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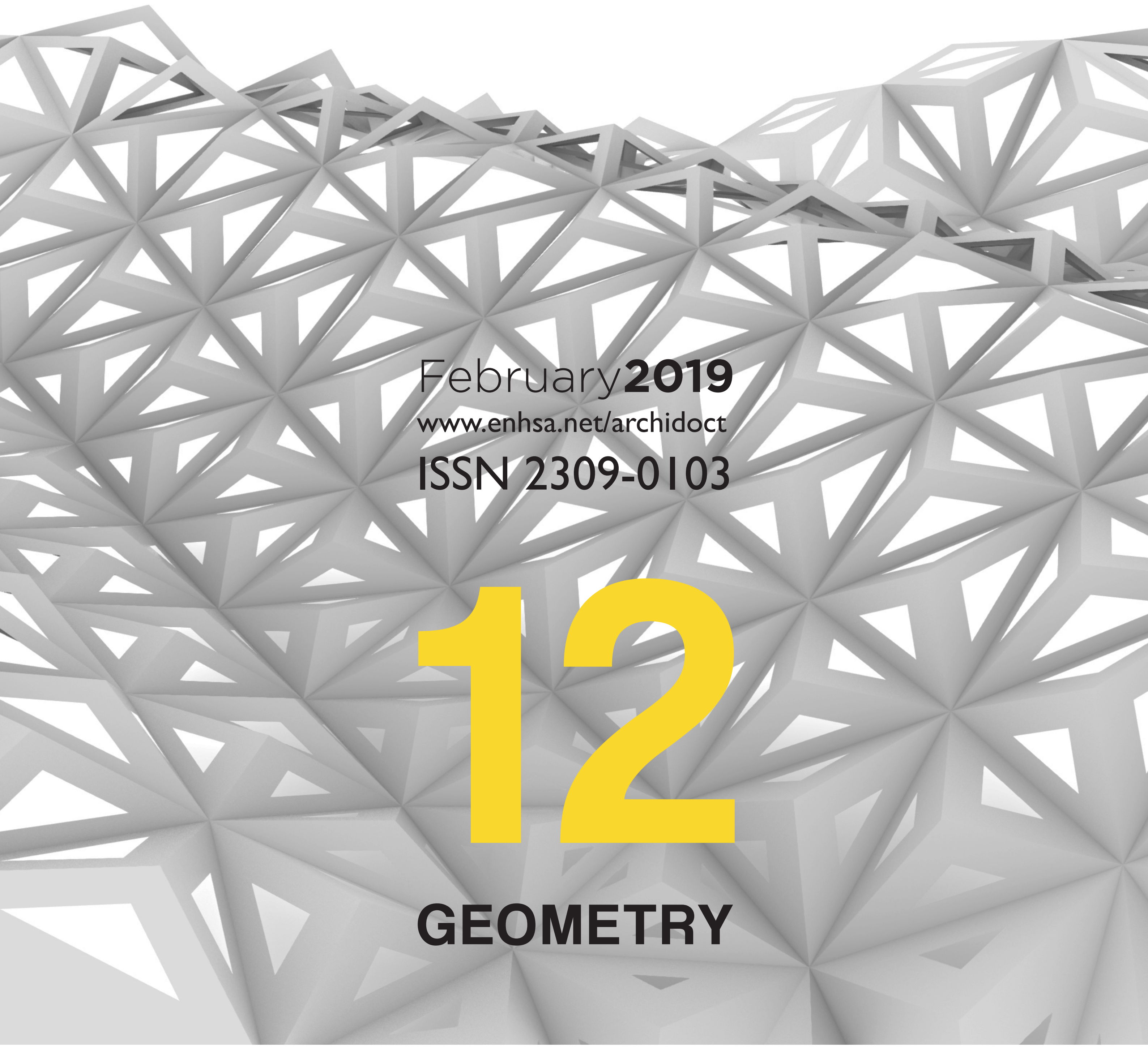

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GEOMETRY

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Geometry

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Geometry has always held a central role in architecture, and this has had an impact on the way we appreciate and analyse built form, the way we design and construct, the way we develop a discourse about architecture. Design and construction media are evolving and the technological advances affect the reciprocities between form, structure, material, design-to-fabrication processes, and morphogenetic strategies. Geometry is inherent to architectural design and production; however the intersection, crossover and revisiting of traditional as well as computational design methodologies have given rise to an unprecedented geometric freedom, new design and production workfl ws and are providing an exceptional opportunity for architectural innovation. Natural forms display a great geometric complexity that inspires engineers in their pursuit for innovation, while currently the advancements in computational design have enabled the integration and feedback among disciplines such as physics, biology and mathematics. Inspiration may be found in the geometry of swarm movement, magnetic fields liquid formations, erosion, plant growth and the underlying logic that produces such forms.

Recent architectural history has showcased innovative paradigms with embedded complexity in terms of form, geometry and structure such as the hyperbolic paraboloids of Felix Candela and the anticlastic surfaces of Frei Otto. In the years to follow the dynamic modelling of lightweight structures was simulated by contemporary numerical tools for design optimization. The ever-growing design explorations with parametric and algorithmic design tools have opened up the design repertoire to non-deterministic design strategies through computational bottom-up processes and performance-oriented geometric articulations that respond to multiple design criteria. As opposed to other approaches to design, where decisions regarding the geometry lie in the starting point of the design process, very often the geometry is developed as a result of simulation, the creative process becomes a negotiation of natural or artificial agents that interact and self-organize giving rise to emergent architectural artefacts.

Geometry relates to both representation as well as materialization; there is an intricate relationship between the tool (analogue or digital) and the form. Tools are mediators between the designer and the object of design. This does not only refer to the design phase where pencils, software, code and physical and digital models are employed to represent the geometry of an object; tools that are used to carve stone, CNC machines or robots have a direct repercussion on the geometry or rather the volumetric qualities of the produced artefact. As Mario Carpo remarks in the The Alphabet and the Algorithm (2011) *"all tools feed back onto the actions of their users, and digital tools are no exception […] manufactured objects can easily reveal their software bloodline to educated observers".*

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The emerging field of computational geometry relates to both the conceptualization as well as the materialization of architecture, ranging from the microscale, to the macroscale, addressing the design of architectural elements, buildings or concepts. This archiDOCT issue with the aim to trace contemporary research on geometry across different media, and its role within the process of architectural morphogenesis, invited doctoral research essays that focus on any field related to architecture where geometry plays a major role.

It is widely accepted that new technologies have accelerated innovation in architecture. This, as a matter of fact, affects all stages of the design process from ideation to production. The way geometric form relates to architecture can receive several different interpretations. Departing from the modernist principle of "Form Follows Function" that dominated architectural praxis and research for decades, there have been several off-springs and conceptual mutations that associate architectural form generation to forces, rules, software or tools. *"Form Follows Force"* [1] addresses efficient structural morphology through the study of the relation between form and force. Traditional form-finding strategies by Frei Otto at the Institute of Lightweight Structures, as well as contemporary simulations for topological optimization are based on the morphogenetic principle of growth under stress, seeing form as a product of dynamic forces as D'Arcy Thomson [2] advocated in *"On Growth and Form"*. Contemporary architects strongly rely on observations of natural phenomena, and computational simulations, moving from Otto's experiments towards artificial intelligence and continuous transformation, often revisiting D'Arcy Thomson's theories of transformation and his work as a classic for its "exploration of natural geometries in the dynamics of growth and physical processes" [3].

The role of nature-inspired algorithms for architectural morphogenesis is among the research agendas of leading architecture schools. Architects are able to simulate phenomena and contextualize emergent forms, discover bottom-up self-organizing structure, assess and optimize a structure based on its topology. Pierluigi Serraino suggested that *"Form Follows Software"*; in his homonymous lecture [4] at ACADIA 2003, and discussed several case studies where the software used had a direct impact on the design outcome. Current architecture research focusing on digital production would generalize the above statement about software and reformulate it in *"Form Follows Tools"*, referring to both algorithms and digital design media as well as fabrication tools and the reciprocal relationship between processes[5].

It has become clear that the available digital fabrication equipment as well as the software used has significant y enriched the repertoire of forms, in digitally produced artifacts. This is intelligently reflected in William Mitchell's famous phrase, that *"architects tend to draw what they*

1. See the article by LI, Qingpeng. *Form Follows Force: A theoretical framework for Structural Morphology*, and Form-Finding research on shell structures. A+BE | Architecture and the Built Environment, n. 2, p. 1-278, feb. 2018. ISSN 2214-7233.

2. D'arcy Thomson in his famous work *"On Growth and Form"* advocated that the shapes of natural forms relate to force fields acting upon them. He exemplifie the relationship between structure and geometry in natural organisms and would describe the cancellous structure of the bones as a "diagram of the lines of stress"

3. For a contemporary reinterpretation see Beesley, P., Bonnemaison, S. (Eds.), 2008. On Growth and Form: Organic Architecture & Beyond. Dalhousie Architectural Pr, Halifax.

4. Serriano, P., 2003. Form follows software, in:ACADIA, Indianapolis. pp. 185–205.

5. Symeonidou, I., 2018. *Digital Creativity: Embracing New Technologies for Architectural Innovation*, in: D'Uva, D. (Ed.), Handbook of Research on Form and Morphogenesis in Modern Architectural Contexts. IGI Global.

6. Mitchell, W.J., 2001. Roll Over Euclid: How Frank Gehry Designs and Builds, in: Frank Gehry, Architect. Guggenheim Museum Pubns, New York; London.

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can build and build what they can draw" [6] .We could further generalize the above statement to include the notion of making, in the sense that we can construct those artefacts that can be produced with CNC machines and robots, altering strategies for construction, sensing and testing, in an analogue-digital interface, where each design decision can be based on the performance of the actual constructed artefact.

The geometry of contemporary architecture may also relate to the socio-economical context, the political significance of the built form, the natural and the human-made environment. The recent exhibition *"Form Follows Rule"* at Architekturzentrum Wien [7] shines a spotlight on building regulations and how these shape the geometry of contemporary cities. The list of aphorisms of *"Form Follows"* could be infinite while all of them display a reductionist scope of geometry and its implications, form does not follow a single attribute and the above could be only understood as a trigger for further discussion on the factors that define architectural form. In reality the geometry of an architectural object is subject to a variety of factors which may vary in nature and level of subjectivity and may act symbiotically or in opposition to one another.

Contemporary computational techniques have enabled formal complexity and a great deal of research over the last decade has focused on ways to materialize non-standard architectures. The seamless transfer of information from File to Factory [8] is gaining momentum while architects realize that the fabrication strategy has a direct impact on the design phase. Especially when freeform designs are to be materialized, the workfl w complexity requires specialized software and knowledge to control all phases of the design and fabrication process. There is no universal software that can directly link CAD systems to different types of manufacturing equipment embedding design constraints and optimization strategies[9], therefore geometrically complex projects are materialized employing ad hoc design solutions and fabrication processes. Both architectural praxis and academia are struggling to fill this knowledge gap within the digital workfl w from design to production. Following this market need specialized companies, that provide consulting related to non-standard geometry and fabrication, have come into existence [10] .

This emerging new profession that combines the skillset of computer scientists, geometers and mathematicians, is rapidly becoming a global core of applied research and practice, offering consulting services, specialized software and training, either in the form of smaller clusters within bigger studios [11] or as University-led research groups that initially conducted scientific research projects within the academia and have evolved into independent consulting services, always maintaining their link to the academia. In the last decade we witnessed the emergence of consulting companies such as Evolute or Design-to-Production, which

7. The exhibition Form follows Rule took place at the Architekturzentrum Wien between 23.11.2017–04.04.2018. Information can be found at : https://www.azw.at/en/articles/form-follows-rule/

8. The concept of *File To Factory* refers to the seamless transfer of data through CAD-CAM workfl ws and is described in Oosterhuis, K., Bier, H.H., Aalbers, C., Boer, S., 2004. *File to Factory and Real Time Behavior in ONL-Architecture*, in: Proceedings of the 23rd Annual Conference of ACADIA and the 2004 Conference of the AIA Technology in Architectural Practice Knowledge Community, Cambridge, November 8-14, 2004.

9. Schmiedhofer, H., Reis, M., Rist, F., Suter, G., 2014. A Framework for Linking Design and Fabrication in Geometrically Complex Architecture. Presented at the ACADIA 14: Design Agency, Los Angeles.

10. See also Brell-Cokcan, S., Braumann, J., 2010. A new parametric design tool for robot milling, in: Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture. pp. 357–363.

11. Advanced Geometry Unit (AGU) at Arup initially founded by Cecil Balmond and currently led by Daniel Bosia, the research group at Adams Kara Taylor (AKT), the Specialist Modelling Group (SMG) at Foster and Partners, and Zaha CODE are some of the most prominent praxis-led clusters that work within the interdisciplinary field of computation, geometry and architecture.

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specialize in the geometry of complex architectural forms, providing the missing link from ideation to materialization.

The newly founded Center for Geometry and Computational Design (CGCD) at Vienna University of Technology, aims to bridge that knowledge gap, by conducting research in the intersection of geometry and computation, fostering engineers and scientists with the necessary skills to be able to address geometrically complex problems. CGCD aspires to become *"a focal point where geometric theory, initiated by technological needs, is turned into next generation tools for computational design"* [12] .

The morphogenetic strategies that extend the formal repertoire to non-deterministic structures, the topological transformations enabled by computational tools and the optimization and rationalization of non-standard structures have all become a hot topic and a great source of inquisitiveness for architects and researchers. The knowledge on that field is building up rapidly and dissemination of research findings is achieved through publications and conferences. Annual or biannual events such as Advances in Architectural Geometry [13], Smart Geometry [14], Shape to Fabrication [15], and FABRICATE [16], have become platforms for exchanging knowledge among researchers and the industry. Often the discourse relates to the geometry and logistics of complex constructions; geometric optimization and discretization of free-form architecture, the developability of surfaces, the mathematics of foldable and bending structures, among others.

It is a natural consequence of the above that the new generation of architects is much more skilled and curious with regards to digital skills and therefore much more prepared to effectively design and suggest a fabrication method that will be applicable, thus defining the entire workfl w from design to production. There is an ever-growing collective knowledge on that topic, freely available to practitioners and students to explore and this is highly reflected in contemporary doctoral research in the field of a chitecture.

In the quest to showcase different aspects of geometry in architectural creation and research, authors were encouraged to present the reasons why geometry plays a central role in their work and how they explore the relationships between applied geometry, engineering and graphics, research and experimentation in computational design, virtual reality and augmented representation, analogue vs digital fabrication and optimization strategies. The issue includes one good practice example and fi e essays by doctoral students worldwide.

The good practice example has been provided by Professor Constantin Victor Spyridonidis addresses the theoretical base of architectural

12. Center for Geometry and Computational Design - Mission 2014.
http://gcd.tuwien.ac.at
(accessed 1.11.18).

13. http://www.architectural-geometry.org/
(accessed 1.11.18).

14. https://www.smartgeometry.org/
(accessed 1.11.18).

15. http://www.shapetofabrication.com/
(accessed 1.11.18).

16. http://www.fabricate.org/
(accessed 1.11.18).

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geometry and how this has changed the way we comprehend the built environment based on its representation throughout the history of architecture. Professor Spyridonidis from Aristole University of Thessaloniki, and the Canadian University of Dubai, affirms that Architecture is addressed to Geometry with entirely different demands in time. As he points out, we could, therefore, suggest there are many versions of Geometry affiliated with architecture, that is to say, many Geometries. His essay examines the role of Geometry in architectural thinking and practice in three major steps of architectural development. The first is the period in which the focal point of architectural thinking is the cosmic and the divine, (from the antiquity till about the 13th Century) where Geometry is that of the Master Builder. The second is the era of humanism where the central preoccupation of Architecture is the human (from the Renaissance to the late 20th Century), and Geometry is that of visual perception. The third is the emerging era of the post-human, where the main focus of Architecture becomes "Gaia," the Planet as an alive ecology that emerges from the synergy between the natural and the artificial and Geometry is that of data.

The first essay by Mads Brath Jensen is entitled Robotic Fabrication of Acoustic Geometries - an explorative and creative design process within an educational context. Mads is a PhD fellow at the Department of Architecture, Design and Media Technology at Aalborg University in Denmark (2017-2020) and has been teaching in the field of computational architecture, parametric design and rapid prototyping technologies on both BSc and MSc level (2008-2017). His essay investigates the relation between creative design processes in the field of architecture and interactive robotic fabrication. It describes and exemplifies a design method for exploring acoustic performance and robotic fabrication of wood panels. Moreover, it studies the cognitive and creative impact of the design method of a 3-week design studio with architectural students, through qualitative observations and a qualitative PCA analysis. The essay describes a computational system that supports non-experts in generating curve-based geometries informed by acoustic analysis and simulation of robotic milling.

The second essay titled Cellular Design is authored by Christoph Klemmt who is currently PhD candidate at the Angewandte Vienna and Assistant Professor, University of Cincinnati. Christoph through his research, teaching and praxis as Founding partner of Orproject has been experimenting with self-organizing principles and their applications to a wide variety of projects. The essay casts light into the notion of self-organizing geometries where the designer defines the components of a project or relationships between components giving rise to emerging systems created through bottom-up logic, so that all parts of the material accumulation are developed through local system interactions only. The research employs simulations of intercellular behaviors as an architectural computational design tool. The intercellular logics attempt to simulate natural systems such as the cellular behaviors and growth in organisms and the generated geometries portray various characteristics of architectural relevance, generated through the emergent intercellular behaviors as well as external influences The essay concludes with test simulations for the design of two case studies: A permanent installation in an offic , and the design of a house.

The third essay of this issue tackles the crucial topic of fabricating free-form architecture. The essay entitled Programming Flat-to-Synclastic Reconfiguration is authored by Yu-Chou Chiang a PhD Student at Delft University of Technology. This essay is investigating strategies of translating free-form synclastic surfaces to flat pre-programmed reconfigurable mechanisms. The presented bi-stable mechanisms are produced by creating voids on flat materials in the form of blocks connected by the hinges. The essay shows how the position and the orientation of the hinges allow the blocks to rotate around each other, and then reconfigu e from flat to synclastic. The research addresses the geometric constraints that need to be met for the design of such mechanisms and demonstrates

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the workfl w of identifying the positions of the hinges. The essay concludes with the validation of the developed methods through prototypes of synclastic surfaces.

The fourth essay further elaborates on notions of constructability by examining the behaviour of active bending and the reciprocities between geometry and structure. The essay, titled Novel Bending-active System with Controllable Curvature-stiffness Relation, is authored by Efilena Baseta, who has been a Marie-Curie researcher of the InnoChain ETN network (2016-2018) and PhD candidate at the University of Applied Arts in Vienna. The essay presents a novel bending-active system of low-tech structural elements which increase their stiffness when they reach a predefined curved geometry, relying exclusively on geometrical configurati ns. The essay presents physical and digital experiments that document the structural performance including the numerical results of load-deflection experiments, as well as the Finite Element Analysis of the joinery detail. The results of the research show change of stiffness of the developed system and its scalability, which renders it an efficient construction method or large-scale curved structures.

The fifth essay of this ArchiDOCT Issue further elaborates on the topic of bending elements, considering the material geometry and introducing an interface of human-machine collaboration. This last essay is titled Using Materially Computed Geometry in a Man-Machine Collaborative Environment and it is authored by Bastian Wibranek PhD candidate and research assistant at the Digital Design Unit at the Faculty of Architecture at TU Darmstadt, where he is currently also teaching in the area of computational design and robotic fabrication. The essay challenges the interweaving of real-world geometry with computational tools for a man-machine collaborative assembly process. It aligns with the current research for robotics in architecture which aims to bridge the gap between digital design and fabrication, but rarely considers manipulation of real-world geometry by human actors. The essay presents a demonstration of the man-machine collaboration, where the designer is engaged with wooden lamellas and a computational tool to build a demonstrator, moving from parametric design tools directly to physical interfaces using real-world geometry, and therefore proposing a stronger participation of human actors within digital fabrication environments.

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Geometries

Constantin Victor Spiridonidis // Canadian University Dubai

Abstract

Architecture is about values. Values are the driving forces of inspiration, the energy of the creative act, its primary material, its intellectual motivation, its main objective. Values or 'arches' form the immaterial realm of Architecture, its internal 'archi-tecture' to be formally manifested in space.

What is the role of Geometry as a discipline related to forms and their order, in the intellectual tectonics of Architecture? What is its contribution, its position? Does Geometry affect this 'archi-tecture' by enriching its contents with notions and meanings or, on the contrary, does it affect it by eliminating or restricting its potential formal configurations? Is this diachronic symbiosis with Architecture dynamic, inspirational, instrumental, deliberative, imposing? Does Geometry act as a framework to create an enclosure or does it constitute an escape room from the ordinary, the established, the regular, the 'out of the comfort zone', and to investigate in freedom the new normal, the innovative, the original or, at least, the different and the better? Architecture is addressed to Geometry with entirely different demands in time. We could, therefore, suggest that there are many versions of Geometry affiliated with architecture, that is to say, many Geometries.

This essay examines the role of Geometry in architectural thinking and practice in three major periods of architectural development. The first is the period in which the focal point of architectural thinking is the cosmic and the divine, (from the antiquity till about the 13th Century) where Geometry is that of the Master Builder. The second is the era of humanism, where the central preoccupation of Architecture is the human (from the Renaissance to the late 20th Century), and Geometry is that of visual perception. The third is the emerging era of the post-human, where the main focus of Architecture becomes 'Gaia,' the Planet as an alive ecology that emerges from the symbiosis between the natural and the artificial, and Geometry is that of data.

Keywords

Geometry; Architectural thinking; Architectural Design, Representation; Digital design tools

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1. Architecture and Geometries

Amongst the affections that Architecture experienced, throughout its history, with various other disciplines and domains of knowledge and practice, Geometry seems to be the strongest and the ever-lasting one. The liaison between Architecture and Geometry transverses centuries and continents and maps different forms of infatuation, trust, dependence or questioning. Architects have been used and are still used to talk about geometry as the language of architecture, as the rational consideration of forms and their order, as the solid ground to define or legitimize beauty, as the tool to think, investigate and create. They tend to consider the bond with geometry as stable and permanent, following a linear evolution of both domains.

However, the relationship between Architecture and Geometry is rather complex, and seems to have followed the unpredictable dynamics of non-linear [1] history. Beyond the declared strong connection between architectural thinking and practice with the discipline of Geometry, Architecture appears selective to the appropriation of concepts and statements of reasoning deriving from different aspects of geometry, not always following the state of development and advancements of the latter. This selectivity is always dictated by the dynamics of the value system that Architecture establishes in different periods of history to define its social p oject and to legitimize its formal preferences.

Architecture is about values. It is about the form of their manifestation in space. Values represent a particular world view and more specifical y a specific conception of the human being therein. They are the driving force of inspiration, the energy of the creative act, its primary material, its intellectual motivation, its main objective. Values shape the expected 'Other,' the different, the desired, the utopic or the heterotopic, the wish, the hope but at the same time the rule, the order, the principle, the law, and often the model, the standard, the 'prototype', the image, the archetype. Geometry as the discipline related to forms and their order, is always cordially invited to support and assist the spatial manifestation of the respective values.

