Universitat Internacional de Catalunya
School of Architecture

Tesis doctoral

Computational Analogies of Biological Systems Applied for Novel Construction Processes

Effimia Giannopoulou

Computational Analogies of Biological Systems Applied for Novel Construction Processes

By Effimia Giannopoulou

Director of the Doctoral DDr. Alberto T. Estévez

Co-Director Dr. Agustí Fontarnau

PhD Program in Architecture

ESARQ | Universitat International de Catalunya

December 2019

In memory of my father,
for the freedom that he has given me
to study whatever I would choose
and the will to accomplish it.

To my mother

Acknowledgements

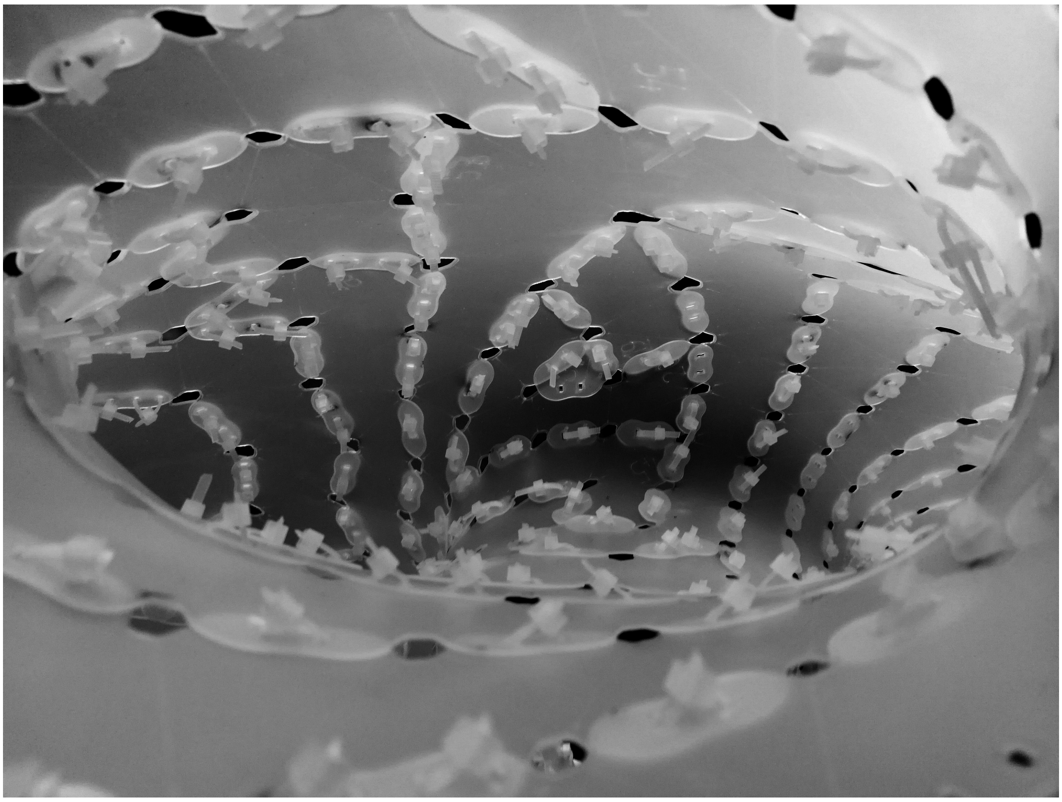
This thesis may seem like a highly specialized proposal with a highly technical background, but in fact it is the result of many years of constant research and creation inside the broad field of architecture. During this trip, I could not have completed this thesis without the support of a number of people who have stood by me.

My deepest gratitude I owe to the supervisor of the master and doctorate thesis Prof. Alberto T. Estévez, who has been the main source of inspiration, beyond nature, with his passion and vehemence for the work and teaching and profound belief in my effort, and Prof. Pablo Baquero, my beloved partner and main collaborator for his great patience and keenness.

Special thanks are owed to the international team of my co-authors of publications, Prof. Affonso Orciuolli for his generosity, support and guidance, throughout the years, PhD Angad Warang and Dr. Miquel Brun Usan for their meaningful collaboration and contribution, to my scientific revisers, Dra. Maria Vogiatzaki and Dr. Marwan Halabi and to the students of the Biodigital Master 2017/18/19, for their enthusiastic participation in the implementation of the projects.

I gratefully acknowledge the contribution of Dr. Nimish Biloria, Dra. Ioanna Simeonidou, Dr. Nelson Montás, *Faberarium.org* collaborators Chrysanthi Becta, Kalliopi Valsamidou and participants since 2012, and Brescan Dragos which have contributed in many different ways to bring this research at this level.

And most of all, to my mother who has always brought me back to reality, has travelled me to escape the pressures of work, and has contributed with her enthusiasm and practice in the implementation of the prototypes and exhibitions related to this work.



Preface

This doctoral thesis is presented as a compendium of publications (indexed articles). This modality of compendium of articles was inaugurated for the first time in the School of Architecture by Dr. Marta Benages, therefore, serves as a model for this doctoral thesis. The thesis consists of a compilation of five articles published or accepted for publication in indexed international scientific journals, by the candidate (together with other expert co-authors), in accordance with the current regulations of the UIC Barcelona PhD Program in Architecture. The thesis consists of the following chapters: introduction, hypothesis and objectives, methodology, results, discussion, conclusions and bibliography. The results include the five articles, from which, the first two and the last one has been published and the third and fourth have been accepted and is going to be published in international journals and in relevant editorials, all of them respectively included in the Data Citation Index - Web of Science (Clarivate Analytics) and SCOPUS database, Taylor & Francis and Cumulative Index on CAD.

The thesis is carried out following the line of Architecture and Projects of the UIC Barcelona PhD Program in Architecture, where inside of it, officially and more specifically, is the research line of the UIC Barcelona Genetic Architectures Competitive and Consolidate Research Group, merging fields such as biology, architecture, informatics, computational design and digital fabrication.

The thesis, consisting of the five articles, demonstrates the stages of research and fabrication experiments carried out in chronological order since 2017. The first two articles, inspired by a biological mechanism of morphogenesis, present a computational design strategy and methodology, applied to the construction of one physical prototype in each article. The third article is examining, through relative projects and bibliography, the feasibility of implementing a machine learning approach to the already established design workflow. The fourth and fifth article explores the potentials and accuracy of a state-of-the-art machine learning approach (as an Artificial Neural Network), re-examining and modifying the previously established generative design workflow for the construction of a third physical prototype. As a whole, contribute to the broader value of providing a practical framework for experimentation in the fabrication field and a systematic design approach of analysis, from concept to materialization of architectural work.

Abstract

Inside the area of computational design and geometry optimization for digital fabrication of thin shell structures opens a new field of investigation related to biological systems and artificial intelligence. This thesis is examining the theoretical and computational modeling frameworks operating on two different simulation domains: the biological pattern prediction mechanism and the architectural generative design for construction. It is bringing insights for the establishment of a design methodology and a scientific approach of analysis that incorporates modeling and simulation techniques for building a machine learning algorithm that could serve both as an understanding mechanism and learning tool, able to predict new building information, saving computational time and making the fabrication process more efficient.

Keywords: Morphogenesis, Shell Structures, Segmentation, Information Analysis, Fabrication.

Resumen

Dentro del área de diseño computacional y optimización de geometría para la fabricación digital de estructuras de concha delgada, se abre un nuevo campo de investigación relacionado con los sistemas biológicos y la inteligencia artificial. Esta tesis examina los marcos teóricos y de modelado computacional que operan en dos dominios diferentes de simulación: el mecanismo de predicción de patrones biológicos y el diseño generativo arquitectónico para la construcción. Aporta información para el establecimiento de una metodología de diseño y un enfoque científico de análisis, que incorpora técnicas de modelado y simulación, para construir un algoritmo de aprendizaje automático que sirve como mecanismo de entendimiento, y sería capaz de predecir nueva información de construcción ahorrando tiempo computacional y realizar el proceso de fabricación más eficiente.

Palabras Claves: Morfogénesis, Piel Estructural, Segmentación, Análisis de Información, Fabricación.

Index

Acknowledgements..i

Preface..iii

Abstract...v

Resumen..vi

Index...vii

1. INTRODUCTION...1

2. HYPOTHESIS AND OBJECTIVES..6

3. METHODOLOGY: FROM INTUITION TO PRECISION TO EXTENDED INTUITION...10

4. RESULTS..16

Article 1: *Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure*......................................21

Article 2: *Employing Mesh Segmentation Algorithms as Fabrication Strategies. Pattern Generation Based on Reaction-Diffusion Mechanism*......... 41

Article 3: *Machine Learning Approach for Biological Pattern Based Shell Structures*.. 67

Article 4: *Stripe Segmentation for Branching Shell Structures - A Data Set Development as a Learning Process for Fabrication Efficiency and Structural Performance*..85

Article 5: *Computational Workflow for Segmented Shell Structures: an ANN Approach for Fabrication Efficiency*... 103

5. DISCUSSION...120

6. CONCLUSIONS..128

BIBLIOGRAPHY..131

---

1. INTRODUCTION

How far mathematics will suffice to describe,
and physics to explain, the fabric of the body,
no man can foresee.

D'Arcy Wentworth Thompson, *On Growth and Form*

Not so long-ago architects have started using computational tools and methods to translate three dimensional virtual models into real constructions. But the conventional design methods are not considering the fabrication technique and material in early design stage. Despite the limitations of parametric design modeling, Computer Numeric Control machines and computational tools are constantly changing the methods of design, specifically for performative purposes in the production process, but still, are not fully integrated inside the design workflow. For us, architects, to develop emergent creative potentials and to produce sustainable design alternatives, is imperative to understand physical phenomena and the mechanisms that describe the world around us. (Baquero, 2016) The rules that describe those mechanisms may come from the mathematical world, but may lack a biological reference. They could be seen only as a first step of analysis of the natural world for inspiration. Physical materialization thought can actively determine the morphology (Giannopoulou, 2009). The scope of this thesis is lying in the intersection of those three disciplines: Biology, Computation, Design and Construction (figure 1).

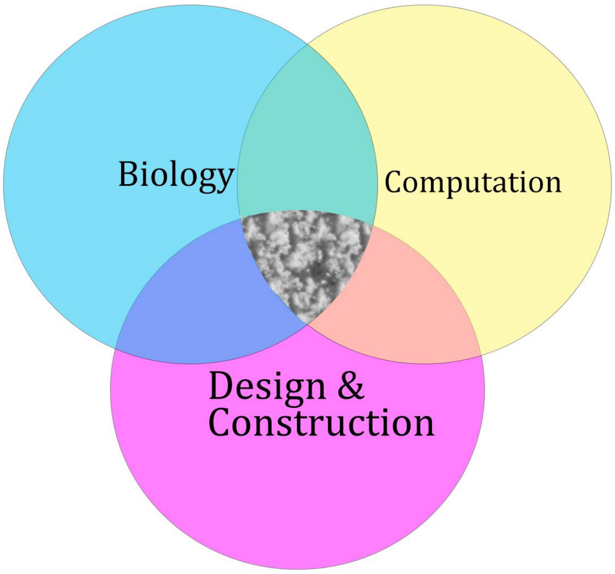


Figure 1. Intersection between disciplines.

Learning from the laws of nature (bio-learning) and dynamical systems that explain them, goes parallel with the environmental, social and economic changes and the technological advances taking place nowadays in science and industry (Estévez, 2003). In fact, to produce a history of technological innovation along the lines suggested by Deleuze and Guattari, will involve some conceptual breakthroughs, in particular, to get rid of the "hylomorphic schema" (form imposed on matter from the outside). If Deleuze and Guattari are correct in saying that it is precisely this schema which makes the machinic phylum "invisible" or "unrecognizable", and what they had in mind when coining the term "machinic," is the existence of processes that act on an initial set of merely coexisting, heterogeneous elements, and cause them to come together and consolidate into a novel entity (DeLanda, 1992), this thesis could be seen as an intention to hack this schema and precisely for the purpose of this “synthesis of heterogeneities” (Deleuze and Guattari, 1980).

The idea of thinking about biological morphogenesis in mathematical terms has emerged long before the discovery of the gene regulatory

---

networks (GRNs) and the establishment of a formal parallelism between the GRN dynamics and the logic gates in computation theory, which paved the way for new approaches, such as the introduction of 2D cellular automata, for the simulation of biological spatio-temporal patterns. To trace the origins of such mathematical or even philosophical concepts, one can start by going back to the ancient Greek philosophers-mathematicians. From Aristotle *Metaphysics and The Physics,* to Charles Robert Darwin *On the Origin of Species, to* D'Arcy Wentworth Thompson *On Growth and Form, to* the topological approach and C*atastrophe Theory* of René Thom, and Alan Turing *Reaction-Difussion* theory.

In advanced computational architecture, biological morphogenesis (or digital morphogenesis) and the emergence of form and pattern in natural systems serves for architects as inspiration and creativity, as an abstract model capable of liberating the tectonics and which could perhaps define new levels of interaction and integration within natural ecosystems. To Weinstock, this means a search on the mathematical basis of processes in nature and in computational environments, the principles and dynamics of organization and interaction and the mathematical laws of natural systems that could be applied to artificial constructed systems. The mathematical models generating designs of evolving forms and structures and the criteria for selection can be developed to correspond to architectural requirements like structurality and *buildability*. Those strategies for design should include iterations of physical modelling, incorporating self-organizing material effects of form finding and industrial logic of production. (Weinstock, 2004)

Inside the area of computational design, data analysis and geometry optimization for digital fabrication, is opening now a new field of investigation related to machines, artificial intelligence, machine learning and material industry. Automated systems in design, neural networks and visual scripting languages with production capabilities are now starting to be used in the fabrication of experimental architectural works (Tamke and Thomsen, 2018). At the same time, breakthroughs are taking place in the area of

---

Developmental Biology (Evo-Devo), computer science, theoretical biology, complex systems and systems biology, through computer simulations and mathematical models (Sharpe, 2017; Brodland, 2015).

This research has started as experimentation in search for the computational design tools and workflows to enhance the fabrication efficiency and structural performance of complex geometries in architecture (Baquero, 2016). The implementation of a biological patterning logic, beyond the formal scope, has been evolved by examining the structurality of such a mechanism as a pre-rationalization design methodology (Stach, 2010). Understanding specifically the underlying mechanism from the theoretical and computational perspective and applying it as construction logic, the form-force dependence, as in the membrane structures, becomes *form-force-pattern* dependence.

The investigation leads to the current rise of the new digital technology, known as Industry 4.0 in the manufacturing industry and the introduction of a machine learning approach for data analysis and decision making, in fabrication to enhance intuition, knowledge and experience in the field. In this learning process of trial and error, the scope swifts from the dynamic form finding techniques to an analytical data approach and prediction mechanism. For this, information and communication technologies play a central role, as the variable, parametrically defined form, can exchange design information in such a way that allows adaptation across multiple types of topological and scale applications, as structural elements and patterns, opening a new field for interdisciplinary investigation.

The outcomes/case studies could be summarized as small-scale prototypes of thin shell structures with minimal surface properties, integrated within a building environment and landscape. Although, they are designed and built entirely digitally, using advanced manufacturing techniques (CNC, laser cutting, 3D printing), they lead to physical objects that

---

incorporate in their entirety the whole process and an entire technological background. The outline of the research is summarized in figure 2.

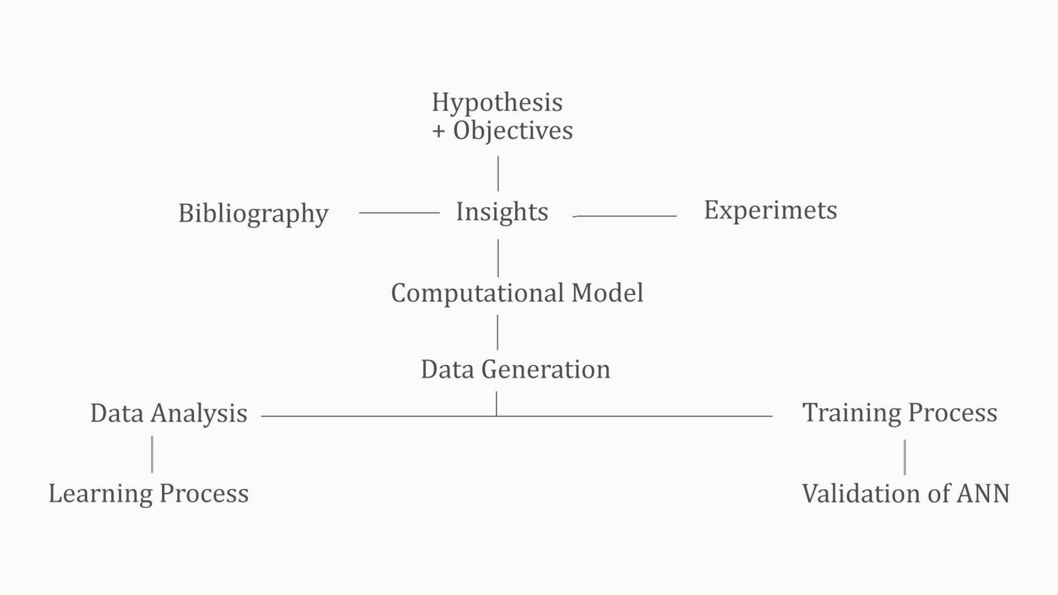


Figure 2. Research process.

2. HYPOTHESIS AND OBJECTIVES

The thesis delves into the computational correlations between artificial and biological systems, if complement each other, and if the morphogenetic processes of the mechanisms that describe phenomena occurring in natural systems can be represented as algorithmic processes for designing and producing novel, sustainable and efficient architectural works. It is examining, if the integration of a machine learning approach could be an alternative research and learning tool for understanding, evaluating and analyzing design outputs based on multicriteria, especially for fabrication.

The general objectives are:

1. To observe the natural mechanism, that is, a simple set of underlying rules and parameters which account for a seemingly complex biological phenomenon. The rationale for this is not for simplicity's sake, but to determine the rules of underline complexity (Camazine, 2003). Doing such an abstraction, is a *sine qua non* requirement to capture the essence and reveal the rules underlying the apparent complexity.
2. To bring insights by examining the theoretical and computational modeling frameworks operating on two different simulation domains: the biological pattern prediction mechanism and the architectural generative design and fabrication.
3. To explore the principles as computational design effects and structural mechanisms, in accordance to the fabrication techniques and materials in each phase of the design process.

---

4. To establish a parametrized continuous design workflow which integrate manufacturing and assembly processes with embedded features which resemble natural phenomena and mechanisms. Those features applied, *mutatis mutandis* as methods of design, are capable to manifest their potential and to enhance geometry, relating the emergent dynamical and generative systems to architectural interpretations and applications.
5. To explore the great potentials of emergence of growth, form, pattern and structure in a coherent design methodology, from concept to realization, as a fabrication experiment.

The specific objectives are:

6. To achieve structural performance, material and machine economy, as part of the design process and consequently to make the fabrication process more efficient and effective.
7. To examine the feasibility of a machine learning approach which will enhance the design space by predicting new results, when there is multi-objectivity.
8. To create a database of more than 1000 variations of branching shell structures with embedded segmentation pattern .
9. To evaluate the results, analyze and have insights, relating numerical values on statistical charts, as a learning process. Directed especially for fabrication, this qualitative approach can lead to a better decision making and inform the design based partly on intuition, partly on the machine.

---

10. To test the feasibility of building a state-of-the-art prediction mechanism of shell and pattern generation with *n* number of branches to reduce computational cost.
11. To define learning goals in order to train and validate an Artificial Neural Network (ANN).

---

3. METHODOLOGY: FROM INTUITION TO PRECISION TO EXTENDED INTUITION

Computer simulations studies are widely used to relate the self-organization exhibited by natural systems from their internal structure and play a crucial role for the development of physical/biological process. Generative computational design systems and advanced physics of nonlinear manner are used to explore the dynamic changes of structures and materials in response to the changing conditions. This thesis is examining the theoretical and computational modeling frameworks operating on two different simulation domains: the biological pattern prediction mechanism (Turing, 1952) and the architectural generative design tools (Terzidis, 2003; Kolarevic, 2003; Roudavski, 2009; Hensel et al., 2013). The method is bringing insights from the conceptual to modeling to metamodeling (Wang, 2006) and to material interpretations for the construction of self-supporting thin shell structures of branching topologies according to the stripe logic..

The methodological framework is examining the evolution of a generative design workflow which integrates structural form finding, advanced manufacturing, material properties, tolerances, constraints, machine limitations, interactivity and data analysis. It is aiming to instil the skills of cutting-edge computational tools that serve as a platform for testing ideas and formulating strategies for breaking down geometries to sub-systems and components, facilitating the production of real physical projects. In fact, those techniques and their applications, if both come hand to hand, then, apprentice is a learning by doing process (Sennet, 2009). So, if the method gives the possibility of trial and error, then is implementing intuition inside the design procedure. The advent of a digitally controlled fabrication means that the 'geometrically aware' and 'computationally enabled' design is as close to the materialization as in the original craft process, but with

---

precision and control and the ability to explore variation which was previously unimaginable (Aish, 2005).

The initial design methodology explores a computational workflow to identify a suitable algorithmic surface pattern with structural properties to be used as fabrication logic. To accomplish this, graph representations for the segmentation and physics-based simulations for interactive structural form finding, implementing material and fabrication aspects are used to generate geometrical configurations of patterns. During this experimental process, crucial role plays the study and analysis of the topology and orientation of the stripe pattern and its transformation in relation to the changing conditions and structural data of the shell topology, defined by the algorithm.

Furthermore, when there are many criteria involved and multi-objectivity, such as structural performance, minimizing material waste, number of stripe components and connectivity elements, to achieve surface continuity, an alternative method of design decision and optimization was needful. For this reason, a machine learning approach is tested to predict simulation results out of precedent, instead of relying only on intuition. The advantage of integrating intelligent design systems, is that they can analyze, process and transform design, expanding the ability to work across knowledge domains and to have potential for innovating existing practice. What Tamke & Thomsen (2018) refer to as extending design intuition, is that "the model becomes a creative-analytical engine into which external data can be ported and analyzed or internally generated to create the basis for intelligent design practices".

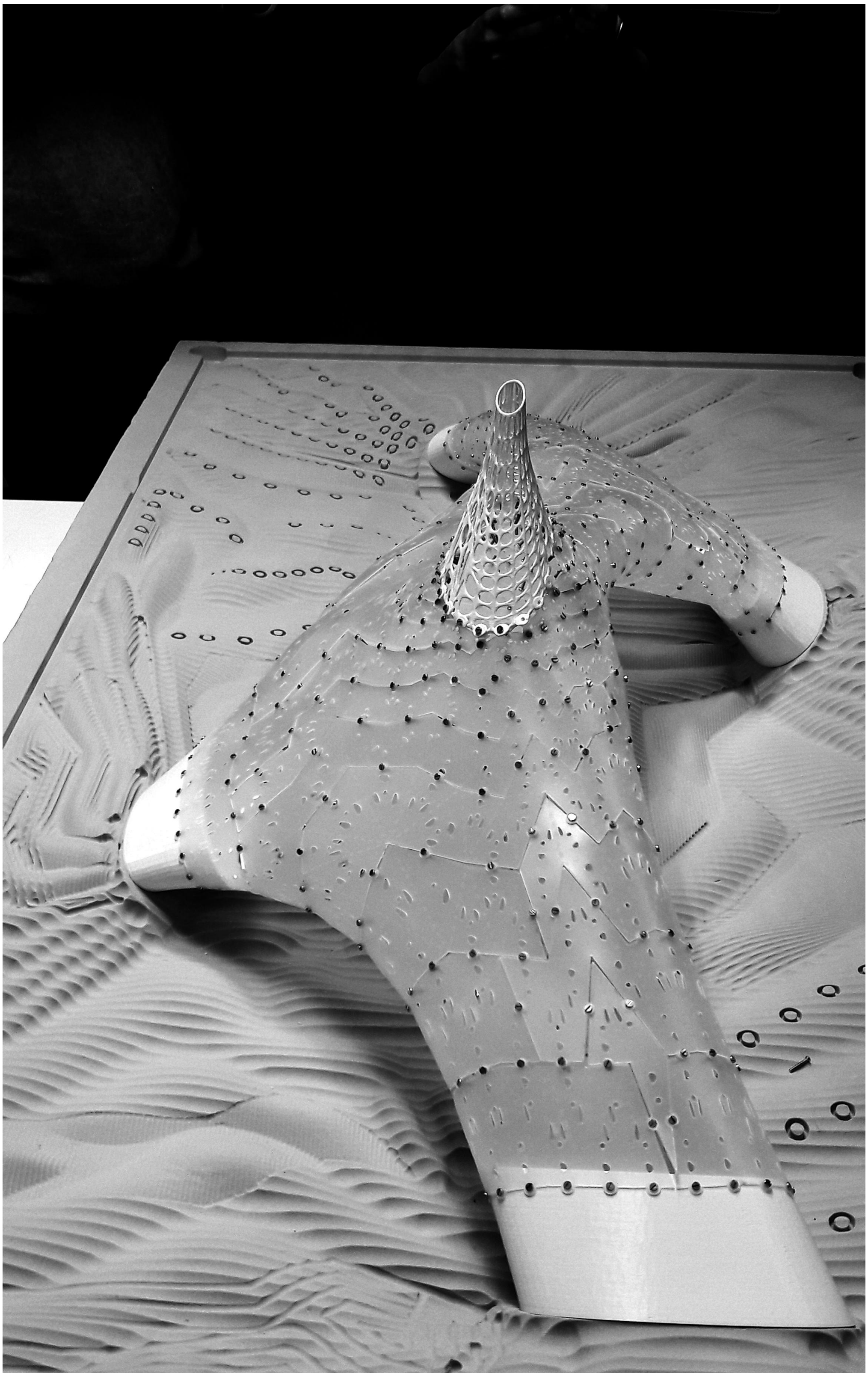
For this purpose, the whole established parameterized design workflow is re-examined in order to allow the model to iterate from the initial input geometry (points on a plane) to the final cutting pieces on flat sheets. This process permits to extract the appropriate data sets in the format of excel sheets and corresponding images. In contrary to the previous static inputs, the new model allows the generation of a dynamic input and output geometry and a qualitative understanding of outcomes based on the required criteria, which can save a lot of computational time.

Specifically, the whole experiment is framed in four computational stages, with relevant sub-phases:

1. The parametric modeling of the shell structure and pattern: geometry construction, fabrication technique and structural analysis (Articles 1, 2).
2. The re-examination of the procedural design workflow for the preparation of the database: development of a database of 1850 alternatives (Articles 3, 4).
3. The training process: development of the prediction mechanism as ANN (Articles 4, 5).
4. The validation of the ANN: Generation of a new database for comparing the computed with the predicted values (Article 5).

The diagram below highlights the continuity and connection between the articles. The three prototypes/case studies, as described in Articles 1, 2, 4, share a similar design workflow (relaxation, segmentation, fabrication) but the initial input geometry differs in the three cases (cubical composition, 2D Voronoi meshes, random 2D points, respectively) and also the output branching topologies .

