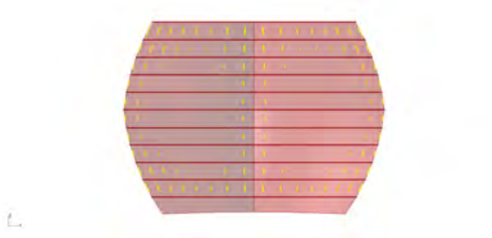


Figure 6
Clash detection at the Shell dome

## *INTEROPERABILITY MODELS*

The initially proposed structural envelope of the Building was abandoned due its geometric complexity and therefore there was a need for a fast development of a new proposal for the structural skin. The central model was therefore modified to include analytical information in combination with the structural geometry information. This provided the basis for an interoperability model which directly connected the geometry with the structural analysis software, ETABS[4] in order for the Structural Engineer to precisely model the structural information, provide feedback and revise the geometry model (Georgiou et al, 2011) (Kolatsou et al, 2017). Due to the complexity of the structural geometry, each design iteration would demand a great amount of time when modelled traditionally. Additionally, in each structural iteration, the geometric information was passed to the Steel Fabricator [3] through tabular data in order for the fabrication model to progress.

The above information could be reinstated at a later stage with the precise setting out information received from site. Structural information was also passed to the Wind Tunnel subcontractor in order to conduct the wind simulation. Incorporating the load information into the central model saved valuable time to the engineers in passing the loading zones into their Structural Analysis software.

## *STRUCTURAL ELEMENTS SETTING OUT*

To ensure a better adaptation to the curved shape, exact setting out information was extracted for the concrete frame for each level of the building. The central parametric model was able to extract setting out data in excel and ASCII format which were used by the Surveying engineers to precisely mark the curvature of the concrete structure. The direct workflow between the parametric model and the Surveying teams Total Station equipment would mean that the setting out marks with the corresponding numbering could be returned back for tolerance checks after each element was cast (Figures 7 & 8).

A setting out management process was adopted by the authors which was biderectionaly linked to the central parametric model. This meant that all the date to and from the model was fully coordinated and controlled. The required positions of the steel anchoring system were input from the structural engineer to the central model and were then exported as data for the Surveyor engineer to stake out. After the concrete casting this data, filtered through the model was sent to the fabrication subcontractor. Following fabrication and installation of the steelwork and as the full adaptation of the proposed Shell shape was crucial, a tolerance check took place which

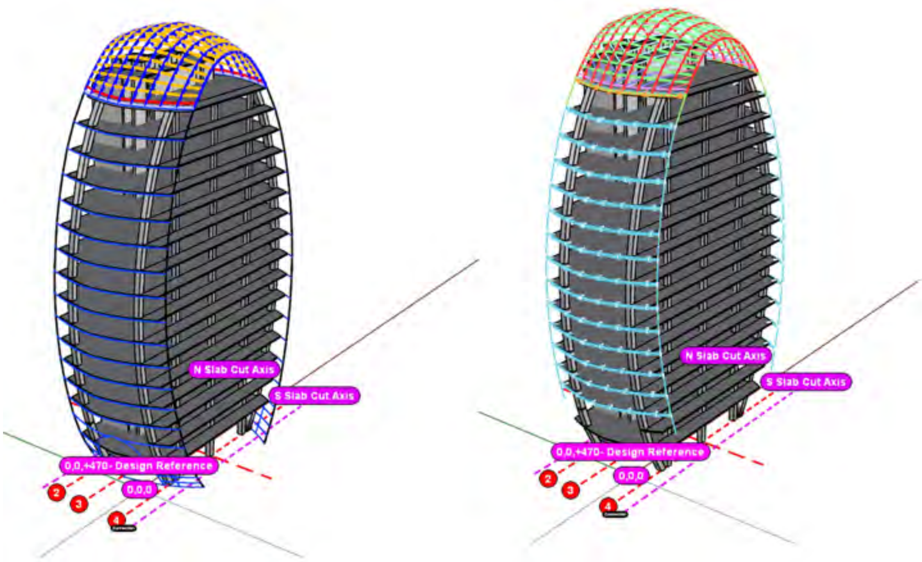



Figure 7
Analytical model translation to CAM model in TEKLA

verified the theorectical geometry and proposed corrections were needed (Figure 9).