Values or 'arches' -archés in the Greek language- structure architecture's intellectual tectonics, its internal 'archi-tecture.' What is the role of Geometry in the intellectual tectonics of Architecture? What is its contribution, its position? Does Geometry affect this 'archi-tecture' by enriching its contents with notions and meanings or, on the contrary, by eliminating or constraining its potential formal configurations? Is this diachronic synergy with Architecture dynamic, inspirational, instrumental, deliberative, imposing? Does Geometry act as a framework to create an enclosure or does it constitute an escape room from the ordinary, the established, the regular, the out-of-the-comfort-zone? Or does geometry act as the deliberating context of investigating the new

1. We use the term non-linear history as it was defined by Manuel Delanda (1997) as part of the materialist philosophy of history in the tradition of Fernand Braudel, Gilles Deleuze, and Félix Guattari in which the unpredictability of the dynamics between material, social and natural worlds play a crucial role.

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normal, the innovative, the original or, at least, the different and the better?

In this essay, the relationship between Architecture and Geometry from Architecture's intellectual tectonics angle is investigated. The questions arising are how and why different stages of the historical development of Architecture have been associated with different Geometries to attest its social project adequately and to shape architectural paradigms introducing a way to think and create possible futures. We intend to examine the role Geometry plays in the way the immaterial and intellectual realm of Architecture is pouring over its tectonics and its materiality.

Three major steps of architectural development are studied. The first is the period in which the focal point of architectural thinking is the cosmic and the divine, (antiquity till about 13th Century). The second is the era of humanism where the central preoccupation of Architecture is the human (Renaissance to the end of 20th Century) and the third is the emerging era of the post-human where the main focus of Architecture becomes "Gaia", the Planet as an alive emerging by the symbiosis between the natural and artificial

Architecture is addressed to Geometry with entirely different demands in time. In the Greek antiquity, Geometry was invited to assure Architecture's association with the divine cosmic order and harmony. In the Renaissance, the importance of the human as the definition of natural beauty was manifested in the created architectural form. In Modernism, Geometry was employed to technically and conceptually support the demonstration of the importance of rationality in the elaboration of architectural form, the defined relationships, and the sizing of the inhabitable enclosures. Throughout post-modernity, the manifestation of the cultural specificities of the designed spaces used Geometry as their core formal language. Finally, in the post-human era, Geometry is implicitly invited to glorify the power and the virtuality of the human-machine affective symbiosis, away from Euclidean constraints, that can yield new forms of artificialit . The very many versions of Geometry affiliated with architecture are evident, allowing us to conclude that there are as many geometries as there are architectures.

Euclidean, Projective, Analytic, Differential, Topological, Algebraic, Discrete, Geodetic, Fractal, Computational, Convex Geometry are some of the foci or biases of Geometry, criss-crossing architectural discourses and practices over time. With almost no exception, the common ground of all these geometrical subject areas is that the foundation of their theoretical construction is a specific appreciation of the primordial geometrical elements: the point, the line, the surface, and the volume.

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2. The Geometry of the Master Builder

The fine or even blurred line of demarcation between Geometry Construction dates back to the third millennium BC, a period when stone progressively replaced sun-dried or baked brick and wood as the primary building material. This replacement was one of the most important revolutions in the history of construction (Kostof, 1977, p. 4). It introduced a new relationship between building and time, built strong(er) bridges between tectonics and Fine Arts, affected the scale of constructions and generated the need for new skills and specialized techniques for which geometry was the most appropriate background. The attachment between Geometry and Architecture was essential for the further development of both domains.

The beginnings of Geometry, as knowledge and expertise, are dimmed back to the period when the Agricultural Revolution was already established together with the commitment for the Homo Sapiens to domesticate plants and animals for his survival. The very first indices of geometrical knowledge and experience are traced in Egypt and the Mesopotamia. This coincides with the development of crowded agglomerations, the establishment of big-ordered empires and the formulation of the relevant myths providing the necessary legitimization[2] of the established power structures and the mechanisms controlling the existing social stratification

The myths and the cosmic references originated from astrology and religion, offered a set of numbers to define proportions and relationships amongst parts. Geometry was invited to sustain the appropriate manifestation of these proportions and relationships either on earth or on constructions and their components by dividing measured lengths into parts to locate the different building elements.

Taxes were the very first imperative for the development of Geometry (Mlodinow, 2001, pp. 5-6). Egyptian landowners had to pay taxes calculated by the height of the flood of River Nile and the surface of the holdings. As the river overfl w fertilized the earth and was, therefore, considered to be a divine gift, the Pharaohs, who presented themselves as the divine mediators, imposed unbearable taxes as a compensation for their mediation. This mythological construction legitimized the need to define ways, not only to calculate the surfaces to be taxed but also to determine the division of the fertile land stably before or after the flood In ancient Egypt, the implementation of geometric measurements was an official and primarily ritual process, always related to power and religion. The calculation of land surface had to be delivered official y and with accuracy as it had direct financial epercussions.

The very first geometric tool for the measurement of land and buildings was a rope with knots at predetermined distances. It had to

2. For a study on the role and the importance of the myth in the foundation of power structures and the control of the production means in precapitalistic societies, see Godelier (1978).

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be stretched, not to sag, having the knobs as vertices of triangles with given lengths and consequently with angles with precise measures. Its use crosses Egyptian, Greek and Roman building tradition. The person who performed these measurements was an office , the harpedonopta, translated as the rope stretcher, while all the foundation measurements on the site of the new constructions followed formal religious rituals. The stretched rope defined points and lines through which ancient Egyptians could form and measure surfaces [3]. Other used geometrical instruments were the triangle, the square, and the compass.

The rope offered an empirical definition of the line as the distance between two points and of the surface as the area defined by three points, as described more abstractly by Euclidean Geometry, a few centuries later. In this conception, a point is either the beginning or the end of the measurement, or the mark of a division following proportions derived from the cosmic and religious interpretations of order [4]. It is interesting to note that, even nowadays, the compass bears the alternative name of the divider.

The emergence of the 'polis' in classical Greece, transformed the contents and the meanings of Geometry radically. The 'polis' as a conception of social condition and as the outcome of a rationalized understanding of cosmos, marginalizes the myth dedicated to the descriptions of the 'origin' by endorsing the strength and by glorifying the powerful. The logos, the discourse, is now excluding the supernatural, and reason wants to be associated directly to the human mind. Humans, nature, and gods become the object of a systematic investigation, history (ιστορία, historía) the outcome of which is a comprehensive view, the theory (θεωρία, theāríā). According to Vernant (1982, pp. 100-107), it is no longer the beginning that illuminates and transfigu es the everyday, but, on the contrary, "it is the everyday that made the beginning intelligible." By referring to nature, the philosopher wishes to repeat what the theologist described by referring to as the divine power. Polis and philosophy, with their reciprocal social and mental structures, are closely linked phenomena.

Geometry undertakes a crucial role in this intellectual project. As now the center of the Greek thought is the relation between humans, geometry is invited to assist the philosophical thinking in constructing its rationality. As Vernant suggests (1978, p.132), this thinking keeps its distance from physical reality as it considers that nature belongs to the realm of the "approximate to which neither exact calculation nor rigorous reasoning could be applied." On the contrary, it elaborates its concepts to prove that the social world can be the subject of number and measure. Geometry is progressively detached from its practicalities related to the 'measurement of the earth' as its etymological origin dictates -geometría γεω-μετρία in the Greek language- to delve into the abstract thinking of relations, laws, and axioms ready to be projected

3. According to Mlodinow (2001: 7) the Egyptians did not form lines but geodetic triangles and curves along the surface of the earth. He detects in this primitive geometrical method the beginnings of what we call today Differential Geometry.

4. Kostof (1978, pp 8-10) presenting the different phases of the construction process in Egypt, describes the geometric system as structured by simple figu es. These fi - ures are the square, the sacred triangle of Osiris having a relation 4 to 3 between the height and the base, the isosceles triangles with the height either equal to the basis or twice the base or height to base to have a ratio 5 to 8. The construction followed different combinations of these figu es.

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onto social reality.

This shift redefines its basics. A point is no longer conceived as the beginning but as the center, and this abstract center expresses or represents Hestia or the Omphalos, the social space. The points of the circular periphery reconstruct with the center the line of the equal distance, the equality (ισότις), the egalitarian concepts forming the deep structure of democracy. The same way, symmetry which presented in the past the divine instructions for order now becomes the rational expression of the principle or arche of the balance of power (ισονομία) as the appropriate foundation of the social order. The geometric grids on the space of the polis implemented by Hippodamus in Miletus did not represent any distribution of the surface of the earth but an "effort to order and rationalize the human world" (Vernant, 1982, p. 125).

From Thales and Pythagoras to Euclides and Archimedes, Geometry became a necessary part of philosophical thinking. Plato declared that no man destitute of geometry could enter his doors (Vernant, 1982, p.129) (Ceccato, 2010, p. 9). Could a master builder be welcome in Plato's place? In other words, did the master builders (the Architects in the Greek language etymology) followed this shift in the meaning and the contents of geometry? Was Architecture directly affected by these changes? There is no clear evidence of that.

On the contrary, we know (Kostof, 1978, pp. 21-22) that the education of the Architect was not related to the school of the philosopher and that the skills they obtained were ensured either from their work alongside a master as an apprenticeship, or from their experience gained by practicing other relative to the construction arts or crafts. There is marginal information about the master builders Architects such as Iktinos, Callicrates, Theodoros, Rhoikos, Skopas, Polykleitos to name a few. Even though the profession was considered noble and well paid, Architects were not considered to be intellectuals.

Architecture's evolution in Classical Greek antiquity offered magnificent works of the highest level of perfection and aesthetic quality, but it seems that this was primarily the outcome more of the development of the available means, techniques, and experiences based upon traditional applications of the Geometry than the systematic pursuit of its further and parallel progress as a distinctive part of the philosophical contemplation. The mathematical number of the golden ratio and its geometrical version as the golden section was one of the fascinating issues of Geometry, and mathematics in all centuries of the Greek antiquity. However, recent researches present clear evidence for golden-ratio application in constructions of ancient Greece: They proved that "the golden ration was absent from Greek architecture of the classical fifth century BC, and only very rarely employed in the third and the second centuries BC" (Foutakis, 2014, p. 86). It is also characteristic that in Roman times as master builders were defined the engineers emphasizing, this way, more the construction and technical aspect of the profession and less the conceptual and the creative one.

3. The Geometries of Humanism

If the stone introduced a new era in Architectural thinking and practice, lasting from antiquity to the Medieval times, the rise of humanism in the Renaissance is accompanied by a new radical turn in Architecture. Stone offered the proper means to manifest enclosure adequately, both in terms of scale and form, a worldview focused on the godly origin of the cosmos and dominated by the desire, or the duty, to glorify the supremacy of the divine as a condition to survive. The intellectual tectonics of the human-centered Architecture replaces the divine from the center of its mental

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preoccupations and positions the human instead. Architecture and its materiality, in turn, undertake to manifest the power of the human spirit and culture. To observe the tangible reality, to appreciate it, to experiment with it and to ensure the survival of the human by acting on this reality, is the ultimate aim of the Renaissance. The eye becomes the most vital human organ to serve the request for truth (Savignat, 1981) as knowledge does no longer belong to the religious order, but becomes the outcome of human intellect revealing the requested truth.

One of the most critical consequences of this shifted worldview is the emergence of the polymath human-observer, whose intellect is mastering a broad spectrum of skills and knowledge crossing art, technique, ethics, and logos. The Architect is coined with this profile by mid 15th Century, as can be traced in Alberti's 'Ten Books of Architecture' which Choay (1980) defines as the inaugurating discourse of the n w Architecture.

This new Architecture takes a distance from the manual part of the building construction. The intellectual part of the creation of space is separated from the manual [5] (Voyatzaki, 2018, p. 7). This division of labor in the domain of building construction removes the conceptual and creative duties from the Master builder to allocate them to the Architect redefining his professional identity. The work of the Architect is no longer to build buildings but to elaborate ideas about (the form of) the buildings which builders will construct.

This detachment of the elaboration of the form from the construction site separates and divides the maker from the thinker. The former works on the real material and physical realm while the latter works on an abstract transcription of the reality on the surface of its representation. The former negotiates with the materiality, acts on it, teases it, fights with it, reconciles and attunes with it (Voyatzaki, 2018, p. 9) to extract the expected form. The latter negotiates with the ideal, the imaginative, the virtual and the possibilities to become real. The one manipulates the details of the parts to assure a not-as-yet precisely conceived total, following a bottom-up process. The other elaborates a well-detailed total to be achieved through components by the construction, in a top-down process starting from the idea and ending up with the matter to bring it to life. In the former case, the authorship is attributed to the one who leads the techniques and the material aspect of the building, while in the latter, authorship is assigned to the one who generates the idea and the formal qualities and meanings of the outcome.

The new task of the architect is to create detailed geometrical drawings of the building to be materialized with the least possible compromise from design to building. The accurate depiction of form and enclosure prior to construction is a recent experience in architecture that marks its development till present times. If what has to be built must be drawn in advance, then what can be built must be possible to be drawn.

5. For a detailed presentation of the transition from the Gothic to the Renaissance see Savignat, (1981, pp 34-56). See also Carpo (2011, pp 53-68).(accessed 1.11.18).

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(Savignat 1981, p. 25, Carpo, 2011, pp.31, 75). That means that the drawing with its techniques, tools, and means defines the context in which the architect is restricted to think and conceive the form of his or her creations.

Even though there is evidence of the existence of architectural drawings in Ancient Egypt and Greece, revealing a capacity to represent form and space (Kostof, 1978, pp 40-4. Ackerman, 2001, p.28), there is no clear evidence of whether these drawings were done before and not after the construction and by whom. On the other hand, these drawings, in most of the cases, presented parts of the building or building elements leaving unclear if they were produced before or during the construction process to facilitate the clarification of technical issues or to guide the builders in particular phases of the construction process. According to Savignat (1981, pp 8-10), the gothic cathedrals were not built following pre-drawn plans, but by implementing in situ formal and construction patterns, proportions, and techniques repeated and tested for centuries.

All these changes mentioned above establish a new relationship between Architecture and Geometry. As the Architect is now working on virtual space, needs to bring an abstract version of the reality onto the drawing board or desktop. This transfer requires new skills and knowledge, and new tools, techniques, and means to be used. Geometry is invited to play a brand-new and decisive role in this new condition. The Geometry used in the past originated from measurements and concerned real space. In the human-centered logic of the Renaissance, representation has to bring on the drawing board an abstraction of the seen and perceived reality. The drawing board represents the perceived space, the visual space exposed to the experience of human observation.

The perspective drawing is an illustration of this new use of Geometry. To construct a perspective image is necessary to have an eye located in the space. The line of the horizon indicates the distance of this eye from the earth, and the 'point of view' its distance from the observed object. A perspective drawing presents what an eye can see from the selected position. As geometric construction, the perspective drawing is a unique creation of the Renaissance mindset marking the history of Art, Architecture and Geometry.

Even though drawing as the new conditional mediation of architectural creation represents the human experience, its consistency is based on the infinit , which is not immediately apparent to the senses.

Euclidian Geometry defines a straight line as drawn between two definite points. It states as an abstract and hypothetical possibility its unlimited extension, as this is not detectable by the human senses. However, in the Renaissance, inspired by Euclidean Geometry, a line is conceived as an entity extended to the infinit , given as a whole, on which we can define parts with points. The presence of the infinite in the Geometrical thinking of this period is important, as in the Christianity the infinite refers to the divine. According to Whitehead (1911, 119), "the spire of a Gothic cathedral and the importance of the unbounded straight line in modern Geometry are both emblematic of the transformation of the modern world." The Architecture of the Renaissance takes the infinite from the sky (or from the end of the Gothic spire) and iconoclastically locates it into the perspective drawing as the vanishing point. Panofsky (1991), revealed the importance of this profoundly symbolic gesture to place the infinite in the center of the drawing board as a glorious manifestation of the liberation from the theocentric world view.

The Perspective could offer a reliable view of the building before its existence, but it was not equally

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efficient to assure measurability in the construction process. For this, architects had to do their drawings in projection so that measurements could be taken from them (Ackerman, 2001, p.29). The coexistence of these two ways to represent space indicates the need or the wish to combine, in the new profile of the architect, the artistic with the technical and to expose the creative work to aesthetic and rational judgments.

Architects practised projection drawings from the 15th to the 17th century. When, by the end of the 18th Century, Gaspar Monge invented and founded Descriptive Geometry following the spirit of the Enlightenment and the Cartesian amalgamation of Geometry with numeric references, Architecture soon embraced this new domain of Geometry in its drawing practices. Architect Jean-Nicolas-Louis Durand, Professor at École Polytechnique in Paris, a prestigious institution founded by Monge just after the French Revolution, embedded principles of Descriptive Geometry into his architectural teaching (Savignat, 1981).

As we move from the Perspective and Projective to the Descriptive Geometry as the context for architectural drawings and the background of architectural creation, the geometric beam of parallel lines replaces the Euclidian visual cone. This shift is fundamental for architectural thinking for many reasons. Architecture is no longer conceived as the outcome of what the human can see and experience but as a purely abstract construction, which re-arranges rationally the relationships between its main elements guided by the rationality of the representation medium. We shift from the polymath human of the Renaissance to the Kantian human of the Enlightenment; from a subject observing the infinite to a subject located in the infinite from the priority to perceive to the priority to arrange; from the superiority of the visual to the supremacy of the functional. Architecture and Geometry re-establish a new solid relationship.

Architecture remains attached to the principles of Euclidian and Descriptive Geometry until the end of the 20th Century. Modernism glorifies this relationship by attributing to this specific Geometry the merit, not only to express exactitude, clarity, rationality and the ruling of forms but also to express the intellect of the human itself as presented in Le Corbusier's 'Le Poème de l' Angle Droit.' (Le Corbusier, 2006). Even though Post Modernity focused on the social and cultural agents of the individual's intellect, the same Geometry is invited to direct the manifestation of this intellect in space. It is interesting that the education of the architect traditionally offered, and to a certain extent continues to offer nowadays, courses on Perspective and Descriptive Geometry even though many other domains of Geometry were invented and enriched this subject area since the 18th Century.

4. The Geometries of the Post-Human

The role of Geometry in the immaterial realm of Architecture over the two previous periods examined in this essay, was to build a bridge between the main poles dominating the mindset of each period: God, the Human, and Nature. Geometry was invited to transverse these polarities and to transcribe essential characteristics of each pole, creating a solid ground, capable of stimulating and directing architectural creation.

The intellect of god-centered cultures was structured upon these three main poles: The God, the Human and Nature. According to Picon (2011, p.30), Geometry translated the demiurgic divine power of creation into proportions. The Architect, as human, developed skills to use this geometric interpretation to surrogate God and to manifest his glory on the secret buildings offering to society

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the possibility to negotiate its protection from the powers of nature.

In the human-centered period, the rational humans dispensed God to stay in a perpetual competition with nature. In this case, Geometry abstracts from the human body its proportions and establishes them as a natural definition of beauty that architecture has to implement on the designed buildings. Geometry is the mediator of human supremacy over the natural world. From the Vitruvian man to the Modulor, Geometry was used to ground architecture theoretically, to invent new formal orders and to control their realization through the developed drawing and construction skills (Picon, 2011, p. 31). In both periods, Geometry acts as a foundational reference and as a tool to create space.

Post-human contemplation shifts the human away from the center of intellectual preoccupations and replaces it with Gaia (planet Earth) understood as a living organism. The concept of Gaia reconciles old polarities founded in anthropocentrism, like life versus matter, given versus constructed, mind versus body, human versus nature, immaterial versus material, humanities versus sciences. Gaia is understood as the declaration of the existence of permanent and necessary symbioses between these polarities, which due to these symbioses blur their lines and refute their established identities. The human is no longer conceived as the dominant agent and controller of natural elements and artefacts. It is now located within the natural and artificial ecologies it created, not recognized as the unique agent who can safely form and transform them (Voyatzaki, 2018, p.12).

In this new intellectual construct, Architecture is released from its previous anthropocentric concerns about the finitude of the human (mind and body) according to which the building was conceived as a reliable image of human beauty or rationality. The building is now redefined as a living artifact. The elimination of the above-mentioned polarities had a direct impact on its relationship with Geometry. The harmony of the human body or the human rationality and intelligence are no longer the subject to be schematized through Euclidean or Descriptive Geometry.

The new Architectural intellect emerging from this philosophical context can be understood as the outcome of the symbioses of three critical parameters: The information-based epistemological understanding of the world, the role of computation in this understanding, and the role of Mathematics (Algebra and Geometry) in scripting the real world into numeric codes.

The establishment of the information as a unifying notion across sciences and humanities is one of the most critical aspects of the posthuman logos and praxis. In epistemological terms, information plays the same role in the construction of the contemporary intellect played by the notion of systems in the positivist epistemology of the '50s and '60s and the notion of structure in the structuralism(s) of the '70s and the '80s. By introducing the binary form one/zero, information can cross all the above polarities and establish a common mental environment, able to transcribe and describe all the crucial agents that form and transform the earth, organic life, materialities, and abiotic actors.

In this understanding, the building is no longer a technical artifact, the formal elaboration and appearance of which is undertaken by Geometry. It is now conceived as the outcome of a morphogenetic process which, through information processing, attributes to its materiality capacities of self-organization and self-adaptation to multiple and dynamic environments. The building is now 'intelligent' or 'smart', an alive artifact. Its design is not directly regulated by Geometry but by information scripting that delivers its own generative code, its DNA, from which its form emerges.

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The importance of information in the understanding of the world, is supported by the relevant technology. Information technology and computation is omnipresent at all levels of the social, cultural and economic globalization in the posthuman era. The introduction of computation in architectural practice has already a half-century history. Computers were initially used in the '60s and '70s to assist the architect on the rational decision making related to functional arrangements. After the '80s, digital tools focused primarily on drawing and presentation techniques, enhancing the drawing speed, accuracy, quality, and information. In all these cases, computers assisted the design process without challenging either the geometries traditionally used by architects or the established values of the time. In this collaborative scheme, between human and machine, it was clear who was enacting and who was representing.

In the posthuman understanding, however, there is a radical shift in the role of computation in architectural design. Intelligent machines, such as the machines that can respond and adapt to a spectrum of external stimuli and learn how to handle them, are no longer conceived as the assistant of architectural practice. They can act as the collaborator or a kind of subcontractor, who grants a particular set of skills to be performed and carries out part of the creative process. Architects can convey part of their work to the machine, introducing this way an informal division of labor in the creative process.

Due to their specific structure as hardware and software, intelligent machines can develop formal interpretations of data, based upon different types of abstractions they can perform, that the human intellect could not define and elaborate. In this scheme, architect and machine form a symbiotic assemblage dominated by the embodiment of two main agents, each one with different intelligence and skills [6] . As Braidoti states (Braidoti, 2013, p.26), this new form of vitality, human and machinic, dominant in the posthuman contemplations, wants to avoid any scripted determinism or inbuilt purpose or finalit . It wants to eliminate the predefined standards of previous forms of computation and to remain open to random and unpredictable stimuli, providing (design) responses as a creative ground on which new ideas and patterns could be tested and implemented.

To ensure a reliable translation of the reality into a computer programming language and algorithms, mathematics that include geometry are necessary. In recent times, new branches of Geometry are used to enrich, through computation, the architect's digital and formal palette. It is, however, interesting to note that most of these branches of Geometry which, through different software, are invited today to collaborate with architects, have been formulated as specific subject areas three centuries ago. Throughout this period, they did not seem attractive to Architecture, and they have never threatened the

6. Cf. D. Coole and S. Frost (2010) p.8

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dominant role of the Euclidian and Descriptive Geometry in the architectural intellect. The reason for this belatedness is that the representation tools that Architects had at their disposal at that time, could not cope with the complex manipulations needed to translate the abstract statements of these Geometries into formal expressions.