***Article 1**: Employing Mesh Segmentation Algorithms as Fabrication Strategies. Pattern Generation Based on Reaction-Diffusion Mechanism.* ***Article 2**: Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure.*	Design workflow from concept to modelling to construction.
***Article 3**: Machine Learning Approach for Biological Pattern Based Shell Structures.*	Examination of a prediction mechanism of shell and pattern, looking to related projects.
***Article 4**: Stripe Segmentation for Branching Shell Structures - A Data Set Development as a Learning Process for Fabrication Efficiency and Structural Performance.*	Re-examination of the design workflow to extract the appropriate data sets.
***Article 5**: Computational Workflow for Segmented Shell Structures: an ANN Approach for Fabrication Efficiency.*	Training and validation of the artificial neural network prediction mechanism.



Rahmani Tarek@2017. Ed. Author

---

4. RESULTS

The thesis consists of a compilation of 5 articles published or accepted for publication in indexed and catalogued international scientific journals, databases and relevant editorials. As a general outline, the first two articles present a generative design workflow and methodology applied to the construction of two physical prototypes. The third article is examining the efficiency of implementing a machine learning approach into the already established design workflow, looking into relative projects. The fourth and fifth article explore the potentials and feasibility of a state-of-the-art machine learning approach. The articles are organized inside the thesis chronologically, in the sequence that the related prototypes were constructed.

(The differences in the bibliographic references styles of the 5 articles and final bibliography are due to the fact that the original format of the articles has been preserved).

Article 1:

Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure.
doi:10.1088/1757 899X/471/10/102053

Giannopoulou E., Baquero P., Warang A., Orciuoli A., Estévez A.T. and Brun-Usan M.A.

IOP Conference Series: Materials Science and Engineering, 471 (9), IOP Publishing Ltd. Year 2019. Data Citation Index – Web of Science (Clarivate Analytics) and in SCOPUS database.

Article 2:

Employing Mesh Segmentation Algorithms as Fabrication Strategies. Pattern Generation Based on Reaction-Diffusion Mechanism.
doi:10.5937/fmet1902379G
Giannopoulou E., Baquero P., Warang A., Orciuoli A., Estévez A.T. and Brun-Usan M.A.

FME Transactions Journal, vol. 47 (2), 379-386. Year 2019. Data Citation Index – Web of Science (Clarivate Analytics) and in SCOPUS database.

Article 3:

***Machine Learning Approach for Biological Pattern Based Shell Structures*.**

Giannopoulou E., Baquero P., Warang A. and Estévez A.T.

VV.AA., *Industry 4.0 – Shaping the Future of the Digital World*.
Taylor & Francis: London. Year 2019.

Article 4:

Stripe Segmentation for Branching Shell Structures -
A Data Set Development as a Learning Process for Fabrication Efficiency and Structural Performance.
Giannopoulou E., Baquero P., Warang A., Orciuoli A., and Estévez A. T.

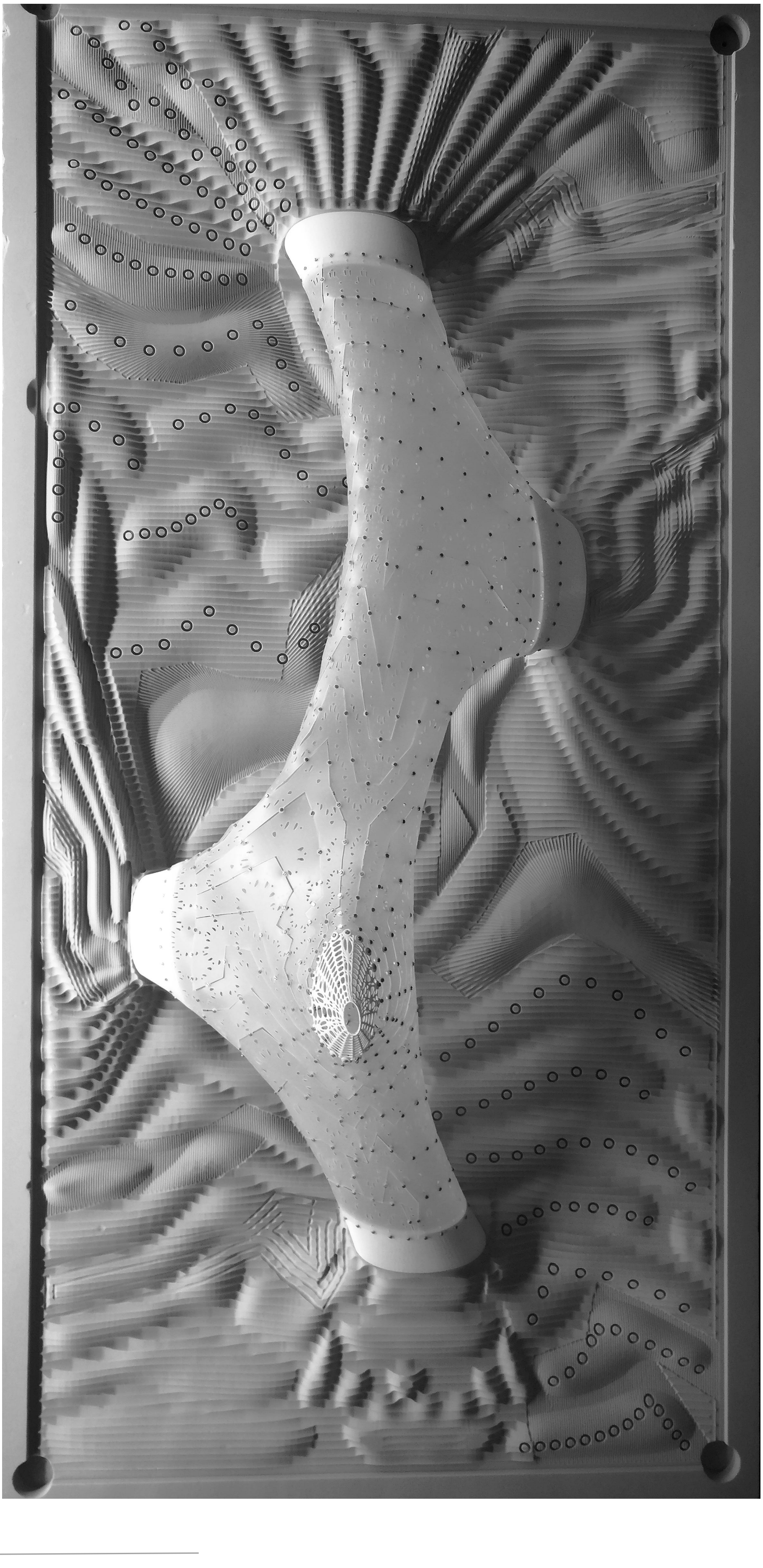
Architecture in the Age of the 4th Industrial Revolution: Proceedings of the eCAADe+SIGraDi joint Conference. Porto.
Year 2019. Cumulative Index on CAD.

Article 5:

Computational Workflow for Segmented Shell Structures: an ANN Approach for Fabrication Efficiency.

Giannopoulou E., Baquero P., Warang A. and Estévez A. T.

In Carlos Lázaro, Kai-Uwe Bletzinger and Eugenio Oñate (Eds.), *FORM and FORCE,* IASS & Structural Membranes 2019, pp. 2598-2605. International Centre for Numerical Methods in Engineering (CIMNE), Barcelona, Spain. ISBN: 978-84-121101-0-4. Year 2019. Data Citation Index – Web of Science (Clarivate Analytics) and in SCOPUS database.



Article 1: Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure.

Effimia Giannopoulou[1], *Pablo Baquero*[2], *Angad Warang*[3], *Affonso Orciuoli*[4], *Alberto T. Estévez*[5], *Miguel A. Brun-Usan*[6].

[12345] UIC, Carrer de la Immaculada, 22, 08017 Barcelona, Spain.

[5] Electronics and Computer Sciences. University of Southampton, UK.

WMCAUS 2018 IOP Publishing

IOP Conf. Series: Materials Science and Engineering **471** (2019) 102053doi:10.1088/1757-899X/471/10/102053

BIOLOGICAL PATTERN BASED ON REACTION-DIFFUSION MECHANISM EMPLOYED AS FABRICATION STRATEGY FOR A SHELL STRUCTURE

***Abstract**. This paper examines how generative architectural design processes aim to apply the principles of biological morphogenesis to the design and building of mechanical or architectural structures. Despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, design processes fail to acknowledge materials, tools and construction logic in an early design stage, as manifested in nature. The objective of this paper is to introduce a design workflow, based on the knowledge of the tool, material properties, design intuition and aesthetic criteria, to translate biological skin patterns to fabrication processes, incorporating three materials and procedures in a single parametric workflow. Mesh relaxation processes and weighted mesh graph representations are examined as design potentials for stripe organization in fabrication in analogy to numerical simulations of a reaction-diffusion (RD) mechanism. A thin shell and landscape emerge as a self-organizing system in equilibrium. The paper argues that skin patterns in fabrication open a new field for interdisciplinary investigation.*

1. Introduction

Architectural design processes and workflows are goal-directed and traditionally driven by optimizing the functional requirements and the structural hierarchy of materials. The process of biological evolution, on the other hand, is blind to any future goals and proceeds by tinkering and reusing previous structures, thus being subject to historical contingency. It is impartial to the complex sequences of the synthesis of materials, which are

---

instead integrated in the coherent, non-linear and often self-organized process of morphogenesis [1]. Generative architectural design processes aim to apply the principles of biological morphogenesis to the design and fabrication of architectural structures. However, despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, they fail to acknowledge materials, tools and construction logic in an early stage of the design process, as manifested in nature. As a result, the realization of specific fabrication processes and their individual constraints often lead to amendments to an already established workflow by making desperate adjustments to rationalize the design.

The objective of this paper is to introduce a design workflow of three digital fabrication techniques (viz. CNC milling, laser cutting and 3D printing), that integrates material properties, tolerances, constraints, capacities, machine limitations and interactivity for the construction of a shell structure and its landscape. Based on the knowledge of the tool, material properties, design intuition and aesthetic criteria, the method tries to translate biologically inspired processes to fabrication processes incorporating three different materials and procedures in a single parametric workflow which manifest a unified patterning system. Motivated by the work of Marc Fornes [2], stripes have many advantages as a construction logic, like minimizing of material and connections, assembly efficiency and structural stability, besides aesthetics and unlimited variations evident in nature. This review first examines biological mechanisms that generate those type of patterns and the available simulation models and computational tools to generate them, as exhibited in biological systems. Secondly, describes how those patterns are incorporated in a form finding process for fabrication. In addition, a qualitative comparison of the shell analysis model, stress lines diagrams, segmented stripe pattern and the physical prototype, offers some potential hints of extracting useful information about stress

---

lines/segmentation relation, skin/stripe performance, structure/landscape continuity and other possible fabrication processes.

2. Reaction-Diffusion (RD) Mechanism and Stripes

Although little is known about the underlying molecular mechanism, many theoretical studies suggest that the skin patterns of many animals are produced by a Reaction-Diffusion (RD) mechanism: a biochemical system involving two interacting diffusible molecules, an activator and an inhibitor, whose dynamics produces putative 'waves' in the spatial concentration of each molecule, thus generating periodic patterns in the field [3]. Alan Turing's theory of morphogenesis [4], based on a RD mechanism, explains the formation of different striped and dotted patterns in a variety of organisms. Mathematical analysis shows that a RD mechanism can generate a wide variety of spatial patterns by varying the few parameters involved, giving this model the potential for application as an experimental working hypothesis in a wide variety of morphological phenomena [5]. The formation of pigmented biological patterns (figure 1), like the stripes or dots on furs, the rings on butterfly wings, the skeletal elements in vertebrate limbs, the scutes in turtle's shells and even the cusps in mammalian teeth, has become accessible to modelling by means of certain RD equations [6].

There is clearly a connection between natural patterns formation and the RD mechanism. But how this mechanism could be computationally applied to generative architectural design and especially as fabrication procedure? From a scientific point of view, RD simulation is much easier in 2D than other phenomena occurring in 3D [7], revealing a surprising variety of irregular spatiotemporal patterns of numerical simulations [8] to apply to the shell surface and landscape.

3. Simulation tools and biological patterns

The idea of comparing systems in biology and engineering dates back to antiquity, but for long time it was mainly thought of just as an inspiration. Only until the discovery of the gene regulatory networks (GRNs) emerged the idea of thinking about biological morphogenesis in purely mathematical terms. This allowed to establish a formal parallelism between the GRN dynamics and the logic gates in computation theory, paving the way for new approaches, such as the introduction of 2D cellular automata [9] for the simulation of biological pattern formation. A sequence of studies about biological pattern formation (most of them based on RD equations) carried on during the 70s were relevant to other related fields, from complex systems and self-organization to synergetic and dissipative structures [10]. In RD mechanisms, as in other kinds of self-organization models, the primary goal is to capture the essence of the system (that is, a simple set of underlying rules and parameters) which account for a seemingly complex biological phenomenon. The rationale for this is not for simplicity's sake, but to determine the rules of underline complexity [11]. Although a striking resemblance are often found between the biological pattern and its simulation, the actual mechanism of pattern formation has still to be confirmed experimentally by means of empirical studies [12]. The modelling strategy described in this paper can be also viewed, in an Aristotelian way of thinking, as a way of deriving process from fundamental principles. By doing such an abstraction, one can capture the essence and reveal the rules underlying the apparent complexity.

Nowadays, the RD mechanism is computationally accessible, and there are many programming languages, and mathematical models like the Gray-Scott RD model, with the ability to produce a varied number of biological looking (and behaving) patterns, both static and constantly changing to simulate fast and computationally efficient finite difference method for the Turing pattern on curved surfaces in the three-dimensional space [13]. Numerical simulations of a simple RD model reveal a surprising variety of irregular spatiotemporal patterns. (figure 2)

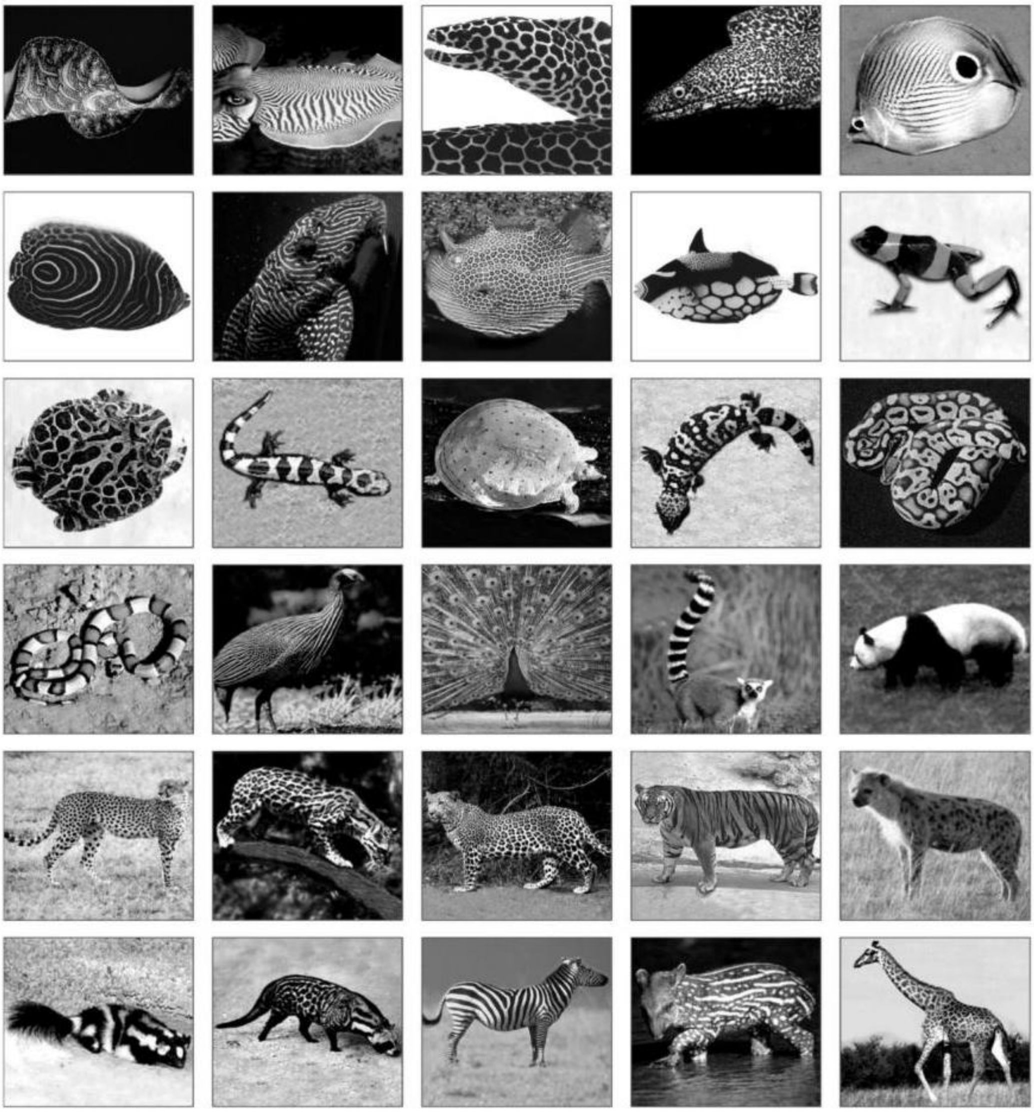


Figure 1. Typical examples of pigmentation patterns on animals. (www.wolframscience.com)

This research demonstrates that an application of weighted meshes representations is suitable for fabrication and provide an efficient design

---

workflow. The network of connected faces and edges of the mesh is a simplified representation of architectonic elements, such as structural framing or facade panels. Recent research demonstrates that approaches bringing together mesh and graph representations drawn from computer graphics can be effective within the domains of applications for which they have been developed [14] [15]. The dual graph concept implemented as a data object called MeshGraph (MGraph) corresponds to the specific purpose of unfolding surfaces and segmentation of triangular meshes. The application is running inside Grasshopper platform and could generates stripe formations in an early design phase, giving at the same time the CNC cut designs and logistics.

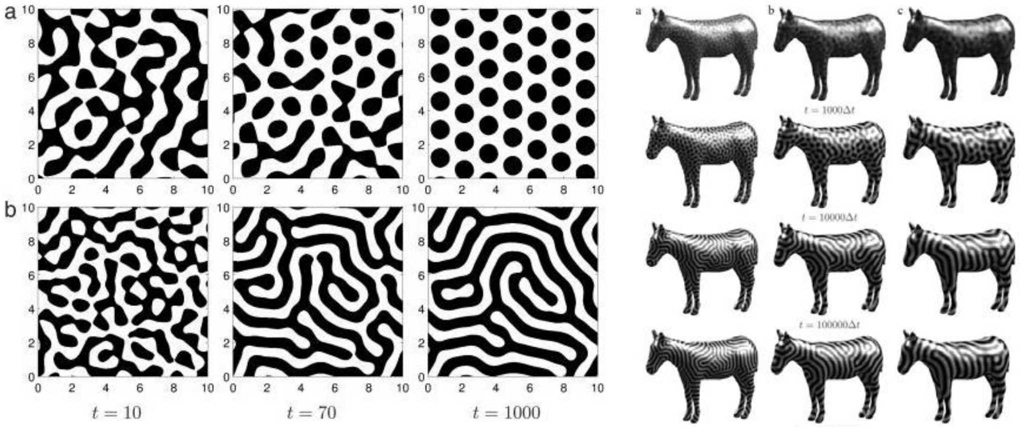


Figure 2. (left) Pattern on two-dimensional rectangular domain, (right) Pattern formation process of the Lengyel–Epstein model on a zebra surface. [13]

4. Design Methodology

This research offers a methodological framework of identifying a suitable surface pattern with similar features to a RD-based stripe formation to be used as fabrication logic for the CNC, laser cutter and 3d printer. We computationally explored and geometrically defined the patterning algorithm with explicit reference to biological morphogenesis and Graph Theory. The approach uses force-based relaxation processes for the structure and mesh segmentation algorithms for the generation of skin and landscape pattern. Eventually, to give the stripe effect, the mesh relaxation process is linked with the segmentation process and the fabrication process. Structure, skin and landscape could be one unified system in equilibrium.

4.1 Mesh relaxation process for the shell structure form-finding

To generate, in a simple and intuitive way, a structure in static equilibrium, with minimal surface properties, dynamic relaxation physical load force of gravity (using Kangaroo physics plugin inside Grasshopper) was applied to the initial surface topologies with boundary conditions defined by anchoring points. An organic structural membrane system of planar quadrilateral mesh faces emerged as a result with near zero mean curvature surface properties (not exactly minimal, because other forces are also applied, but could be fixed by applying more strength during the relaxation process). During the relaxation process, the real-time dynamic physics engine allowed to visually and intuitively interact with “virtual” physical forces applied to the pre-defined geometry, translating mesh lines and vertices to a network of springs and particles. The load, spring length and strength is controlled by the algorithm, to generate the proper height of the shell. Piker [16], mentions that the models we use for physical form-finding are usually not simply a scaled down version of the real structure, but involve a level of abstraction. We use materials which are quite different from those we will eventually build with at full scale but have key behaviours and geometric properties relevant to their construction in other materials. The shell structure was generated taking in count material properties of the prototype and fabrication technique.

4.2 Mesh segmentation process for the shell skin and landscape

The project employs computational techniques of weighted-mesh representations for the generation of 2D geometrical configurations of stripe patterns for the surface skin (figure 3) and landscape, analogous to the skin patterns emerging from RD mechanisms. As a construction logic, each stripe is conceptualized as a ruled surface (developable, with zero Gaussian curvature), which is unrolled according to two valence nodes mesh. The relaxed mesh was given as input to the segmentation algorithm to compute the minimum spanning tree for the mesh graph using a modified Kruskal's algorithm with max valence preference. Specifically, the Input parameters were:

- G (MGraph): The MGraph object used for MST calculation
- W (Domain): Optional domain for the weights to be considered
- V (Integer): The maximum valence for the node. This value signifies a preference not a limit
- S (Integer): The maximum number of nodes in one piece. (or number of faces)

The Output parameter:

- G (MGraph): The minimum spanning tree/trees MGraph object, which defined the pattern.

The algorithm was also controlling the amount of mesh faces, that is the size of stripes to appropriately fit to the machine for fabrication. A series of fixed initial anchor points were given as an input for the generation of parallel surface stripes and profile landscape lines. The form-finding of the landscape stripes, followed the same process as the skin, with an additional operation, after the segmentation, of generating 3D wave pattern. The MGraph lines are

---

used as mountain lines and the stripe edges as valleys as appear in the prototype.

Figure 3. Shell model MGraph lines and two valences segmentation (image by authors)

4.3. Fabrication process of the shell and landscape

The entire fabrication process was accomplished in three parts. The outcome prototype, constructed during a five days master workshop, required full coordination between teams, each one responsible to deliver the G-code for a specific fabrication technique.

4.3.1. CNC milling

The landscape stripes were milled on the polystyrene foam using various tools and milling methods (figure 4, bottom right). The profile lines were inputted as tool paths, generated using RhinoCam2016. Several milling operations were used to generate the desired pattern. First, the horizontal roughing with a 50mm diameter ball-mill with 2 mm stock and 50% step-over. Second, was the parallel finishing with a 20mm diameter ball-mill with 1.5mm stock and 50% step-over. In-order to create laser cutting, (top) 3D printing piece (images by authors) different patterns on the first parallel finishing, different milling operations, like radial machining, parallel finishing

---

and 3D offset pocketing were implemented with a 6mm diameter ball-mill with different step-overs like 200%, 100% and 50%. The 3mm diameter flat-mill was used to make the hole pattern and 6mm diameter flat-mill to make the frame using the engraving milling operation. Eventually, the surface that attaches the 3D printed structural legs, was flattened using sandpaper to have stability, ease of drilling and inserting the fisher screws. The entire CNC milling process took 2 days for the result.

4.3.2 Laser cutting

The unrolled surfaces were systematically numbered and labelled to create assembly guidelines after being individually cut (figure 4, bottom left). The triangulation of the meshes further exemplified dashed score lines to add slight flexure to the otherwise stiff polypropylene stripes. After being labelled and scored, the stripes were treated as individual 2D shapes, and additional semi-circular loops were added at the naked edges of each triangulation. At the assembly stage these loops would serve as overlapping washers for screw and nut fixing. The labelled, loop-edges 2D shapes were nested on 1050x750mm sheets using RhinoNest for optimization of material use and then exported to the laser cutter using AutoCAD 2007. The 0.8mm thickness of the polypropylene sheets, and the melting point of the material dictated the speed of cutting, the overall outcome and the level of detail obtained. The laser cut pieces were connected to each other, based on the label numbers, and by means of 2.5mm diameter screws and nuts. Here, the tolerance between stripes could have been adjusted by this diameter. The entire laser cutting process of took 4 hours.

Figure 4. (Bottom right) First milling operation, horizontal roughing, with ball mill (50mm diameter). Stock of 2mm and stepover 50%. (bottom left) nested pieces for laser cutting, (top) 3D printing piece (images by authors)

4.3.3 Printing 3D

The 3D printed legs were employed as the structural interface between polypropylene stripes and the CNC milled landscaped polystyrene foam. An additional piece was designed additionally to close the top hole of the shell (figure 4, top). The design of the structural legs mediates between the structural properties of the polystyrene foam and the polypropylene sheets to accommodate their respective design. To avoid over designing and over complication, the structural legs were made to be robust, engineered junction pieces accommodating the sizes of holes for the screw and nut connection. The four designed structural legs were first made to be watertight, by closing all naked edges. To create the G-code, the designs were sliced in Cura Engine and 3D printed using FDM (Fused deposition modelling) additive printing on Felix 3.1 with a build volume of 255x205x225mm, extrusion speed of 15mm/s and motion speed of 150mm/s. The material used for printing was PLA(Polylactide) filament with 1.75mm diameter requiring working temperature of 190-210°C and platform temperature of 50-60°C. The structural legs were printed without any supports, directly available for assembly. Although, the screw holes required sanding and smoothing with a drill machine. The entire 3D printing process took 3 days on 3 Felix 3.1 printers for the result.

4.4 Assembly

The four printed structural legs were first mounted on the polystyrene foam by means of fisher screws and had the first connecting layer of the polypropylene stripes securely connected to them. The other layers of the polypropylene were subsequently added based on their labelled numbers. All teams came together in a collaborative assembly process where the sequential roles and responsibilities based on the material were fulfilled. The entire assembly process was finished in 12 hours, without any eventual amendments to the already established workflow. The stripe formations not only generated the shape, but also aided in ease of assembly, thereby reducing time. (figure 5)

5. Discussion

Using generative architectural design processes, the design workflow intends to translate biologically inspired processes with similar features to a RD-based stripe formation to fabrication processes. A qualitative study of the shell FEM analysis model, stress lines diagrams, segmented stripe pattern and the physical prototype, offers some potential hints of extracting useful information about stress lines/segmentation relation, skin/stripe performance, structure/landscape continuity and other fabrication processes.

Figure 5. Prototype model (image by authors).