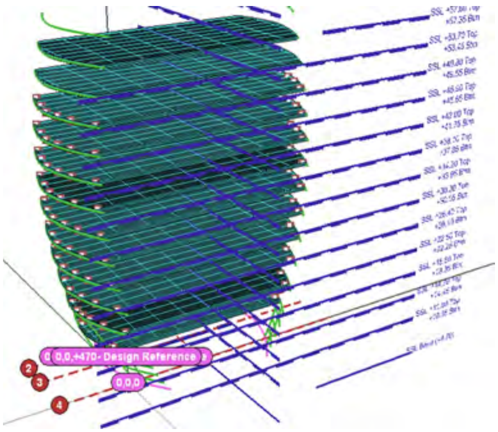



Figure 8
Monitoring stage

## *PANELISATION AND CLADDING FABRICATION*

The parametric framework had also aided the most demanding aspect of the project, the cladding. Data related to the doubly curved shell built up consisting of the secondary steelwork, the aluminium standing seam membrane and the quadrilateral panels had to be extracted from the central model. These elements were included and were constantly coordinated with their interfering elements like the concrete and steelwork primary structure.

The build-up elements were initiated from the shell surface used to generate the structural geometry and were offset accordingly to the desired depth. The standing seam aluminium sheets (Kalzip) were produced using information extracted from the central model. Due to the fact that these elements were doubly curved at their majority and needed to be produced overseas there was a demand great accuracy both during the fabrication and during the installation of their fixings on site.  These meant that

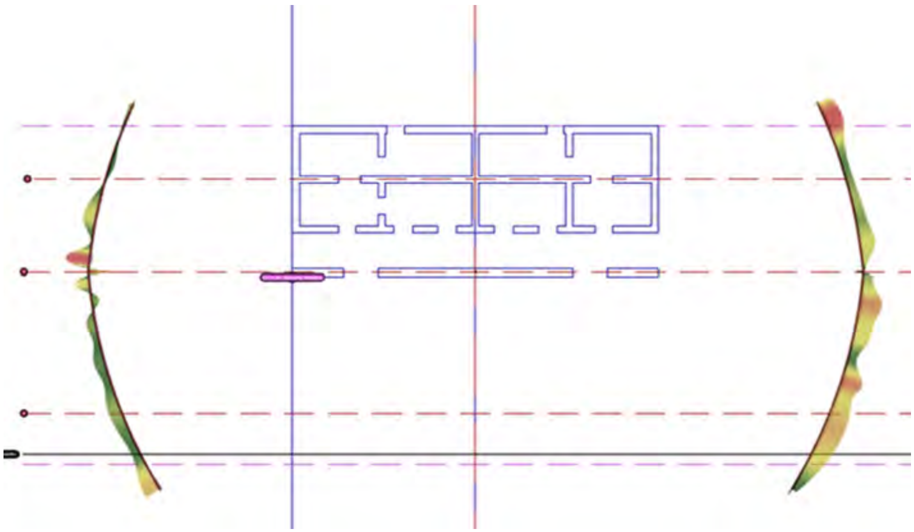


Figure 9
Curved Steelwork tolerance checks

big amounts of data needed to be passed to the Surveyors for the accurate placement of the supporting elements.

The shell panelisation scheme was proposed by the author as the most adequate for the adaptation to the geometry and the horizontal elements of the structure. The scheme suggested horizontal joints, aligned with the slabs of the building.

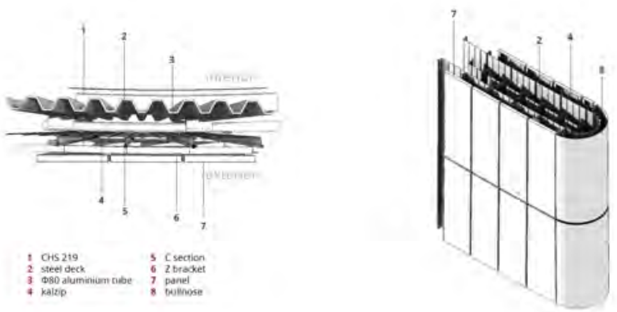
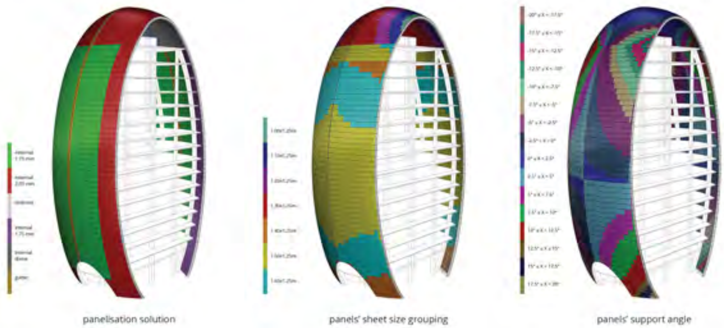



Figure 10
Cladding build-up

Figure 11
Installation of doubly curved aluminium membrane substrate.