To better appreciate this discrepancy, we need to examine the origin of the Geometries used by the contemporary machines and the underlined logics that formulated their contents and directed their development.

Architectural drawing tools were built to represent Euclidean space. Till the end of the 18th century, Geometry and arithmetics were two different subject areas, by and large with clear boundaries. Both, as knowledge and tools, offered their input to architectural intuition and the understanding of space, inspiring, controlling or standardizing the creative process and its outcomes. Drawing tools were tailored to elaborate this input. Descartes's idea of coordinates opened in 17th Century the window to the association of Geometry with Algebra by defining a point with a numeric reference and the connection between two points, the line, by a mathematical equation. The Cartesian method was able not only to transcribe Euclidean Geometry in algebraic terms, but also to offer the ground for the invention of other branches of Geometry.

Based upon the Cartesian method, Newton and Leibniz introduced Calculus to study continuous changes in natural phenomena and Gauss and Bolyai founded non-Euclidian Geometry. Picon (1911, p. 12) argues that the appearance of calculus marks the starting point for the estrangement of Geometry from Architecture. Calculus was the background of the development of Differential Geometry initiated by Euler, providing techniques to study geometric structures on differentiable manifolds. From Differential Geometry and Euler's studies, Poincare formulated Topology, which studied the properties of space that are preserved under continuous deformations, such as stretching, twisting, crumbling and bending (Mlodinow, 2001).

The development of these branches of Geometry, generated by the end of the 19th Century new ones like Convex and Discrete Geometry which study convexity, polyhedra and tessellations, Algebraic Geometry which examines multivariate polynomials, and more recently Fractal Geometry and Computational Geometry. The first studies the 'mathematical shapes that display a cascade of never-ending, self-similar, meandering detail as one observes them more closely' (Bovill, 1996, p.3), and the second transcribes in algorithmic terms the outcomes of all the above branches.

All these new Geometries were attached to a new worldview, introduced by the Enlightenment, and a set of new priorities and foci. Renaissance thinking was grounded upon the Aristotelian definition of immobility as the natural condition of the empirical world (Savignat 1981). Galileo and Keppler proved that this assumption was not valid since movement is the physical condition of the permanently rotating planet. The Cartesian method and the Calculus, upon which all other new branches of Geometry were developed, reflect this new worldview. Movement is the change of the location of a point according to the modification of its coordinates determined by the relevant equation. The geometrical point is no longer stable but moves, and guided by the equation. The line, on the other hand, is not the link between two points becoming the trace of a point's movement.

Change and movement introduced the notion of time that played a significant role in the development of sciences after 17th Century. As Picon (2011, p. 33) states, calculus, at its profound structures, has to do primarily 'with the consideration of time, instead of dealing with purely spatial

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dimensions'. Architecture always conceived the building as static and not dynamic, a conception that rendered calculous rather incompatible with the architectural intellectual construct and the established drawing tools.

The emerging new geometrical and mathematical thinking removed from its vocabulary the notion of harmony, which was for centuries the center of architectural narratives. As calculus and the new mathematics dealt with dynamic phenomena, they appeared to architects more appropriate for the study of the strength of materials or the hydraulics and fl ws, but not for the study of static idealized proportions and standardized formal relationships.

The fact that Architecture was alienated from the development of all the branches of Geometry over the last three centuries, does not mean that the new worldview established by the Enlightenment did not affect Architecture. On the contrary, the main concepts structuring the value system introduced by this worldview were approached through other disciplines with which architecture was associated over this period.

History, for example, was used to elaborate the concepts of change and time and to make them operational in design thinking and formal elaboration. Gottfried Semper used history to reveal the condition of becoming and to scrutinize the tension between continuity and innovation as Mari Hvattum explains in her book (Hvattum, 2004). The question of harmony was transcribed in Semper's historical discourses as a question of style. In a similar way, history becomes the medium to elaborate and to establish the development of the technological subject in the case of the restoration studies of Viollet-Le-Duc (Bressani, 2014).

Similarly, we can recall the strong affection that Architecture had for other disciplines like systems theory in the '50s and the '60s, the social and political sciences and anthropology in the '70s, the semiotics in the '80s, the philosophy and biology in the '90s. All these disciplines nourished architects' inspiration and directed their practices. It was clear that in this period a distance was taken from mathematics and more specifical y from the areas of Geometry developed after the Enlightenment. Even though Le Corbusier glorified Geometry as the unique source of the sense of order (Le Corbusier, 1987, pp 65-86), he makes reference only to classical geometry and to the Platonic solids (Schumacher, 2018, pp.3-4) and not to the more recent Geometries.

The non-Euclidian Geometries emerged in the architectural scene when computation could calculate the complex mathematic relationships scripted by the software, but primarily when computers offered the possibility to visualize their outcome graphically via graphic user interfaces. This way, Geometry could enhance the creativity of the architect in elaborating ideas about buildings in the virtual space of representation.

The new tools expanded the formal vocabulary of Euclidean Geometry by introducing the curve as a new expressive component of form. The elaboration of the curve was ensured by the calculus-based Topology and its more recent developments that the Bézier Curve used in automobile industry. The splines and Non-Uniform Rational Splines (NURBS) labeled as 'folding', influenced a large number of architectural creations and experimentations. (Schumacher, 2018, pp.8-10). Folding was not only a formal achievement offering the possibility to shift from the established angularity to a promising curvilinearity by smooth curves. It also ensured continuity between parts and components, canceling their borders and limits. It was also a formal expression of the profound philosophical foundations of the post-human era. It introduced the continuum, and the integration

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of differences within a continuous and heterogeneous system, initially proposed by the works of Deleuze and Guattari (Carpo 2004, p. 14 and Carpo, 2013, pp 9-12). Different elements with different characteristics could be blended within a continuous field without losing their integrity (Lynn, 1993, p. 24).

In the same period and as a continuation of the use of spline and NURBS geometry in Architecture, another application of Topology is invited to extend the existing formal repertoire: The Isomorphic Surfaces or Blobs introduced by Greg Lynn (1998). This approach is dealing with surfaces or volumes of different objects that can deflect each other or fuse with each other, depending upon their relative proximity, creating complex surfaces (Schumacher, 2018, pp. 10-11). As in the case of folding, blobs map the contextualized sensitivity and adaptability of the elements of a system. In the overall system's dynamics, each one of its components is dependent upon and regulated by the others. This condition also meets the main lines of the post-human worldview, the dynamic interdependence of all kinds on the planet, organic, material, and inorganic.

The dependence of the form and the location of a system's elements from the specific and unstable characteristics of the other elements, renders the overall form and functionality of the system unpredictable. The new digital tools are promising to provide simulations of such systems and to elaborate for inspiration, forms that could not be conceived outside of these models. This is the case of swarm models that since the last decade try to simulate principles of nature and to incorporate a cross-disciplinary definition of properties and conditions of their models. By introducing parameters coming from different types of data and subject areas, these models raise the complexity of the model whilst offering a simpler understanding of the surrounding complexity. By incorporating technical aspects in the formulation of these models like construction, material, fabrication, environmental and cost parameters, these models can offer formal proposals to enhance design creativity. Schumacher (2018, p. 23) defines these parametric models as tectonic articulations.

5. What next?

Could we argue that nowadays Geometry is regaining the position of a foundational reference in the contemporary architectural intellect as it used to have in the theocentric and human-centric periods? It is rather difficult to gi e an affirmati e answer to this question.

On the assumption that the architect, as a human, has to have the absolute control and sovereignty over the creative process and over all the artifacts used in this process, then the answer would be undoubtedly negative. The principles and the techniques of the non-Euclidean Geometries remain almost unknown in the architectural circles. These Geometries are not part of the education of the architects in the vast majority of Schools worldwide, and consequently, they cannot have any impact on architectural thinking.

Those who believe in human superiority and sovereignty would argue that nowadays machines can design what humans cannot (or do not want to) design; that humans do not need any theoretical investigation of geometrical principles, axioms, and hypotheses since human-made machines can offer humans the expected outcome; that we can control machines to do what humans want them to do for them, there is no need, then, to learn anything that machines know and can do.

For those who believe that the architect and the machine together form ecologies in a symbiotic

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action, the question who is more competent has no real meaning, and the answer could certainly be positive. Geometry is again in the heart of architectural creation as the abstract concretization of philosophical values and understandings of the world, as it has almost always been the case in both periods examined. It drives the manifestation of these values so that architectural creations are meaningful statements about life and time.

Followers of this view realise, to their frustration, that the contribution of the architect to the construction of the respective software is marginal, and that the majority of this software is designed for other creative disciplines. Scripting, as a process to develop or adapt the digital design tools in use, is not at all between the expected skills of an architect, while at the same time these skills are not embedded in the interfaces companies create.

If machines are not just the artificial extension of our body and brain but an agent that forms and transforms us, as it happens with all human artifacts, then the further efficiency of machines will not automatically imply a better architecture. Together with machines, humans will expand their sensorial domains and will gain from nonhuman creativity, towards constructing speculative scenarios for a technologically- advanced and innovative architecture to come.

The core trait of our times is not the change that calculus and topology elaborate. It is rather the speed of change that contemporary machines help us gain awareness of. It is rather difficult to predict if this generation of architecture is lucky enough to experience a new revolution in architecture similar to the ones examined in this essay. As Mario Carpo states (2011, p. IX), "it may be too soon to tell if the digital is a revolution in architecture, but it is not too soon to ask what may be upended if it is".

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Essays

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Robotic Fabrication of Acoustic Geometries - an explorative and creative design process within an educational context

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Abstract

The aim of this paper is to describe and exemplify a design method for exploring acoustic performance and robotic fabrication of wood panels. Cognitive and creative impact of the design method will be investigated through qualitative observations, complemented with a qualitative PCA analysis, of a 3-week design studio with architectural students on master level. The paper describes a computational system that supports non-experts in generating curve-based geometries informed by acoustic analysis and simulation of robotic milling. The results of implementing the design method into the early design process of a mobile library structure will be presented followed by a discussion of the implications that this design method could have for the explorative and creative design process as well as the competencies required of potential users.

Keywords

Robotic fabrication; Acoustic performance; Computational design; Creative design processes; Design methodology

Note

The design method and the 3-week design studio was created and conducted in collaboration with the author's supervisor Isak Worre Foged. The author would like to thank both Isak and the author's main supervisor Hans Jørgen Andersen for valuable input to this paper.

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1. Introduction

When perceiving a building and the individual architectural geometries of which it is constructed one often relies on the visual sense - sizing the structure, detecting its patterns, its colours, its textures, the light that hits its surfaces. The process of architectural design is equally based on a visual exploration of sketches, drawings, physical- and digital models.

When perceiving the acoustic properties of an architectural building the visual sense is of no use and one must rely on one's sense of hearing. For the design process the same shift from visual to hearing has not been possible and during the design process the acoustic aspects has been based on practical knowledge and experience as well as theoretical knowledge about the properties of sound waves. Recently, new computational simulation methods have made it possible for architects to calculate and digitally visualize acoustic properties and how geometric variations affect its performance (Foged, 2018b). These computational tools thereby open for new opportunities for creative design of acoustically-driven geometries.

In the last decade, the development of new computational tools and corresponding methods has had a huge impact on the field of architecture. Utilising the power of computation architects have explored new ways of generating, analysing and simulating complex geometric structures. One of the many benefits of these new computational tools is the ability to communicate with CNC production machinery – including industrial robotic arms. New interfaces for popular CAD-software has enabled both simulation and toolpath-generation for industrial robotic arms (Brell-Çokcan and Braumann, 2010) allowing architects to explore aspects of design and fabrication in a parallel process – thereby internalising material properties and manufacturing aspects in the process of design exploration. The integration of both geometrically based design generation conducted in parametric software, acoustic simulation of design options, and robotic simulation of the fabrication process calls for an integrated and explorative design process (Foged, 2018a).

The creation and application of integrated computational-based design processes has the potential of revealing new solution spaces and new ways of searching these spaces for viable or optimal solutions. Exploring this type of computational design process sets new requirements to the technical and software-based skills of the architect, but the cognitive load of simultaneously handling many design parameters and constraints can also pose a challenge and have an impact on the creative fl w and thereby the ability to construct and explore a given design space.

During the last decade, several commercial and research-based projects has investigated the use of computational design in architecture and explored the potentials of using computer simulations to inform and guide geometric variations of architectural objects. Although most attention has been on simulating structural properties (ex. FEA) other performance criteria such as solar radiation, view analysis and acoustics, has also been explored in recent years (Reinhardt et al., 2016).

The field of robotic architecture is largely build on the pioneering work of Fabrio Gramazio and Mathias Kohler from ETH Zurich (Gramazio, Kohler and Willmann, 2014) and on the activities of international networks such as the Association of Robotics in Architecture (Brell-cokcan and Braumann, 2017). The versatility and adaptability of industrial robotic arms and their potential for exploring new building techniques and engaging with new materials has fostered a plurality of methods and design processes. One of these processes is Subtractive Manufacturing, where 3D objects are created by the removal of material. This process covers standard industrial techniques such as

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milling (Jung, Reinhardt and Watt, 2016) and hot-wire cutting, but recent work has also implemented chiselling (Steinhagen et al., 2016) and carving techniques (Clifford et al., 2014).

Recent work by (Reinhardt et al., 2016) combines acoustic performance and robotic milling in a search for "acoustic effects of complex architectural geometries". Their research proposes an iterative design process consisting of the following steps:

> "(i) specification of the architectural design parameters, along with the acoustic design aims (e.g. scattering coefficient spectrum); (ii) computational design of specific surface micro-geometries; (iii) fabrication of physical scale model test samples in the form of discs; (iv) acoustic measurement and analysis of sample performance; and (v) refinement of the design with potential further iteration." (Reinhardt et al., 2016)

In their work the designs of the specific micro-geometries are informed by the theoretical knowledge of acoustic scattering and specular reflection while the robotic manufacturing process is tested through digital simulations before the actual robotic manufacturing of the sample discs occurs. Driven by the physical measurements of the acoustic performance of the sample discs the next iteration can be further improved and refined

With the continuously improving software for parametric design found in the CAD-software Rhinoceros 3D (McNeel, 2018) and its embedded plugin for editing graphical algorithms Grasshopper, as well as the functionalities of the Grasshopper add-ons Pachyderm Acoustics (Harten, 2018) for acoustic analysis and KUKAprc (Brell-Çokcan and Braumann, 2010) for robotic simulation, this software package now supports the development and investigation of new design methods. Methods that supports architects and students of architecture in a design exploration of performance driven geometries based on acoustic analysis and robotic manufacturing.

By following a primary generator methodology, where aspects are successively investigated (Foged, 2018a), the work presented in this paper seeks to establish a design method that incorporates simulation of acoustic performance and robotic fabrication of milled wood panels.

The potentials and challenges involved in adopting the established design process is investigated through its implementation in a design studio with architectural master students - thereby investigating the challenges that non-experts meet when exploring a design space for which possible solutions can be simulated and tested against specific performance criteria. Through evaluation of the students' final design solutions and based on qualitative observations conducted during the design studio the research project also seeks to record the impact that the design process has on creativity and the associated cognitive processes.

This paper will present the established design method, including the processes of generating geometric variations, visualization of expected output of the milling process, performing acoustic simulations, and the generation of robotic toolpaths and the visual simulation of running these toolpaths. With the design method being implemented in a design studio on architectural master level, the paper will also present selected student work along with the physical 1:1 prototype of a mobile library structure that concluded the studio. The paper will also elaborate on the potentials and limitations of acoustic and robotic simulation, and reflect on the design method's impact on the creative and cognitive process of designing performative wood panels.

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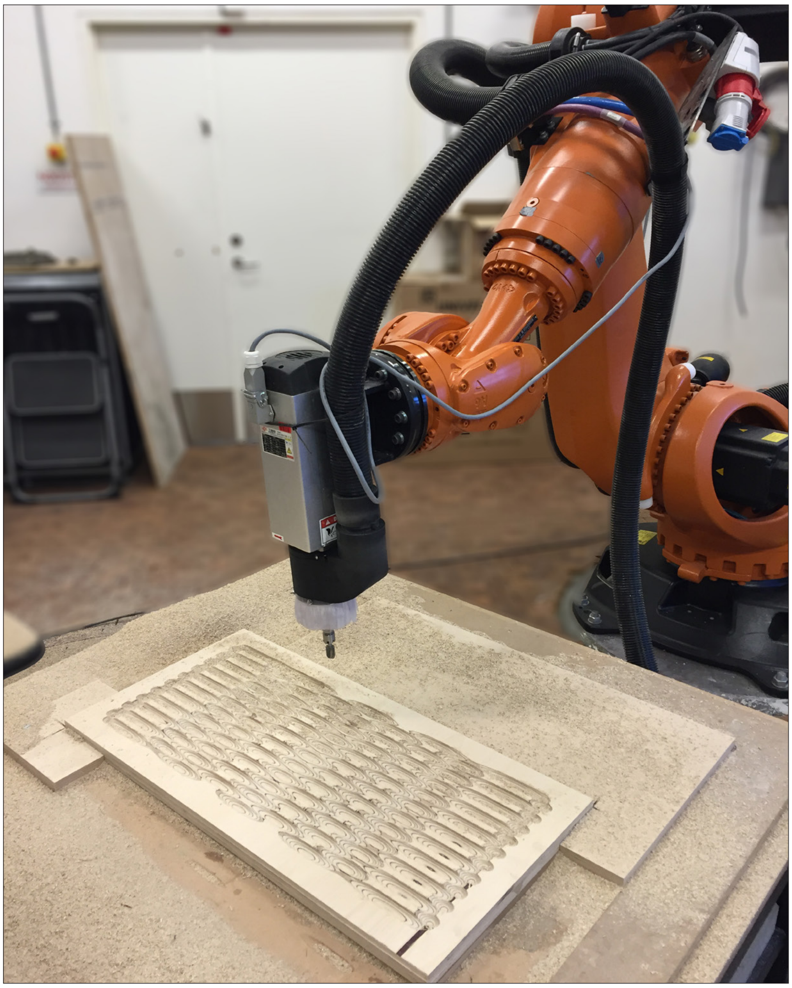

Figure 1.
Robotic milling of prototype for acoustic panel.
Photograph by Jacob Hilmer.

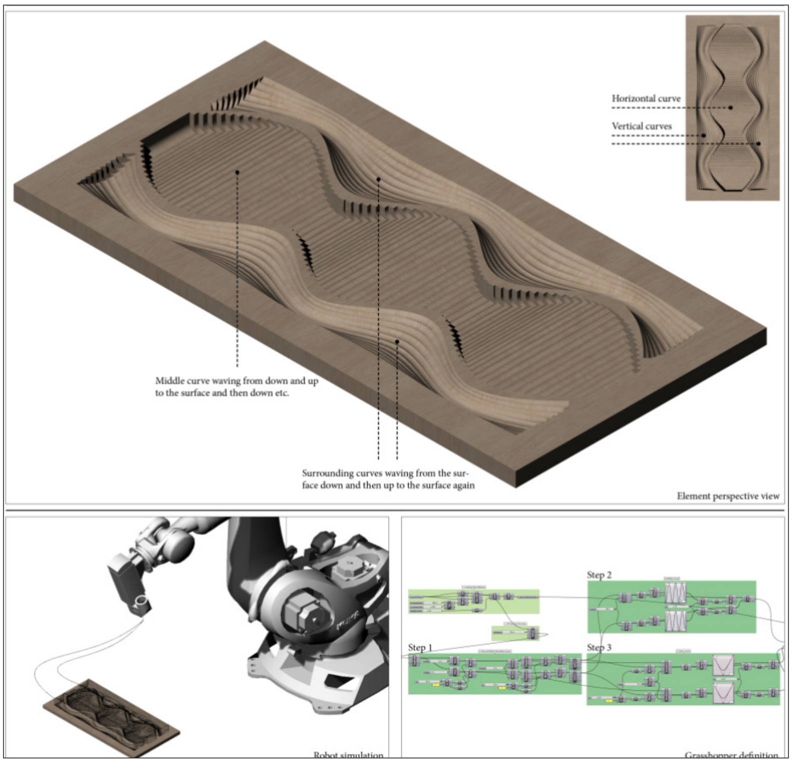

Figure 2.
Image showing a parametric design system (bottom right), with one out of many possible geometric compositions (top) and the corresponding simulation of the robotic fabrication.
Credit: student Maria Møller Salling.

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2. Methods

The reason for developing a new design method was to enable a design process where geometric composition, acoustic performance, and robotic fabrication could be explored in parallel. To achieve this the design method is constructed such that the designer, through direct manipulation and design of digital curve geometry, receives the geometric solution that results from milling a wooden plate using the selected curves as milling paths. These milling paths and the given geometric solution allows for both a simulation of the robotic milling process and an acoustic analysis of the milled wooden plate – both simulations holds the potential of acting as valuable feedback for the next iteration of re-designed and increasingly informed curve geometry.

To examine the design method's ability to assist in the exploration of acoustic geometries and robotic milling of wood panels, the method was implemented in a 3-week design studio with architecture students on their master level. The aim of the design studio was to explore and apply architectural acoustics in the early design processes through to robotic manufacturing processes and the production of 1:1 prototypes. Structured in three phases the first week explored spatial- and material systems, robotic manufacturing constraints, and parametric modelling. The second week architectural acoustics was introduced together with robotic simulation. During the last week, the students explored their own design systems and iteratively improved the acoustic and manufacturing performance of their geometric solutions. Each student worked towards a final design for a mobile library shelf system consisting of empty shelfs for books and shelfs containing their acoustically performative plywood panels. The studio ended with each student fabricating one panel of their own design for mounting in a 1:1 prototype of the mobile library. The design method consists of a computational design system and a physical robotic setup.

The Robotic Setup

The robotic setup consists of an industrial robotic arm (KUKA KR300R2500) with a 7.5KW CNC spindle mounted as its end effector (see figu e 1). With a ball nose milling bit (19 mm. diameter) attached to the spindle this setup allows for a milling angle of up to 25 degrees away from the vertical axis (z-axis in this case) without colliding with the 800x400x24mm plywood plates that were chosen for the acoustic panels.

The Computational Design System

The computational design system is constructed in Rhino+Grasshopper, and consists of four parametrically related sub-systems, or clusters, named: Path Generation, Geometry Generation, Acoustic Analysis, Robotic Simulation.

In the Path Generation cluster, users can directly interface or manipulate with the curve-based milling paths, the paths that the milling robot will follow during fabrication, thereby indirectly controlling the appearance of the resulting milling geometry. Design of the milling paths is a three-dimensional design challenge as the curves can be defined as moving through varying xyz-position, thereby defining their location on the wood plate and the depth they are moving down into the wood plate. There are numerous ways to generate and control curves, making this area open for a creative and explorative design process.

The Geometry Generation cluster performs the subtractive process of removing material. Using the milling paths, their connected planes, the cross section of the chosen milling bit, and the stock

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material (plywood plate) the cluster performs boolean (subtractive) operations and graphically visualizes the resulting milling simulation (see figu e 2).