5.1 Simulation models

From the initial form-finding of the shell with near minimal surface properties, the skin is segmented and constructed as developable stripes using thin planar sheets of material. The landscape is milled, applying similar stripe generation process. The simulations were made as two different stages with different parameters controlling, for the skin and landscape, but it is possible to be in one single. It depends on the computational power available and the fabrication method used. As a discussion we could say that other programming languages could have been used to generate stripe formations. What has been as advantage using MGraph was that allowed the whole process, from concept to fabrication, to be generated inside the same platform, without program exchange complications.

5.2 Structural model

In this project the intention was to examine how a thin shell, constructed by connected stripes, would behave without extra structure but just counting in the equilibrium stage of the relaxation process. A very fast linear elastic analysis of shell element, made with Millepede plugin gives a hint of the spatial distribution of deflection across the structure, suggesting and revealing some of the prototype’s vulnerable areas. In relation with the stress lines, we observe concentration of lines on the deflected areas. For the structural model, material data of polypropylene was used (elasticity, density and yield strength [17], and poisson’s ratio [18]). Stress (force) lines reveal where the shell could be topologically optimized or accordingly arrange stripes direction for best performance. We observe that in most of the cases stress lines became perpendicular to the stripe segmentation. (figure 6).

Another structural aspect to be considered related to the fabrication process, is that nested pieces, should take in count the material properties when arranged into the material to be cut. A way of arranging the pieces that

---

go against the grain of the wood for example, would weakening them, as happened in the case of Mark Fornes project [19].

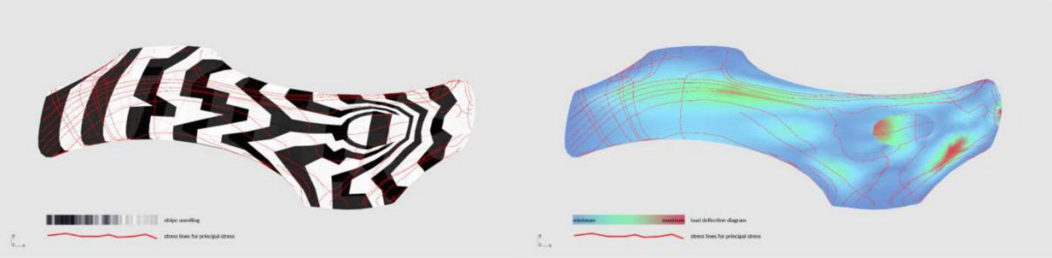


Figure 6. (left) Stress lines in relation with stripes, (right) stress lines in relation with deflection model (images by authors).

5.3 Conclusions and future work

We argue that the proposed method has many design potentials as stripe organization for fabrication, thus opening a new field for interdisciplinary investigation between engineers, programmers and scientists and fabricators. A deeper study of pattern formations and simulation models performed by mathematicians could address insights in the field of adaptive design systems in terms of temporal dynamics of changes in the pattern, as occurs in the skin stripes of fishes formed by waves [20], or the viability of an experimental implementation of 3D patterns with geometrical and topological properties of Turing patterns (area, boundary length, cluster numbering, connectivity, and so on) as described by Guiu-Souto et al. [21] inside a generative fabrication context.

Acknowledgments

We would like to thank the students of the Biodigital Master, 2017, UIC Barcelona, helping with the realization of this project.

References

Lev. V. Beloussov, “Morphogenesis as a macroscopic self-organizing process”, *Biosystems* 109.3, pp. 62-279, 2012.

M. Fornes, “MARC FORNES & THEVERYMANY”, https://theverymany.com/, Accessed February 1st 2018.

S. Kondo, “The Reaction-Diffusion System: A Mechanism for Autonomous Pattern Formation in the Animal Skin.” *Genes to Cells*, vol.7, pp. 535–541, 2002.

A. Turing, “The Chemical Basis of Morphogenesis.” Phil. Trans R. Soc. Lond. B1952 237, pp. 37–72, 1952.

S. Kondo, & T. Miura, “Reaction-diffusion model as a framework for understanding biological pattern formation”, *Science* (N.Y.), vol. 329, pp. 1616-20, 2010.

H. Haken (eds), “Introductory Remarks. In: Evolution of Order and Chaos”. *Springer Series in Synergetics,* Springer, Berlin, Heidelberg, vol. 17, 1982.

S. Kondo, “The reaction-diffusion system: a mechanism for autonomous pattern formation in the animal skin”. *Genes to Cells*, vol. 7: pp. 535–541, 2002.

J. E. Pearson, "Complex Patterns in a Simple System," *Science*, 261(5118), 1993 pp. 189–192.

S. Wolfram, A new kind of science, Wolfram Media, Champaign, IL, 2002, pp. 1004

S. Wolfram, A new kind of science, Wolfram Media, Champaign, IL, 2002, pp. 862

Scott Camazine, Jean-Louis Deneubourg, Nigel R. Franks, James Sneyd, Guy Theraulaz, & Eric Bonabeau, Self-organization in Biological Systems, Princeton University Press, 2003, pp.91

Scott Camazine, Jean-Louis Deneubourg, Nigel R. Franks, James Sneyd, Guy Theraulaz, & Eric Bonabeau, Self-organization in Biological Systems, Princeton University Press, 2003, pp.83

D. Jeong, Y. Li, Y. Choi, M. Yoo, D. Kang, J. Park, et al. "Numerical simulation of the zebra pattern formation on a three-dimensional model". *Phys A Stat Mech its Appl* 475 (2017): 106–16.

A. Nejur, K. Steinfeld, "Ivy: Bringing a Weighted-Mesh Representation to Bear on Generative Architectural Design Applications" ACADIA 2016 36th Annual Conference of the Association for Computer Aided Design, pp. 140-151.

A. Nejur, K. Steinfeld, "Ivy: Progress in Developing Practical Applications for a Weighted-Mesh Representation for Use in Generative Architectural Design" ACADIA 2017 37th Annual Conference of the Association for Computer Aided Design in Architecture, pp. 446- 455.

D. Piker. "Pseudo-Physical Materials". SpaceSymmetryStructure. May 18th, 2011. https://spacesymmetrystructure.wordpress.com/page/2/.

Makeitfrom. "Polypropylene (PP) Copolymer". Accessed by March 2018. https://www.makeitfrom.com/material-properties/Polypropylene-PP-Copolymer.

Polymerdatabase. "Typical Poisson's Ratios of Polymers at Room Temperature". Accessed by March 2018. http://polymerdatabase.com/polymer%20physics/Poisson%20Table.html.

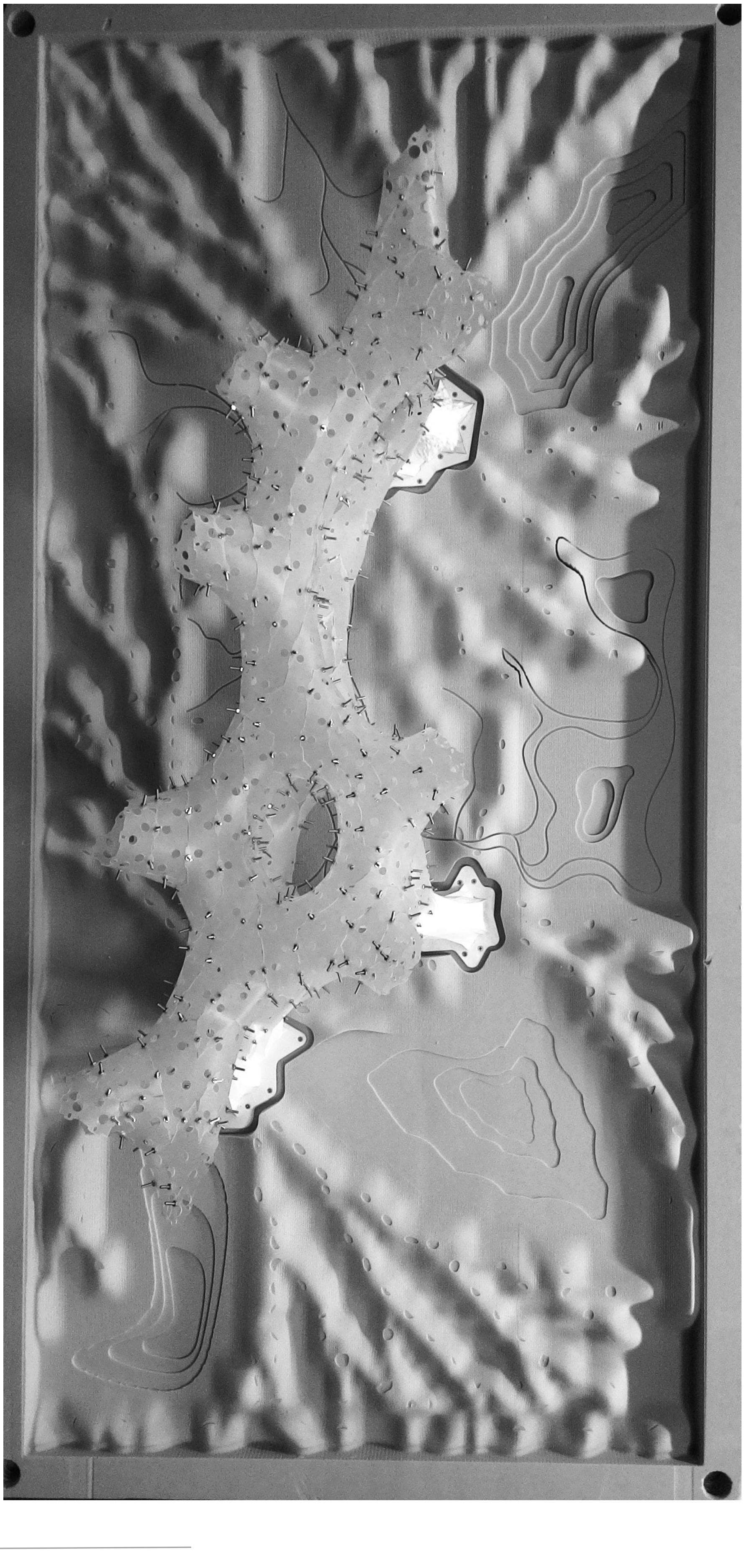
F. Hecker. "Creating the Chrysalis: Design". CivilityAndTruth. July 1st, 2017.

---

https://civilityandtruth.com/2017/01/07/creating-the-chrysalis-design/.

S. Kondo, “The Reaction-Diffusion System: A Mechanism for Autonomous Pattern Formation in the Animal Skin.” *Genes to Cells*, vol.7, pp. 535–541, 2002.

J. Guiu-Souto, J. Carballido-Landeira, A. P. Muñuzuri. “Characterizing topological transitions in a Turing-pattern-forming reaction-diffusion system”. *Phys Rev E* 2012, 85(5), pp. 1–8.



Article 2: Employing Mesh Segmentation Algorithms as Fabrication Strategies. Pattern Generation Based on Reaction-Diffusion Mechanism.

Effimia Giannopoulou[1], Pablo Baquero [2], Angad Warang[3], Affonso Orciuoli[4], Alberto T. Estévez[5], Miguel A. Brun-Usan[6].

[12345] UIC, Carrer de la Immaculada, 22, 08017 Barcelona, (Spain). estevez@uic.es

[6] Electronics and Computer Sciences. University of Southampton, (UK), M.Brun-Usan@soton.ac.uk

---

EMPLOYING MESH SEGMENTATION ALGORITHMS AS FABRICATION STRATEGIES. PATTERN GENERATION BASED ON REACTION-DIFFUSION MECHANISM

Abstract: *This article examines how the evolution of architectural generative design processes aim to apply similar physical and geometrical principles of biological processes taking place during development and to translate them to fabrication processes. In analogy to the reaction-diffusion mechanism for biological pattern prediction, the logic of stripe is used as construction system and examined for its structural behaviour. Both, mesh relaxation processes and weighted mesh graphs representations are employed as design tools for the construction of a minimal thin shell structural skin with branching topologies. Eventually the design workflow is extended to engage also collaborative fabrication processes and to steer the design based on intuition, knowledge of the fabrication tools, properties of the materials, manufacturing simulations and logic of assemble. This approach could lead to the optimization of material usage and machine time and facilitate the assembly process of a physical object which integrates the whole process into its form. The outcomes have been used to fabricate a prototype, using three different materials and digital fabrication methods, to examine the stability and the mechanical connectivity by taking in count the tolerances. The article argues that biological skin patterns and segmentation in fabrication open a new field of interdisciplinary investigation and architectural applications.*

Keywords: *Fabrication methods, Stripes, Skin pattern, Morphogenesis, Shell structure.*

---

1. Introduction

Architectural design processes and workflows are goal-directed and traditionally driven by optimizing the functional requirements and the structural hierarchy of materials. The process of biological evolution, on the other hand, is blind to any future goals and proceeds by tinkering and reusing previous structures, thus being subject to historical contingency. It is impartial to the complex sequences of the synthesis of materials, which are instead integrated in the coherent, non-linear and often self-organized process of morphogenesis [1]. Generative architectural design processes aim to apply the principles of biological morphogenesis to the design and fabrication of architectural structures. However, despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, they fail to acknowledge materials, tools and construction logic in an early stage of the design process, as manifested in nature. As a result, the realization of specific fabrication processes and their individual constraints often lead to amendments to an already established workflow by making desperate adjustments to rationalize the design.

One of the objectives of this paper is to re-examine the design workflow, as part of a digital fabrication course, with the integration of three digital fabrication techniques (CNC milling, laser cutting and 3D printing). Taking in count the material properties, tolerances, constraints, capacities of the machines and interactivity between them, to steer the design and the construction of minimal surface structures and landscape design. The method also tries to implement biologically processes, such as the reaction-diffusion (RD) mechanism, as fabrication process, incorporating three different materials and procedures in a single parametric workflow to manifest a unified patterning system. Examining the work of Marc Fornes [2] and Vlad Tenu [3], stripe patterns have many advantages as a construction logic, like minimizing of material and connections, assembly efficiency and

---

structural stability. Besides the unlimited variations evident in nature, the aesthetics and visual effects may act also as a form of motion camouflage [4].

In order to understand the morphogenetic process, this research refers to the RD pattern mechanism, the available simulation models and also the computational tools to generate them. Secondly, describes the evolution of how those patterns are incorporated in a form finding process of minimal surfaces, from simple to more complex, to the fabrication. And thirdly, the real fabrication process. In addition, a qualitative comparison of the shell FEM analysis model, the stress lines diagrams and segmented pattern of stripes of the physical model is offering some potential hints of extracting useful information about stress lines and segmentation relation, the skin and stripe structural performance, and the shell with the landscape continuity.

2. Simulation of Biological Patterns

Only until the discovery of the gene regulatory networks (GRNs) emerged the idea of thinking about biological morphogenesis in purely mathematical terms. This allowed to establish a formal parallelism between the GRN dynamics and the logic gates in computation theory, paving the way for new approaches, such as the introduction of 2D cellular automata [5] for the simulation of biological pattern formation. More recent research includes the morphogenetic engineering field [6] which explores the possible parallels between naturally-evolved and artificially-engineered systems and synthetic biology construction [7], a new engineering design process. This goes beyond finding inspiration from biological systems and propose a system in which both modelling and manufacture are combined into an engineered biological system. Bionic basic principles are found in mechanical engineering also and especially in robotics. Research was carried out on the movement of different biological systems, which have legs. By observation, it is attempted to define some general principles that are necessary for the task of moving legged robots [8].

2.1 Reaction-Diffusion (RD) Mechanism

In order to find a way of implementing the stripe patterning logic to fabrication, this research seeks to understand the underlying mechanism of skin formations from scientific and mathematical references. The seminal 1952 article of Alan Turing, “The chemical basis of morphogenesis” [9], base a whole notion of natural patterns, such as the zebra's stripes, on the relationship between two competing tendencies: one that activates the growth of an effect and one that it inhibits it. The mechanism is called reaction-diffusion (RD) system and mathematical analysis shows that a RD mechanism can generate a wide variety of spatial patterns by varying the few parameters involved, giving this model the potential for application as an experimental working hypothesis in a wide variety of morphological phenomena [10]. The formation of pigmented biological patterns, like the stripes or dots on furs, the rings on the butterfly wings, the skeletal elements in vertebrate limbs, the scutes in turtle’s shells and even the cusps in mammalian teeth, has become accessible to modelling by means of certain RD equations [11].

Nowadays, the RD mechanism is computationally accessible, and there are many programming languages, and mathematical models, like the Gray-Scott RD model, with the ability to produce a varied number of biological looking (and behaving) patterns, both static and constantly changing, or have developed fast and computationally efficient finite difference method for the Turing pattern on curved surfaces in the three-dimensional space [12]. Although a striking resemblance are often found between the biological pattern and its simulation, the actual mechanism of pattern formation has still to be confirmed experimentally by means of empirical studies [13].

2.2 Animal Skin Patterns

Patterns are all different but share some specific characteristics, like the zebra's stripes (Fig. 1) which are perpendicular to a centre-line running

---

through each of the more tube-like parts of the body: the neck, legs, and middle part of the torso. The morphogenetic process runs quite uniformly over these more Euclidean areas, and as parts merge smoothly, the pattern on the zebra' s back must transform from vertical stripes to horizontal ones that wrap the hind legs, bending the stripes into a C- figure, by deforming the pattern over the haunches, or transforming front legs to Y-figures. Figures play the role of the joints in the tessellated model and the pattern should be constantly modified and adapted deformed and transformed. Whenever the system cannot manage the changes in geometry by stretching and deforming the stripes, the pattern does it by inserting an extra stripe, i.e., transforming [14].

But how this mechanism could be computationally applied to generative architectural design and especially as fabrication procedure? From a scientific point of view, RD simulation is much easier in 2D than other phenomena occurring in 3D [15], revealing a surprising variety of irregular spatiotemporal patterns of numerical simulations [16] to generate the shell surface and landscape. The design strategy extract processes from fundamental principles that govern both the biological and the fabrication machine. By doing such an geometrical abstraction, one can capture the essence and reveal the rules underlying the apparent complexity.

Figure 1. The pattern on the zebra’ s back must transform from vertical stripes to horizontal ones that wrap the hind legs, bending the stripes into a C- figure, by deforming the pattern over the haunches, or transforming front legs to Y-figures. Grevy's Zebra Stallion (commons.wikimedia).

2.3 Graphical Computation Tools and Fabrication

There is a long history of the equilibrium analysis of structural systems with graphical methods. (Fig.2) According to Block, an application of thrust lines emphasizes the relationship between the forces and geometry of structures with the key mathematical principle of use of graphical analysis and interactive computer methods to determine possibleg equilibrium states [17]. The three new ideas of this approach are: the interactive graphic statics, geometry controlled loads, and animated kinematics. He mentions also about the challenge when working with new efficient materials, that scaling the problems is not possible anymore, since stresses do not scale linearly. The equilibrium shapes are correct, but how to assign the material becomes now an issue. Not only stability, but also material stresses, including buckling of compression elements will have to be checked [18].

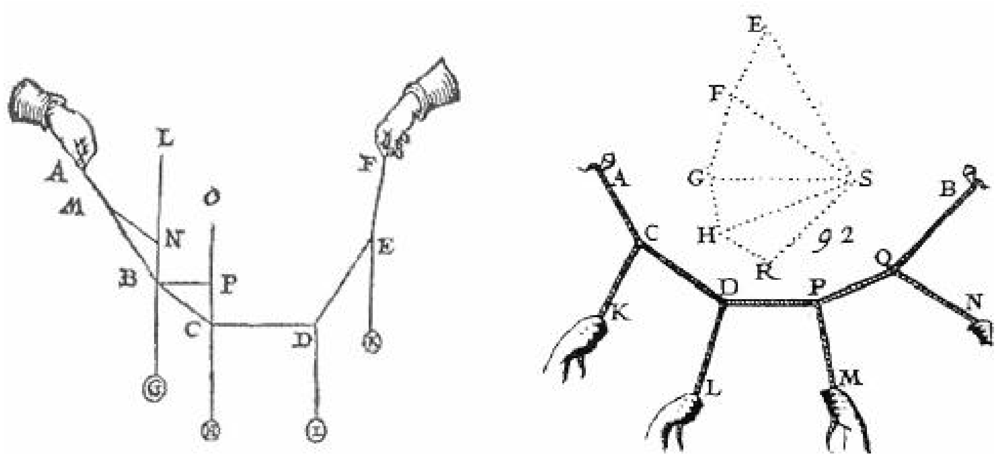


Figure. 2. (Left) One of Stevin's drawings of force equilibrium of hanging weights on a string (1586), and (Right) an illustration by Varignon showing a graphical analysis of a funicular shape (1725) [17].

Another recent research demonstrates that approaches bringing together mesh and graph representations drawn from computer graphics can be effective within the domains of applications for which they have been developed [19], [20]. The dual graph concept implemented as a data object that is called MeshGraph (MGraph) corresponds to the specific purpose of unfolding surfaces and segmentation of triangular meshes. The application is running inside Grasshopper platform and could generates stripe formations in an early design phase, giving at the same time the CNC cut designs, connection system and logistics. In this case, the application of edge weighted meshes representations provides an efficient design workflow of generating the stripe patterns for fabrication. The network of the connected mesh faces and edges is a simplified representation of architectonic elements, such as structural framing or façade panels and could be applied to any shell form.

3. Design Methodology

This research offers a methodological framework of identifying a suitable surface pattern with similar features like a RD-based stripe formation to be used as fabrication logic. The patterning algorithm was computationally explored and geometrically defined using both force-based relaxation processes and mesh segmentation algorithms to generate a shell skin pattern. Eventually, to give the desired stripe effect, the mesh relaxation process is linked with the segmentation process and the fabrication process in one unified system in equilibrium.

3.1 Mesh Relaxation Process for the Shell Structure

To generate in a simple and intuitive way a structure in static equilibrium, with minimal surface properties, dynamic relaxation physical load force of gravity was applied using Kangaroo physics engine inside Grasshopper [21]. The initial input geometry/topology consisted of a bottom and a top voronoi system joined with columns and beams with boundary conditions defined by three bottom strong anchoring points and nine weak anchors in the top.

The objective was to investigate the limits for constructing tubular minimal forms with branching connections using the stripe logic and the specific material. The bottom boundary geometry of the structure was modified to achieve stability and continuity with the landscape pattern. During this phase, the dynamic physics engine allowed to visually and intuitively interact in real-time with the “virtual” physical forces applied to the pre-defined geometry input and to translate the mesh lines and vertices to a network of springs and particles. The load, spring length and strength was controlled by the algorithm, to generate the proper height of the structure. From the relaxation process emerged an organic structural system of triangulated mesh faces, with surface curvature arriving to almost zero

---

mean. This was achieved by applying extra strength and variant anchor's strength to the boundaries to control the geometry output. (Fig. 3)

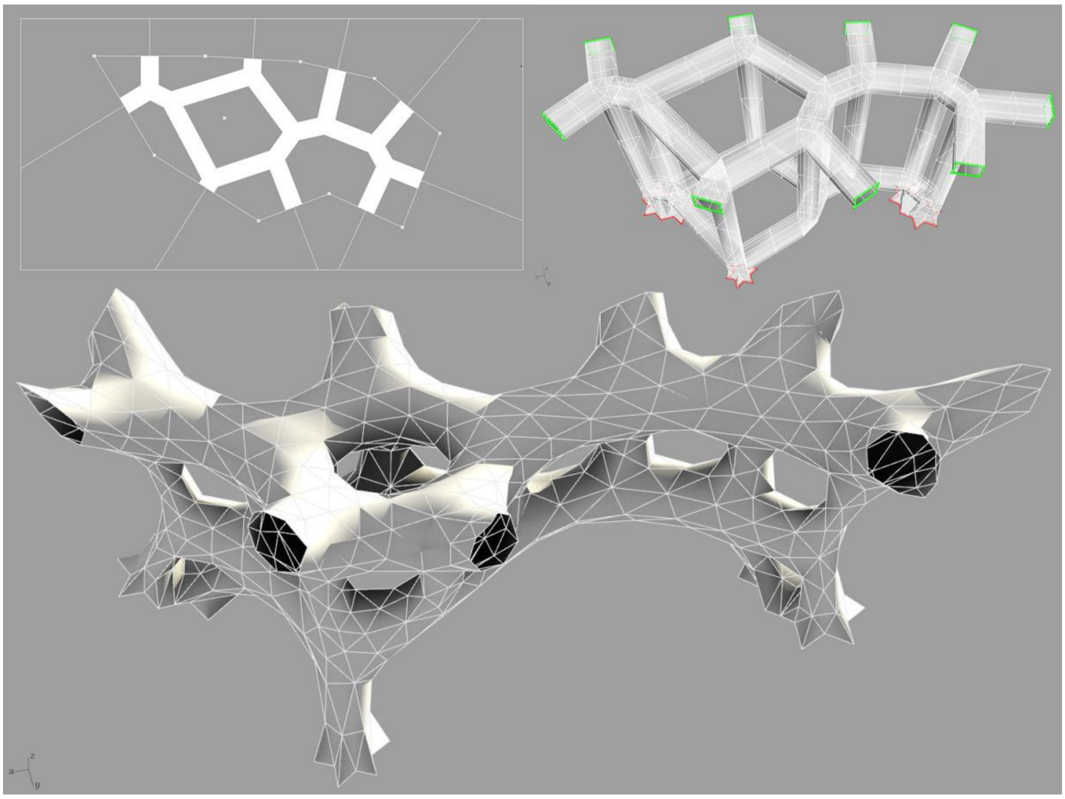


Figure 3. Initial voronoi points and lines selected (Top left). Top right, shows the two sets of voronoi trusses connected with vertical columns. The green naked edges are anchors with not much strength and the red naked edges of the base have very strong strength. (Bottom), the triangulated mesh obtained after the relaxation method described. (Image by authors).

3.2 Mesh Segmentation Process for the Shell Skin

In a second phase, computational techniques of weighted-mesh representations, using IVY plugin [19,20] inside Grasshopper, were employed for the generation of stripe configurations on the surface, analogous to the skin patterns emerging from a RD mechanism. As a construction logic, each stripe was conceptualized as a ruled surface (developable, with zero Gaussian curvature). The relaxed mesh in equilibrium was given as input for the MGraph creation, where face centers become nodes in the graph and

---

mesh topological edges become edges. Custom weight was applied to the edges using the Orange Peel Edges (OPE) to generate ripples. This algorithm separates layers, creating a pattern of nodes that develop concentrically, radiating from a set of specific input vertices. The input mesh vertices were defined as the naked edges of the top voronoi of the shell to achieve a pattern of stripes that starts as rings from the top and arrive to the bottom legs perpendicular to the ground (Fig. 4).

Using as primary segmentation the MST Kruskal (mstK) Minimum Spanning Tree disjoint algorithm, the graph was separated into subgraphs while transforming it into a tree and in parallel removing edges. The goal was to arrive to the least amount of stripes with the most vertical strength given by the connection system of screws and bolts, along the edges of each stripe. This required two inputs: (G) MGraph – the MGraph object and (W) Weight Limit – the interval of weights to considered, giving as output: (G) MGraph – the tree/trees MGraph object.