Figure 12
Panelisation scheme panel grouping and fixing rotations




This scheme would greatly improve the intersections of the interior panels with the afformentioned elements and would ease the setting out process of the intermediate supporting elements. All the supporting elements and fixings would be parallel to the horizontal plane which meant that they could be linearly set out. The scheme however created a large domain of unequal panels

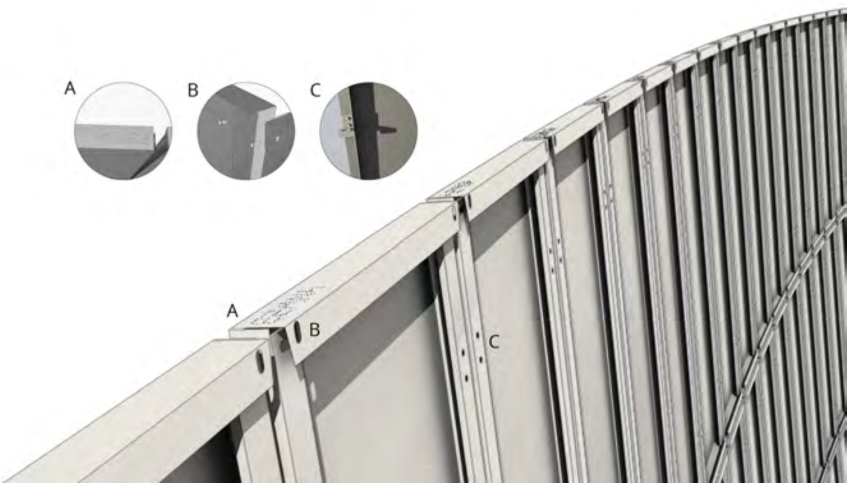



Figure 13
Panel trays in simplified breps

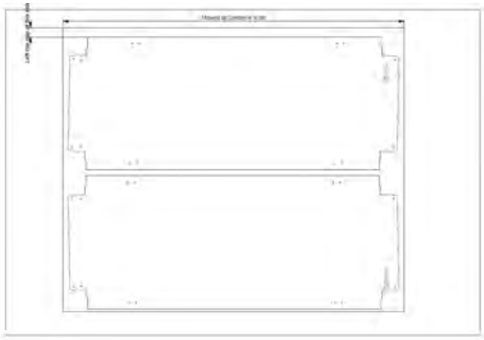


Figure 14
Unrolled cutting layout

The panels were designed to be constructed out of 1.75mm and 2mm aluminium sheet bent to form trays, The panels were adapted onto the original surface, initially as single surfaces in order to create a light-weight model responding to architectural and aesthetic decisions. This was later developed to incorporate the trays and be continuously informed by the fabricator regarding the parameters influencing primarily the CNC bends. It was decided for the panels to be fabricated locally in order to achieve speed in production and affordability. Due to the installation limitations and the tight vertical and horizontal gaps (20mm) the allowable tolerances were relatively small. Less than 5mm was allowed for vertical movement for alignment, which meant that the supporting structure needed to be precisely set-out. The setting out data for the supporting elements was returned for each installed floor and fed the model generating the hanging holes for all the different supporting heights. Precise fabrication data and cutting layouts was automatically exported directly to the CNC puncher. A custom algorithm translated the markings for approximately 10000 different panels in a dot format to be read by the Puncher CNC machine.

## CONCLUSIONS

The Oval was delivered in the summer of 2017 despite the numerous technical difficulties arising due to its geometric complexity, many of which were overridden using bespoke computational tools. The use of a central information model was used for managing both the design development and the construction of the project successfully, solving numerous issues arising during the projects progress. The high non-linearities opposed by the unequal discretisation of the shell meant that the construction site

Figure 15
Installed panels at the dome

had to deal with huge logistics administration, which proved to be a big challenge for the whole team. A big amount of data, other than machining data, was communicated to all involved parties using excel sheets, Ascii files and simplified sketches, removing the need for complicated construction documentation. This also released some valuable time from the contractors of the project directing them on specific items and tasks of the project.

The Oval case study proves the need for an application and control of a holistic BIM model able to inform the various consultants, contractors and fabricators that contribute to a project. This need is apparent in geometrically complex structures which feature non-rational shapes. A bespoke computational framework which is project-specific enables a lightweight solution for handling large scale and geometrically demanding projects, like the Oval, provided there exists a clear CAD project plan from the initial design stages. If not, even if BIM models are adaptive in changes, a much more effort is required from the model vendor in order to incorporate additional capabilities and a larger amount of errors is anticipated during the process.

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