In the Acoustic Analysis cluster the Pachyderm Acoustic plugin is utilized to simulate the acoustic performance of the geometric shape from the Geometry Generation cluster (see figu e 3). Depending on the acoustic aim (ex. low reverberation time, high scattering coefficient high absorption level) varying geometric shapes can be compared and the search for a better acoustic performance can inform the generation of new milling paths, thereby creating new and acoustically improved geometric shapes.

The cluster containing the Robotic Simulation largely consists of components from the KUKAprc package. Specifying the model of the robotic arm, the tool that it is equipped with (in this case the spindle) and the base coordinates (the robots position relative to the plywood plate) this cluster can simulate and visually represent the exact movements of the robotic arm by following the planes that are generated in the Path Generation cluster. Another important output is the estimated time that the robot needs to fabricate a given design – together with the results from the acoustic analysis the fabrication time can contribute to the overall performance of a given design solution.

An important aspect about the computational design method is that all feedback is visualized graphically (see figu e 1). The dynamic simulation of the robotic movements, the visualization of different geometrical compositions for the acoustic panels, and the graph-based visualization of the results from the acoustic analysis, all serves as visual feedback that supports an iterative exploration of design solutions.

Design Studio Observations Setup

The results of applying the design method on non-expert users was gathered through qualitative observations during the day-to-day interaction with the students as well as observations gathered during the final presentation and evaluation of student projects. The author's role as teacher and supervisor during the design studio made observations overt and with a shifting role of the observer, as defined by Gold R. L. (Gold, 1958), between 'observer-as-participant' and 'complete observer'. Assisting students with design questions regarding tectonics, aesthetics, robotic manufacturing, acoustics, etc. as well as technical/mathematical issues of parametric modelling and geometrical understanding, means the observer will participate in, and thereby influenc , the observed situation. These participant observations were complemented with non-participant observations where the author observed the design process of the students from a distance and without interaction.

Based on the experience from previous explorations of computational-based design method (Jensen and Foged, 2014; Foged, Pasold and Jensen, 2014; Foged et al., 2012) the processes and issues of interest were already narrowed in and the participant observations could be conducted through 'focused observations' (Spradley, 1980) centred on the following research questions:

"Can students with little or no experience in parametric design thinking or architectural acoustic establish a creative and explorative design process using the proposed design method?"
"How will the technical challenges influence the design process and the design qualities of the physical outcome?"
"To what degree will the proposed design method enable a parallel exploration of acoustic architecture, parametrically generated geometries and robotic manufacturing?"

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To complement the qualitative observations a quantitative method was applied. Based on observations deducted from the final presentation of student projects an anonymized score board was constructed, showing performance within six different categories: Tectonic Design Quality, Implementation of Design Method, Parametric/Fabrication Level, Acoustic Integration Level, Analytical/Reflecti e Level, and Representation Level. The scoreboard, with its six grading dimensions for each student, was analysed using the statistical procedure Principal Components Analysis (PCA). The aim of running this analysis was to explain the variation in scores and expose any pattern that could assist in further improvements to the proposed design method. An example could be that if high performance in acoustic integration had a negative impact on the fabrication level then improvements of the design method could be made to ensure better integration between these two performance aspects.

3. Results

Evaluation of the proposed design method should be based on both the technical aspect of establishing the computational system and its impact on the creative and cognitive processes when adopted by non-expert architectural students.

Design and development of the computational system has shown that it is technically possible to combine the generation of geometric patterns, acoustic analysis, and robotic simulation in an integrated computational workfl w. Clustering the computational system into four sub-systems simplified the workfl w and enabled the user to iteratively shift focus between the four clusters, for instance working on the geometric composition of the path curves in the 'Path Generation' cluster and when satis ed enabling the other clusters to witness the effects. Although aiming for a continuous data fl w between the four clusters it was not technically possible to implement the acoustic analysis in the Grasshopper environment with the consequence of having to transfer the geometric output to Rhino and running the simulation there. This resulted in a break in the data stream and the need for repetitive manual work for each design iteration.

The qualitative observations of the 3-week design studio, including the robotic manufacturing of the acoustic plywood panels, shows that, with only few days of parametric design teaching, it is possible for non-experienced students to adopt the proposed design method and explore the design and fabrication of acoustic panels. The clear structure of the design process – create milling curves, generate milling surface, analyse acoustic performance, simulate robotic fabrication, (repeat process) – allowed all students to iteratively explore various designs while searching for better performing versions. The fact that each part of the process was graphically visualized increased the students' understanding of their own design choices and the consequences thereof – making clear the limitations and potentials of the design system.

A challenge facing many students was the transition from exploring the geometric system of curves that were given to them during the introduction of the design method, to designing their own geometric system. For most students, the design of a new geometric system was not based on the idea or concept of a system, but instead on an aesthetic-driven concept for the appearance of the final geometry. This often resulted in students exploring a design system with a very narrow solution space and with aesthetic performance as the main design driver, as also witnessed in the studies by I.W. Foged (Foged, 2018a).

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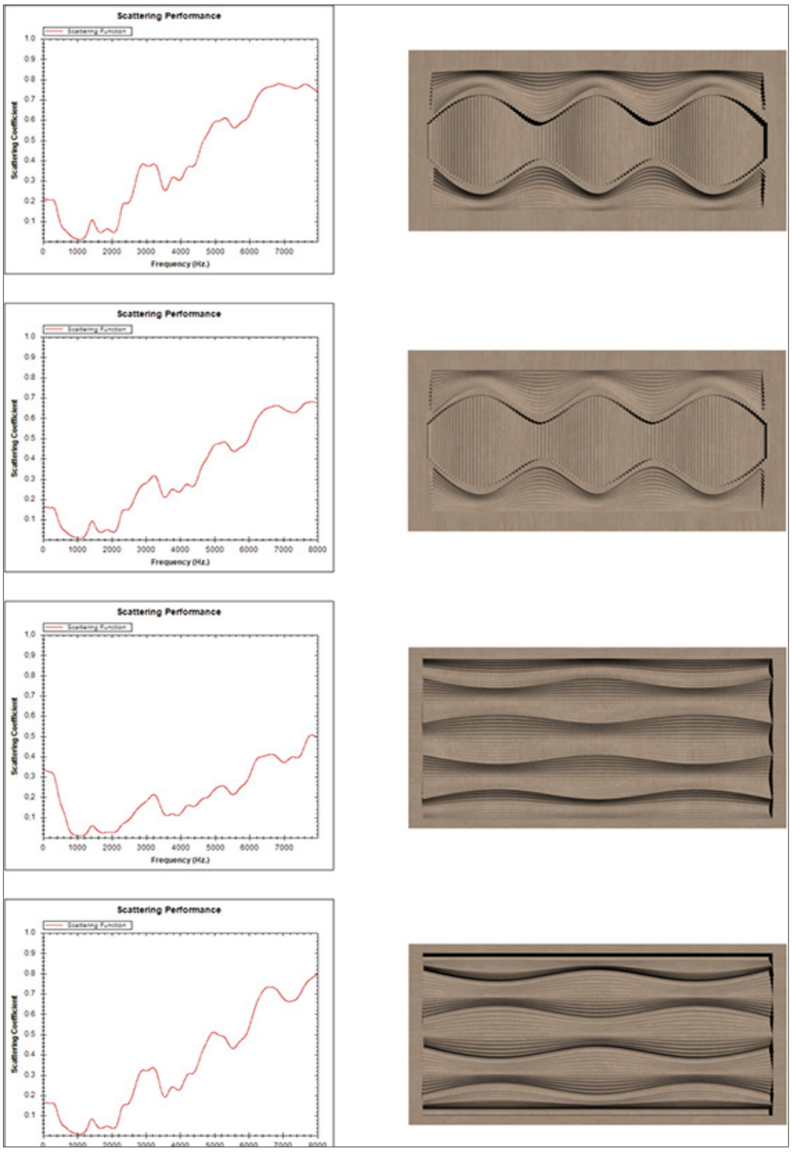

Figure 3.
Image showing the acoustic performance (scattering values) of the corresponding geometrical composition.
Credit: student Maria Møller Salling.

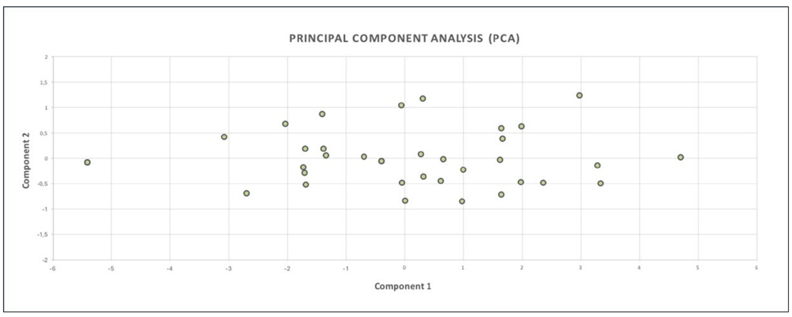

Figure 4.
A scatter graph showing the result of the PCA with the most influential principal component (Component 1) on the x-axis and the second principal component (Component 2) on the y-axis.

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Observing the design process also made it clear that there was a general unwillingness among the students to initiate their design exploration with geometrically simple systems, but instead more advanced designs were pursued, often leading to more time being used on solving complex geometrical problems than on iteratively exploring the design system.

Another challenge for students with only little experience in parametric modelling was their lack of knowledge regarding geometric modelling techniques and methods available in the parametric software. This often resulted in a very limited exploration of geometric systems or in design trajectories with unsolvable geometric challenges. For both scenarios, a negative result on the creative fl w was observed as either no new design potentials were recorded by the student or the speed of each design iteration was too slow for upholding a suitable - and thereby creative - fl w. As opposed to these scenarios, for the more experienced and skilled students a much smoother creative fl w was witnessed, where the geometric solution and performance of one design iteration lead to quick changes of established design parameters or to the creation of new parametric relationships within the design system.

The result of applying the proposed design method can also be witnessed in the full-scaled physical prototype for the mobile acoustic-driven library (see figu e 5). The library structure consisted of one robotic-milled wood panel per student and the geometric variation across the panels is an indicator of the explorative potential of the design method. Another important observation made during the fabrication phase was that when each student started the robotic milling of their own wood panel they expressed a clear expectation to the sequence of movements to be made by the robot. The continuous computer simulations of the robotic fabrication process meant that even with no prior experience with industrial robotic arms or with milling as a fabrication process, the students were in control not just of the final shape of their design, but also of the process in which it was made.

The results of conducting the PCA on the six quantifiable performance aspects used in the score board, was that the first principal component, a weighted average of all grades (eigenvalue > 1), explained 85% of the variation within the grades (see figu e 4). The second principal component was the contrast between the scores given for "Tectonic Design Quality & Parametric/Fabrication Level" and "Experimental Method Level & Analytical/Reflecti e Level" (eigenvalue = 0.3). This second component explained another 5% of the variation.

4. Discussion

Based on the setup of the computational design system it is evident that several design aspects (generation of geometry, architectural acoustics and robotic manufacturing) can be explored through an integrated parametric workfl w. Except for a full parametric implementation of Pachyderm Acoustics, an issue that is more than likely to be overcome with future software updates, the parametric workfl w enables an interrelated and parallel exploration of selected primary design drivers.

Insights based on the qualitative observations of the 3-week design studio showed that students with little or no experience in computational design quickly adopted the design method, but also that some student struggled with technical challenges and that this led to less successful explorations of potential design solutions. This point towards the need for a certain skillset and experience, not just with the technical aspect of computational design, but also within computational design

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thinking. As the best student projects showcased, there's a huge potential in a parallel exploration of performative design drivers, but harvesting this potential requires dedicated teaching of skills and competencies in the field of computational design

With the analysis and simulation methods implemented in the proposed design method, it is possible to explore geometrical variation and complexity based not merely on aesthetic motivations, but also performative qualities on means of fabrication. During the design studio, most students iterated through the design method numerous times and by starting with simple geometric solutions they were able to understand the results of their acoustic simulations, relate these acoustic performance values to the given geometry, and merge this knowledge with the theory of acoustic taught in the beginning of the design studio. The design studio was constrained to acoustic performance and robotic milling, but both the design method and the affordance of the robotic setup serves as a framework capable of adapting to the exploration of a wide variety of performance aspects and fabrication methods.

The implementation of the robotic arm and the visual-based simulation of the movements it would perform during the milling process resulted in a fabrication process that was highly integrated in the early design process. From observations during the fabrication of the students' final prototype it was clear that a very valuable insight concerning the robotic fabrication was present even before their first actual hands-on encounter with the robotic arm. Due to the limited time schedule of the design studio the students were only given the chance to produce one milled prototype of their wood panel, but based on their reflections a lot of production and material knowledge was gained during this fabrication process, which could potentially be fed directly back into their design system and further inform their design process. The fabrication of multiple prototypes based on continuously improved design solutions therefore shows to have a huge potential for informing the design process.

Introducing the principal component analysis (PCA) as a supplement to the quantitative observations showed that the variation in grades could be explained by the average of all six grades - if a student is performing good in one category, for instance Tectonic Design Quality, the student is also likely to perform on the same level in the other fi e categories. This pattern could be explained by the computational-based skills and design capabilities of the student – if a student doesn't succeed in creating and exploring complex computational design systems he/she is unlikely to conduct a good exploration of the acoustic integration and the robotic fabrication aspect.

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5. Conclusion

Based on the results of the qualitative observations of the 3-week design studio it is evident that the proposed design method enables non-expert architecture students to conduct an explorative and creative design process that integrates acoustic performance and simulation of robotic fabrication.

The observations also exposed that the capacity and level of computational design thinking, including technical software skills and geometrical understanding, had a significant impact on the students' creative fl w during the design process. When iteratively exploring new ways of generating complex and performative geometries the students are continuously faced with new geometric and parametric challenges and not being able to solve these, results in a very limited design exploration where only few design parameters were investigated.

The studio also showed that integrating simulation of robotic fabrication had a very positive impact on the design process and ensured a seamless transition between designing and the production of prototypes (or final products). The implementation of robotic simulation revealed interesting potentials for further exploration and questioning in future work: What skills are needed to engage in a parallel design exploration between a human designer and a sensing robotic arm? If the robotic arm can sense its environment how could this information be implemented in new creative design processes?

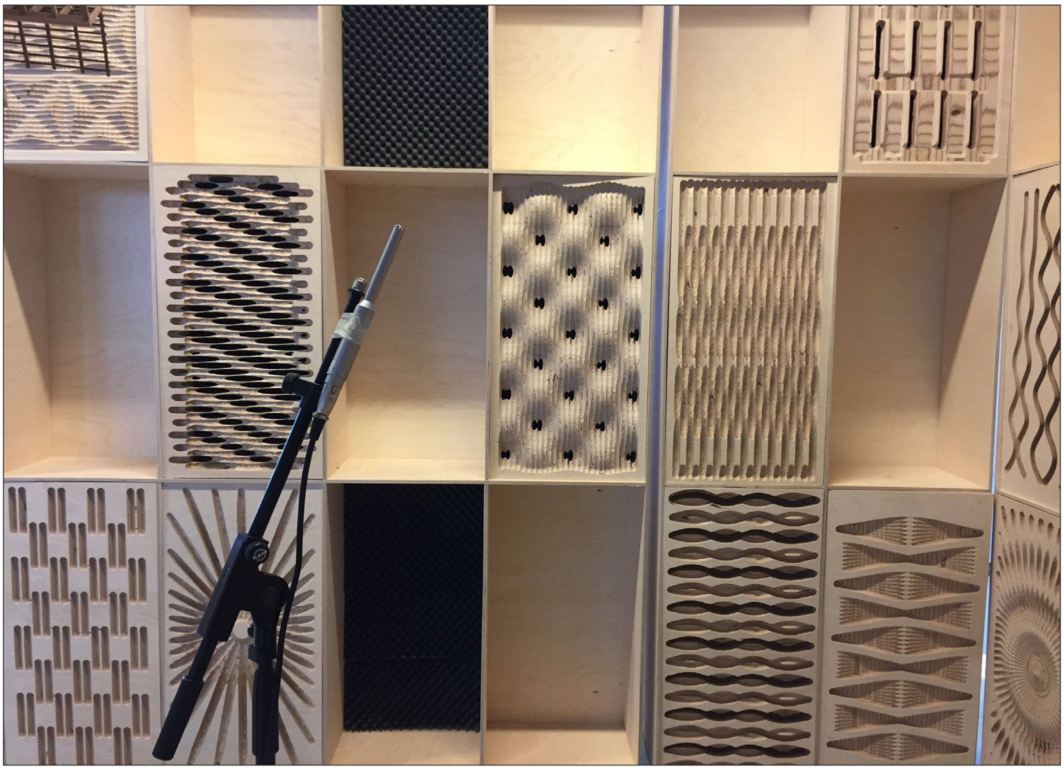

Figure 5.
Physical measurements of the acoustic performance were performed on varying configurations of the students' milled p ywood prototypes. Image credit: Isak W. Foged.

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Cellular Design

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Abstract

Architectural designers have had a long interest in self-organizing principles and designers have applied emerging systems to a wide variety of projects. Often, components of a project or relationships between components are defined by the designer while the emerging system reacts to those, or self-organizing geometries are made to suit a given site and program. This research instead attempts to build a self-organizing system from the bottom up, so that all parts of the material accumulation are developed through local system interactions only. We therefore propose the use of simulations of intercellular behaviors as an architectural computational design tool. Small units of material, the cells, are programmed to arrange themselves according to intercellular as well as external behaviors. The intercellular logics can be geometric or mathematical rules, or they can attempt to simulate natural systems such as the cellular behaviors and growth in organisms. Different types of cellular simulations have been programmed. A set of behaviors has been developed in order to generate a variety of morphological traits for potential applications in architectural design. The generated geometries portray various characteristics of architectural relevance, generated through the emergent intercellular behaviors as well as external influences. The simulations have been tested with the design of two case studies: A permanent installation in an office, and the design of a house. While the simulations require significant improvements in order to become more effective as design tools, they have generated promising designs for the case studies.

Keywords

architecture; structure; cell division; cell proliferation; intercellular behavior; developmental biology; growth

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1 Introduction

In the fields of architecture, design and engineering, concepts of biomimicry have been applied to various design problems such as structural systems, architectural form or new materials, usually by applying specific isolated geometries from nature to the design field (Benyus 1997, Pawlyn 2011, Panchuk 2006, Barthelat 2007). This research instead attempts to apply one of the general concepts of form generation in nature to the field of design: The creation of form through an iterative incremental development and accumulation of material via processes of growth by cell division. (Figure 1)

Falling within the realms of both Generative Design (Shea et al. 2005) as well as Artificial Life (Langton 1998), computational simulations are used for the creation of those processes. Whereas in Artificial Life a main focus is on the study of life processes, this research specifical y aims at the generation and control of the resulting geometry. This development of form for architectural use is based on the simulation of behaviors and arrangements of small units of material. The units can be simulated to behave similarly to the cells that make up living organisms, or their behavior can follow material, geometric or mathematical logics.

Architectural designers have been interested in self-organizing systems for several years and have applied emerging geometries to various projects. However, usually components and their relationships are predefined the self-organization is limited to react to given geometries, or emerging geometries are made to fit a given site and program. Instead, the aim of developing forms through an iterative growth process is, similar to nature, to continually evaluate and influence the geometry during its formation, so that the final form is solely generated through a bottom-up system of local material interactions (Kwinter 2008). In this way, the system can be universally responsive without being bound by the preconceived conditions that need to be set out in a parametric relational model (Leach 1999, Liaropoulos-Legendre 2003).

The cells are calculated iteratively by their center points and can reconfigu e in 3d space while attempting to keep a specified distance towards their neighboring cells. This results in larger accumulations of adjacent cells. Growth and decay processes can be simulated by triggering the addition or removal of cells. Cells can be differentiated by the assignment of specific behaviors or functions. The work in this paper is a generalization of the existing algorithms as presented in section 'Related work'. The simulations in this paper allow the cells to continually change their cell neighborhood based on their movement. Also they allow for volumetric cell accumulations with a thickness of several cells, rather than accumulations of only linear or single layer surface formations as in previous work. Different typologies of the cell accumulations were investigated, and different intercellular behaviors and external influences were tested, with the aim of generating a variety of morphologies that can become useful for architectural design.

2 Related work

Similar simulations to the ones proposed in this paper have been developed by artists and designers as well as by scientists. In art and design, the main aim of the simulations is to generate morphologies, which can become artworks as final objects or which can be used as animations. In science, the aim of the simulations is to gain new knowledge and understanding of biologic processes.
Early simulations such as cellular automata (Wolfram 1983), the Game of Life (Gardner 1970)

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or diffusion limited aggregation (Witten and Sander 1981) all use small units of material as their basis, the voxels or solid cells, similar to the proposed simulations of this paper. However, in those simulations the voxels are usually positioned in regular lattice arrangements such as orthogonal equidistant grids.

2.1 Cellular growth simulations in art and design

George Hart developed a system based on a manifold mesh arrangement of cells, with only specific bud-cells allowed to divide (Hart 2009), generating tubular and branching structures with this algorithm. Andy Lomas uses a similar system based on a manifold mesh arrangement of cells, with cell division based on a nutrient distribution (Lomas 2014). Lomas uses significant y larger numbers of cells than Hart. Surface behaviors emerge as the cell layer expands and starts to fold. Neri Oxman, Christoph Bader and Dominik Kolb presented the artwork series Wanderers, described as being developed through growth (Patrick 2015). Based on the visualizations, it is assumed that linear and manifold surface based simulations have been used similar to those presented in this paper, with cells pulled towards external geometries. Alisa Andrasek developed architectural geometry using manifold surface based simulations at the Bartlett University College London (Andrasek 2016).

2.1 Cellular growth simulations in science

In developmental biology, assumptions on the development of organisms on a cellular level are tested through computational simulations (Merks and Glazier 2005, Palm and Merks 2014). Those are applied to various processes such as embryonic growth (Wolpert et al. 1998), plant development (Merks et al 2010), the development of marine life (Kaandorp et al. 2005, Kaandorp and Kübler 2001), or at the level of cells and molecules (Merks and Glazier 2005). The study of the processes using computational simulations allow for a research at a precision that would otherwise not be possible (Walpole et al. 2013). In cancer research, the growth of tumors is simulated computationally in order to understand the precise mechanisms that lead to its development and to the adverse proliferation of the cells (Shirinifard et al. 2009, Milde 2013, Jiao and Torquato 2012, Gevertz and Torquato 2009, Bearer et al. 2009, Neufeld et al. 2013).

3 Simulation Typologies

During the setup of the simulations, some of the major behaviors are defined that allow for a classification of the g owth simulations according to these characteristics:

3.1 Cellular neighborhood

The set of surrounding cells that a cell regards as its neighbors shall be referred to as the cell neighborhood. In a simulation with static cell neighborhood, a cell keeps its neighbors from iteration to iteration. All the connections to direct neighbors that it has in one iteration it will still have in the next iteration. Only the division or the removal of a neighboring cell will result in a change of its set of neighbors.

In a simulation with dynamic cell neighborhood, the neighbors are re-established in every iteration according to distance and neighbor count. A dynamic cell neighborhood allows for changes in the network graph and for behaviors like cell migration or the merging and separation of adjacent cell agglomerations.