A secondary segmentation algorithm, the Weight Deviation Split Graph (DevSplit), splitted the tree MGraph into more subgraphs by deleting more edges with a specified edge weight larger or smaller than the previous. This required three inputs: (G) MGraph – the MGraph object, (D) Deviation – the amount the edge weight needs to deviate from the previous one in order to be deleted, and (M) MinFaces – the minimum number of nodes/mesh faces a piece needs to have in order for the split to be validated, giving as Outputs: (G) SubGraphs – the list of MGraph pieces. The numbering order of the 28 stripes, before the unrolling, was arranged to give the black and white effect and the same arrangement was used to facilitate the assembling.

4. Fabrication Process

Current design to production processes do not take into account the machines to use on the fabrication. Design procedures have to be aware of the fabrication methods, such as CNC milling, 3D printing and laser cutting, which are mostly used nowadays in architecture and design. These workflows need to be combined and performed in a seamless process in order to process data without any noise [22]. Merging digital manufacturing methods have the advantage of understanding the machines' working area and the permissible range of variation in the projects dimension, besides understanding the importance of preparing geometry for different fabrication methods [23]. This requires more time to understand deeply the potential applications for prototyping. The combination of three materials with different geometrical aspects of connectivity and three manufacturing techniques add more complexity to the process. In order not to multiply errors, geometrical configurations require to consider the tolerances together with the machine procedures and material behaviour, like, polypropylene's (PP) material expansion [22].

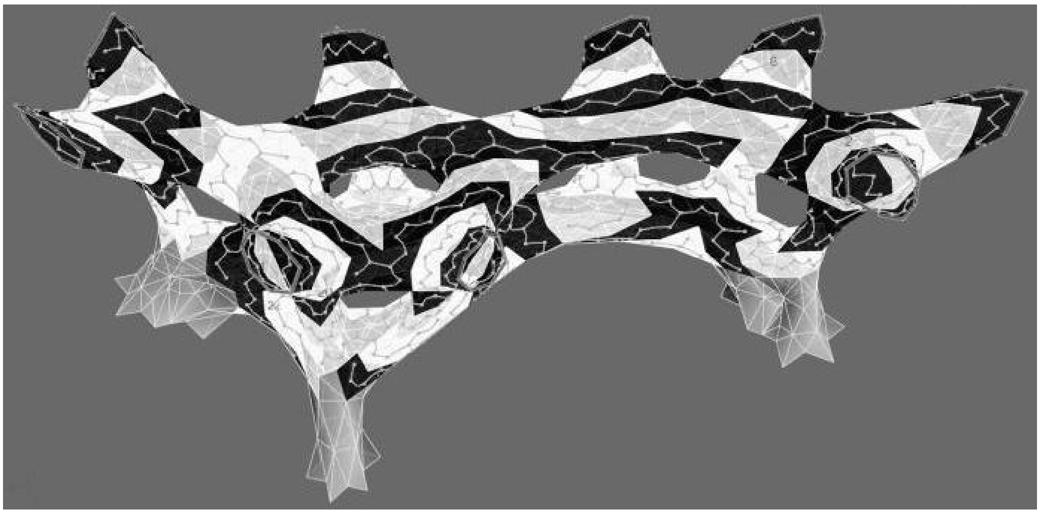


Figure 4. Image showing the naked edges on green, in which the (OPE) starts striping selection towards the center and perpendicular to the legs. (Image by authors).

4.1 CNC Milling Method

The profiled lines of the landscape were designed for a 2x1m polystyrene foam panel adapting a different logic and milled utilizing various tools and methods. The lines were inputted as tool paths generated using RhinoCam2016. Some of the strategies used for the CNC milling were Horizontal roughing, Parallel finishing, Pocketing and Engraving. Different types of drill bit were used to perform the specific strategies. The entire process was simulated in the RhinoCam2016 environment to check for clashes and machine times. The pockets to accept the structural legs were slightly modified to avoid clashes with the steeper angles of the overall geometry and the 3D printed piece. This could be dealt more effectively by modifying the pattern on the Polystyrene. The mountains and valleys on the pattern were slightly decreased in height and depth towards the sides, so as to minimise material erosion and maintain stability. This could also have been dealt with by modifying the pattern to accommodate the overall stability. The entire CNC milling process took two days for the result.

The most important aspect of this part of the production is the reducing of machinic time. If more than one tool is used for machining a single part, the total machining time for that part will be considerably longer compared to the situation when one complex-geometry tool is used. A complex-geometry tool, on one hand, can replace several tools but, at the same time, it reduces the total machining time, the most significant reduction being that of idle times [24]. In the case of the pavilion made of aluminium sheets, for further contribution to the market, would have been to design and digital fabricate different types of mass production aluminium profiles so each piece would not need to be CNC machined [25]. In such cases a complex-geometry tool in combination with design adaptations would be a meaningful solution for reducing cutting time.

4.2 Laser Cutting Method

The unrolled surfaces generated by implementing MGraph, were systematically numbered and labelled so as to create assembly guidelines. The primary segmentation produced 28 stripes, but the unrolling generated some overlapping. These overlapping were non-conducive to the laser cutting. After re-numbering from one end to another and separating the overlapped pieces, the definition generated 108 stripes. After being labelled in the 3D and 2D design, the unrolled surfaces were treated as individual 2D shapes, to which additional semi-circular loops were added to the naked edges of each triangulation. At the assembly stage these loops served as overlap washers. An empty pattern was added at the center of each face, to reduce the overall weight. The stripes were then arranged on 1050x750mm sheets, using RhinoNest. This stage helped in nesting the shapes on the available sheet size of PP for optimization of material use. The nested geometries were then exported to Autocad 2007 file to be fed into the laser cutter. The thickness of the PP sheets, 0.8mm and the melting point of the material dictated the speed of cutting, the overall outcome and the level of detail obtained. The laser cut pieces were then arranged based on the label numbers and connected to each other by means of 2.5mm diameter screws and nuts. To help in the assembly process, the screws were inserted pointing outwards rather than inwards, so that the bolts could be comfortably fastened. The entire laser cutting process took 6 hours for the result.

From assembly perspective, more holes, not just at the naked edges, but also at the vertices of the naked edges would have been more effective. This would have made stripes more prominent and structure more robust. The order of assembly of the stripes was depended heavily on the fabrication workflow and the manual pick-and-chose process. The numbering and labelling system could be optimized to make the assembly process more fluid.

4.3 3D Printing Method

The 3D printed legs were the structural interface between the cut stripes and the milled landscape (Fig.5). This required the design of the structural legs to mediate between the structural properties of the polystyrene foam and the PP stripes to accommodate their respective design. The three designed structural legs were made to be water-tight by closing all naked edges. To create the G-code, Simplify3D platform was used for slicing. During this process, the slicing simulation allowed to optimize geometrical and printing time issues. The legs were then printed using FDM (Fused deposition modelling) additive printing on two Felix 3.1 printers with a build volume of 255x205x225 mm, extrusion speed of 15mm3/s and motion speed of 150mm/s. The material used was PLA (Polylactide) filament with 1.75mm diameter requiring working temperature of 190°C-210°C and platform temperature of 50°C-60°C. Owing to the higher complexity and steeper angles (the angles were designed to arrive to no smaller than 45 degrees) of the geometry, the prints were done with structural supports, which were easily removable by hand. The screw holes for anchoring to the landscape required sanding and smoothing with a drill machine. The entire printing process took three days.

The printed pattern on a structural leg was being isolated from the whole system, which made it redundant. If, it was emerged from the concept of MGraph, it would have effectively maintained the continuity. The selection of the printed parts from the whole structural mesh was made so that geometrically will require:

- to fit the printable area of the Felix 4.0.
- the angles to be minimum 45° to avoid, or minimize supports.
- to weave the PP and PLA for stability reasons and continuity.

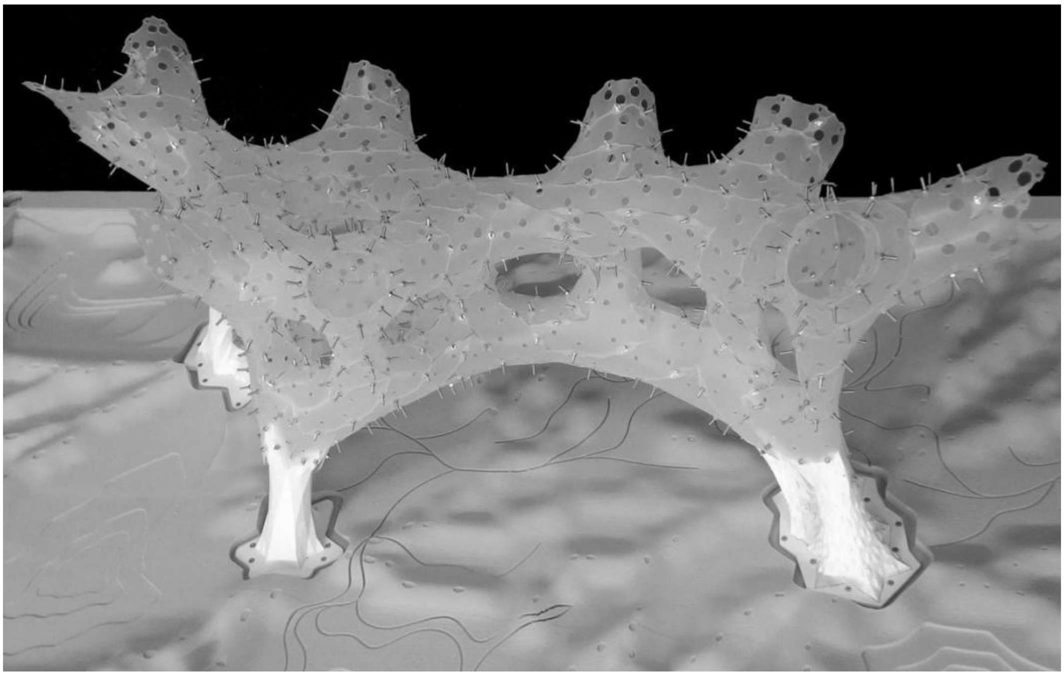


Figure 5. Perspective view of final prototype. (Image by authors).

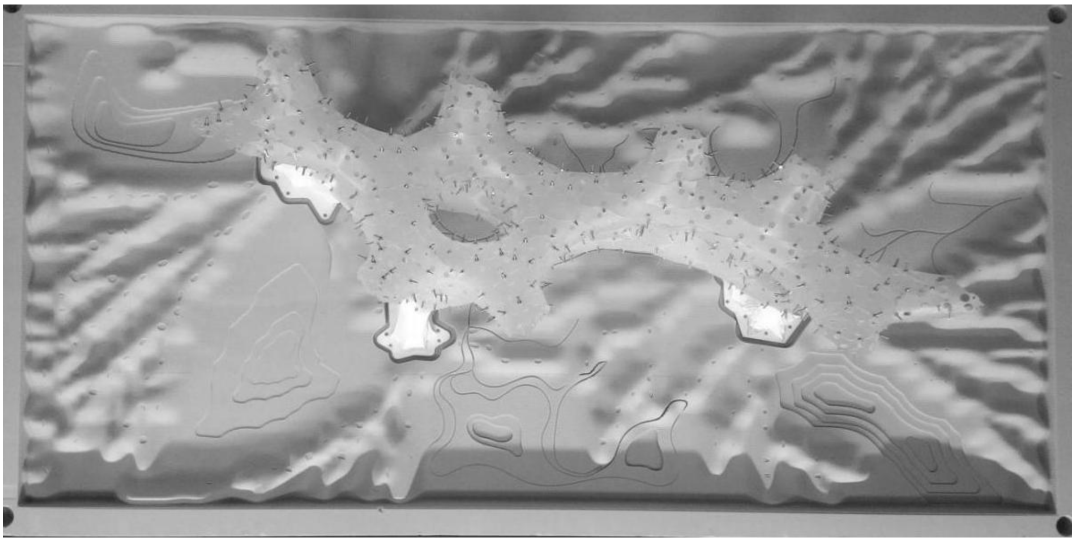


Figure 6. Final assemble. (Image by authors).

4.4 Assembly Process

During the construction, three student teams, represented the simultaneous fabrication with the three materials, polystyrene foam, PP sheets and PLA filament and delivered the G-code of each fabrication techniques vis. CNC milling, laser cutting, 3D printing respectively. The outcome prototype, (Fig.

5,6) required full coordination of all the teams in a collaborative assembly process where the sequential roles and responsibilities of each material were fulfilled. The three legs were connected on the shell and then mounted to the polystyrene foam by means of fisher screws. The entire assembly process was finished in 12 hours, without any eventual amendments to the already established workflow. The stripe formation not only generated the shape, but also aided in the assembly, and reducing time. Owing to the impetus on a predetermined fabrication and assembly strategy that relies on material properties and manufacturing simulations the assembly culminated as one unified fabrication process in spite of unclear interoperability between materials and machines.

5. Discussion

Similar to a previous project of connected PP stripes [26], the intention was to examine how a thin structural shell behave without extra supporting structure, only relying on the equilibrium stage of the relaxation process, that is, in geometry and the stripe logic. However, a discussion is raised about the stripes topology and direction. In comparison with the previous project in which the stripes were rings, the performance of a more complex stripe pattern with boundary rings, does not appear to affect the structural behaviour, at least of the prototype. A parallel goal was, taking in count the tolerances, to test the stability between the three materials and the mechanical connectivity of screws, taking in count the tolerances. During the construction, the stripe formation not only generated the shape, but also aided in the assembly, reducing time.

5.1 Structural Model

In this project, the minimal branching topologies were examined with a very fast linear analysis of shell elements, made with Millepede [27] plugin to extract useful information. For the FEM analysis, material data of PP was used (elasticity, density and yield strength [28] and poisson's ratio [29]). The distribution of deflection across the structure revealed some of the structure's vulnerable areas. (Fig. 7). In the physical prototype though, such problem was not observed. The plugin also generated stress lines, curves that at each point are tangent to one of the principal stress directions. In relation with those stress (force) lines, we observe concentration of lines on the deflected areas. Also, in the stripes diagram, (Fig.8) in most cases, the lines are perpendicular to the direction of the stripes. The direction of the stress lines and the direction of stripes have definitely a relation, but in this case this is not very clear. According to Tam and Mueller, the noise of the stress lines is due to the low-resolution

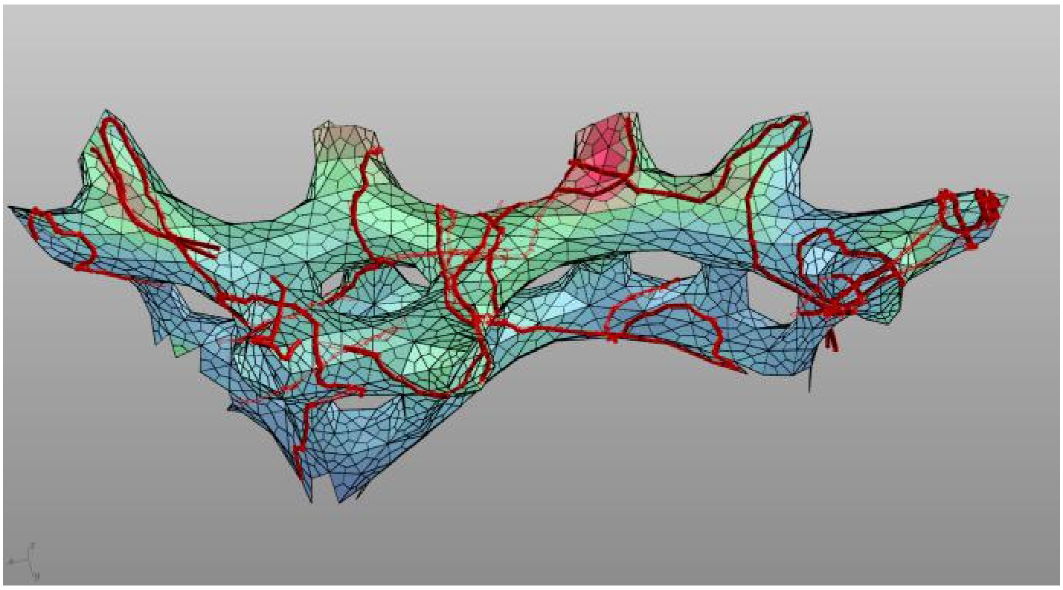


Figure 7. Stress lines and deflection. (Image by authors).

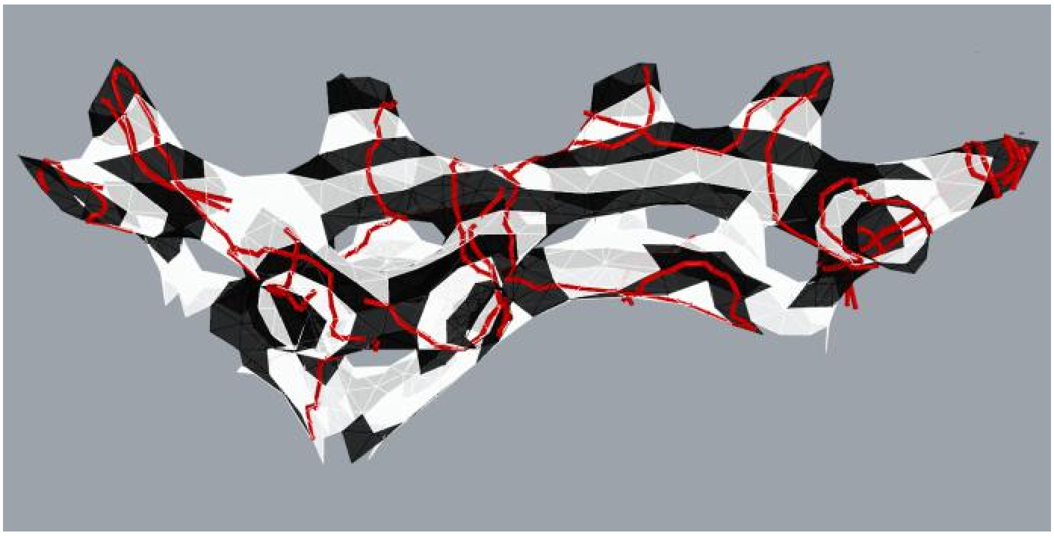


Figure 8. Stress lines and stripes. (Image by authors).

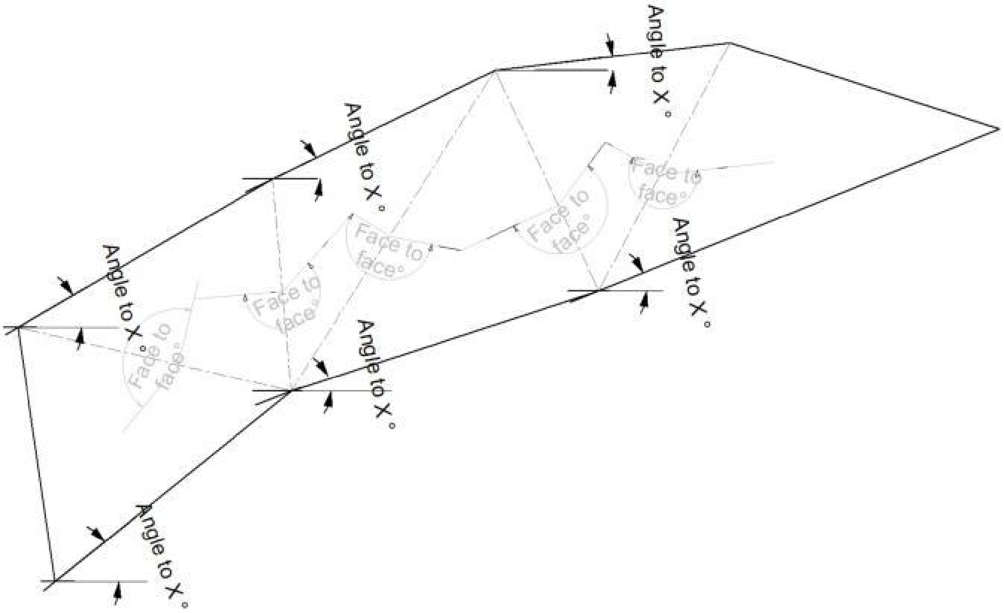


Fig 9. Each stripe is analysed in the naked cantilever with the X axis, and in the folding angle between faces. The average angles are compared in the graph (fig.10). (Image by authors).

and mesh topology. Also, there is no guarantee that the produced stress lines, from conventional tools integrated with parameterized design interfaces available to designers for generating stress lines, such as Millipede and Karamba will lead to usable structural patterns, nor is there documentation evaluating the performance of stress line generation methods [30].

If we assume that the stripes are reinforced on their naked edges with the overlapping material and screw connectivity, then the direction of the stripes is also important to analyze for structural reasons. The parametric model allowed the extraction of data information for the analysis of the verticality of the connections that are under compression. Figure 9 demonstrates the diagram of the extracted angles. An experimental way of translating this data shows on the graph (Fig. 10). The comparison here is between the average angles between each stripe's naked edges and the X vector (top, dashed line), and the average angles between the faces of each stripe (bottom line). The closer to 1.58 radian average, stripes are mostly vertical, so pulling forces are applied to the screws. The bottom line shows the curvature continuity for each stripe, indicating that all are near to minimal surfaces.

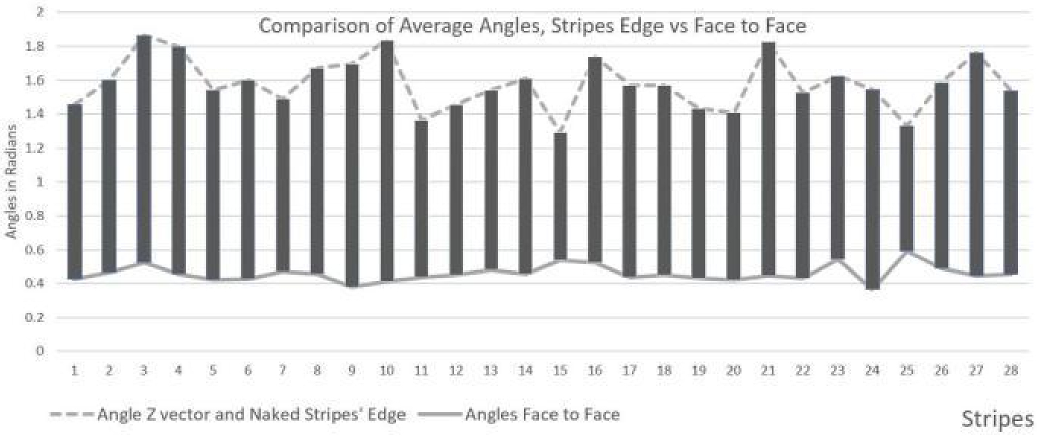


Figure 9. Comparison of average stripe's edges angles vs. face-to-face angles (rad). (Graph by authors).

5.2 Conclusion

Biological morphogenesis has been raised in discourses on computational methods in architectural design through the paradigms of parametric and procedural modeling of form. A distinction needs to be made, however, between what might be described as bio mimicry of form and morphogenesis [28], or bio inspiration. Since architectural practice is still depending on the process of breaking things into discrete elements as a way of construction, design workflows, as the one described in this paper, could offer many design applications as stripe organization for fabrication, thus opening a new field for multidisciplinary investigation between engineers, programmers, scientists and fabricators.

Future work could include dynamic changes of the pattern applied to adaptive design systems and 3D simulation techniques of other biological patterns found in nature, with similar structural characteristics like stripes.

Acknowledgement

We would like to thank the students of the Biodigital Master 2018, UIC Barcelona, helping with the realization of the project, and the institute for Biodigital Architecture and Genetics for the support.

References

[1] Beloussov, L.V.: Morphogenesis as a macroscopic self-organizing process. *Biosystems*, Vol.109, No. 3, pp. 262-79, 2012.

[2] Fornes, M.: MARC FORNES & THEVERYMANY,

https://theverymany.com/ Accessed Feb. 2018.

[3] Tenu, V.: Architecture, Design, Art,

http://www.vladtenu.com/Accessed April 2018.

[4] How, M.J., Zanker, J.M.: Motion camouflage induced by zebra stripes. *Zoology*, Vol. 117, No. 3, pp.163-170, 2014.

[5] Wolfram, S.: *A new kind of science*. Wolfram Media. Champaign, IL, pp. 1004, 2002.

[6] Doursat, R., et al. (eds.): *Morphogenetic engineering: Toward programmable complex systems*. Springer, New York, 2012.

[7] Dade-Robertson, M. et al.: Synthetic biological construction: Beyond 'bioinspired' in the design of new materials and fabrication systems, in: *3rd International Conference Biodigital: Architecture & Genetics*, ESARQ-UIC, Barcelona, 2017.

[8] Stevanović, I., Rašuo, B.: Development of a miniature robot based on experience inspired by nature. *FME Trans*. 2017, Vol. 45, No 1, pp.189–97.

[9] Turing, A.: The Chemical basis of morphogenesis. *Phil. Trans R. Soc. Lond.* B1952 237, pp. 37–72, 1952.

[10] Kondo, S., Miura, T.: Reaction-diffusion model as a framework for understanding biological pattern formation. *Science* (N.Y.), Vol. 329, pp. 1616-20, 2010.

[11] Haken, H. (eds.): Introductory remarks, in: Evolution of order and chaos. *Springer Series in Synergetics*, Springer, Berlin, Heidelberg, Vol. 17, 1982.

[12] Jeong, D., et al.: Numerical simulation of the zebra pattern formation on a three-dimensional model. *Physica A: Statistical Mechanics and Its Applications*, 475, pp. 106–16, 2017.

[13] Camazine, S., et al.: *Self-organization in biological systems*. Princeton University Press, pp. 83, 2003.

---

[14] Spuybroek, L.: *The Sympathy of things: Ruskin and the ecology of design.* Bloomsbury, pp. 100, 2006.

[15] Kondo, S.: The reaction-diffusion system: a mechanism for autonomous pattern formation in the animal skin. *Genes to Cells*, 7, pp. 535–541, 2002.

[16] Pearson, J.E.: Complex patterns in a simple system. *Science*, 261 (5118), pp. 189–192, 1993.

[17] Block, P., et al.: As hangs the flexible line: equilibrium of masonry arches. *Nexus Network Journal*, 8, pp. 9-19, 2006.

[18] Block, P.: *Equilibrium systems. Studies in masonry structure*. M.S. dissertation, Department of Architecture, Massachusetts Institute of Technology, p. 36, 2005.

[19] Nejur, A., Steinfeld, K.: Ivy: Bringing a weighted-mesh representation to bear on generative architectural design applications, in: *36th ACADIA*, pp. 140-151, 2016, University of Michigan Taubman College.

[20] Nejur, A., Steinfeld, K.: Ivy: Progress in developing practical applications for a weighted-mesh representation for use in generative architectural design, in: *37th ACADIA*, 2017, MIT.

[21] Piker, D.: Kangaroo: Form finding with computational physics, *Architectural Design*, Vol. 83, No 1, pp. 136–137, 2013.

[22] Orciuoli, A., Baquero, P., Giannopoulou, E.: Experimental methods on unifying computational and manufacture workflows, *e-Revista LOGO*, Vol. 6, No. 3, 2018.

[23] Baquero, P., Orciuoli, A., Calixto, V., Vincent, C.: Simulation and prototyping benefits on digital fabrication, in: *SIGraDi:Crowdthinking. XX Conference of the Iberoamerican Society of Digital Graphics*, November 2016, Buenos Aires.

[24] Pjevic, M., Mladenovic, G., Tanovic, L., Puzovic, R.: Contemporary approach to the design of circular form tools for complex-geometry part manufacture. *FME Trans*, Vol. 46, No. 1, pp. 80–5, 2018.

[25] Baquero, P., Giannopoulou, E. and Cavazos, J.: Strategies for Metallic Vault Structures, in: *33rd eCAADe Conference Proceedings*, 2015, Vienna, Vol. 2, pp. 169-176.

[26] Giannopoulou E., Baquero B., Warang A., Orciuoli A., Estévez T. A., Brun-Usan M.: Biological pattern based on reaction-diffusion mechanism employed as fabrication strategy for a shell structure, in: *3rd World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium*, 2018, Prague.

[27] Michalatos, P. (2014). *Millipede. Grasshopper*. http://www.grasshopper3d.com/group/millipede. Accessed, March 2018.

[28] Makeitfrom. *Polypropylene (PP) copolymer*. https://www.makeitfrom.com/material-properties/PP-PP-Copolymer. Accessed, March 2018.

[29] Polymerdatabase. Typical poisson's ratios of polymers at room temperature. Available at: http://polymerdatabase.com/polymer%20physics/Poisson%20Table.html. Accessed, March 2018.

[30] Tam., K.M.M., & Mueller, C.: Stress line generation for structurally performative architectural design in: L. Combs, & C. Perry (Eds.), *Computational Ecologies: Proceedings of the 35th ACADIA*, 2015. Cincinnati, OH.

[31] Synbio Construction. Synthetic Morphologies. Available at: http://www.synbio.construction/n-synthetic-morphologies. Accessed, April 2018.

Article 3: Machine Learning Approach for Biological Pattern Based Shell Structures.

Effimia Giannopoulou[1], *Pablo Baquero*[2], *Angad Warang*[3], *Alberto T. Estévez*[4]

[1234] UIC, Carrer de la Immaculada, 22, 08017 Barcelona, Spain.

MACHINE LEARNING APPROACH FOR BIOLOGICAL PATTERN BASED SHELL STRUCTURES

Abstract: *Following previous research towards the subject of digital fabrication of thin shell structures, architectural generative design processes sharing similar physical and geometrical characteristics with biological processes were translated to fabrication processes, blurring the lines between physical, digital and biological, and allowed to examine the structural efficiency of segmented stripes arrangements of complex surfaces with less material usage. The goal of this paper is to examine the efficiency of implementing a machine learning approach into an already established design workflow and to develop a creative methodology for decision making. In order to specify the appropriate features we look to related work that integrate machine learning inside the design and fabrication process.*

---

1. The Challenge

The ability to integrate intelligent design systems that can analyse, process and transform design challenges how we understand our practice. The model becomes a creative-analytical engine into which external data can be ported and analysed or internally generated, to create the basis for intelligent design practices. Rather than continuing the neo-rational design ethos of early performative architecture that have suggested similar trajectories of interfacing external data and employing generative logics for design search and evaluation, these methods aim to expand our ability to work across knowledge domains and explore potential for innovating existing practice (Tamke & Thomsen 2018).

Automated processes are already integral to design; we've just labeled them differently. According to Stoddart, "The idea of automation taking that human agency in design out of the problem is something that I have no interest in exploring because I think you lose the value of design at that point," he says. "But we have to address our hubris in understanding our ability to predict solutions to increasingly complex problems." (Muklashy 2018)

Recent advances in contemporary biology shows that it has largely become computational biology. The same arise for architectural transdisciplinary practice which merge computational and biological and fabrication processes inside the design to construction workflow. Menges, argues that the introduction of cyber-physical production systems in the manufacturing industry will also have a major impact on architecture and will not only challenge our understanding of how buildings are made, but more importantly how we think about the genesis of form, tectonics and space. (Menges 2015).

One of the first objectives of this article is to analyze how recent architectural projects have creatively implemented machine learning strategies into their design process, understand how those strategies assisted

---

in the design to fabrication process. Finally, a case study demonstrates a creative approach of implementing machine learning and Artificial Neural Networks in an architectural design and fabrication workflow.

2. Multi Objectivity & Decision

The integration of simulation into computational design workflows gave rise to a performance-based design methodology. Intersections between machine learning and simulation can enable a practice of structural intuition. The use of parametric as well as generative design tools with structural, energetic or other simulation tools is today state-of-the-art practice. While experienced practitioners rely in these situations on intuition, machine learning can act similarly and predict simulation results out of precedent, how new systems would behave. (Tamke et al. 2018). Moreover, solution spaces are always multi-objective bringing together divergent criteria that don't map to a single optima. As a result, solutions are assessed not absolutely as true or false, but rather qualitatively as better or worse. To employ machine learning strategies in architecture therefore necessitate methods by which results can be evaluated holistically. (Tamke et al. 2018). Multiscale architectural models that attempt to describe, predict, and design precinct-scale and material-scale behavior inherently depend on the knowledge of multiple disciplines, and hence multiple methods. These complexities require the profession to develop its own methods for combining models borrowed from other disciplines and validating the handshakes across their respective system boundaries (Faircloth et al. 2018).

The linkage of machine learning with a database enables the memorization of solutions, in order to build up a kind of experience over time, as in case of Lace Wall. (Fig. 1) The machine learning-based approach in this case demonstrates how neural networks can categorize the shape of complex geometries based on high-dimensional discretization with up to a hundred

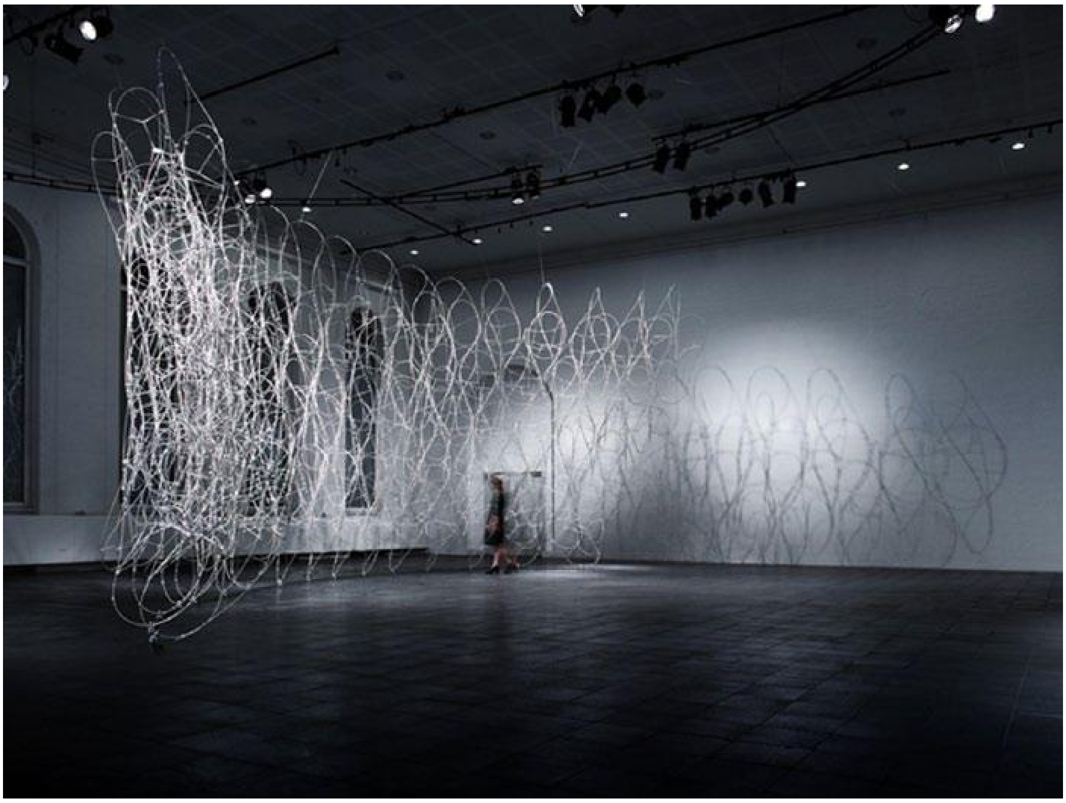


Figure 1. Lace Wall demonstrator during the Complex modelling exhibition Copenhagen in September–December 2016. (Tamke et al. 2018)

input parameters, instead of other classification methods, offering flexibility and precision of previously unseen data and reusing the optimized solutions database and the trained network in multiple iterations of the design. The intuition that a designer builds upon to make design decisions for both complex structural performance choices and behavior can be effectively supported by machine learning. It is supervised machine learning with artificial neural networks which provides a kind of intuition (the means to select) alongside a linked database of previously evaluated solutions, which provides the experience on which the selection is based (Zwierzycki et al. 2017).

Fabrication-aware models are not a new idea within architecture. These models typically incorporate fabrication limits and material behavior, informed by descriptions of process constraints and predictions of expected behavior. Sourcing information from material data sheets, machine limitations or directly from empirical testing, they seek to incorporate material and fabrication limits into the design process and the definition of machining instructions to avoid detrimental incidents during fabrication. However, a significant limit is the separation of Fabrication-aware models and fabrication into sequential activities, which prevents such models from including any actual behavior as it occurs during the fabrication process. As in the case of Bridge Too Far (Fig. 2), it is here that machine learning could provide new opportunities (Tamke et al. 2018).

Some cases prohibit traditional computational design optimization approaches. Connecting machine learning to the results of a generative design process can advance the flexibility of parametric models as performative instruments by breaking the link between prescribed performance measures that might drive a generative process and emergent evaluation variables that structure design understanding of the results. (Stasiuk & Thomsen 2014) This offers the designer an alternative means to more effectively understand, search and discover the complex and varied design outputs that high-dimensional multi-objective optimization algorithms produce (Tamke et al. 2018).

Although it is still in the experimental stage, there have been multiple attempts by researchers to apply machine learning approaches into building performance prediction and building optimization process. Geyer & Singaravel (2018) were able to develop an artificial neural network model for thermal performance prediction for a building as an example of performance-based design. They have used training data from a physical simulation software for the energy performance for the buildings, and were able to get satisfactory results.

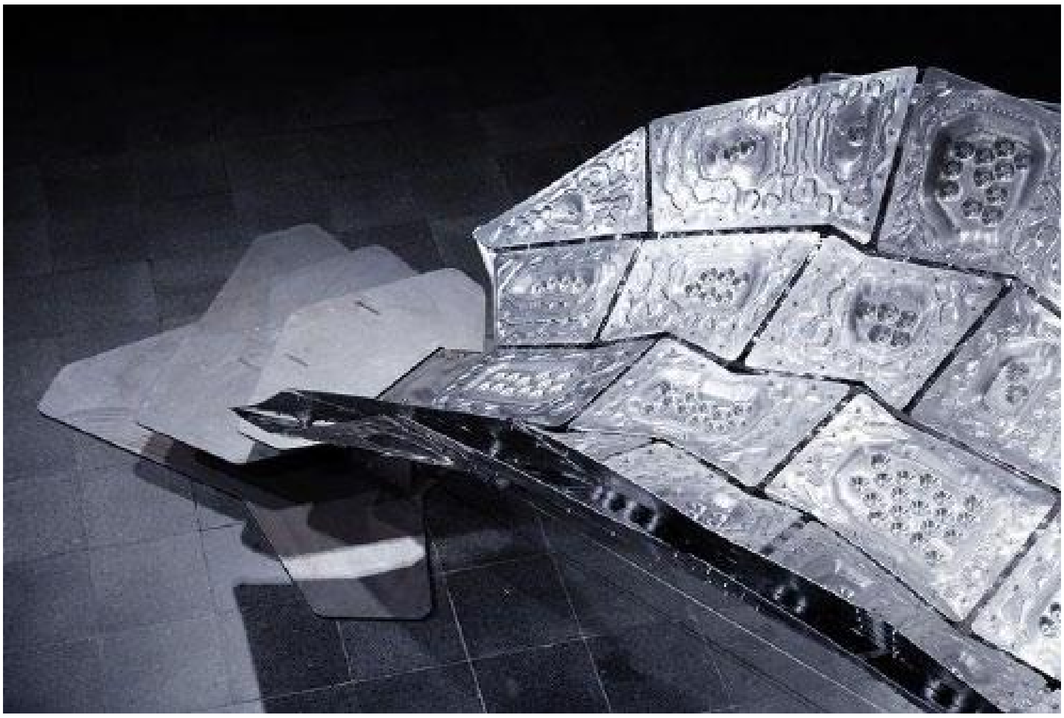


Figure 2. A Bridge Too Far exhibited in Copenhagen at the Complex modelling exhibition in September– December 2016. (Tamke et al. 2018)

3. Case Study

This research is the evolution towards the subject of digital fabrication of thin shell structures (Bechthold 2008), focusing on the search of a machine learning algorithmic methodology and subsequent computational design techniques which will allow to produce data sets of segmented pattern arrangements in order to help decision making, based on intuition, structural performance and less material usage in one single design workflow. Following the line of previous research (Giannopoulou et al. 2019a,b), also conducted during the Biodigital Architecture Master courses and fabrication workshops, it has been examined how the evolution of architectural generative design processes aimed to apply similar physical and geometrical principles of biological processes, in analogy to biological morphogenesis (Beloussov 2012), translating them to fabrication

---

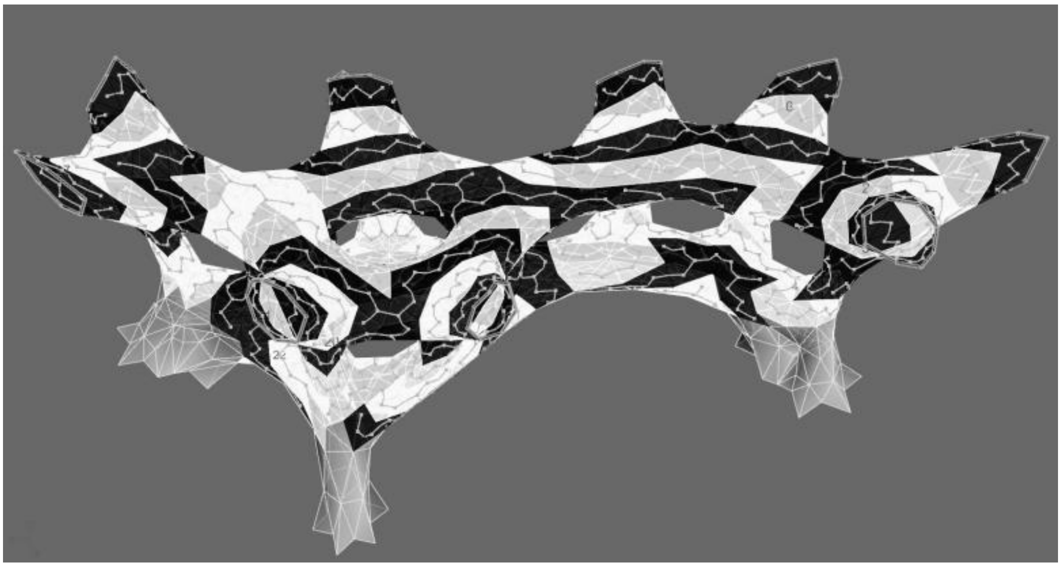


Figure 3. Project analysis of stripe distribution, in order to unroll later for fabrication (Biodigital Master course 2018).

processes and to test the structurality of branching shell topologies of bifurcating or multifurcating trees which would not require extra support and withstand an additional weight apart from the material itself. As Stach says (2010), instead of post-rationalizing complex geometrical structures the goal is to "pre-rationalize" the design method.

The logic of stripes has been used as a pre-rationalization construction system (Fig.3). Some of the most recent examples in practice related to this research is the work of Mark Fornes, who invented a unique approach to describing and building a form: Structural Stripes. (Schumacher & Fornes 2016).

Patterns were examined for structural behavior in several physical prototypes. Mesh relaxation processes (Piker 2013) and weighted mesh graphs representations (Nejur & Steinfeld 2016) were employed parallel as design tools for the development of minimal structural skins integrating the whole process into the form. The relaxation process, which allowed to arrive close to minimal surfaces, was linked with the segmentation process, which divided the mesh into stripes which in turn was linked with the fabrication

---

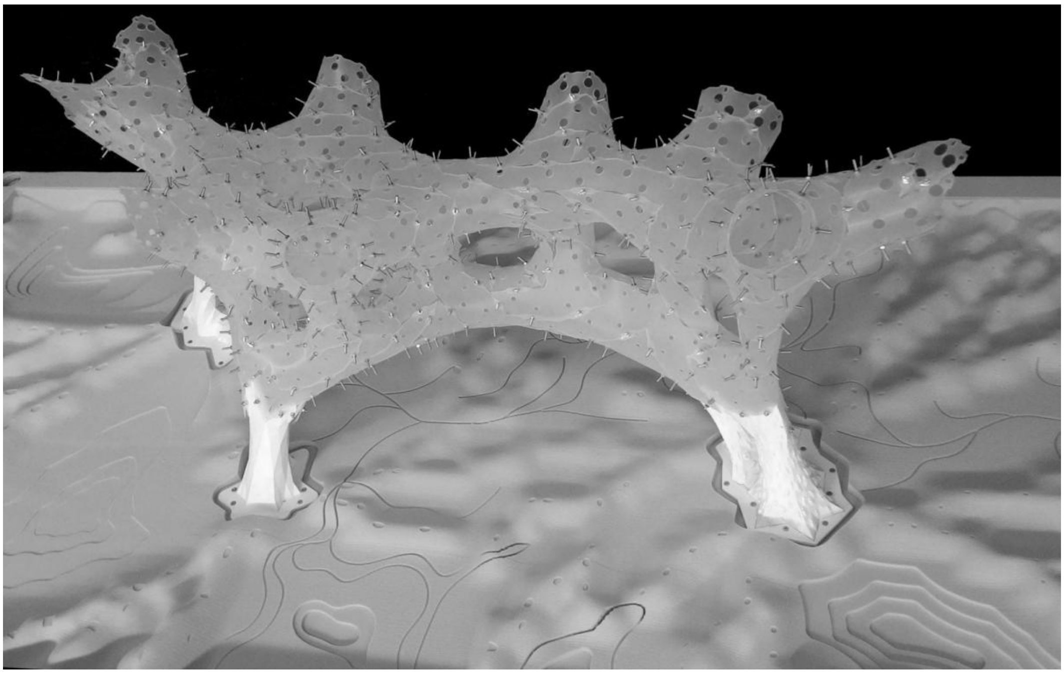


Figure 4. Project constructed and assembled with 3d printed pieces (Biodigital Master course 2018).

process, that integrated material properties, tolerances, constraints, capacities, machine limitations and interactivity, to give eventually the desired structural stripe effect as one unified system in equilibrium as shown in the physical model (Fig. 4). The construction logic, of stripes is conceptualized as a ruled surfaces (developable, with zero Gaussian curvature).

However, a discussion has been raised upon the stripes topology, if they are closed, or open, and their direction, in relation with the branching topology of the shell structure and its performance. Also, a relation has been observed between stress lines (curves that at each point are tangent to one of the principal stress directions), and the deflected areas, although this could not guarantee that leads to usable structural patterns (Tam & Mueller 2015). Besides, the dual graph concept implemented as a data object, called MeshGraph (Nejur & Steinfeld 2016), is capable of generating a vast amount of patterns with stripe connectivity, to choose from.

Standard topological, shape, size, structural optimization methods nowadays, give standard results but without allowing creativity or the designers interference. It is here that the idea of using a machine learning and artificial neural network approach was introduced.

3.1 Objectives

This paper serves as a first attempt and linkage to study intelligent design processes based on ad-hoc machine learning approaches for transdisciplinary architectural paradigms, which will provide alternative or additional tools to help decision making based on multitask criteria. Oriented to fabrication, ultimately could allow the designer to interfere/select manually or by intuition that which fits most to his/her desires. The objective is to develop a creative methodology for decision making based partly on the intuition, designer skills and experience, and partly on the machine intelligence and to explore the potentials of state-of-the-art machine learning approaches for the selection process between many geometrical configurations of stripe patterns, for the one with the best structural performance, and which consequently makes the fabrication process more effective.

3.2 Methodology

To bridge this gap the idea is to re-examine and modify/extend an already established methodological design workflow of the parametric model. The model should be capable to iterate and to generate datasets in comma-separated values (CSV) file format with the corresponding 3d models which will ultimatly serve to predict unexpected outcomes and get insights in order to make better decisions. As a matter of fact the most interesting part of the method is to determine those sets of attributes/features/behaviors inside the design workflow with which we train the artificial neural network to predict.

The general points of reference/criteria are stated: structurality, minimizing waste of material, less configurations of stripes, less connectivity which means less assembly time and less weight of connection elements (such as screws). Based on the above criteria and looking at the parametric model and geometry, the attributes/inputs for the neural network may defined as:

1. Bottom And Top Number Of Points
2. Bottom And Top X Location Of Points
3. Bottom And Top Y Location Of Points
4. Structures' Height
5. Mesh Subdivision Value
6. Springs Strength Value
7. Segmentation Algorithm
8. Material Thickness

One of the attributes introduced in an early design stage is the initial geometry/topology which consists of a bottom and a top system of points joined with a network of columns/lines with boundary conditions which later is converted into quad meshes, like a network of tubules, or hollow vessels referring to a cytoskeleton. In contrary to a static input geometry, the approach allows the generation of a dynamic input geometry which permits the selection between various options that fit best the above criteria. A series of datasets consisting of geometrical outputs are generated, based on the above criteria, to help the designer to have a visual judgement of the numerical values. Those outputs are defined as:

---

1. Stripes Quantity
2. Connections Quantity
3. Structures' Deflection
4. Material Area Needed
5. Total Weight Of The Structure

The distribution of deflection is generated across the structure using the finite element analysis. The database can give the branching connectivity which defines the initial input geometry, the quantity of stripes and material, the deflection and weight values. The proposed structure of the network is shown in figure 5.

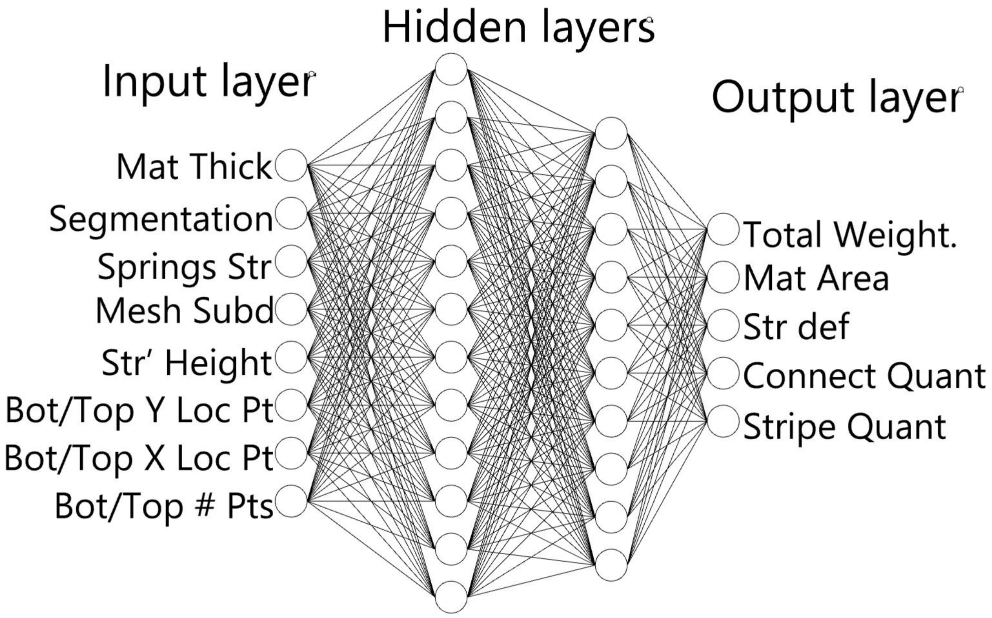


Figure 5. The artificial neural network structure, showing the 7 nodes on the inputs layer, the 2 hidden layers and the 5 nodes on output layer.

4. Conclusions and Discussion

The research re-examines and upgrades an already established design workflow to develop a methodology for decision making which allows to produce concatenated taxonomies in the form of datasets. These datasets, which are geometrically segmented patterns and deflected outputs help in the assessment, manipulation and control of the design workflow. The generative method gives the designer the possibility to choose between alternatives which respond to either discrete or associated preset requirements. The vital benefit of creating databases is to be utilized specifically in machine learning to train an artificial neural network and to be able to predict a new building information based on combination of desired parameters. As a result, the algorithm generates an extended amount of possible outputs based on the geometrical, machine and material criteria.

The design strategy extracts processes from fundamental principles that govern both the biological and the fabrication machine. By doing such a geometrical abstraction, one can capture the essence and reveal the rules underlying the apparent complexity. Although biological skin patterns (Kondo 2002) and segmentation in fabrication open a new field of interdisciplinary investigation and architectural applications, there are still many key issues to be further developed, such as the structurality, different material usage and apparently the fabrication technique used, especially for real scale projects.

It is an advantage to use artificial neural network for the prediction of new input values for the thin shell structure and its fabrication from the early stage of design. These methods are very useful especially when the designer wants to have an approximation of the connections and pieces during the design process. Machine learning drastically affects the field of design and architecture through its direct link to computational design and industry, however its applications are still in an experimental stage.

Apart from the many applications and future directions that this generative approach can lead into, the fact that it preserves the intuitiveness of a generic design process is the most important landmark to note. This can be further expanded by saying that the implementation of machine learning and artificial neural network in a design workflow can enhance a designer's inventory by providing control over the scalability of a design process or a design outcome.

Experimentations could also be done in assessing if an machine learning algorithm can predict, assess and analyze input/output parameters for structurally different elements. For example, consider an algorithm trained for analysis of a column structure, and predicting similar attributes for a beam, slab, pedestal or bridge. This research and its explorations could then advance in generating machine learning libraries for different components in architecture with their individual families interacting in a giant, symbiotic, synchronous system, while managing and monitoring a humongous database.

References

Bechthold M. 2008. *Innovative surface structures: technology and applications.* 1st Edition, Taylor & Francis.

Faircloth, B., Welch, R., Tamke, M., Nicholas, P., Ayres, P., Sinke, Y. & Thomsen, M. R. 2018. Multiscale modeling frameworks for architecture: Designing the unseen and invisible with phase change materials. *International Journal of Architectural Computing* 16(2): 104–122.

Geyer, P. & Singaravel, S. 2018. Component-based machine learning for performance prediction in building design. *Applied Energy*. Elsevier, 228(C): 1439-1453.

Giannopoulou, E., Baquero, P., Warang, A., Orciuoli, A., Estévez, A.T. & Brun-Usan, M.A. 2019a. Biological Pat- tern based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure. *IOP Conference Series: Materials Science and Engineering*, 471, 102053.