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Figure 1.
Cellular growth structure

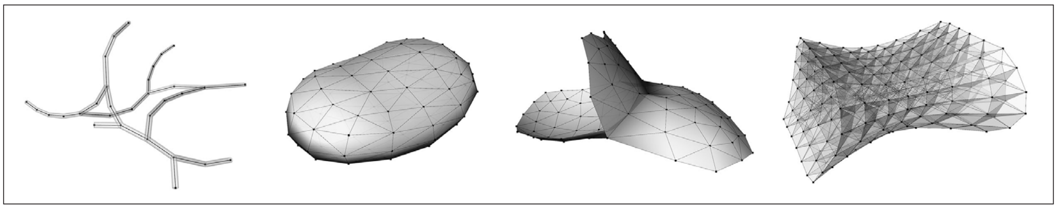

Figure 2.
Structural typologies: Linear system, surface-based manifold system, surface-based non-manifold system, volumetric system

Attraction Force	Cells move towards each other.
Repulsion Force	Cells move away from each other.
Spring Force	Cells attempt to stay at a defined distance.
Planarization by attraction force	Cells generate local planarity through a combination of attraction between neighbors and repulsion towards non-neighbors.
Planarization by local normal force	Cells generate local planarity by moving towards the plane through their closest neighbors.
Strata Force	Cells generate parallel strata by moving towards a plane through their closest neighbors that is oriented along a globally defined normal.
Orthogonal Force	Cells generate orthogonal planes by moving towards the XY, XZ or YZ plane through their closest neighbors that is oriented closest to the cell's local plane.
Attribute Force	Cells react to additional attributes of their neighbors such as an assigned vector.
Drag	Drag slows down a cell's velocity.
Unary Force	A unary force such as gravity acts equally in space.
Position dependent directional force	A vector field has varying directions and strengths depending on the location in space.
Object forces	Attraction or repulsion forces towards objects in space.

Table 1.
Intercellular and External forces

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3.2 Structural Typologies

The simulation can be set up so that the cells form linear chain-like accumulations, accumulations based on single-layer surfaces, or they can form volumetric accumulations (Figure 2):

Cells in linear cellular systems are arranged to form chain-like formations. Examples are the venation networks developed with the algorithm of the University of Calgary (Runions et al. 2005, Runions et al. 2007, Runions 2008). Possibilities of branching or network formations exist if some cells have more than two neighboring cells. (Figure 2a). In a surface based manifold cellular system, all cells are arranged on a single surface, similar to the vertices of a manifold mesh. Examples are the models as described by Hart and Lomas (Hart 2009, Lomas 2014). (Figure 2b). In a surface based non-manifold cellular system, cells have several neighboring cells that they are surrounded by and which tend to locally lie on a surface. However, they do not form a manifold closed mesh and can have open edges or intersect each other (Figure 2c). In volumetric cellular systems, cells form volumetric instead of mono-layer arrangements, similar to the way that multiple cell compounds make up most living organisms (Figure 2d).

3.3 Developmental Typologies

The simulations can develop in different ways over time: The main focus of a simulation can be on growth, on decay or on the reconfiguration of the cellular accumulation. Simulations may commonly be a combination of those typologies. Due to the large amount of possible morphologic variations, most of the examples of this paper are surface-based growth systems. However linear and volumetric systems have also been explored.

4 Simulation Behaviors

The following computational set-up and behaviors have been used for the calculation of the simulations:

4.1 Basic set-up

The examples in this paper have been developed using the ICE simulation in Autodesk Softimage and Processing. The simulations are calculated iteratively, the positions of cells are calculated based on their center points in three-dimensional space. In each iteration, a set of forces is used to calculate a cell's next position, and rules for cell proliferation and differentiation are applied.

Every cell has an acceleration and a velocity. In each iteration, the vectors of the forces that are acting on a cell are added as acceleration onto its velocity, and the resulting velocity vector is added to its previous position in order to calculate the new position.

The following intercellular behaviors and external forces can be applied in varying combinations and intensities to the cells (Table 1). The intercellular behaviors can also simultaneously be applied to different groups of other cells, such as the direct neighbors, the neighbors of neighbors, or to cells that are at a certain distance.

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4.2 Intercellular behaviors for linear and surface based simulations

Let a cell have the position C.

The amount of direct neighbors of a cell may vary for different force calculations in the same iteration. Let a cell have n direct neighbors with positions P_r.

$$Let\ a\ point\ or\ vector\ have\ the\ coordinates = \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix},\ P_r = \begin{pmatrix} P_{r,x} \\ P_{r,y} \\ P_{r,z} \end{pmatrix}.$$

The diameter of a cell, which equals the target distance between neighboring cells, be d.

4.2.1 Attraction force

In order to achieve accumulations of cells that cluster together, rather than individual disconnected cells, neighboring cells can be defined as being attracted to each othe .

$$acceleration\ Attraction\ = \frac{1}{n}\sum_{r=1}^{n}\frac{P_r - C}{|P_r - C|^m}$$

with m being an exponent which can be used to control different types of attraction forces (Figure 3)

4.2.2 Repulsion force

In order to generate cell accumulations, cells need to be attracted to each other while at the same time keeping a certain distance between each other. This can be achieved by having an attraction force between neighboring cells while at the same time having a larger repulsion force between them if their distance becomes smaller than d.

$$acceleration\ Repulsion\ = \frac{1}{n}\sum_{\substack{r=1 \\ |C-P_r|<d}}^{n}\frac{C - P_r}{|C - P_r|^m}$$

with m being an exponent which can be used to control different types of repulsion forces (Figure 4)

4.2.3 Spring force

In order to generate cell accumulations, alternatively to the attraction with repulsion for cells closer than d, a spring force can be applied between neighboring cells with d as its rest length. This option was used in the simulations by Hart and Lomas (Hart 2009, Lomas 2014). (Figure 5)

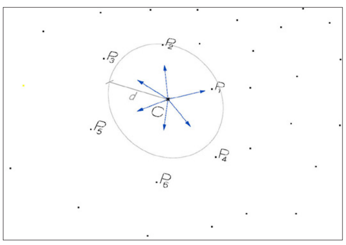

Figure 3.
Attraction force

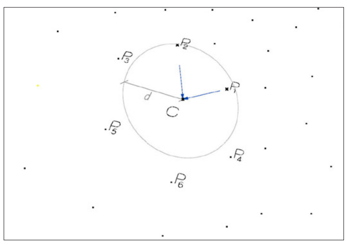

Figure 4.
Repulsion force

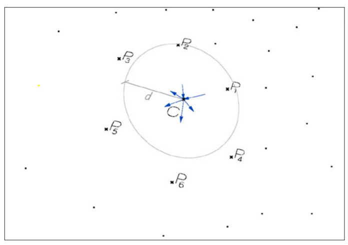

Figure 5.
Repulsion force

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$$acceleration\ Spring\ = \frac{1}{n}\sum_{r=1}^{n}(d - |P_r - C|) \cdot k \cdot \frac{C - P_r}{|C - P_r|^m}$$

The spring constant k of Hooke's law can vary between different types of cells (Fenster & Ugural 2011). The exponent m can be set to 1 for springs which are acting linearly proportional to their displacement as in Hooke's law, or otherwise to define non-linear y acting springs.

4.2.4 *Planarization by attraction force*

Surface-based cellular systems require a force to generate local planarity, so that volumetric accumulations of cells are avoided. In surface based manifold systems as described in 3.2, which have a static cell neighborhood and no edge conditions, this can be achieved through a combination of an attraction force between neighboring cells and a repulsion force between non-neighboring cells (Figure 6).

4.2.5 *Planarization by local normal force*

For surface-based non-manifold systems as described in 3.2, a planarization by attraction force will cause cells at edge conditions to only be pulled inwards so that the whole geometry continuously contracts. To avoid this, alternatively cells can be pulled towards the plane through its three closest neighbors (Figure 7).

$$acceleration\ Planar\ = \left((P_2 - P_1)\widehat{\times}(P_3 - P_1)\right) * -1 * \left((C - P_1) \cdot ((P_2 - P_1)\widehat{\times}(P_3 - P_1))\right)$$

4.2.6 *Strata force*

In order to generate parallel strata of cells, in an architectural context for example for the generation of parallel floor plates, a strata force can be applied to the cell. The direction of the strata is defined by the given normal N. A plane is defined with the normal N and with its origin at the center of the cell's neighbors. The strata force then pulls the cell towards the closest point on this plane (Figure 8).

$$accelerationStrata\ = \left[N \cdot \left\{\left(\frac{1}{n}\sum_{i=1}^{n}P_i\right) - C\right\}\right] \cdot N$$

In the case of layers parallel to the YZ-plane, $N = \begin{pmatrix}1\\0\\0\end{pmatrix}$*, the force is*

$$accelerationStrataYZ\ = \begin{pmatrix}\left(\frac{1}{n}\sum_{r=1}^{n}P_{r,x}\right) - C_x\\ 0\\ 0\end{pmatrix}$$

4.2.7 *Orthogonal force*

A force can be applied to the cells that directs them into orthogonal arrangements. This can be done via identifying the plane of the cell's local environment, the plane that passes through its three closest neighbors. Depending if this plane's orientation is closest to the XY, XZ or YZ plane, a force is applied along the normal $N=\hat{Z}$, $N=\hat{Y}$ or $N=\hat{X}$ respectively. A plane is defined with the normal N and with its origin at the centre of the cell's neighbors. The orthogonal force then pulls the cell towards the closest point on this plane (Figure 9).

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Let M be the normal of the plane through the cell's three closest neighbors:

$$M = (P_2 - P_1) \times (P_3 - P_1)$$

From this, select the coordinate axis s that represents the maximum of the coordinate values:

$$M_s = \max(|M_x|, |M_y|, |M_z|)$$

If, for example, s=x, then the YZ plane is regarded as the best fitting orthogonal plane and the orthogonal force pushes C in direction of the plane with normal N through the centre point of all of its neighbors.

$$N = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

Thus the force according to 4.2.6 would be

$$accelerationOrthogonalYZ = \begin{pmatrix} \left(\frac{1}{n}\sum_{r=1}^{n} P_{r,x}\right) - C_x \\ 0 \\ 0 \end{pmatrix}$$

4.2.8 Attribute force

A cell can have information attributed to it that can define a force or a behavior acting on its neighbors. A cell's movement is then influenced by the attributes of its neighboring cells. This can be used to create effects similar to the alignment as in the Boids algorithm (Reynolds 1987).

$$accelerationAttribute = \frac{1}{n}\sum_{r=1}^{n} A(P_r)$$

with A being the force vector which is attributed to a cell (Figure 10). Green vectors are attributed to a cell and applied to its neighbors.

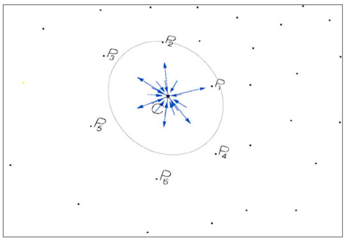

Figure 6.
Planarization by attraction force

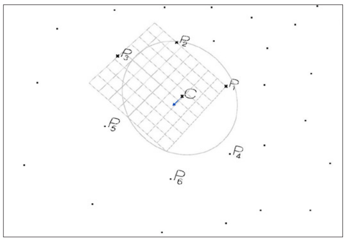

Figure 7.
Planarization by local normal force

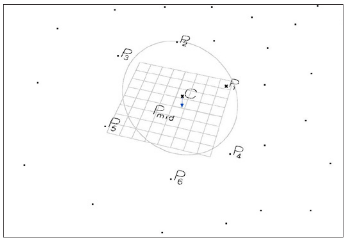

Figure 8.
Strata force

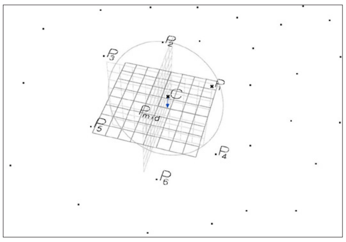

Figure 9.
Orthogonal force

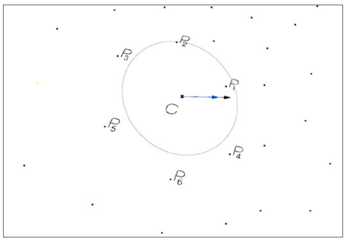

Figure 10.
Attribute force.

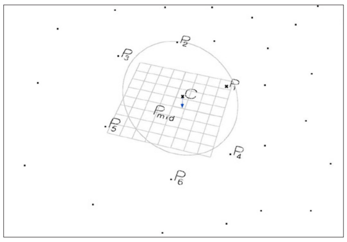

Figure 11.
Drag

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4.2.9 Drag

Drag, a direction dependent factor, can be applied to the cells, especially in order to avoid excess cell movement. Drag is mainly used to reduce the cell velocity.

$$velocityAdjusted = \begin{pmatrix} velocityX \cdot a \\ velocityY \cdot b \\ velocityZ \cdot c \end{pmatrix}$$

with a, b, c being factors in each Cartesian direction. (Figure 11)

4.3 External Forces

External forces are not related to a cell's neighborhood, but usually to the cell's location in space.

4.3.1 Unary Force

A unary force can be applied to the cells, for example to simulate gravity:

$$accelerationUnary = \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix}$$

with U_x, U_y, U_z being the forces in each Cartesian direction (Figure 12).

4.3.2 Position dependent directional force

A position dependent directional force can be applied to the cells. This force can be given by an external vector field V that defines varying vectors depending on a cell's position in space. (Figure 13)

$$accelerationField = V(x, y, z)$$

4.3.3 Object forces

Various external forces and movement restrictions can be applied, such as attraction and repulsion towards geometric objects, forces or movement restrictions which act within certain areas of the world space or which act on selected cells (Figure 14).

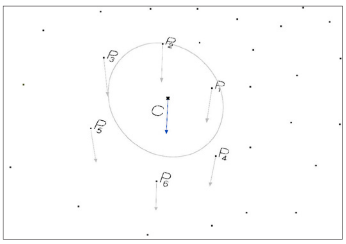

Figure 12.
Unary force

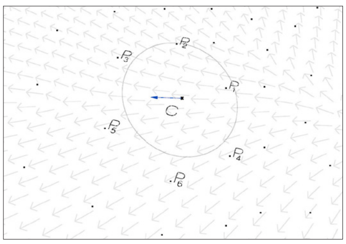

Figure 13.
Position dependent force

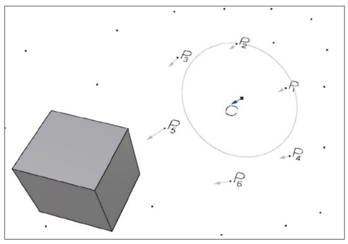

Figure 14.
Object force

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4.4 Intercellular behaviors for volumetric cellular simulations

Volumetric cellular simulations do not use generally applied planarity forces as described in points 4.2.4 and 4.2.5. Component thickness, which is a driving factor for the development of morphogenesis, can be identified by the differentiation of surficial versus interior cells. The amount of neighboring cells in one cell's proximity can be used to evaluate the component thickness.

4.5 Cell Proliferation

Cell proliferation is controlled by the trigger of the division as well as by the local positioning of the child cell. A division triggers can be age, resulting in an evenly distributed growth of the system. In order to generate a marginal growth that extends the agglomeration on its outer edges, two types of triggers have been used: A trigger based on the distance to a cell's neighbors, and a trigger based on the amount of direct neighbors. Both attempt to identify the cells on the edges of the agglomeration for proliferation. The position of a cell in space or its proximity towards external geometries, can be used to enhance or inhibit the cell's proliferation behavior. The local direction of the cell division process can be used to influence the edge conditions of the structure, for example to create a smooth or serrated edge.

4.6 Cell Differentiation

Cells can be programmed to take on specific functions and behaviors. A cell type can be defined at the beginning of a cell's existence, or a cell can change its type according to a trigger. Cell differentiation has been used in the examples of this paper to define cells that have location constraints or are fi ed in space, or cells that are constrained in their movement. Cell differentiation has also been used in the volumetric simulations to define interior cells, surficial cells and cells with the possibility to divide.

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5 Results

5.1 System with planarity force

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Spring force towards direct neighbors	strength 0.2, d=0.0, m=2.0
• Planarity by local normal force	strength 0.9
Trigger for cell division	less than 3 direct neighbors

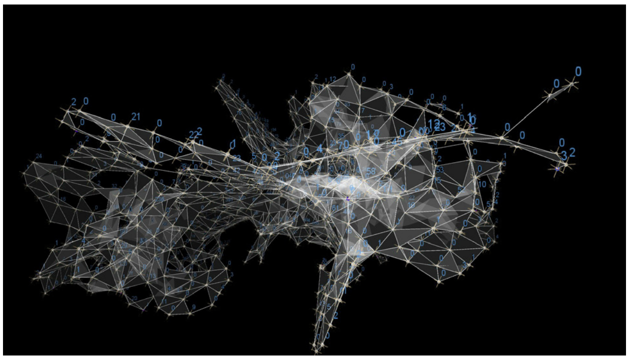

Figure 15.
A basic surface based non-manifold system with planarization by local normal

5.2 Surface-based manifold growth

Cell neighborhood	static
Structural typology	surface-based manifold
Forces acting	
• Spring force towards direct neighbors	strength 1.0, d=1.0, m=5.0
• Repulsion towards cells closer than 10.0	strength 5.0
• Planarity by local normal force	strength 1.0
• Normal force	strength 1.0
• Unary force	z=-0.1
• Drag	0.2
Constraints	ground surface
Trigger for cell division	random uniform

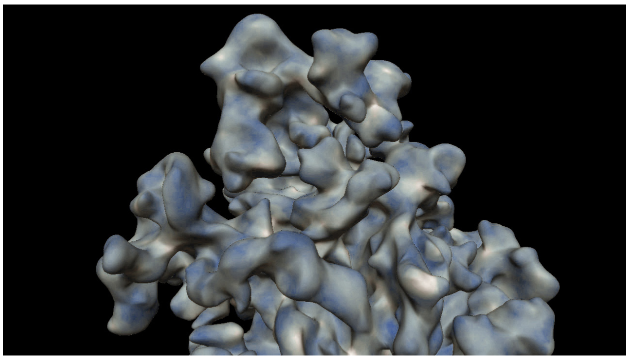

Figure 16.
A surface-based manifold growth simulation

5.3 System with unary force

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Unary force	z=-0.01
• Drag	0.5
Constraints	ground surface
Trigger for cell division	average distance >1.5 for 2 closest cells

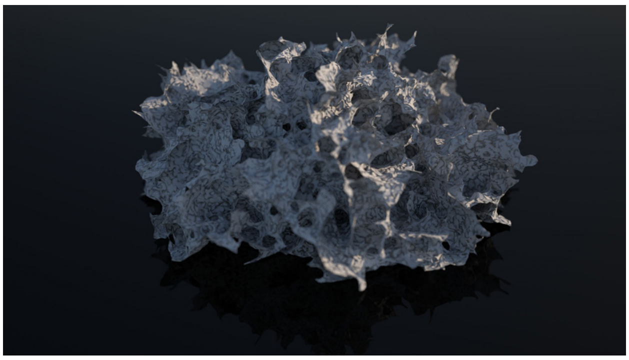

Figure 17.
A surface based non-manifold system with planarity force, unary force and a surface boundary condition.

5.4 Shell structures

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Surface force	strength 0.1
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	less than 3 cells at a distance of 1.5

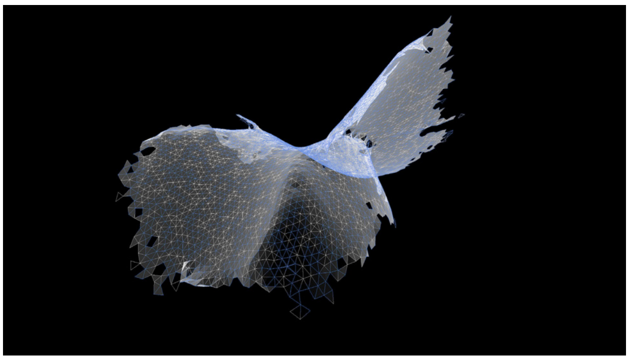

Figure 18.
Shell structure, generated by using gravity in combination with movement constraints for specific cells

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5.5 Horizontal strata

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Strata force	strength 0.04
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	less than 3 cells at a distance of 1.5

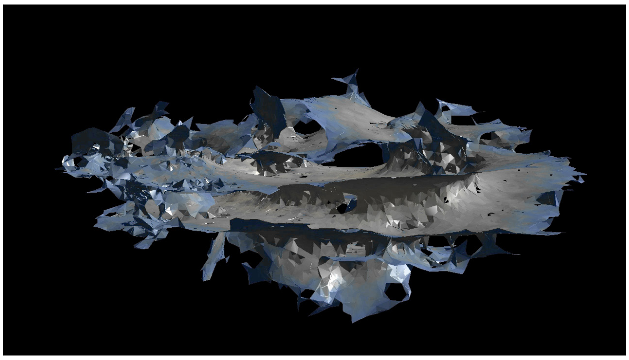

Figure 19.

A surface based non-manifold system with strata force. The cells agglomerate in parallel orientated fieldsthat orm at roughly equal distances

5.6 Orthogonal structure

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.4
• Repulsion towards direct neighbors closer than 1.0	strength 2.2
• Repulsion towards cells closer than 5.0	strength 1.1
• Planarity by local normal force	strength 0.5
• Orthogonal force	strength 0.1
• Unary force	z=-0.1
• Drag	0.1
Constraints	containing box
Trigger for cell division	average distance >5.0 for 2 closest cells

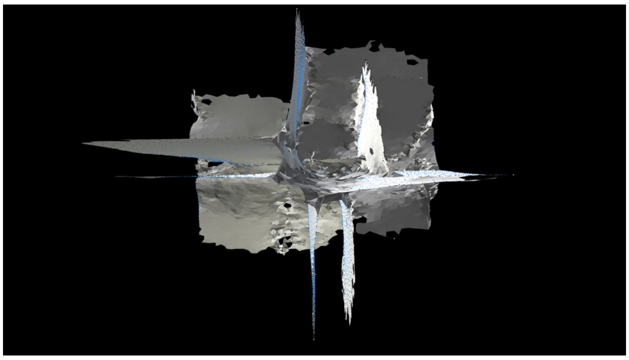

Figure 20.

A surface based non-manifold system with orthogonal force. The system is constraint to a rectangular volume

5.7 Network generation

Cell neighborhood	dynamic
Structural typology	linear
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 2.0
• Planarity by local normal force	strength 0.5
• Surface force	strength 0.3
• Drag	0.1
Trigger for cell division	less than 2 cells at a distance of 6.0

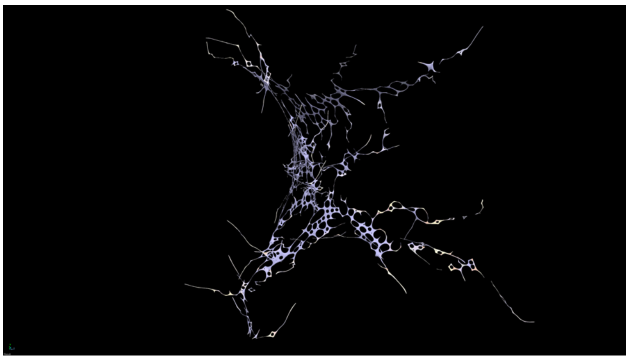

Figure 21.