Giannopoulou, E., Baquero, P., Warang, A., Orciuoli, A. & Estévez, A.T. 2019b. Employing Mesh Segmentation Algorithms as Fabrication Strategies: Pattern Generation based on Reaction-Diffusion Mechanism, *FME Transactions*, 47(2): 379-386.

Kondo, S. 2002. The reaction-diffusion system: a mechanism for autonomous pattern formation in the animal skin. *Genes to Cells* 7(6): 535-541.

Menges, A. 2015. The New Cyber-Physical Making in Architecture: Computational Construction. *Architectural Design* 85 (5): 28–33.

Muklashy Wasim, (2018, May 3) How Machine Learning in Architecture Is Liberating the Role of the Designer. https://www.autodesk.com/redshift/machine-learning-in-architecture/

Nejur, A. & Steinfeld, K. 2016. Ivy: Bringing a weighted-mesh representation to bear on generative architectural design applications. *Proc. 36th ACADIA*, Michigan, US: University of Michigan.

Piker, D. 2013. Kangaroo: Form finding with computational physics. *Architectural Design* 83(1), 136-137.

Schumacher, P. & Fornes, M. 2016. The Art of the Prototypical. *Architectural Design* 86 (2): 60-67.

Stach, E. 2010. Structural morphology and self-organization. *Journal of the International Association for Shell and Spatial Structures* 51(165): 217–231.

Stasiuk, D. & Thomsen M.R. 2014. Learning to be a Vault. Implementing learning strategies for design exploration in inter-scalar systems. Thompson, Emine Mine (ed.), *Fusion; Proc. 32nd eCAADe Conference: 381-390.* Newcastle, UK.

Tam, K.M. & Mueller, C.T. 2015. Stress line generation for structurally performative architectural design. *Computational Ecologies; Proc. 35th ACADIA*, University of Cincinnati, School of Architecture and Interior Design, Cincinnati, Ohio, US.

Tamke, M., Zwierzycki, M., Deleuran, A. H., Baranovskaya, Y. S., Tinning, I. F. & Thomsen, M. R. 2017. Lace Wall: Extending Design Intuition Through Machine Learning. In Menges A., Sheil B., Glynn R., & Skavara M. *Fabricate 2017:* 98-105. London: UCL Press.

Tamke, M., Paul N. & Zwierzycki M. 2018. Machine Learning for Architectural Design: Practices and Infrastructure. *International Journal of Architectural Computing* 16 (2): 123–43.

Tamke, M. & Thomsen M.R. 2018. Complex modeling. *International Journal of Architectural Computing* 16 (2): 87–90.

Article 4: Stripe Segmentation for Branching Shell Structures - A Data Set Development as a Learning Process for Fabrication Efficiency and Structural Performance.

Effimia Giannopoulou[1]*, Pablo Baquero*[2]*, Angad Warang*[3]*, Affonso Orciuoli*[4]*, Alberto T. Estévez*[5]*.*

[12345] UIC, Carrer de la Immaculada, 22, 08017 Barcelona, Spain.

[5] Electronics and Computer Sciences. University of Southampton, UK.

STRIPE SEGMENTATION FOR BRANCHING SHELL STRUCTURES - A DATA SET DEVELOPMENT AS A LEARNING PROCESS FOR FABRICATION EFFICIENCY AND STRUCTURAL PERFORMANCE

Abstract: *This article explains the evolution towards the subject of digital fabrication of thin shell structures, searching for the computational design techniques which allow to implement biological pattern mechanisms for efficient fabrication procedures. The method produces data sets in order to analyse and evaluate parallel alternatives of branching topologies, segmentation patterns, material usage, weight and deflection values as a user learning process. The importance here is given to the selection of the appropriate attributes, referring to which specific geometric characteristics of the parametric model are affecting each other and with what impact. The outcomes are utilized to train an Artificial Neural Network to predict new building information based on new combinations of desired parameters so that the user can decide and adjust the design based on the new information.*

Keywords: *Digital Fabrication, Shell Structures, Segmentation, Machine Learning, Branching Topologies, Bio-inspired.*

---

1. Introduction

According to the line of previous research, conducted during courses and workshops, it has been examined how the evolution of architectural generative design processes aim to apply similar physical and geometrical principles of biological processes and to translate them to fabrication processes (Giannopoulou et al. 2019a); (Giannopoulou et al. 2019b). The theoretical framework speculated processes which implement manufacturing knowledge inside a computational design system. Inspired by the effects on pigmentation patterns of shell growth (Figure 1) and biological pattern prediction of reaction-diffusion mechanism (Turing, 1952), the logic of stripe has been tested as a construction system in several different prototypes (Figure 2). As Stach (2010) said, instead of post-rationalizing complex geometrical structures the goal is to "pre rationalize" the design method.

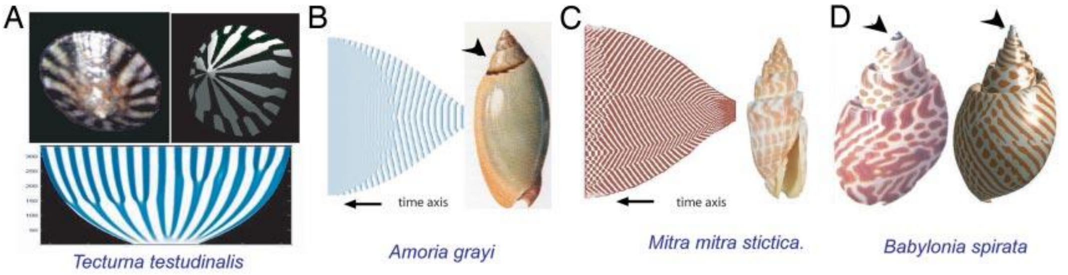


Figure 1. The effects on patterns of shell growth and perturbations. As the shell grows, the width of the pattern domain increases leading to changes in the pattern. (Boettiger et al., 2009).

The logic of stripes was used as a pre-rationalization construction system. Relaxation processes (Piker, 2013) and weighted graphs representations (Nejur and Steinfeld, 2016) have been employed parallel as design tools for the development of structural rigid skin and pattern, made of flexible sheets of material (polypropylene). The spring system, which allowed to arrive close to minimal surfaces was linked with the segmentation process, which divided the mesh into stripes, which was linked with the fabrication process, that integrated material properties, tolerances, constraints, machine limitations and interactivity. The desired effect was manifested in one unified system in equilibrium, merging three design methods, three materials and three corresponding fabrication techniques (CNC, Laser cutting, 3D printing). The dual graph concept implemented as a data object was capable of generating a vast amount of interconnected complex networks of stripe configurations to choose from with possible structural characteristics.

However, a discussion has been raised upon the stripes topology (if they are closed rings, or open), their direction (if they are vertical or horizontal), in relation with the branching topology of the shell structure and its performance. Also, from the structural analysis with a very fast linear analysis of shell elements in 3D [1], a relevance has been observed between stress lines (curves that at each point are tangent to one of the principal stress directions), and the deflected areas. Those lines could not guarantee usable structural patterns (Tam and Mueller, 2015). This has led to the study of an intelligent design processes for developing a creative design methodology of decision making based partly on the intuition, designer skills and experience and partly on the prediction capabilities of machine intelligence (Giannopoulou et al., in press a).

Further development is proposing a machine learning approach, using the already established parametric design workflow, as a method of expanding the design space of segmented thin shell structures. The extracted data sets serve as a first filter of visualizing those attributes that are affected and/or mostly affecting each other. The goal is to achieve better understanding of which control parameters that define the geometric characteristic of the shell, influence mostly the structural performance, material usage and number of segmented pieces and to adjust the design based on the new information.

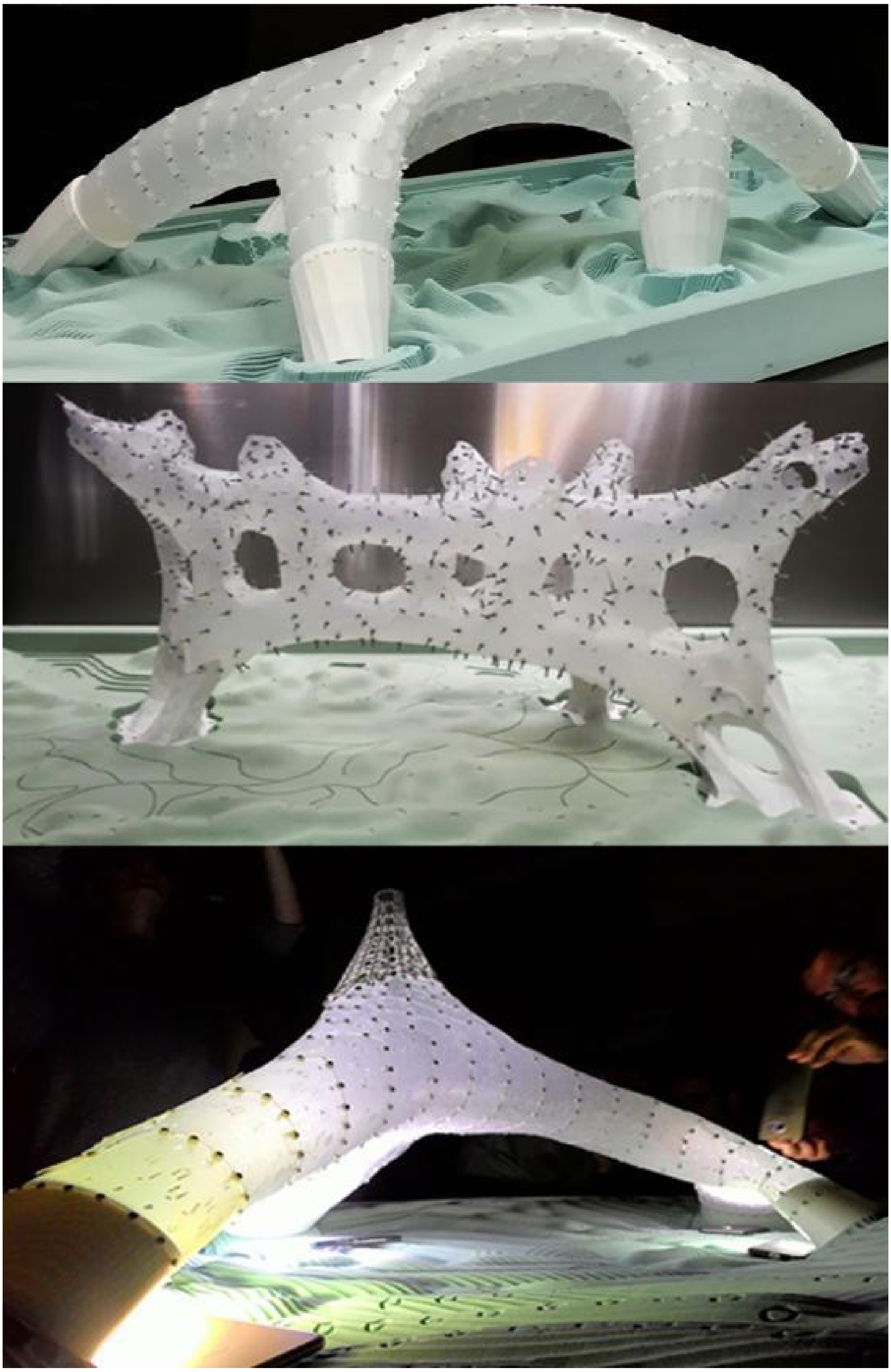


Figure 2. Biodigital Fabrication Studio Series 2017/2018/2019, University Master in Biodigital Architecture, ESARQ-UIC Barcelona, (bottom) open branching network with three legs, (center) cantilever with four anchors, open topology (top) cantilever with six anchors, closed topology. (Image by authors).

The graphs demonstrate a relation between the periodic or non periodic pattern changes of the input and out- put attributes. Finally, a vital benefit of creating the database is to be utilized to train an Artificial Neural Network to be able to give approximations of new building information based on some desired parameters and to save computational time (Giannopoulou et al., in press b).

2. Background Methodology

Based on Sennett (2009), that in the learning process, “technique -considered as a cultural issue rather than as a mindless procedure” and its applications, both come hand to hand, then, apprentice is in fact a learning by doing process. So, if the method gives the possibility of trial and error, then is implementing intuition inside the design procedure. On the other hand, Hanna and Mahdavi (2007) state that “for several centuries the mathematical tools for explicit analysis have been dominant, but the vast majority of design decisions throughout history have been based on experience of precedents. In a similar way, once a machine learning algorithm is trained, the advantage is the same advantage as the human builder’s training and experience”. But the problem has to be simple and well defined.

Examining the intersections between machine learning and simulation could enable a practice of structural intuition. The integration of simulation into computational design workflows give rise to a performance-based design methodology. Using parametric as well as generative design tools with structural, energetic or other simulation tools is today state-of-the-art practice. While experienced practitioners rely in these situations on intuition, machine learning can act similarly and predict simulation results out of precedent, how new systems would be- have (Tamke et al., 2018). In addition, “solution spaces are always multi-objective bringing together divergent criteria that don’t map to a single optima. As a result, solutions are assessed not absolutely as true or false, but rather qualitatively as better or worse. To

---

employ machine learning strategies in architecture therefore necessitate methods by which results can be evaluated holistically" (Tamke and Thomsen, 2018).

Apart from examining the available simulation models and computational tools employed in other domains, as have been briefly described in previous papers by the authors, the ability to integrate intelligent design systems that can analyze, process and transform design, could expand the ability to work across knowledge domains and explore potential for innovating existing practice. What Tamke & Thomsen (2018) refer to as extending design intuition, is that "the model becomes a creative-analytical engine into which external data can be ported and analyzed or internally generated to create the basis for intelligent design practices".

Nowadays, apart from standard topological, shape, size, structural optimization methods, that give standard results without allowing creativity or the user participation, it is difficult to find an alternative method, oriented to fabrication that could enable the designer to intervene. Also, during a generative process with evolutionary algorithms, the system allows you to see only the final optimized option, it is time consuming, computationally demanding, requiring repeated iterations and is subject to error due to local optima in the search space (Hanna and Mahdavi, 2007).

Also, coming from the field of statistical studies, there are some techniques (as subdividing, prioritizing, tracking impact of sensitive variables) to process the larger design spaces produced by taking advantage of the constantly growing computational power. Using simulation models for analysis the designer could be seen as an analyst who must assume that only few factors of the simulation are really important (Kleijnen, 1997), because of the computational time required and the learning goals. Linear growth of variables or ranges, as parametric modelling, triggers an exponential growth of the resulting design space, but mainly produce geometric variations with limitations in terms of topological transformations during the exploratory design tasks (Bernal, 2016).

Under this context, the case study is examining the feasibility of a machine learning approach which will enhance the design space by predicting new results. The first step, described in this paper, is to automatically generate a database of 1890 possible alternatives, which could be evaluated with reference to the whole and partially based on the experience of the user and intuition. A series of images and statistical charts will allow to visually compare parallel results, rather than one optimized option and to analyze and have insights, relating numerical values for the purpose of gaining experience and knowledge. This learning process, directed especially for fabrication, can also lead to a better decision making and inform the design. When there are many criteria involved and multi-objectivity, such as structural performance, less material waste, less stripes, less connectivity, surface continuity this method consequently, it will make the fabrication and assembly process more efficient.

3. Case Study

Owing to the limitations of parametric modelling, the design methodology has an obvious obligation to follow into the footsteps of its predecessors and pursue a generative model that can iterate several design solutions with manageable inputs and outputs. Moreover, considering the challenges offered by fabrication, the design methodology is compelled to accommodate constraints related to material, fabrication tools and methods, assembly processes and the general structural-aesthetic integrity. The objective at this stage is to establish a parameterized design workflow that revolves around actualizing the amalgamation of branching structures and thin shell structures.

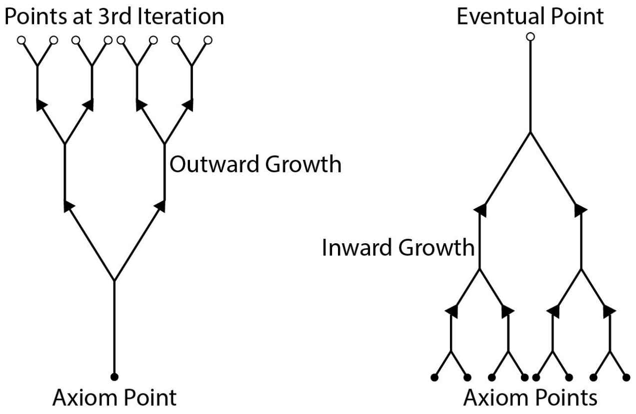


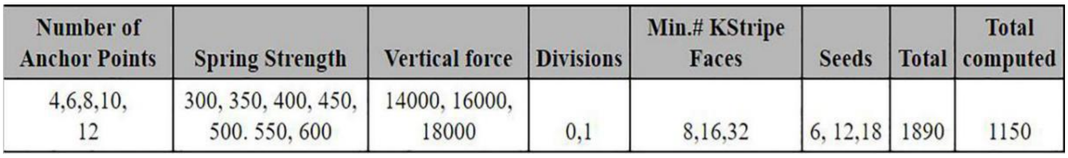
Figure 3. Branching/Unbranching, (left) a typical Lindenmeyer system with an outward growth of branching, (right) the adopted inward growth of unbranching.

Unbranching Skeleton and Shell

Branching structures are based on geometric systems that expand through bifurcation without returning to form closed cells. In this sense, branching structures resemble the structure of trees that branch continually outward (von Buelow 2007), following their phototropic trajectories while maintaining a dynamic structural equilibrium. Thus, branching patterns generated traditionally, for example following an L-System will have its origins in an Axiom. This means it will have more points at a certain iteration than it had at its origin. In our case, the design of the branching pattern needs to follow an opposite process, if the thin shell structure needs to be mounted on the base. Which means that each iteration must have less points than its origin, or to move from outwards towards inwards. This significant parameter further dictates the design methodology to perform a virtual unbranching of origin points into an eventual nodal iteration (Figure 3). Thus, an unbranching algorithm is generated following an inwardly growing progression that is programmed to start from 4, 6, 8, 10 and 12 random points to end in 1 single point that refers to the average point location between 2 or 3 points.

]]>

The shell structure is achieved by considering the initial unbranching structure as a skeletal shape, in which each point is a branch node. The skeletal system, used as medial axes, is converted into a net- work of tubular quadrilateral meshes. To generate the right sizes of branch nodes, a proximity algorithm is generated so that a relation between the thickness of the node is established with its distance from the eventual pinnacle node. This relation is very essential in a generating a smooth, minimal, non-self-intersecting mesh with equidistant subdivisions throughout its topology.



Number of Anchor Points	Spring Strength	Vertical force	Divisions	Min.# KStripe Faces	Seeds	Total	Total computed
4,6,8,10, 12	300, 350, 400, 450, 500. 550, 600	14000, 16000, 18000	0,1	8,16,32	6, 12,18	1890	1150

Table 1. Explains the quantity of total iterations based on all combinations of input attributes and the total computed, where the process stopped for unknown reason.

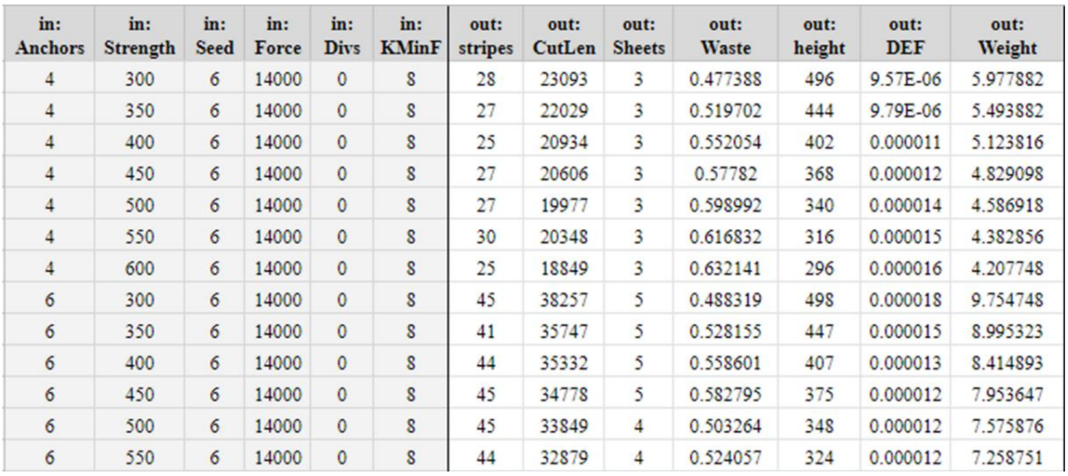
Learning Goals

The goal is to experiment the structurality of thin shells with branching topologies so that they would self-support and might withstand an additional weight apart from the material itself, taking in count at the same time the material usage. In contrary to a previous design methodology of static inputs, the approach allows the generation of a dynamic input geometry which permits the selection between various outcomes that fit best the criteria. General reference/criteria are defined as: deflexion, material usage, configuration and number of stripes, connectivity and surface continuity. The learning goals to examine are: How topology and spring strength affect the number of stripes, how topology affect material usage, and how topology affects structurality. The learning process suggests that the combination of some attributes indicating an efficient fabrication process which is balancing assemble time, number of sheets and extra weight due to the connecting elements and is up to the user to decide.

Database Preparation

The branching shell structure was geometrically constructed to iterate. The database was based on the selected input and outputs parameters as attributes of the structure. Modifications, extensions and clustering operations are applied to the initial model in order to extract he appropriate data sets in the format of CSV data and corresponding images. As a matter of fact, the most interesting part of this process is to determine, based on intuition and by experimentation, those sets of attributes/features/behaviours that influence most, inside the design workflow and which ultimately will train the model to predict.

The input attribute introduced in the initial de- sign phase is the Number of Anchor Points creating a branching network of connected lines, the foundation of a skeletal shape, second, third and fourth input attribute are introduced, the Spring Strength of the spring system, the loading vertical force - Strength and the mesh triangular subdivision parameter -Division, after the relaxation. A segmentation parameter, the minimum amount of faces per stripe-Kmin, is introduced as input as well. A Seed also acted as a modification factor, giving new anchor point lo- cations. The output attributes are chosen based on structural and fabrication criteria: Number of Stripes and Sheets of Material, Cutting length in mm, Waste of Material in sq. mm, Height in mm, Deflection in meters and Weight in kilos.



in: Anchors	in: Strength	in: Seed	in: Force	in: Divs	in: KMinF	out: stripes	out: CutLen	out: Sheets	out: Waste	out: height	out: DEF	out: Weight
4	300	6	14000	0	8	28	23093	3	0.477388	496	9.57E-06	5.977882
4	350	6	14000	0	8	27	22029	3	0.519702	444	9.79E-06	5.493882
4	400	6	14000	0	8	25	20934	3	0.552054	402	0.000011	5.123816
4	450	6	14000	0	8	27	20606	3	0.57782	368	0.000012	4.829098
4	500	6	14000	0	8	27	19977	3	0.598992	340	0.000014	4.586918
4	550	6	14000	0	8	30	20348	3	0.616832	316	0.000015	4.382856
4	600	6	14000	0	8	25	18849	3	0.632141	296	0.000016	4.207748
6	300	6	14000	0	8	45	38257	5	0.488319	498	0.000018	9.754748
6	350	6	14000	0	8	41	35747	5	0.528155	447	0.000015	8.995323
6	400	6	14000	0	8	44	35332	5	0.558601	407	0.000013	8.414893
6	450	6	14000	0	8	45	34778	5	0.582795	375	0.000012	7.953647
6	500	6	14000	0	8	45	33849	4	0.503264	348	0.000012	7.575876
6	550	6	14000	0	8	44	32879	4	0.524057	324	0.000012	7.258751

Table 2. Sample of the training data.

4. Results and Analysis

Based on the above input and output attributes, the database (Table 2) was generated, computationally extensive, performing all possible combinations in an excel sheet, including the image for each alternative (Figure 4). Table 1 explains the quantity of total iterations. As a result, different types of graphs were tested to visualize which combinations of attributes are giving a clear image of the relationship.

Charts with Vectorial Data

The real values of each attribute were converted to vector values from 0 to 1, using the remapping component and finding the minimums and maximums bounds of each in all the database to be used as a source. The same process happened for all the inputs and outputs values.

The vectorial analysis demonstrate how attributes behave, throughout the timeline. We observe that the Cutting Length and Number of Stripes do not affect Deflection (orange bars) (Figure 5). From the analysis of the Height, shown in blue bars, (Figure 6) we observe that it is affected, hierarchically, mostly by the amount of anchors (grey line),

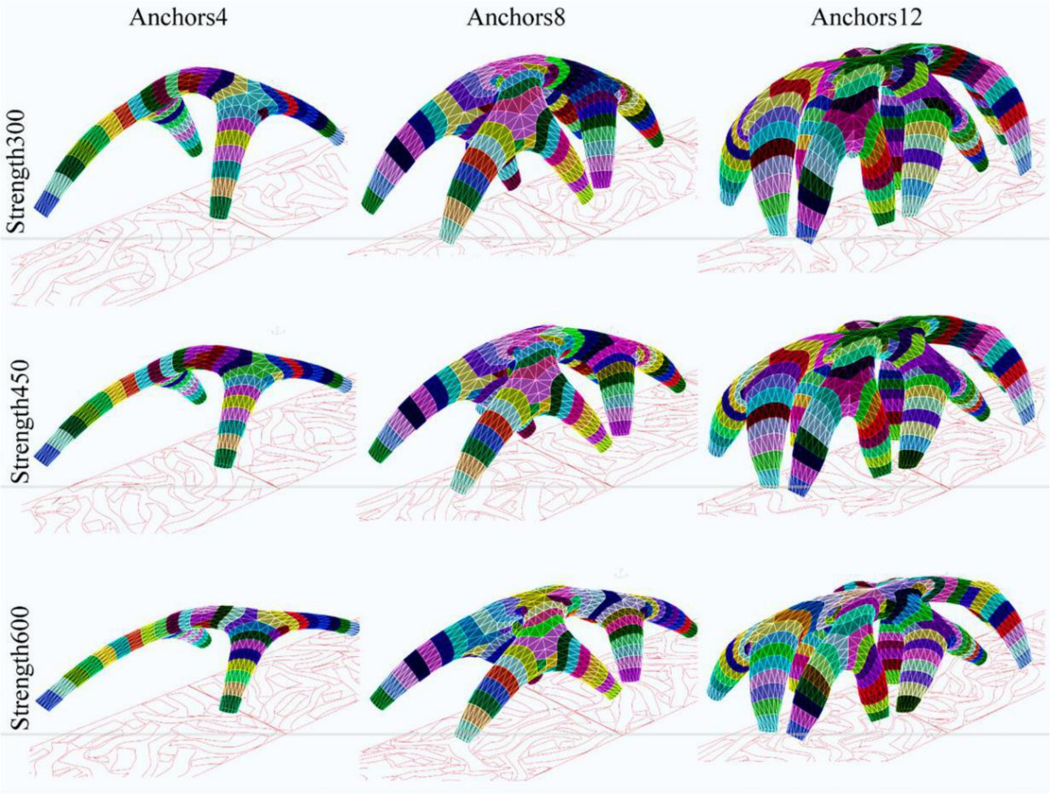


Figure 4. Sample of the images, in a table organization.

second by the Strength (higher values in the middle of every 35 iterations, that could mean that some specific point lo- cations are generating higher structures), third, is following the Seed pattern and forth is affected by the Force.

In the vectorial data analysis (Figure 7), it is possible to compare and see the patterns of change for each attribute. More Subdivisions do not affect Weight, Number of Sheets, Waste of Material.

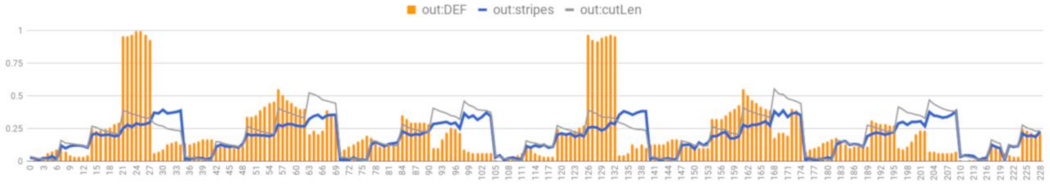


Figure 5. Chart of 230 iterations. Showing the Deflection pattern (orange bars) how it coincides with the Seed (red line, figure 6), every time it restarts its loop.

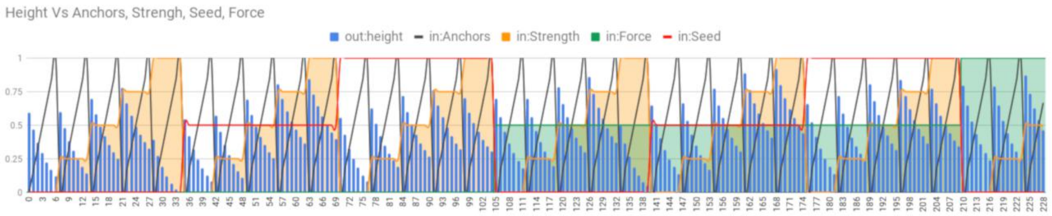


Figure 6. Chart of first 230 iterations. Showing the Height (blue line) attribute pattern that coincides with the Anchors and Strength loop dramatically.

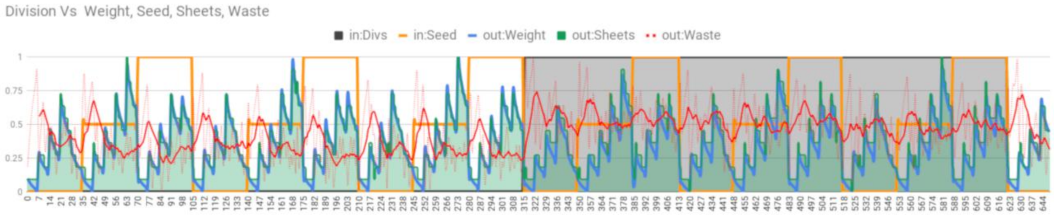


Figure 7. Chart of 650 iterations with vectorial data. A periodic pattern of Seed, Weight, Sheets, Waste, remains quite constant, in all iterations, even when Division attribute (grey area) is changed. The Waste of Material (red line) gets slight modification.

5. Conclusion

The proposed research examined a design work-flow that allows to produce sets of segmented shell topologies. This generative method gives the user the possibility to learn, analyze and balance priorities between alternatives that respond to various needs and to adjust the design based on the new information. The vital benefit of creating such database is to be utilized specifically to train an ANN to be able to predict new models information based on a new combination of desired input parameters (Giannopoulou et al., in press).

According to Wujec [3], machine learning drastically affects the field of design and architecture through its direct link to computational design, how- ever its applications are still in an experimental stage. Although biological skin patterns (Kondo, 2002) and segmentation in fabrication open a new field for interdisciplinary investigation and architectural applications, a machine learning approach to solve the complexities of such integration need to be further developed. Under the framework of Ito's ex- tended intelligence (Ito, 2018), "the convergence of cyber, physical and biological systems of production" (Sousa et al., 2019), requires not only new tools, methods and ways of understanding, but to question the purpose as observers and designers of a machine-based system of thinking to help developing sustainable and safe societies.

Acknowledgements

We greatly appreciate the students of the University Master in Biodigital Architecture for their contribution to make the projects real.

References

Bernal, M. 2016. 'From Parametric to Meta Modeling in Design', Proceedings of 20th SIGradi, Buenos Aires, pp. 579-583.

Boettiger, A., Ermentrout, B. and Oster, G. 2009. 'The Neural Origins of Shell Structure and Pattern in Aquatic Mollusks', Proceedings of the National Academy of Sciences, pp. 6837-6842.

von Buelow, P. 2007. 'A Geometric Comparison of Branching Structures in Tension and Compression versus Minimal Paths', Proceedings of 7th Seminar of the IASS-Shell and Spatial Structures: Structural Architecture – Towards the future looking to the past.

Giannopoulou, E., Baquero, P. and Estévez, A.T. In press, a. 'Machine Learning Approach For Biological Pattern Based Shell Structures', in VV.AA., Industry 4.0 – Shaping the Future of the Digital World. Taylor & Francis: London.

Giannopoulou, E., Baquero, P., Warang, A. and Estévez, A.T. In press, b. 'Computational Workflow for Segmented Shell Structures: an ANN Approach for Fabrication Efficiency', in Proceedings of International Association of Shell Spatial Structures Symposium: Form and Force, Barcelona.

Giannopoulou, E., Baquero, P., Warang, A., Orciuoli, A.,Estévez, A.T. and Brun-Usan, M.A. 2019b. 'Employing Mesh Segmentation Algorithms as Fabrication Strategies: Pattern Generation based on Reaction-Diffusion Mechanism', FME Transactions, vol. 47, no. 2, pp. 379-386

Giannopoulou, E., Baquero, P., Warang, A., Orciuoli, A., Estévez, A.T. and Brun-Usan, M.A. 2019a. 'Biological Pattern based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure', IOP Conference Series: Materials Science and Engineering, 471 (10)

Hanna, S. and Mahdavi, S.H. 2006. 'Inductive Machine Learning in Microstructures', in Gero, J.S. (ed.), Design Computing and Cognition '06, Springer.

Kleijnen, J.P. 1997. 'Sensitivity Analysis and Related Analyses: a Review of some Statistical Techniques', Journal of Statistical Computation and Simulation, 57 (1- 4), pp. 111-142.

Kondo, S. 2002. 'The Reaction-Diffusion System: A Mechanism for Autonomous Pattern Formation in the Animal Skin', Genes and Cells, 7, pp. 535-541.

Nejur, A. and Steinfeld, K. 2016. 'IVY: Bringing a Weighted-Mesh Representation to Bear on Generative Architectural Design Applications', Proceedings of 36th ACADIA, pp. 140-151.

Piker, D. 2013. 'Kangaroo: Form Finding with Computational Physics', Architectural Design, 83 (1), pp. 136-137.

Sennett, R. 2009. The Craftsman, Yale University Press

Sousa, J.P., Xavier, J.P. and Castro, H.G. 2019. 'Architecture in the Age of the 4th Industrial Revolution', Proceedings of eCAADe+SIGraDi 2019 Conference, Porto.

Stach, E. 2010. 'Structural Morphology and Self-Organization', Journal of the International Association for Shell and Spatial Structures, 51 (165), pp. 217-231.

Tam, K.M. and Mueller, C.T. 2015. 'Stress Line Generation For Structurally Performative Architectural Design', Proceedings of 35th ACADIA.

Tamke, M. Paul, N. and Zwierzycki, M. 2018. 'Machine Learning for Architectural Design: Practices and Infrastructure', International Journal of Architectural Computing, 16 (2), pp. 123-143.

Turing, A. 1953. 'The Chemical Basis of Morphogenesis', Philosophical Transactions of the Royal Society B: Biological Sciences, 237, pp. 37-72.

http://www.sawapan.eu

http://www.felbrich.com/projects/Crow/Crow.html

https://www.autodesk.com/future-of-making-things

https://pubpub.ito.com/pub/extended-intelligence

Article 5: Computational Workflow for Segmented Shell Structures: an ANN Approach for Fabrication Efficiency.

Effimia Giannopoulou[1], Pablo Baquero[2], Angad Warang[3], Alberto T. Estévez[4].

[1234] UIC, Carrer de la Immaculada, 22, 08017 Barcelona, Spain.

COMPUTATIONAL WORKFLOW FOR SEGMENTED SHELL STRUCTURES: AN ANN APPROACH FOR FABRICATION EFFICIENCY

Abstract: *An already established generative design methodology for bifurcating thin shell structures with similar physical and geometrical principles of biological processes, is using the logic of stripes as a construction system, linking relaxation, segmentation and fabrication processes as one unified system in equilibrium. However, a discussion is been raised upon the amount of stripes and their topology in relation with the branching system, structural performance, connectivity system, and material usage. The objective of this article is to explore the potentials and feasibility of a state-of-the-art machine learning approach which is based partly on the user's experience and knowledge. The method consists of a generation of a database of branching topologies which are utilized to train an Artificial Neural Network. This will allow the user to have a visual judgement of the numerical values based on multifunctional criteria and adjust the design based on the new information. The fact that the prediction mechanism preserves the intuitiveness of a generic design process enhances the designer's inventory by providing control over the scalability, is saving a lot of computational time and consequently helps in the design to fabrication process.*

Keywords*: Machine Learning, Digital Fabrication, Mesh Segmentation, Shell Structures, Bio-inspired.*

---

1. Introduction

As the advances in architectural practice become even more interdisciplinary, the research of biological pattern mechanisms and segmentation in construction opens a new field of investigation and architectural applications. Previous research by the authors [1], [2], explored how generative architectural design processes aim to apply similar principles of biological morphogenesis to the design and fabrication of thin shell structures [3]. To deepen into the subject of fabrication of bifurcating shell structures the on-going research [4], [5], leads to some experimental attempts to build up a machine learning (ML) methodology which will enhance the design space and help for quick estimations for decision making inside the design process. The case study is using previous insights and results to test the feasibility of building a prediction mechanism of shell and pattern generation with n number of branches. An already established parametric workflow allowed the development of a database [4] which is used to train an Artificial Neural Network (ANN). The ANN instantly gives numerical outputs based on the specific chosen characteristics/attributes. Finally, the ML accuracy is tested by comparing the ANN outputs with the computational outputs.

2. Branching shell design methodology

Branching topologies of closed and open tubular minimal shell structures have been tested on different small prototypes (Figure 1). Following a similar design process as in tensile/membrane structures, the simulation with particle spring system, achieves surfaces near to minimal and the structure in an equilibrium state. This form and function dependency allow the branching shells structure to be self-supportive and withstand an additional weight apart from the material

---

itself. In addition, the realization of the fabrication process acknowledges materials, tools and construction logic in an early stage of the design process, as manifested in nature. The logic of structural stripes [6] is used to pre-rationalize the design method [7], where each stripe is conceptualized as a ruled surface, developable, with zero Gaussian curvature, made of curved sheets of material.

Figure 1. Biodigital Fabrication Studio Series 2017/2018/2019, University Master in Biodigital Architecture, ESARQ-UIC Barcelona, School of Architecture - Universitat Internacional de Catalunya, (top) open branching network with three legs, (bottom) cantilever with four anchors, open topology (right) cantilever with six anchors, closed topology. (Images by authors).

2.1. Define Branching Topology

Topology refers to the system of anchoring points creating a branching network of connected lines, the foundation of a skeletal shape, in which each point is a branch node. The positions of the points change randomly

---

with a seed value and follow some rules that preserve some symmetry. The skeletal, used as medial axes, is converted into a network of quadrilateral meshes. This system of tubules, or hollow vessels is referring to a cytoskeleton or branching shell structure. This point/skeletal approach for the shell structure is especially designed to accomplish two basic needs. Firstly, the system to be able to iterate through different configurations and the same time the points to serve as anchoring locations of the structure with the base. This is achieved by considering an unbranching structure as the skeletal shape, following an inwardly growing progression of the branching system and thickening of the nodes [4].

2.2. Simulation

In order to generate in a simple and intuitive way a structure in static equilibrium, with minimal surface properties, dynamic relaxation is applied to the skeletal quad mesh edges using a physics engine [8]. Following a similar form-finding process as in membrane structures and grid shells, skin and structure are formed as one. Mesh is subdivided and boundary conditions are defined as the naked edges of the mesh. Applying different forces (gravity loads, spring length) to the springs is possible to interactively control the thickness of the shell branches, estimate the desired height of the structure and influence the smoothness and surface continuation, especially in the saddle locations, taking in count material bending properties. The last one could be also controlled by the stripes topology and orientation. The branching shell structure was examined with a very fast linear analysis of shell elements [9]. The analysis of structural parameters was using material data of PP (elasticity, density yield strength and poisson’s ratio) [2].

2.3. Define Pattern and Fabrication

Given a parametrized tubular minimal shell structure in static equilibrium and a set of weighted conditions for the mesh nodes and edges, various segmentation algorithms, coming from graph theory [10] are tested to discretize effectively the given topological mesh. Custom weights applied to the edges using Orange Peel (OPE) algorithm to generate ripples, following primary and secondary segmentation algorithms [2]. Throughout this process is possible to manage the amount of cutting stripes, topology, orientation and maximum amount of faces per stripe. Using the Opennest plugin [11], the 3D stripes are oriented on 2D rectangular sheets with specified material dimensions.

3. Methodology for machine learning implementation

The ANN experiment is framed in four computational stages and different grasshopper definitions were developed:

1. Parametric Shell Structure: Geometry construction and structural analysis.
2. Database preparation: Develop a 1150 Shells database [4].
3. Training process: Develop the layout of network structure.
4. Validation: Generate new database to compare the computed with the predicted values.

3.1 Learning objectives and criteria

The ML methodology is re-examining the already established parametrized design workflow. Modifications, extensions and clustering operations are applied to the initial model in order to extract the

---

appropriate data sets in the format of excel sheets and corresponding jpgs [4]. As a matter of fact, the most interesting part of this method is to determine those sets of attributes/features/behaviours inside the design workflow to train the model to predict. The designer can have a visual judgement of the numerical values based on multifunctional criteria. The goal is to experiment the structurality of thin shells with branching topologies taking in count at the same time the material usage. In contrary to a previous design methodology of static inputs, this approach allows the generation of a dynamic input geometry which permits the selection between various outcomes that fit best the criteria.

General reference/criteria are defined as: deflection, material usage, configuration and number of stripes, connectivity and surface continuity. The learning process suggests that the combination of some attributes indicating an efficient fabrication process which is balancing assemble time, number of sheets and extra weight due to the connecting elements and is up to the user to decide [4].

3.2 Training

For the training process a grasshopper definition was made using Crow [12], a machine learning plugin, extension of NeuronDotNet.dll developed by Vijeth Dinesha. The Crow component requires three input parameters:

1. The quantity of iterations to give good accuracy was set to 12000 cycles.
2. The network structure was set up with six nodes in the input layer, twelve and fourteen nodes in the two Sigmoid hidden layers and seven in the output layer (Figure 2). After many trials of changing

---

the number of cycles, the learning rate was set to 0.2 to obtain the smallest MSE of 0.017516.

3. The datasets for training: 1150 branching shells, generated by the input attributes (Spring Strength, Number of Anchor Points, Minimal Number of Faces per Stripe, Random Seed Generating Point Locations, mesh subdivision), and outputs attributes to train (Number of Stripes, cutting length, Number of Sheets, Material Wasted, Height, deflection, weight).

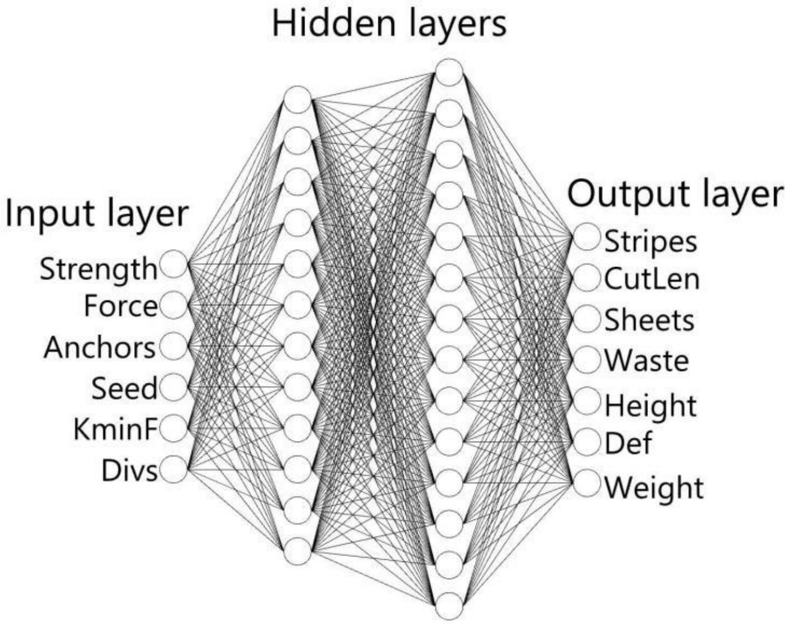


Figure 2. Layout of network, showing 6 nodes for input layer, 12 and 14 nodes in the hidden layer and 7 in the output layer. (Image by author).

3.3 Limitations and constraints

The database was generated using colibri plugin inside grasshopper. During the simulation, for some few cases, the combination of input parameters failed to give a geometrical results and the corresponding numerical values. Although current parametric modelling systems can capture best practices and facilitate the generations of design alternatives, models are not capable to support variations beyond the scope of their hierarchical structure of the geometric relationships prematurely limiting the potential design space [13]. Another limitation of the parametric model is that it did not allow to switch between different paths of segmentation algorithms (SA) (different IVY components giving different stripe pattern effects, based on different inputs like valence, deviation, angles, etc.) in order to have them in one run. This indicated another limitation of the proposed methodology and tools. Creating parallel databases by iterative runs, using different SA each time, would not allow even to be introduced as attributes at the same time due to the different type of segmentation input parameters that each algorithm requires. The idea of creating a machine prediction for pattern generation was limited to specific combinations of SA. We can observe though that changes in the branching topology (number of anchor points, spring strength, etc.) affect also the stripe configurations, especially in the top part of the shell. To avoid these type of issues and let it run in multiple generations, the definition had to be arranged properly to work for all cases providing a generic framework for future experiments of biological based segmentation for branching shells.

4. Results and Analysis

4.1 Validation process

For the validation, another database was made out, with the purpose of comparing the tested iterations with its outputs attributes. It is using the 1150 database computed previously, in order to make a validation with the ANN prediction and compare the computed versus the predicted, both with vector information and with real information. Backpropagation classifier component was used for testing the 6 inputs vector information, which gives 7 output vector data for each iteration.

The graphs demonstrate the accuracy of the ANN for each attribute with real values. The scatter type of charts is useful for comparing two sets of data sets. The closer the points to the trend line (diagonal line) the closer the prediction (Figure 3).

4.2 Error estimation

To estimate the errors a comparison is made throughout the timeline calculating the difference between predicted and computed values. The Waste attribute is the one which shows bigger errors (Figure 4). To see closer the error the Waste comparison is focused to 200 iterations, showing both predicted and computed vector values (Figure 5).

5. Discussion and Future Work

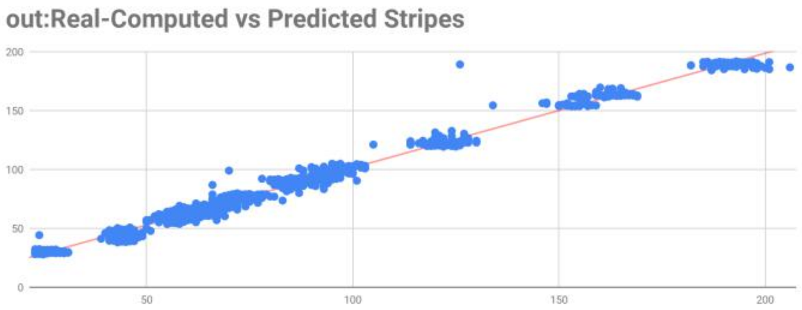
The general hypothesis is questioning the feasibility and purpose of a prediction mechanism of branching and pattern generation for segmented shell structures, analogous to the biological skin patterns. In this case only lateral branching is examined following simple rules to avoid complications for the generation of the data sets. The viability of the implementation of 3D patterns with geometrical and topological properties of Turing patterns (area, boundary length, cluster numbering, connectivity, and so on) as described by Guiu-Souto et al. [14] inside a generative fabrication context would be a future idea to explore.

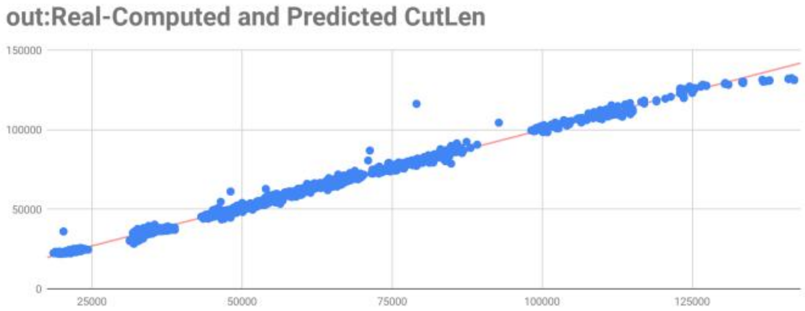
A discussion has been raised about the importance of a structural investigation on the segmented stripe shell. The problem was how to set up the loading conditions in order to test the structurality and connectivity of the stripe pattern. A finite element setup method based on springs, as in the cases of segmented shells composed of planar plates [15], [16], may be a possible solution in case of bigger scale construction.

Under the framework of complex modelling [17], [18], and Ito's extended intelligence [19], the idea of bringing design and science together can foster new, productive and flexible antidisciplinary work, this research triggers not only new ways of thinking about tools and methods that transform design, but to question the purpose as observers and designers of a machine-based system of thinking and a new understanding of architecture. Learning from nature's laws ("bio-learning") and computation as a powerful tool to solve problems.

Acknowledgements

We greatly appreciate the students of the University Master in Biodigital Architecture and Professor Affonso Orciuoli of iBAG-UIC Barcelona for their contribution to make this research real.


out:Real-Computed vs Predicted Stripes


out:Real-Computed and Predicted CutLen


out:Real-Computed vs Predicted Waste

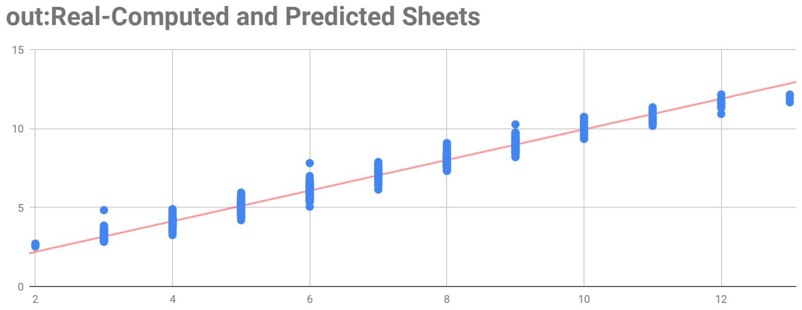

out:Real-Computed and Predicted Sheets

*Image continue in next page

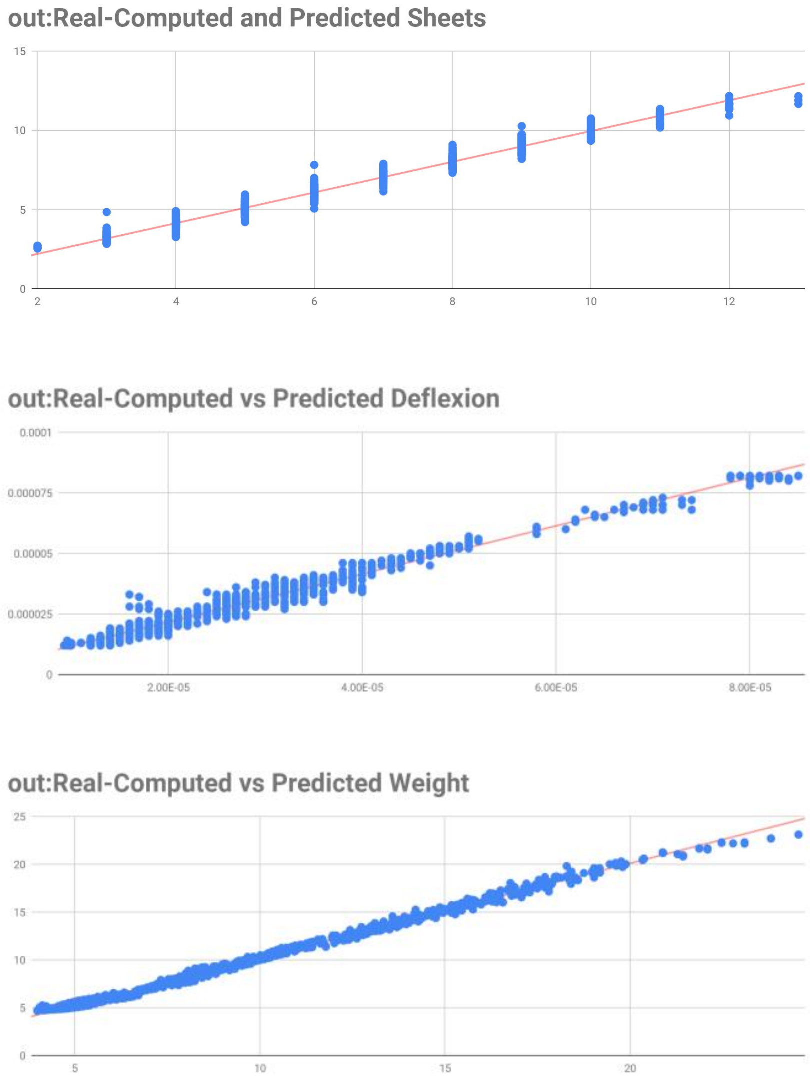


Figure 3. The 7 graphs correspond to the 7 output attributes. The scatter type of charts is useful for comparing two sets of data sets. The closer the points to the trend line the closer the predicted to the computed.

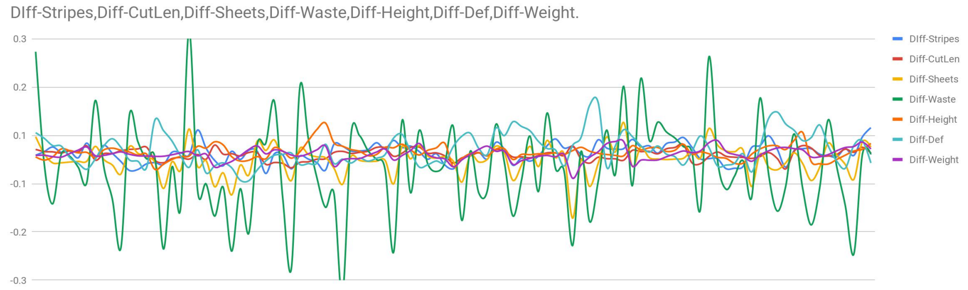


Figure 4. Chart of all attributes with Vector values, showing the difference between the predicted and the computed attributes in 100 iterations. The Waste attribute (green line) is the one which shows bigger errors.