Network morphology generated through a linear growth of the cells. A dynamic cell neighborhood allows cells from different strands in close proximity of each other to connect in order to form loops

5.8 System with volumetric accumulation

Cell neighborhood	dynamic
Structural typology	volumetric
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Drag	0.2
Trigger for cell division	less than 7 cells at a distance of 2.0

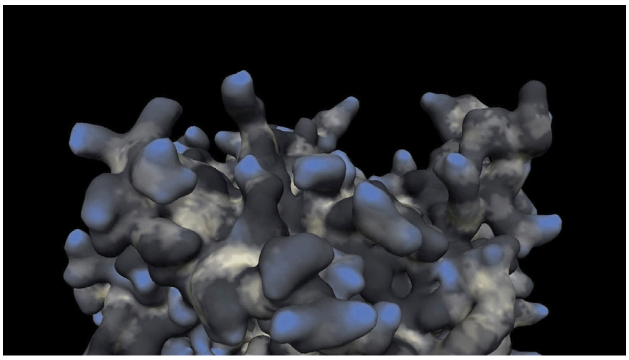

Figure 22.

A volume based system with cell proliferation defined y cell neighborhood

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5.9 Reaction diffusion patterns

Cell neighborhood	dynamic
Structural typology	volumetric
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Drag	0.2
Trigger for cell division	less than 7 cells at a distance of 2.0

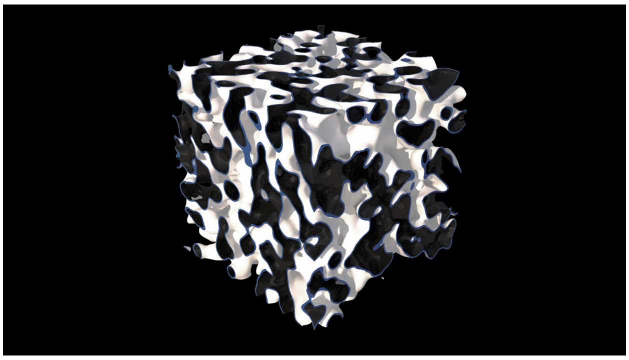

Figure 23.

A volume based system with patterns similar to reaction diffusion systems

5.10 Attribute force to control cell proliferation

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Attribute force	average of 5 closest cells at creation
• Drag	0.5
Trigger for cell division	average distance >1.5 for 2 closest cells

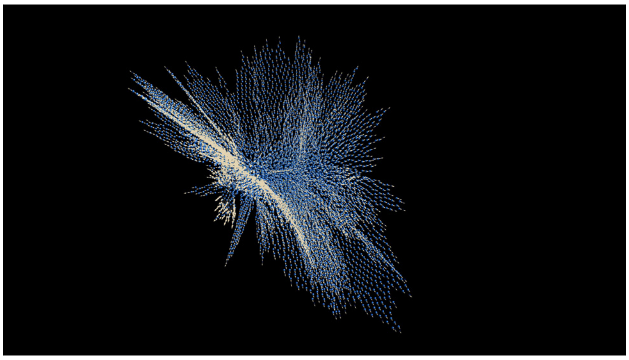

Figure 24.

A surface based non-manifold system. The proliferation direction is influenced y the neighboring cell's attributed vector

5.11 Vector Field as cellular force

Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Unary force	z=5.0
• Vector field force	strength 10.0
• Drag	0.5
Trigger for cell division	average distance >1.5 for 2 closest cells

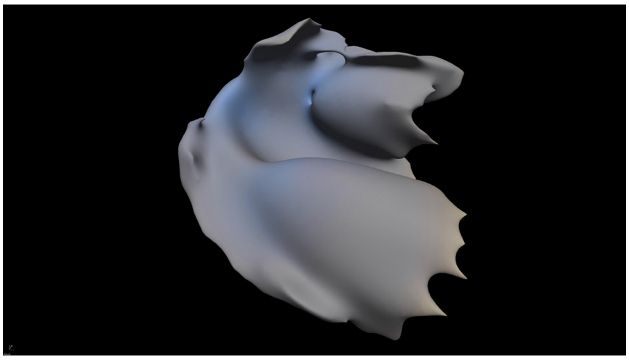

Figure 25.

A surface based non-manifold system. A unary force in combination with an attractor based vector field a e acting on the movement of the cells

5.12 Procedural cavitation

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	average distance >1.5 for 2 closest cells and less than 3 cells at a distance of 1.5

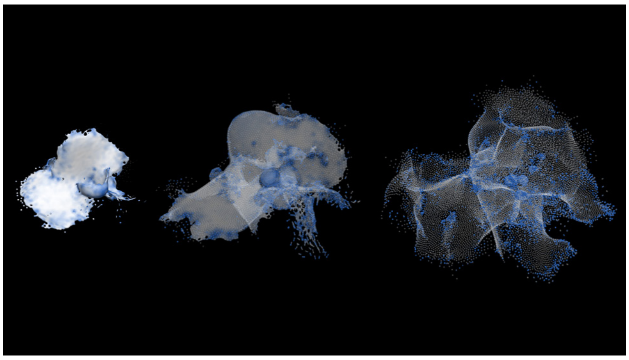

Figure 26.

Procedural cavitation generated through an increased contraction of peripheral cells. 3 stages of a simulation from left to right: The first semi enclosed bowl-like cavitation; the first ful y enclosed cavity with a second one forming at the top left; a later stage with several fully enclosed cavities

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6 Design Applications

The proposed simulations have been applied to the design of two case studies: The design of a permanent installation in an offic , and the design of an unbuilt house.

6.1 Gaizoshoku

The installation Gaizoshoku has been designed and constructed for the offices of IT company Baishan in Beijing and incorporates the company's reception area and desk. Various requirements had to be taken into account for its design, such as structural stability, human circulation around the structure, access to the surrounding spaces and the lighting conditions that the installation creates. Instead of generating a geometry and post-processing it to fit those needs, all of the requirements have been translated into intercellular behaviors and external influences Due to the highly emergent nature of the growth simulations, the fine-tuning of those behaviors was a time-consuming process that required extensive re-running of the simulations with slightly adjusted parameters in order to guide the geometry into its required form. It was nevertheless possible to achieve a suitable geometry solely through the simulation process, that at the same time generated a very characteristic geometry.

The growth simulation started at the bottom with a tendency to grow upwards. A central vertical line acted as an attractor that decreased in strength towards the top, while also the rough outline of the reception desk attracted cells. A strata force was used to generate parallel horizontal layers, with its strength increasing towards the top, thereby creating a relatively flat layer below the ceiling and more curving and inclined layers further down. Those forces then resulted in a geometry that allows for human circulation around it while still creating the desired surface and lighting effects above. Gaizoshoku was then constructed out of polypropylene sheets and assembled on site (Figure 27).

6.2 Ntopios

For the design of the house Ntopios, the client asked for a free form design that can be built using a cellular fabrication system of robotically extruded polymer. Instead of designing a geometry that can be built using the technology, Ntopios incorporated the logic of formation into the robotically constructed lattice system. The basic behavior of every cell to keep a specified distance towards its neighbors was used to generate the required regular lattice for the extrusion, while other behaviors cause the cells to form horizontal floor plates, enclose volumes with roofs and create a network of interconnected spaces with a useful circulation.

The algorithm has been successful in generating the geometry of a functional single family house with living, sleeping and auxiliary spaces. A strata force was used to create the horizontal surfaces for floors and roofs, while the resulting inclined areas between them form the vertical circulation. The cell division was terminated once large enough spaces had been generated. The grown lattice itself, which forms the logic of the robotic cellular construction system as well as the logic of the house, is also being used as the defining aesthetic element. It is exposed underneath the ceilings and continues out of the walls as furniture (Figure 28 & 29).

Compared to Gaizoshoku, the design of Ntopios required much less experimentation with the simulation parameters and relatively quickly resulted in a geometry that was suitable for the project. However, the design remained conceptual only and did not move to the construction stages.

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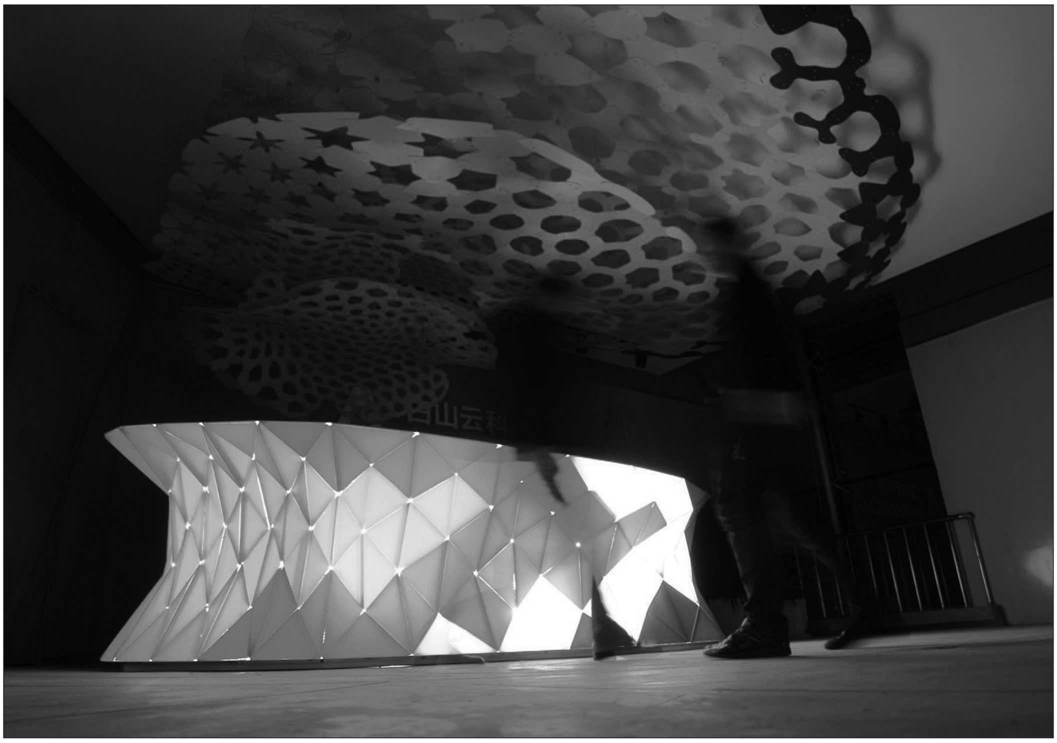

Figure 27.
Gaizoshoku

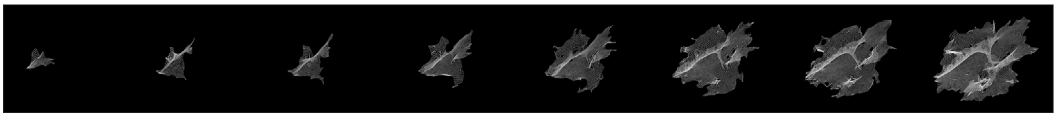

Figure 28.
Ntopios, cellular growth development.

Figure 28.
Ntopios, cellular growth development.

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7 Conclusions and future work

The The cellular growth simulations presented in this paper provide a novel tool for the computational generation of form for art and architecture. The proposed algorithms have been shown to be able to generate a wide variety of morphologies many of which show characteristics relevant for architectural applications.

The generalizations from previous work, especially the possibilities of surface-based non-manifold geometries and of volumetric geometries, allow for morphologies such as open geometries, multiple-cavity formations or continually expanding systems, which all provide important arrangements for the development of architectural space.

The results show that the growth simulations can generate networks, surfaces and volumes. Different degrees of enclosure can be created. The generation of parallel and orthogonal surfaces can be used as floo , wall or structural systems. Specific structural behaviors can be generated by applying gravitational forces onto the system. The morphologies can be free-form but can also be programmed to follow rectangular or other geometric systems. Various types of patterns, often organic or fractal in nature, can be generated on a small as well as a large scale.

It has been found that the intercellular behaviors have a high degree of emergence (Kwinter 2008). Due to this implicit rather than explicit nature of the systems (Liaropoulos-Legendre 2003), already small changes to the variables can result in very different outcomes. This makes it more difficult to generate a specific preconceived outcome, but it allows for unexpected characteristics of the resulting geometry. One of the main tasks for further development will therefore be the creation of mechanisms that let a user more easily influence the design outcome. The external influences on the contrary can very easily be set up to guide the growth of the cells towards a required overall geometry. Further research could therefore focus on the use of attractors, imported geometries as attractors and imported geometries as areas that constrain cell movement.

Also a growth according to structural constraints could be explored, with the aim of generating geometries that are suitable as load-bearing systems. The cell network could be analyzed iteratively as a Finite Element system, with the cells reacting locally to the forces or deformations that are identified

On a programmatic level it would be of interest to further explore the generation of enclosed spaces and their relation to each other, possibly similar to the way that the cells in an embryo start to form separate cavities and later organs. This could lead to a tool for space planning in order to develop occupiable spatial arrangements.

Acknowledgements
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Programming Flat-to-Synclastic Reconfiguration

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Abstract

Advances in architectural geometry make free-form architecture explicitly definable and economically manufacturable. Enhancing the efficiency of fabrication, this research investigates strategies of translating free-form synclastic surfaces to flat pre-programmed reconfigurable mechanisms. The presented bi-stable mechanisms are produced by creating voids on flat materials. In such mechanisms, the generated blocks are outlined by the voids that are connected by the hinges. The position and the orientation of the hinges allow the blocks to rotate around each other, and then reconfigure from flat to synclastic. During the reconfiguration process, the blocks are temporarily deformed. As the elasticity brings the blocks back to the original dimensions, the materials reach the second stable states. Distribution of hinges on the flattened surface needs to be designed according to certain geometric constraints. This paper demonstrates the workflow of identifying the positions of the hinges. The developed methods are validated through prototypes such as a spherical surface and a free-form synclastic surface.

Keywords

bi-stable mechanism; auxetic mechanism; flat-to-cu ved reconfi uration; programmable material; discrete differential geometry

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1 Introduction

The emerging demand for bespoke double-curved surfaces challenges designers and manufacturers. Utilizing sheet materials to produce curved-surfaces is an economical solution, given that such materials are easy to be industrially produced and processed. Exploiting economic benefits of sheet materials, numerous researchers investigate how to decompose a free-form surface to planar components on architecture scale (Pottmann, 2013). Meanwhile, various advanced approaches have been proposed to transform sheet material to double-curved surface, and pilot prototypes have been produced on laboratory scales, such as paper origami (Tachi, 2013), reconfigurable prestressed composite (Aldinger, Margariti and Suzuki, 2018) or deployable auxetic shells (Konakovic-lukovic, Konakovic and Pauly, 2018). These approaches make materials reconfigurabl , yet leave them vulnerable to bending stresses.

This paper proposes an approach that allows the reconfigu ed double-curved surface to resist bending stresses. The synclastic surfaces can be produced by introducing voids or slits on flat sheet materials. By either squeezing or expanding the materials, which closes the voids or opens the slits, then the sheet materials can be reconfigu ed into curved states (Figure 1). The voids creates gaps between the edges of blocks, while they remain interconnected via the tilted compliant hinges on the vertices. Additionally, these hinges allow the bending stresses to transmit across the blocks.

Geometrically, the major challenge lies in how to identify the set of hinges that can allow the blocks to be reconfigu ed from flat to curved state without residual strain or permanent deformation. Such hinges enable the material to stably maintain the desired shape instead of resuming its initial configuration Figure 2 illustrates an overview of the methods, which are explained in the following sections.

1.1 Outline

In the following sections, relevant research and mechanisms are reviewed in section two. Section three introduces the mechanical principles and the geometrical features of the reconfigurable mechanism. With these fundamental insights in mind, section four explains how to employ the explored approaches to transform a synclastic surface into its flat configuration For validation, pilot prototypes have been produced, and the production is reported in section fi e. Consequently, features of the current method and future works are summarized in section six.

2 Background

Since the 2000s, the demand for free-form architectures has gradually increased (Pottmann et al., 2015). The most effective way to build a large free-form surface is considered to be decomposing the curved surface into a series of flat panels (Pottmann et al., 2007). Although a considerable amount of unique components will be generated in the design process, the numerically controlled machinery can economically produce all the components from either 2D sheet materials (e.g., steel plates, float glass) or 1D profiles (e.g., steel tubes, extruded aluminum). However, the assembly of all the components is still a labor-intensive and challenging task for builders. Introducing bi-stable mechanism, the research aim is to develop a fabrication method of flat materials that can be reconfigu ed into the target curved states. With this objective, the research is built around the premises that such mechanisms can make the assembly process more efficient and less labou -intensive.

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In recent years, numerous ways have been proposed to deliver flat-to-cu ved reconfiguration for fast deployment. The reconfigurable systems may include embedded actuators or focus on the mechanisms to be actuated. In the first category, there are two distinct approaches. Some researchers control the reconfiguration through stacking materials with different expansion rates that create a composite system which respond to moisture or temperature changes (Tibbits, 2014; Reichert, Menges and Correa, 2015; van Manen, Janbaz and Zadpoor, 2017). During the ambient changes, the layered materials expand unevenly, cause curvatures on the composites. Meanwhile, some other researchers deposit stiff components on pre-tensioned membranes (Guseinov, Miguel and Bickel, 2017; Aldinger, Margariti and Suzuki, 2018). Once the pre-tensioning is removed, the contracting membranes actuate the composites to the curved configurations

On the other hand, the research in the second category concentrates more on the mechanism to be actuated. The researchers investigate how to arrange the flexible joints to permit mechanisms to be reconfigu ed into desired shapes. In the research pursued by Konakovic et al. (2016), the sheet materials are homogeneously cut into triangle panels, and the connections between the triangles are considered as ball joints. Then, the material can be stretched and bent into various free-form shapes. In the cases of origami and kirigami explored by Tachi (2013) and Liu et al. (2018), all the components are connected by linear hinges, or the crease lines, laying in the plane of the sheet material. The sizes and shapes of the components are informed by the desired curved surface. The difference between these two approaches is that origami forbids the designer to cut the sheet materials while kirigami allows one to do so. In these approaches, the ball joints and the linear hinges make the flat materials pliable. This attribute makes the products, in their target configurations incompatible with bending stresses.

In contrast to arrange linear hinges in the plane, Haghpanah et al. (2016) place the hinges vertically and produce another type of mechanism. The mechanism consists of multiple units that can be sequentially expended to other configurations and stably maintain the shapes. The features is termed bi-stability. Although both the initial shape and the reconfigu ed shape are confined in the plane, it suggests that the shape reconfi urable mechanism can also work on thick materials, which promise certain bending resistance.

A revised bi-stable mechanism is proposed in which the linear hinges are arranged in various orientation in the thickened sheet that allows one of the stable states to be on a plane and the other on a double-curved surface (Chiang, Mostafavi and Bier, 2018). However, the actuation of each bi-stable unit can happen independently or in sequence, which causes challenges of actuating mechanisms with in the multiple units. Figure 3 recapitulates the classificati n of the state of the art in reconfigurable mechanisms

In this research, the approach of tilted hinges on thick materials is adopted. proposing a more applicable reconfibration method that avoids sequencial actuation, the approach is integrated into the bi-stable auxetic mechanism proposed by Rafsanjani and Pasini (2016). Auxetic mechanism (i.e., a mechanism shrinks in all directions when it is only compressed in one direction) can distribute actuating force to the whole system and activate all the reconfigurable units at once. Introducing tilted cutting in design and production process, the bi-stable auxetic mechanism can be compatible in transforming from flat to double-cu ved.

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Figure 1.

Two examples of the proposed programmable material. Both of them can be manufactured in the flat configuration (left column) By either compression (top row) or tension (bottom row), the material can be mechanically activated and then rests at the curved configuration (right column)

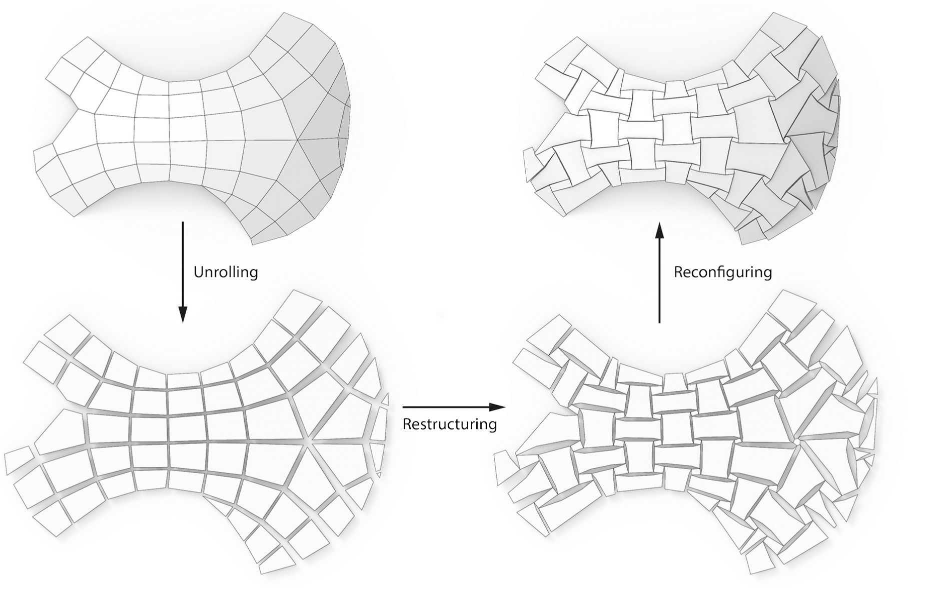

Figure 2.