Figure 5. Chart showing the predicted (red) vs computed (blue) for the Waste attribute in 200 iterations with Vector values.

References

[1] E. Giannopoulou, P. Baquero, A. Warang, A. Orciuoli, A.T. Estévez and Brun-Usan, M.A., “Biological pattern based on reaction-diffusion mechanism employed as fabrication strategy for a shell structure”, *IOP Conference Series: Materials Science and Engineering*, vol. 471 (10), 2019a.

[2] E. Giannopoulou, P. Baquero, A. Warang, A. Orciuoli, A.T. Estévez and. Brun-Usan, M.A, “Employing mesh segmentation algorithms as fabrication strategies: Pattern generation based on reaction-diffusion mechanism”, *FME Transactions*, vol. 47 (2), pp. 379-386, 2019b.

[3] M. Bechthold, *Innovative surface structures: technology and applications.* London: Taylor & Francis, 2008.

[4] E. Giannopoulou, P. Baquero, A. Warang, A. Orciuoli and A.T. Estevez, "Stripe Segmentation for Branching Shell Structures - A Data Set Development as a Learning Process for Fabrication Efficiency and Structural Performance", in *Architecture in the Age of the 4th Industrial Revolution: Proceedings of the eCAADe+SIGraDi joint Conference 2019, Porto, Portugal, September 11-13, 2019*, eCAADe / SIGraDi, 2019. (in press).

[5] E. Giannopoulou, P. Baquero, A. Warang and A.T. Estévez, "Machine Learning Approach for Biological Pattern Based Shell Structures", *Industry 4.0 - Shaping the Future of the Digital World*. London: Taylor & Francis, 2019. (in press)

[6] P. Schumacher and M. Fornes, "The Art of the Prototypical", *Architectural Design*, vol. 86 (2), pp. 60-67, 2016.

[7] E. Stach, "Structural morphology and self-organization", *Journal of the International Association for Shell and Spatial Structures,* vol. 51 (165), pp. 217-231, 2010.

[8] D. Piker, "Kangaroo: Form finding with computational physics", *Architectural Design*, vol. 83 (1), pp. 136-137, 2013.

[9] P. Michalatos, *Millipede. Grasshopper*. http://www.grasshopper3d.com/group/millipede. Accessed March 1st, 2014.

[10] A. Nejur and K. Steinfeld, "Ivy: Bringing a weighted-mesh representation to bear on generative architectural design applications", in *36th ACADIA 2016, Ann Arbor, U.S.A., 2016*, ACADIA / University of Michigan, Taubman College, pp. 140-151, 2016.

[11] P. Vestartas, *OPENNEST*. Retrieved from: https://www.food4rhino.com/app/opennest

---

[12] B. Felbrich, *Crow plugin for Grasshopper.* http://www.felbrich.com/projects/Crow/Crow.html. Accessed April 27th, 2019 (2016).

[13] M. Bernal, “From Parametric to Meta Modelling in Design”, in *SIGraDi 2016, XX Congreso de la Sociedad Iberoamericana de Gráfica Digital, 2016 Buenos Aires, Argentina*, SIGraDi, pp. 579-583, 2016.

[14] J. Guiu-Souto, J. Carballido-Landeira and A.P. Muñuzuri, “Characterizing topological transitions in a Turing-pattern-forming reaction-diffusion system”, *Physical Review. E, Statistical, Nonlinear, and Soft Matter Physics*, vol. 85 (5), pp. 1-8, 2012.

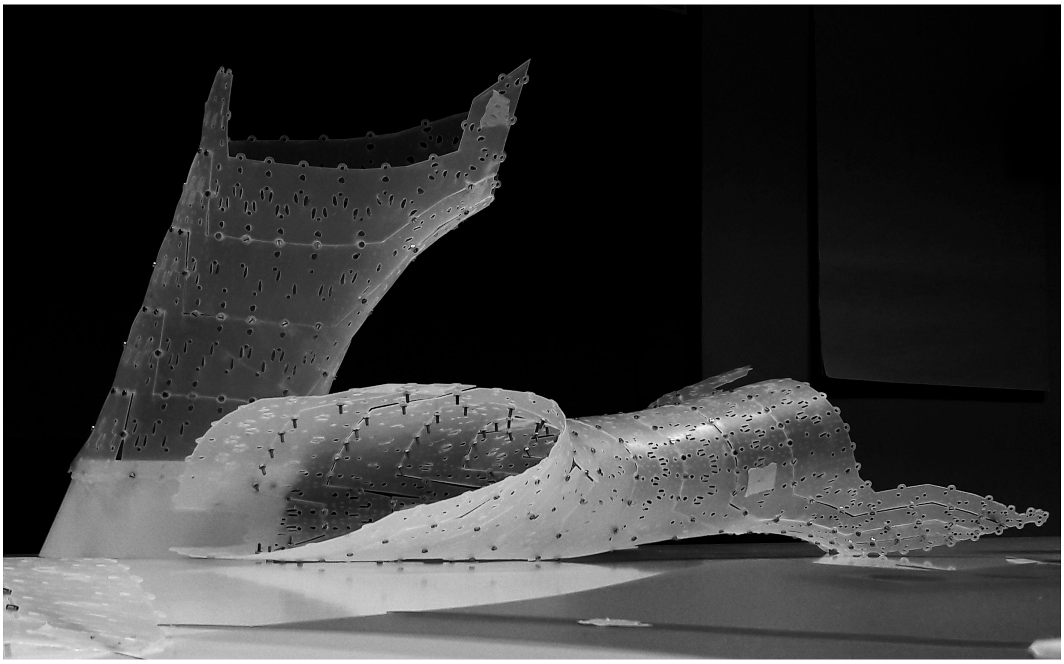
[15] L. Jian-Min and J. Knippers, “Pattern and Form: Their Influence on Segmental Plate Shells”, in *Proceedings, International Association of Shell Spatial Structures Symposium 2015, August, 2015*, IASS, 2015.

[16] R. La Magna, F. Waimer and J. Knippers, “Nature-inspired generation scheme for shell structures”, in *Proceedings of the International Symposium of the IASS-APCS Symposium, Seoul, South Korea, May, 2012*, IASS, 2012.

[17] M. Tamke and M.R. Thomsen, “Complex Modelling”, *International Journal of Architectural Computing*, vol. 16 (2), pp. 87-90, 2018.

[18] M.R. Thomsen, “Complex modelling - questioning the infrastructures of information modelling”, in *Proceedings of the 34th eCAADe conference complexity & simplicity (eds. A. Herneoja and T. Österlund), University of Oulu, Oulu, 22-26 August 2016*, vol. 1, pp. 33-42, eCAADe, 2016.

[19] J. Ito, “Extended Intelligence”, *Joi Ito’s PubPub*, pp. 1-6, 2018.



Rahmani Tarek@2017. Ed. Author

---

5. DISCUSSION

The hypothesis of this thesis assumes the morphogenetic processes and mechanisms that describe phenomena occurring in nature can be represented as algorithmic processes for designing and producing novel, sustainable and efficient architectural works. It examines how the integration of a machine learning approach could be an alternative research and learning tool for understanding, evaluating and analyzing design outputs based on multicriteria for fabrication purposes.

As a result, this research demonstrates an evolution of a generative design workflow which translates a biological pattern mechanism to fabrication processes. Computational design techniques of weighted mesh graphs representations, physics-based simulation, finite element analysis and machine learning, employed in parallel, are used for the data analysis and the construction of minimal thin shell structures with branching topologies. The workflow is linking relaxation, segmentation and fabrication processes in one unified system, implementing the patterning logic of stripes as a construction system. The application of the Artificial Neural Network approach, based partly on the user's experience and knowledge, is using the data from the generative process, which allows the development of parallel alternatives and a clear visualization of the relationships between the attributes. The Artificial Neural Network is able to predict accurately, in most cases, new building information, according to new combinations of desired parameters, saving computational time.

In this section are summarized and explained some interpretations and implications of some specific aspects related to the outcomes of this thesis, the limitations that have been encountered and some recommendations for further development.

Multi-objectivity

The computational framework is for the purpose of multi-objective decision making and optimization of material and machine time and cost, based on specific geometrical characteristics, inherent inside the parametric model which define the structure (anchors, strength, etc., as shown in table 2, article 4, page 83). Those characteristics/attributes are chosen based on structural and fabrication criteria, as the most crucial, and are re-evaluated. Throughout the generation of different types of graphs, it is possible to have a holistic visual judgement of the numerical values and geometrical outcomes, in relation to the desired multifunctional criteria. The vectorial analysis of different combinations of inputs and outputs helps to identify the relationships, observe and understand from the changing patterns of the variables, how attributes behave, throughout the timeline, and/or which input parameters are affecting mostly the outputs. For example, the height output values, coincides with the number of anchor points and strength loops dramatically in a cyclic pattern (figure 6, article 4), in comparison with the deflection pattern (figure 5, article 4) that doesn't follow the same loop but coincides with the force loop. Basically, those types of observations, can have multiple interpretations in relation to geometrical and simulation aspects, for example, when, how and why the stripe pattern transforms in the locations where the branching topology changes in some cases, as in the top of the shell (figure 4, article 4).

This qualitative approach of understanding shell and pattern behaviour has potential to traverse domains. In line with the hypothesis, this mechanistic and analytical data approach, preserves inside the generic morphogenetic process the intuitiveness of understanding and representation of the natural phenomena and mechanisms, while ultimately could lead to physical objects which incorporate in their entirety the whole process and an entire technological background. The model serves for its explanatory value and for its predictive one: indicates which attributes from the designer's point of view, are more appropriate to account for the given phenomenon and also facilitate the exploration of particular complex structures, which sometimes challenge our individual possibility of calculation and imagination (Cazzaro, 2019).

Two domains - Interdisciplinarity

Since architectural practice is still depending on the process of breaking things into smaller discrete elements as a way of construction and building logic, this thesis proposes a useful design methodology, opening a new field for interdisciplinary investigation between architects, engineers, programmers, scientists, industry and fabricators.

The results indicate that biological patterns in architecture have design potential as stripe organization in fabrication and construction. However, a design methodology to be interdisciplinary is questioning the communication and the new perceptions of representation language (Voyatzaki, 2007). An examination of the self-organized process of the morphogenesis of biological forms, of current evolutionary computational techniques and of self-organizing mathematical systems, reveals consistency between the domains and some intractable incompatibilities. (Weinstock, 2005) To facilitate the union of the two domains, he proposes that it is essential to search for techniques that have the potential to traverse domains and from then to identify the critical vector of convergence between them.

The collaboration with the biologist and computer scientist was very stimulating and in future projects could be beneficial to both, but more knowledge interchange is required. As Roudavski (2009) says, while the architects can extend their models conceptually and benefit from existing formalisms and techniques in computational simulations, biologists and other scientists, also, can benefit because they want to extend their models to operate in three dimensions, making them more dynamic and able to simulate mechanic and other physical processes.

The case studies of this thesis rely mostly on the available generative design tools, without interchanges between platforms or external data resources, except of the essential for the fabrication process, like material data and tolerances. In this way, the design approach becomes more efficacious and safer. However, what is found as common ground on the two simulation domains, the biological pattern prediction and the architectural generative design and fabrication, is the computational thinking and terminology, as communication tool, and a scientific method of analysis to address aspects inherent in digital morphogenesis (Kolarevic, 2000). An examination of the two theoretical and computational modeling frameworks and testing with real physical models offers a continual dialogue informing each other as a design workflow and advancement in construction.

Sustainability

In architecture, the conception of a lighter building, meaning less material usage, reduces the impact on our environment and makes it more sustainable. Shell structures (Adriaenssens et al., 2014), like the ones described in this thesis, are exceptional examples of lightweight frameless envelopes. The advantage of avoiding any supporting frame and to rely only on the minimal surface properties of the dynamic relaxation process, is one of the initial goals fulfilled. Curved sheets of polypropylene material, as any other similar material, have increased stiffness, related to flat sheets. Bending makes them more rigid. Furthermore, the analysis confirms that through the proposed computational procedure (article 4 and 5), it is possible to calculate the material usage, and based on that, to make the appropriate decisions in early stages of the design process, in relation to the rest of input and output features of the ANN. This allows a holistic approach of evaluation, combining performance, functionality and efficiency.

Biological and geometrical representations of findings

Many mathematical models have shown that the reaction-diffusion system is able to produce most of the animal skin patterns (Koch and Meinhardt, 1994; Ball, 1999). The study of the Turing mechanism, of reproducing the stripe or any other class of patterns, is represented geometrically here, by a discretization process of separating parts based on mesh weights and angles between their boundary edges. According to the graph (article 1, figure 10), if the average angle is closer to a specific value (1.58 in radians), the stripes become vertical, if it is smaller, become horizontal. This fact also led to the conclusion that tubular forms, with small angles between faces, could be generated with parallel stripes, which actually makes the whole structure stronger.

The mathematical equations, architecturally, are represented with the segmentation algorithm, the initial boundary conditions and the relaxation process. Furthermore, there is an underlying rule, apparent in the biological system, a threshold value of diffusion, responsible for spontaneous symmetry breaking (Dutta, 2017), that could be, geometrically, this specific value of average angles. Finally, the use of the stripe pattern is not for aesthetic purposes, or for mimicking natural forms, but because it indicates a well-structured autonomous mechanism, independent from the internal structure and individual skin cells (Asai, R. et al., 1999).

Stripification

The experiment provides a new insight into the discussion of segmentation for fabrication. On Nejur and Steiner (2017) research, stripification, is described as a process by which single face mesh strands are identified, and is generally regarded as one of the best ways to decompose a mesh while avoiding overlaps in the unfolded state. It is a specific case of general segmentation: a strip-like segmentation, achieved by constructing a tree (via

---

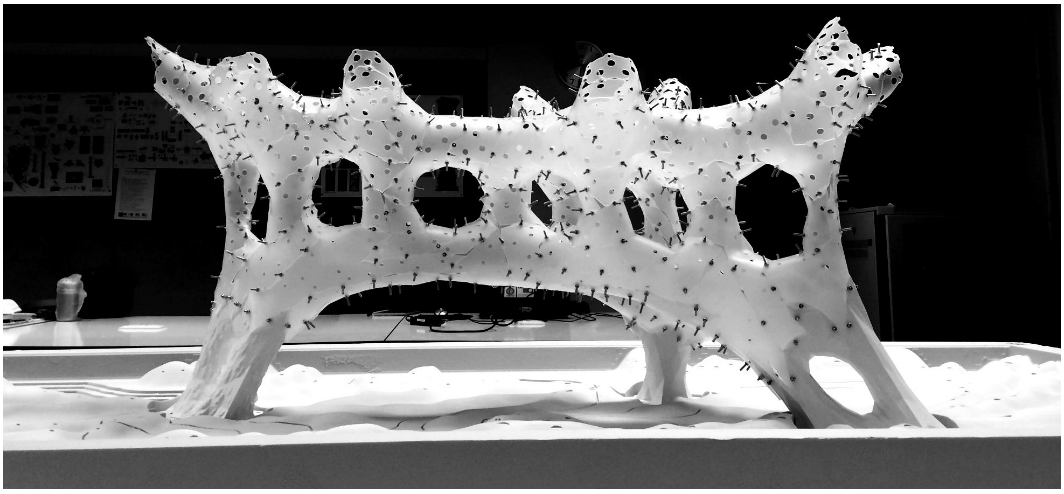
any means, including agent segmentation or the Kruskal-Valence algorithm). Ivy plug-in inside Grasshopper, implements research from computer graphics of Taubin and Rossignac (1998), as the *orange-peel*, algorithm, which is used in the experiments of this thesis. Also, the approach is similar to the *Meshwalker* of Anders Holden Deleuran (2015) at CITA who uses Python scripting, and Fornes structural stripes (2015). Mesh segmentation plays a major role in modeling, shape compression, simplification, texture mapping, and skeleton extracting (Wu, 2017) and findings from one discipline could be very helpful to another. While those examples have focused on the stripe logic of construction, this thesis demonstrates an analytical framework of modeling and evaluation of a construction system which may allow scientific data and methods to be implemented.

Limitations

Despite limitations in terms of design exploration and topological transformations (Bernal, 2016; Harding and Shepherd, 2017), a parametric design workflow, inside the same platform, directed for fabrication has many advantages. It permits continues workflows and the integration of multiple design tasks, inside the same interface allowing a fluent flow of information for the specific task. Simplifications thought were necessary to be applied in the rules for the branching of the shell and the structural analysis model, due to computational cost. Also, it wasn't possible to test different segmentation algorithms at the same time, because of different number of input parameters for the ANN to train, however changes in the branching topology (number of anchor points, spring strength, etc.) affected also the stripe configurations, especially in the top part of the shell, which indicates a form-force-pattern dependency.

Future lines of research and recommendations

This thesis serves as a methodological framework for future development and further interchange of scientific data and methods. The viability of implementing 3D patterns with geometrical and topological properties of Turing patterns, dynamic changes of the pattern applied to adaptive design systems, and other simulation techniques of biological patterns found in nature with structural characteristics, inside a generative fabrication context are among future lines for research explorations which will require new design approaches and further collaborations. More experimentation with machine learning can include algorithms that can predict, assess and analyze input/output parameters for structurally different elements. This research results could be further developed for the generation of machine learning libraries for different components in architecture, while managing and monitoring a humongous database. For this, it will be necessary to collaborate with data scientists for the setup of the models and evaluation of the results.



---

6. CONCLUSIONS

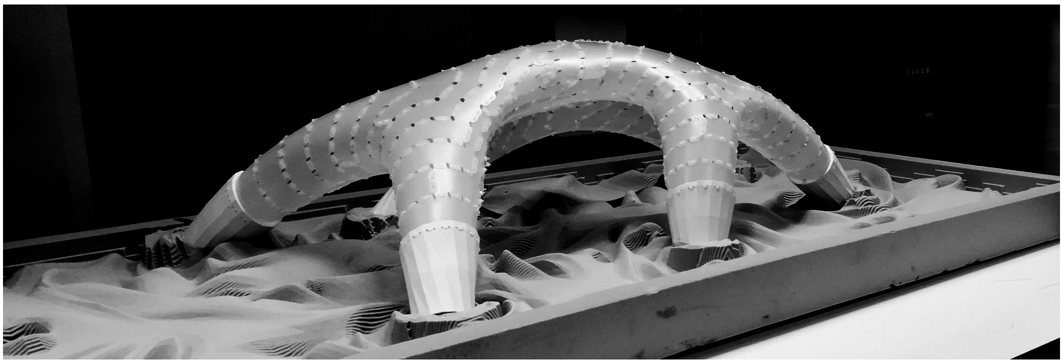
The hypothesis delves into the computational correlations between artificial and biological systems, and how they could complement each other for producing novel architectural works. This thesis proposed a generative framework for modeling and constructing thin shells inspired by a biological patterning mechanism for the purpose of balancing structural performance of frameless shells and the amount of material to be constructed with. By examining the feasibility and purpose of a prediction mechanism of branching and pattern generation for segmented shell structures, analogous to the biological skin patterns, the results indicate that such an approach can be very useful and can enhance the fabrication efficiency, giving many insights, as a learning and evaluation process. Specifically:

1. It was possible to incorporate physical form-finding and structural simulations, graph representations and fabrication procedures, in one unified system that could iterate and generate a database of more than 1000 variations of buildings. This could provide a generic framework for future experiments of segmentation for branching shells.
2. It was possible to build and validate a state- of- the- art prediction mechanism of shell and pattern generation with *n* number of branches to reduce computational cost. In most cases the ANN gave accurate approximations.
3. The machine learning algorithm enhanced the design space by predicting new results, with characteristics related to the specific criteria (deflection, material usage, configuration and number of stripes, connectivity and surface continuity). It played a crucial role in

the decision making, informing the design based partly on intuition, partly on the machine.

4. The qualitative approach of generating and comparing statistical charts, was a key factor for understanding and having unexpected insights of the relationships between the specific input and output attributes. It is concluded that the combination of some of the attributes indicate a more efficient fabrication process, which is balancing priorities between alternatives that respond to various needs (assemble time, number of sheets and extra weight due to the connecting elements) and is up to the user to decide.

This is an ongoing research and such unconventional approaches are still in an experimental stage in architecture, but they are opening a new field of investigation in design research. It can be concluded that a new understanding of architecture is possible, partially machine - partially intuited. The computational thinking and hands-on experimentation with nature aside are the fundamental tools to begin.



BIBLIOGRAPHY

Aish, R. (2005). “From Intuition to Precision”. In: VV.AA., Digital Design: The Quest for New Paradigms: 23rd eCAADe Conference Proceedings, Lisbon, Portugal, pp. 10-14.

Adriaenssens, S., Block, P., Veenendaal, D., Williams, C. (2014). “Shell Structures for Architecture: Form Finding and Optimization”, Routledge.

Asai, R., Taguchi, E., Kume, Y., Saito, M., Kondo, S. (1999). “Zebrafish Leopard gene as a component of the putative reaction-diffusion system”, Mechanisms of Development, 89 (1–2), pp. 87-92.

Ball, P. (1999). The Self Made Tapestry: Pattern Formation in Nature. Oxford University Press.

Baquero, N.P. (2016). “Architectural workflows for digital materialization informed design. Experiments with particles simulations for digital fabrication”. PhD Thesis, ESARQ, UIC, Barcelona.

Bernal, M. (2016). “From Parametric to Meta Modelling in Design”. In: VV.AA. SIGraDi 2016, XX Congreso de la Sociedad Iberoamericana de Gráfica Digital, Buenos Aires, Argentina, pp. 579-583.

Brodland, G. W. (2015). “How computational models can help unlock biological systems”, Seminars in Cell and Developmental Biology. Elsevier Ltd., pp. 47–48, 62–73.

Cazzaro, I. (2019). “Cellular Automata Between Life Science and Parametric Design: Examples of Stochastic Models to Simulate Natural Processes and Generate Morphogenetic Artefacts”. In: Cocchiarella, L. (ed.). ICGG 2018 - Proceedings of the 18th International Conference on Geometry and Graphics. ICGG 2018. Advances in Intelligent Systems and Computing, vol. 809. Springer, Cham.

Camazine S., Franks R.N., Sneyd J., Bonabeau, E., Deneubourg J.L., Theraula G. (2001). “Self-organization in Biological Systems”. Princeton University Press.

DeLanda, M. (1992). “War in the Age of Intelligent Machines”, Zone Books, New York.

Deleuze, G., Guattari, F. (1980). “A Thousand Plateaus”, University of Minnesota Press, pp. 330.

Dutta, K. (2017). “Reaction-diffusion Dynamics and Biological Pattern Formation”, Journal of Applied Nonlinear Dynamics, 6 (4), pp. 547–564.

Estévez, A.T. (2003). “Genetic Architectures”. In VV.AA., Genetic Architectures, Sites Books / ESARQ (UIC), Santa Fe (USA) / Barcelona.

Fornes, M. (2016). “The Art of the Prototypical”, Archit. Design, 86 (2), pp. 60-67.

Giannopoulou, E. (2009). “Simple Invisible”, Master thesis, ESARQ, UIC, Barcelona.

Harding, J. E., Shepherd, P. (2017). “Meta-Parametric Design”, Design Studies, 52, pp. 73–95.

Hensel, M., Menges, A., Weinstock, M. (2013). “Morphogenesis and Emergence”. In: Carpo, M. (ed.), The Digital Turn in Architecture 1992-2012. John Wiley & Sons Ltd.

Koch, A.J., Meinhardt, H. (1994). “Biological pattern formation: from basic mechanism to complex structures”, Rev. Mod. Phys. 66, pp. 1481-1507.

Kolarevic, B. (2003). Architecture in the Digital Age: Design and Manufacturing, Taylor & Francis.

Kolarevic, B. (2000). “Digital Morphogenesis and Computational Architectures”. In: VV.AA., SIGRADI 2000 - Constructing the digital space. Rio de Janeiro, pp. 98-103.

Nejur, A., Steinfeld, K. (2017). “Ivy: Progress in developing practical applications for a weighted-mesh representation for use in generative architectural design”. In: VV.AA., Proceedings of 37th ACADIA, MIT.

Roudavski, S. (2009). “Towards Morphogenesis in Architecture”, International Journal of Architectural Computing, 7 (3), pp. 345–374.

Sennet, R. (2009). The Craftsman, Yale University Press.

Sharpe, J. (2017). “Computer modeling in developmental biology: growing today, essential tomorrow”, Development, 144 (23), pp. 4214–4225.

Stach, E. (2010). “Structural morphology and self-organization”, Journal of the International Association for Shell and Spatial Structures, 51 (165), pp. 217–231.

Tamke, M., Thomsen, M.R. (2018). “Complex Modelling”, International Journal of Architectural Computing, 16 (2), pp. 87–90.

Taubin, G., Rossignac, J. (1998). “Geometric compression through topological surgery”, ACM Transactions on Graphics, 17 (2), pp. 84–115.

Terzidis, K. (2003). Expressive Form: A Conceptual Approach to Computational Design. Spon Press, London / New York.

Thompson, W. D’Arcy (1917). On growth and form, Cambridge University Press.

Turing, A. (1952). “The Chemical basis of morphogenesis”, Phil. Trans R. Soc. Lond. B1952 237, pp. 37– 72.

Voyatzaki, M. (ed.). (2007). “Accommodating New Aspects of Interdisciplinarity in Contemporary Construction Teaching”. In: VV.AA., Proceedings of International Conference, EAAE-ENHSA, November 2006, Transactions on Architectural Education, No. 34, Venice, pp. 100-112.

Wang, G.G., Shan, S. (2006). “Review of Metamodeling Techniques in Support of Engineering Design Optimization”, ASME Transactions, Journal of Mechanical Design, 129 (4), pp. 1–42.

Weinstock, M. (2004). “Emergence:Morphogenetic Design Strategies”, AD 74, (3), Wiley-Academy, UK, pp. 17.

Weinstock, M. (2005) On self-organization: Stress driven form-finding in architecture , Estévez. A., Genetic architectures II: Digital tolls and organic forms (p. 94). Santa Fe, New Mexico ESARQ/SITES books

Wu, K. (2017). “A Review on Mesh Segmentation Techniques”, IJEIT, 6 (8), pp. 18–26.

Links

Center for Genomic Regulation. (2014, July 31). A mathematical theory proposed by Alan Turing in 1952 can explain the formation of fingers. ScienceDaily. Retrieved November 21, 2019 from www.sciencedaily.com/releases/2014/07/140731145839.htm

Deleuran, A.H. (2015). “MeshWalker Algorithm”. Video, 3:50. https://vimeo.com/118487290.

Ito, J. (2018). “Extended Intelligence”, Joi Ito’s PubPub. doi: 10.21428/f875537b.