The proposed workfl w of the design process. a. The quadrilateral conical mesh. b. Unrolled panels. c. Restructured panels with connectors. d. The free-form synclastic surface formed by the reconfigurable mechanism

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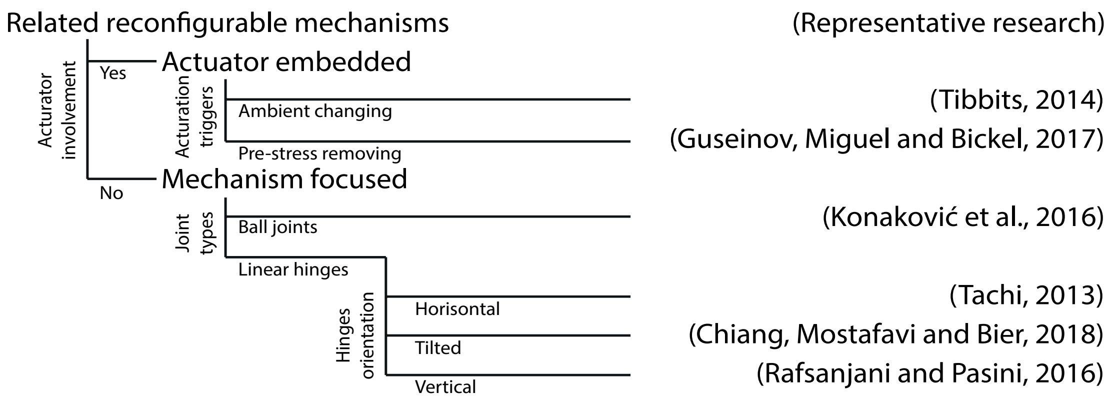

Figure 3.
The classification of elated reconfigurable mechanism

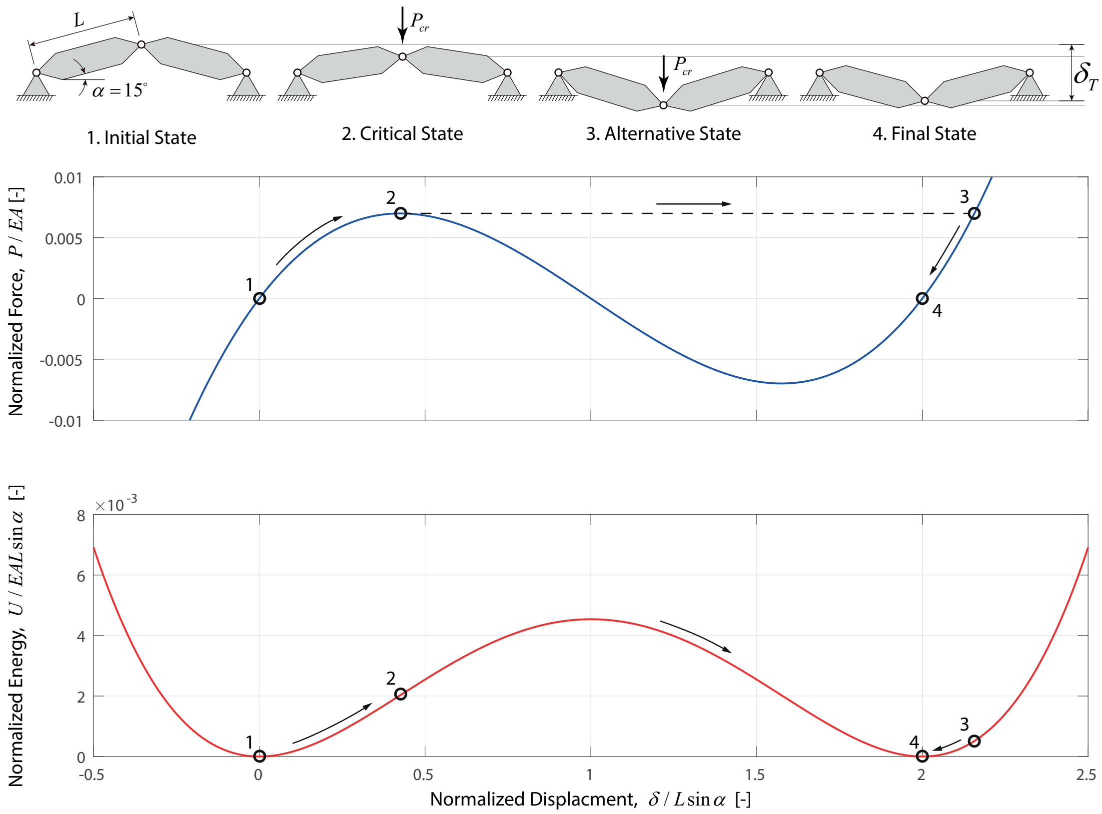

Figure 4.
The reconfiguration p ocess of the idealized bi-stable mechanism with two elements.

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3 Principles of bi-stable reconfiguration

The bi-stable mechanism is also termed as snap-through buckling (Huang and Vahidi, 1971). The term refers to the features that when the mechanism is switched from one stable state to another, the mechanism snaps-though. This section reviews the mechanical features of snap-through buckling, and introduces the principles of designing a snap-through mechanism capable of spatial reconfiguration

One of the simplest in-plane bi-stable units is illustrated in Figure 4, which consists of two linear structural members (with cross-sectional area *A* and material elastic modulus *E*) hinged to each other at one ends and pinned to the supports at the other ends. When an external force applies at the middle hinge, the two members are compressed and inclined. Until the external force exceeds the critical load, the reconfigur ble unit will suddenly deviate from the critical state to the alternative state. After the external force is removed, the elasticity of the material brings the mechanisms back to the relaxed length, which leads the unit to the final state. The total displacement of the middle hinge during the reconfiguration ollows

$$\delta\tau = 2L * \sin a \quad (1)$$

which suggests that the total displacement $\delta\tau$ is proportional to the rotating arm L and the sine of the tilting angle a.

Form the energy point of view, the stable states are corresponding to the local minimum points of the energy-displacement graph. When the hinges are ideally dissipating and storing no energy, the stable states are the mirror images of each other. In this paper, all the hinges are assumed to behave ideally, in order to design bi-stable mechanisms with geometric principals.

To make the mechanisms capable of conducting spatial reconfi uration, the hinges are designed to be not parallel to each other. As illustrated in the top row of Figure 5, given that three rigid blocks interconnected with ideal hinges and the four anchors are coplanar, the other stable configuration would be the mirror image against the plane defined by the four anchors. Between the two configurations the centre blocks rotate around the dash-dotted line. To physically made a mechanism resemble the ideal case, the material must be thickened to approximate the stiff blocks while the compliant hinges must be notched to minimize the strain energy it might store.

To be noted that due to the hinges are not parallel to each other, the connecting blocks (i.e., side blocks) have different rotating arms at the top and bottom surfaces, which result in different displacements at the two surfaces. To be more precisely, the magnitude of the rotating arms are proportional to the distances from the rotation axis, so as the displacement. In the case shown in Figure 5, there are no residual stresses in the blocks. Only if the hinges are compliant hinges, some stresses will occur locally at the compliant hinges.

This section has described the temporary elastic deformation during the reconfiguration After the bi-stable unit sets in the stable states, the deformation dissolves. Nevertheless, given that the hinges store negligible stain energy, the two stable states are simply mirror images of each other against the plane defined by the corner anchors. The next section introduces the method for applying this spatial reconfigurable unit to synclastic surfaces

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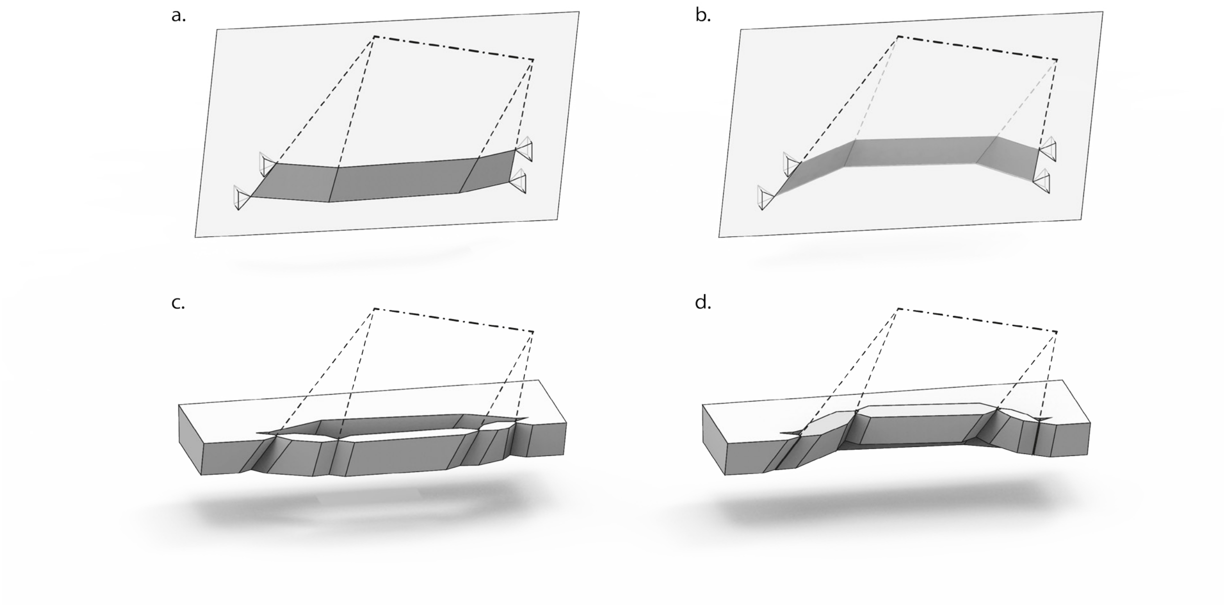

Figure 5.

The applied spatial bi-stable unit. a. and b. are the two stable states of a conceptual bi-stable unit. They are mirror images of each other against the mirror defined y the four anchors. c. and d. are the two stable states of the corresponding physically manufacturable bi-stable unit. The dashed lines are the extension of the hinges. They intersect at points defining the dash-dotted line which se ve as the virtual rotation axis of the center piece.

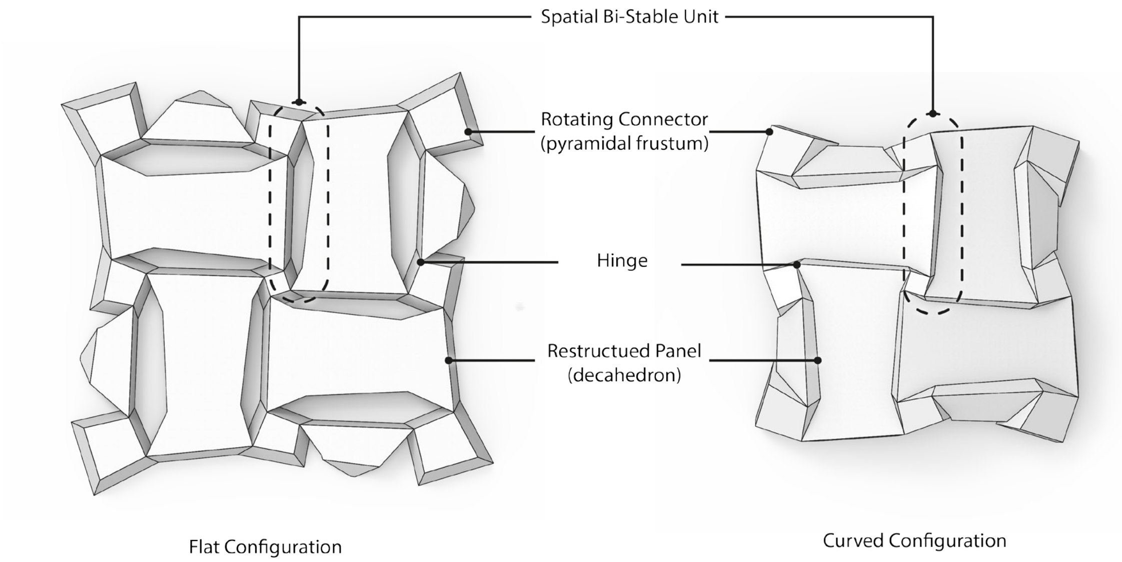

Figure 6.

The reconfigurable material consists of t o types of blocks: rotating connectors and restructured panels. The blocks are interconnecting each other with hinges.

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4 Geometrical design processes

4.1 Basic elements in the proposed mechanism

As demonstrated by Rafsanjani and Pasini (2016), the bi-stable auxetic mechanism can be achieved by arranging rotating quadrilaterals around concave octagons for in-plane reconfiguration To create a flat-to-cu ve mechanism, this paper revises two approaches of the previous research. The homogeneously repeated pattern and the perpendicular cutting are replaced by a heterogeneously graded pattern and tilted cutting. In this way, the thick sheet material can be reconfigu ed from flat to doubly curved.

Figure 6 illustrates how to build up the proposed mechanism with the spatial bi-stable units. Basically, every spatial bi-stable unit defines a hexagonal void in the sheet material, and the void can be closed in the other configuration Between the hexagonal voids, there are the rotating connectors and the restructured panels, which are discussed in section 4.3 in more detail. Additionally, the rotating connectors were prisms in the case presented by Rafsanjani and Pasini (2016). Here, the connectors are rendered as pyramidal frustums. The different lengths at the top and the base cause different displacements as suggested by equation (1). In the case depicted in Figure 6, the bottom surfaces with larger rotating arms introduce larger displacement during the reconfiguration and deliver the desired curvature without troubling bending stresses, which are commonly observed in other formative manufacturing processes, e.g. cold forging.

To arrange the hexagonal voids, the designers have to consider the voids as an interrelated system rather than multiple independent units. Given the fact that each hinge affiliates to two hexagonal voids, the two units have to agree on the position and the orientation of the shared hinges. Furthermore, the rotation angle of the hinge is also shared by the two voids. However, there is an outward method to design the interrelated voids, for an arbitrary conical synclastic mesh; in other words, no recursive iteration is required. In the following sub-sections, a workfl w is proposed to locate such solutions of the synclastic surfaces. The process starts with a conical mesh, which guarantees that the solution exists.

4.2 Unrolling an arbitrary synclastic conical mesh

This research designs the bi-stable auxetic mechanisms from conical meshes following the recommendation from Chiang, Mostafavi and Bier (2018). In conical mesh, each node has an axis intersected by all the bisector planes of the dihedral angles between surrounding facets. For detail concerning the definition and the features of conical mesh, readers are referred to the paper presented by Liu et al. (2006).

Here, a method for unrolling a synclastic conical mesh is proposed and demonstrated of flattening a mesh to make all the normal vectors of the facets point up. The targeted normal vector can be expressed as $(1, 0, 1)$ in Cartesian coordinates or as $(1, 0, \varphi)$ in spherical coordinates, where the vector has a unit length, a zero polar angle, and an azimuth angle φ that can be any real number. Let $\vec{n}_{P,i}^{\,c}$ be the normal vectors of panels in the curved mesh (where P stands for panels and c for the curved mesh), which can be expressed as $(1, \theta_i, \varphi_i)$ in spherical coordinates. Here, a "Neutral Surface" is proposed, which is defined that all the normal vectors of the mesh panels on the neutral surface have half as much polar angles as their corresponding panels have. As a result, the corresponding normal vectors $\vec{n}_{N,i}^{\,c}$ (where N refers to the neutral surface) equal to $(1, \theta_i/2, \varphi_i)$. Regarding the position of the neutral surface, the distance between it and the mesh can be arbitrarily decided. Once the distance is set, the vertices of the neutral surface can be determined by

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the extensions of the nodes' axes.

To unroll the conical mesh, the neutral surface would be turned concave-side convex, or be turned inside out (or be mirrored against the horizontal plane). Therefore, the normal vector of the flipped neutral surface $\vec{n}_{N,i}{}^{f}$ (where f stands for both flipped and flattened) becomes $(1,-\theta_i/2, \varphi_i)$. Before and after the unrolling, the facets of the neutral surface are turned $-\theta_i$ in total. Let every mesh panel of the curved conical mesh be turned as the corresponding facet on the neutral surface does, which means that the inclination of the mesh panel will also be turned $-\theta_i$. Then the normal vectors of the unrolled panels will be $\vec{n}_{P,i}{}^{f} = (1, 0, \varphi_i)$. During the flipping of the neutral surface, the rotation angles make the normal vectors point upright as desired. The unrolling process is illustrated in Figure 7. Unrolling a synclastic conical mesh via such a neutral surface guarantees a smooth journey to locate the legitimate hinges. The application of the unrolling method is also demonstrated in Figures 12 & 13.

The term neutral surface echoes the neutral plane in the conventional bending theory. In the bending, all the lengths on the neutral plane are preserved, which means that there is no compression or tension. While the material in one side of the neutral plane get either compressed or tensioned. A similar feature can be observed in the reconfiguration process, as shown in Figure 10. The material above or below the neutral surface reconfigu es to the curved state by either stretching or contracting.

4.3 Connecting panels with rotating pyramidal frustum

The primary task of this section is to locate the legitimate hinges, which dictate how the blocks rotate around each other. Ideally, the hinges should bring all scattered nodes in the flat configuration back to the same position in the curved configuration Figure 8 shows a set of functional hinges (dashed lines) that merges the panels and closes the gaps.

There are only three independent degrees of freedom for a node to design the hinges, considering the hinges and the rotating have to coordinate with each other. In general, there are fi e degrees of freedom in a rotation in 3D space. Two of them are the position of the rotation axis, two of them are the orientation of the axis, and the other one is the rotation angle. For a unrolled node (as shown in Figure 8), the rotation axes should pass through the node on the neutral plane which fi es two of the degrees of freedom for every panel. If one of the panel is assigned with the three undetermined, all the other panels have to rotate dependently to the first panels. Therefore, there are only three independent degrees of freedom; two of them can be regarded as the orientation of the merged axis (black dotted line in Figure 8), and the other one is the magnitude of the rotation angle.

Once the hinges are determined, the intersection points of the hinges and the mesh panels define a polygon. For a four-edge node, the polygon is quadrilateral. When the sheet material has a certain thickness, the quadrilateral turns out to be a frustum of a quadrilateral pyramid. The gaps between the mesh panels have to be restructured accordingly as shown in Figure 8.

As discussed, for each node, there are three independent degrees of freedom to define the rotating connectors. But the nodes on the same edge of the mesh still have to agree on the inclination of the gap in the flat configuration In other words, for a mesh with n nodes and m edges, there are $3n$-m degrees of freedom to be determined for all the rotating connectors. One way to omit the iteration is to determine the rotating connectors node by node. A node that is determined later has to align itself to the previously determined nodes. Therefore, only the first node has three degrees

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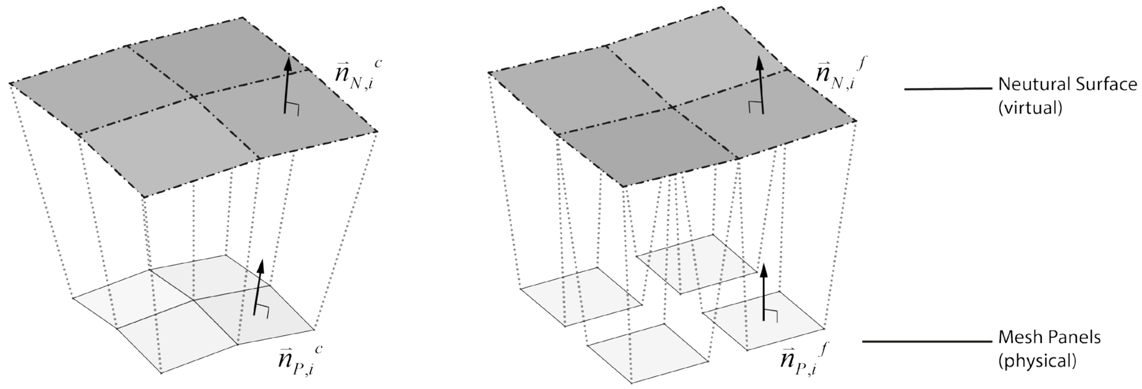

Figure 7.
The axes (dash-dotted lines), which the mesh panels rotate around, form the "Neutral Surface." The inclination of the neutral surface is half of the corresponding mesh panel. During the reconfiguration the neutral surface is turned inside out, which suggest that the inclination angles are opposite to the original. Then the corresponding mesh panels will follow the rotation of the neutral surface and turned to be zero inclination in the end.

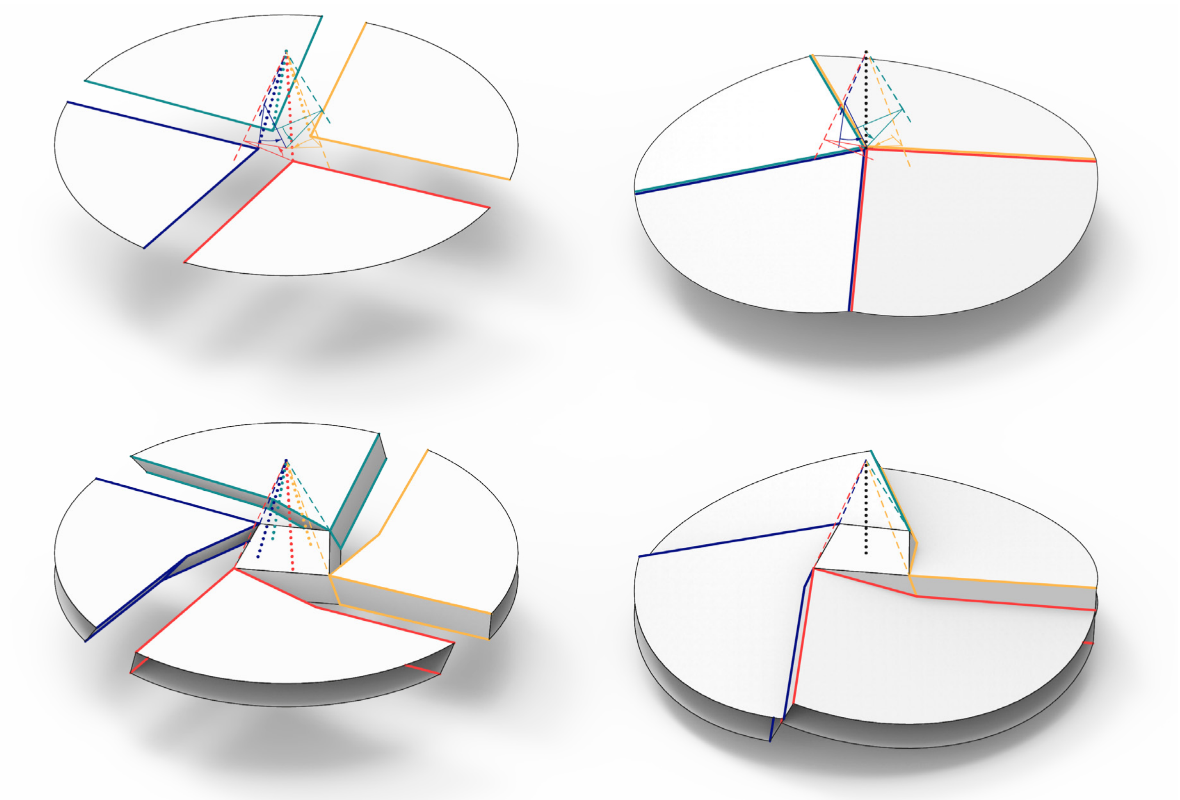

Figure 8.
Close up on panels rotated around the hinges (dashed lines). Each panel has its hinge (in the same color), while all the panels merge at the same axis (the center black dotted line).

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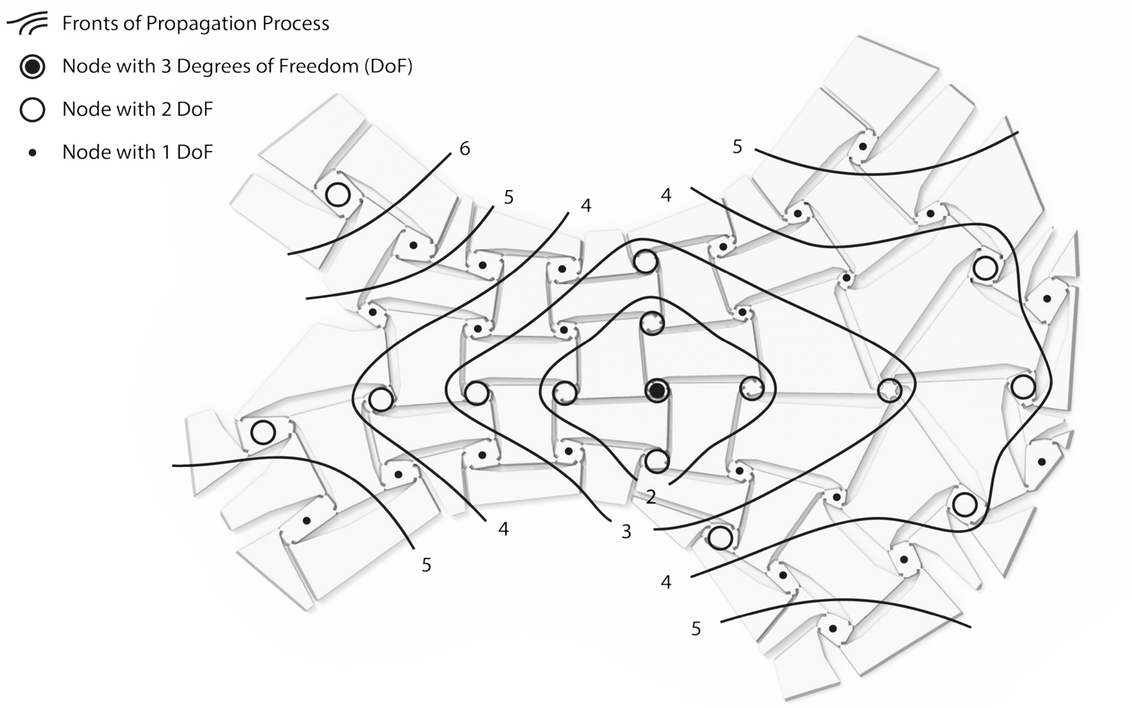

Figure 9.
The propagation map of the free-form conical mesh.

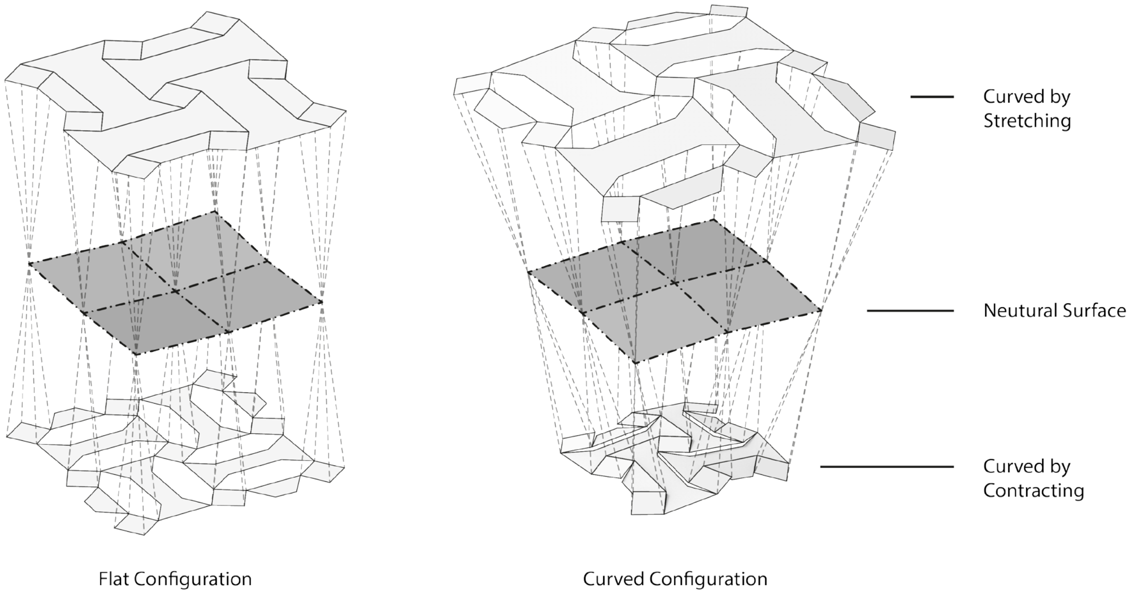

Figure 10.
The focal points of the hinges locate on the neutral surface. The neutral surfaced is mirrored during the reconfiguration which means that all the length on the neutral surface remains constant before and after the reconfiguration On the other hand, above and below the natural surface are expanding the zone and contracting zone respectively.

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of freedom. Other nodes may have two or only one degree of freedom, depending on how the determination propagate. Figure 9 shows an example of how the process propagates throughout all the nodes of a free-form mesh. So far, this section has presented the methods to unroll a synclastic conical mesh, to locate the legitimate hinges, and to restructure the mesh panels. Figure 10 visually recapitulates the relationship between the neutral surface and the legitimate hinges. It is noteworthy that if hinges are extended to the other side of the neutral surface, a solution of curved by stretching can also be identified

5 Prototyping with 5-axis CNC waterjet

The previous sections have introduced the mechanical property of the proposed spatial bi-stable unit and the method of applying such units to form an auxetic mechanism. In this section, the discussion is focusing on how to transform the geometrical solution to physically producible cutting tool path.

To provide the general idea, Figure 11 shows a glimpse of the process, modifying a geometrical solution to a producible solution, which leads to the waterjet cutting path. To make the design physically producible, the hinges must have physical widths. On the contrary, the hinges are regarded as mathematical lines with zero widths, in the previous geometrical analysis. To make the hinges have a physical width, the process explained by Figure 5c & 5d is adopted, thickening the bi-stable units and notching the compliant hinges. The 200mm-by-200mm prototype shown in Figures 11 & 12 is made from 4mm thick polypropylene sheet with 5-axis CNC waterjet machine, and the width of the compliant hinges is set to be 0.8 mm after a few trial and error tests. Polypropylene is a flexible and resistant to fatigue. These material properties make the prototype repeatedly reconfigurabl .

The proposed workfl w has been validated on a spherical surface. The design and analysis methods have also been applied to a free-form surface (Figure 13). The production with a 5-axis waterjet is under the arrangement.

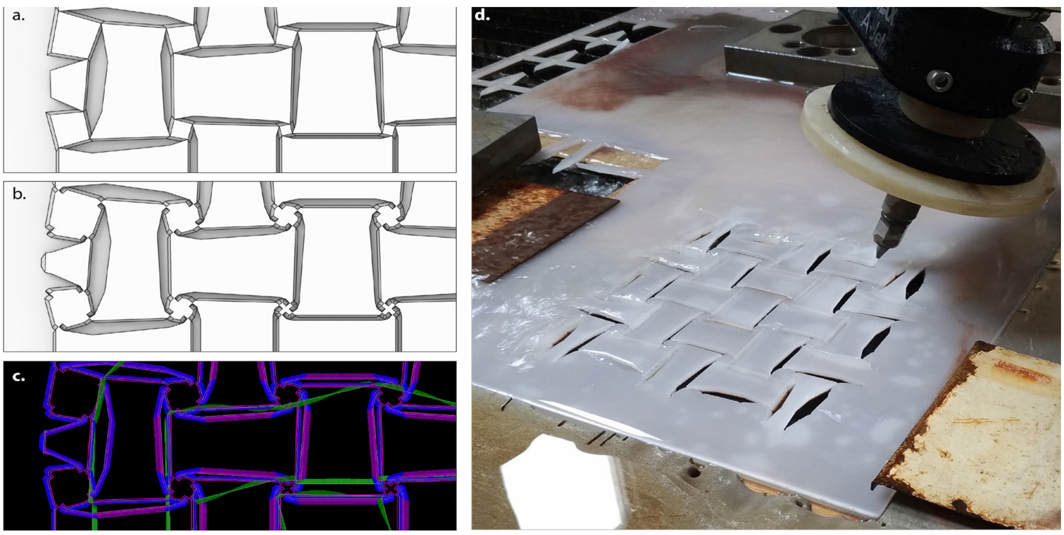

Figure 11.

The production process and the result of a 25-panel spherical surface. a. The close up of the geometrical solution. b. The producible solution. c. The tool path for waterjet cutting. d. The production with a 5-axis CNC waterjet machine.

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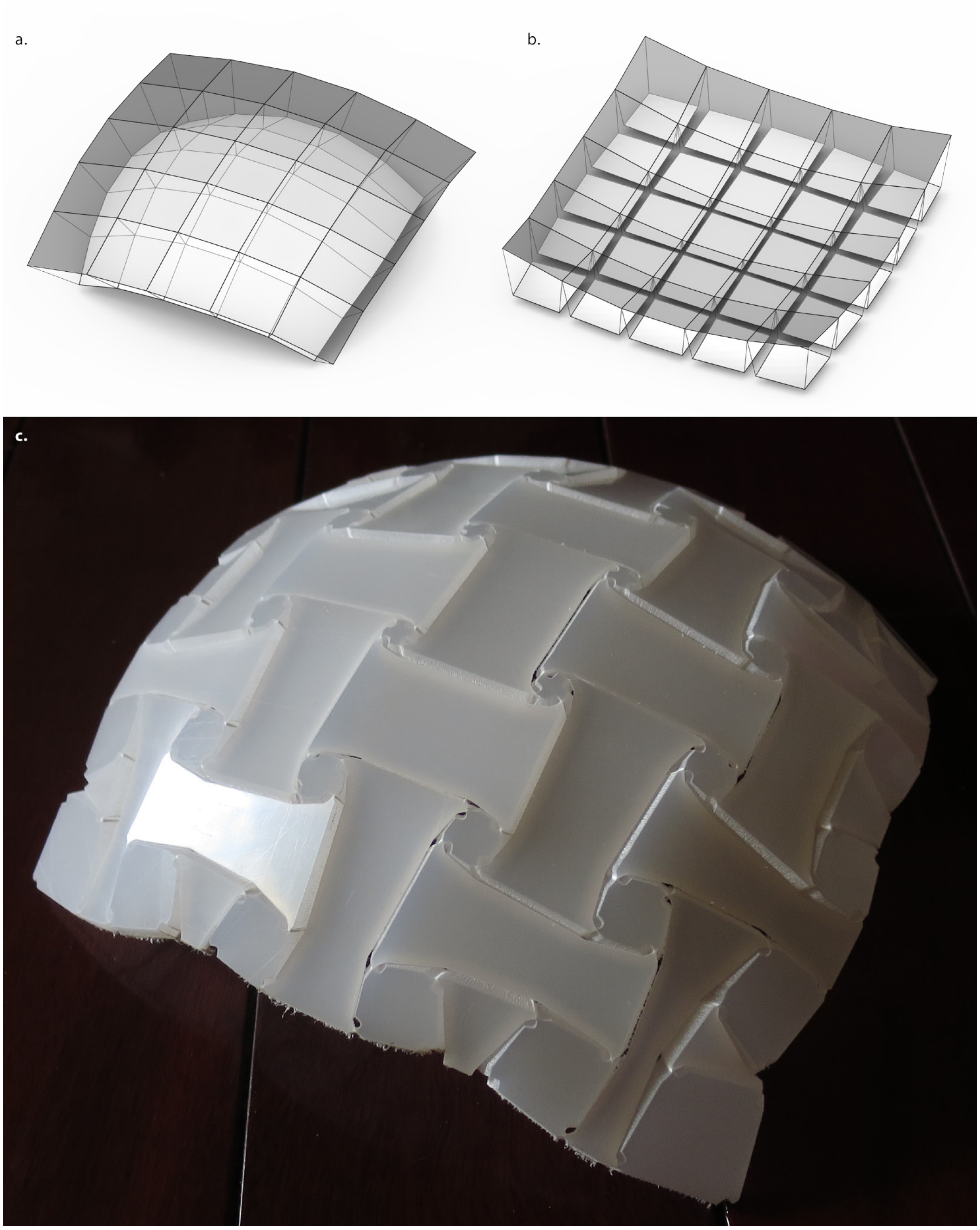

Figure 12.
The process of designing the spherical surface. a-b. Unroll the mesh panels with the Neutral Surface. c. Physically produced results.
The video of the flat-to-cu ved reconfiguration p ocess can be accessed via https://youtu.be/KvPXyMupNOA.

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6 Conclusion and future works

This paper has presented a method to translate free-form synclastic conical meshes to cutting patterns on sheet materials. Then, the cutting patterns enable the sheet materials to be transformed into the desired shapes when the mechanisms are mechanically activated. The activation can also be pre-designed as either stretching or contracting. The design processes of the cutting patterns consist of three steps. In the first step, unrolling the synclastic conical mesh with the proposed neutral plane automatically introduces the gaps with appropriate widths. In the second step, the proposed frustum connectors can automatically distribute different reconfiguring displacements at top and bottom surfaces. With these two steps, there is neither bending stress nor residual strain in the blocks. In the third step, the geometrical solution is revised into the producible solution for 5-axis waterjet cutting machine. Due to the hinges are compliant hinges in this production method, there will be local strains at those hinges.

To investigate the capacity of the proposed mechanisms, some future works have to be continued. So far, neither the applicability on larger scales nor the dynamic behavior of the mechanism during the reconfigura ion has been explored yet. Additionally, the proposed neutral plane are not compatible with anticlastic surfaces. Methods to unroll an anticlastic surface are important topics to increase the applicability. After these topics are addressed, broader applications may be achieved. I believe a pavilion-like shell structure can be erected with this mechanism in the coming years.

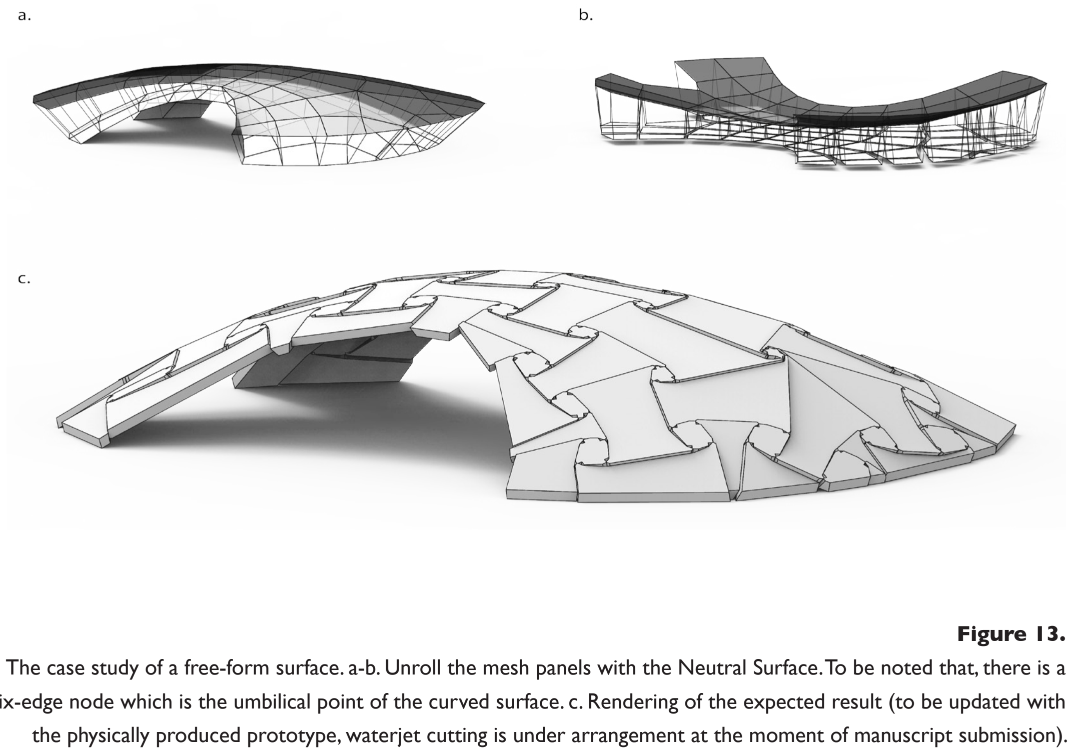

Figure 13.

The case study of a free-form surface. a-b. Unroll the mesh panels with the Neutral Surface. To be noted that, there is a six-edge node which is the umbilical point of the curved surface. c. Rendering of the expected result (to be updated with the physically produced prototype, waterjet cutting is under arrangement at the moment of manuscript submission).

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Novel bending-active system with controllable curvature-stiffness relation

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Abstract

This research presents a novel bending-active system, whose maximum curvature is not constrained by the required final stiffness of a given structure. This has been achieved by the development of low-tech structural elements which increase their stiffness when they reach a predefined curved geometry, relying exclusively on geometrical configurations. Physical and digital experiments have been conducted in order to document the structural performance of the latter system. More specifically, the numerical results of load-deflection experiments, as well as the Finite Element Analysis of the joinery detail are presented in this paper. The latter results prove the change of stiffness of the developed system and its scalability. The fact that the construction manual is embedded in the internal geometry of the elements, constitutes them ideal for the efficient construction of large-scale curved structures.

Keywords

Active-bending; free-form; adaptive stiffness; wood joinery; scalable systems

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1. Free-form structures

Curved elements are known for their high structural performance. Thus, they have been used to solve construction challenges through history. For instance, Romans were able to build large-span structures and revolutionized architecture by using curved architectural elements, such as arches, vaults and domes. Previous examples refer to vernacular architecture such as the easily erected temporary shelters of Arabs (Mudhif since 3300 BC), which consist of arches made of bent reeds. In addition, a pioneer Swiss engineer of the 18th century, Hans Ulrich Grubenmann, achieved to build large span timber structures, such as roofs and bridges, by using bent layered beams.

At more recent times, during 19th and 20th century, a set of simple structural typologies controlled the geometrical complexity. This was caused due to the development of reinforced concrete, as well as the industrial revolution and the need for cheap mass production (Lienhard et al. 2013). Nevertheless, in 1990s, the first digital revolution took place and affected broadly the architectural realm. A new digitally driven architectural style which illustrated the technological change of the epoch evolved; the style of spline (Carpo, 2017). At that moment, various architects proved that complex geometries can be designed and materialized by using computational software, digital fabrication techniques and materials with enhanced properties. On top of that, after the construction of the Sydney Opera (1957-73) a tendency for a 'New Structuralism' emerged. During that period, the dialogue between the architects and the engineers started to appear from the early design stages, encouraging geometrical complexity. The material started to play a very important role on the development of a structure and subsequently at the design of a form (Oxman and Oxman, 2010), likewise in vernacular architecture. Nevertheless, it was not until the second digital turn (2010s) that the construction of free-form surfaces became affordable due to technical virtuosity (Carpo, 2017).

Summarizing, it is evident that nowadays the production of curved geometries preoccupies the construction industry. However, the latter still remains expensive and labour intensive despite the fact that technology progressed. One reason is that the production of custom curved elements is time-consuming. Additionally, it requires highly qualified manufacturers and construction workers. Moreover, the need for moulds increases the construction cost and the material waste. Finally, the logistics of free-form elements are more costly compared to planar elements since they occupy larger storage and transportation space.

2. Active-bending as a construction technique for free-form geometries

In the 1960s Frei Otto initiated the construction of large-scale free-form gridshell structures (e.g. Mannheim Multihalle) out of flat beams, which were formed on-site into the desired geometry by cranes and scaffold systems (Liddell, 2015). The latter construction process was an efficient way to build curved structures since a) it eliminated the need for moulds, b) simplified the manufacturing of the elements, and c) minimized the transportation space. However, the installation was very complicated and many elements broke. As a result, in the last decade, several researchers have focused on the further development of such construction processes by implementing form-finding techniques using computational methods. Thus, active-bending, a structural system that takes advantage of the elastic deformation of specific materials in order to form curved geometries, has evolved as a new research thematic.

Many experimental pavilions have been built with the latter technique from various universities in order to optimize the design and construction processes, as well as the material performance.

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Besides that, several elastic gridshells have been built by various materials, such as aluminium tubes, glass fiber reinforced polymer (GFRP) tubes, stainless steel lamellas and bamboos (Lienhard and Gengnagel, 2018).

However, existing active-bending systems have limitations in scale (Lienhard and Knippers, 2013). The biggest the curvature that should be constructed is, the thinner the elements are, and thus the final structure is less stiff. One way to confront the latter problematic can be found in the StrechPLAY, textile-hybrid prototype. The structure is made of a laminated beam which consists of 3 GFRP rods combined into a knitted sleeve. As a result the beam is flexible during the construction (3 small cross sections) and once formed into its final configuration is impregnated with epoxy resin in order to gain its final stiffness (one larger cross section). Other researches solve the problematic by introducing additional stiffeners in the bending-active structures, such as cables and tensile fabrics (Lienhard and Knippers, 2015) (Gengnagel, Alpermann and Lafuente, 2013). Despite the good structural performance of the aforementioned structures, their construction process is complicated and time consuming.

On the contrary, the presented system suggests a novel, rapidly erected bending-active system with controllable curvature-stiffness relation, eliminating the need of extra stiffeners. This low-tech system has been achieved by leveraging geometrical configurati ns and material properties, like in vernacular architecture. More specifical y, the system is created by multi-layered linear elements with embedded shear blocks (Fig. 1). The relative slip between the layers defines the flexibility and the final stiffness of the element. The slip is enabled by small gaps that are designed between the shear blocks of consecutive layers. The calculation of the gaps and thus the design of each element is the output of an algorithm. The input of the latter algorithm is a curve, with the predefined desired curvature, a cross section, material properties and the length of the shear blocks. The algorithm calculates the strain developed at the layers when they bend at the predefined curvature and subsequently the lengths of the required gaps (Baseta et al., 2018). The layers can be produced by digitally fabrication techniques and assembled together. The result is an element that is flexible when it is flat and stiff when it reaches its predefined curvature. The flexibility and the maximum curvature depend on the gap length. On the contrary, the final stiffness of the element depends on the number of the layers, their cross section and the frequency of the shear blocks. Thus, for the realization of an element with big curvature and high stiffness, multiple layers with small cross sectional height and big gap lengths should be made.

3. Research methodology

The methods which have been used for the development of the aforementioned bending-active system are based on physical and digital experiments. On one hand the physical experiments focus on prototypes of different materials and scales which are produced with various digital fabrication techniques. The performance of the latter prototypes is thoroughly tested and documented. On the other hand, the digital experiments rely on performance simulations and provide feedback in order to improve the physical prototypes. The evaluation of both types of experiments is vital for the optimization of the suggested construction system.

More specifical y, two gridshell prototypes have been built with notched double-layered elements. The latter prototypes proved that double-layered notched linear elements, made of timber, can bend in a controlled manner. Thus, they can be self-organized into curved gridshells which consist of planar curved elements (Fig. 2) (Baseta and Bollinger, 2018). Finally, given that the discussed el-

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ements can be reverted back to their original flat configuration and this process can be repeated several times, the system is ideal for temporary structures. The latter structures can be easily transported considering that they consist of flat elements. Moreover, they can be quickly assembled since the construction manual for each curved element is embedded in their geometry.

4. Load-deflection diagrams

In order to prove that the stiffness of the aforementioned system is controllable and independent of the curvature, physical experiments have been conducted. In the latter experiments, the deflection of cantilevering, double-layered beams with embedded shear blocked (notched) has been measured under various loads applied at the tips of the cantilevers. More specifical y, three experiments have been conducted in different scales with different cross sections and lengths of the specimens (Fig. 3). The specific scales have been chosen in order to demonstrate the functionality of the system and thus its potential application in three market sectors: a) Small products, b) Furniture, and c) Architecture.

To better understand the experimental data from the tests, a basic background on the deflection of a cantilever is given here. The numerical model for the calculation of the maximum deflection of a cantilevering beam is given in the following equation:

$$u\_max=(F\ l\^3)/(3\ E\ I)$$

where umax is the maximum deflection in z direction, F the induced load, l the length of the cantilever, E the modulus of elasticity and I the moment of inertia.

Applying the above equation for solid beams to draw the corresponding load-displacement curves, a straight, inclined line is given (red curves in Fig. 6, 9 and 13). The inclination of the latter line indicates the load-deflection ratio which corresponds to the stiffness of the beam. The lines start from 0,0 since from the above equation derives that the deformation is 0 when there is no load. However, the curves that illustrate the experimental data (blue curves in Fig. 6, 9 and 13) do not start from 0,0. This is due to the deformation caused by the dead load of the specimens which is considered as the starting point of the curves.

The first experiment tests two 3D printed sticks, with a rounded zig-zag joinery detail and different gap lengths (Fig. 4). The cross section of the double layer is 5x5 mm and their length is 0.2 m. Each specimen was digitally fabricated in high quality by an Ultimaker 2 in 30 minutes. The fill was 100%, the layer height 0.2mm and the used material was Polylactic Acid (PLA). The flexibility of the latter material enables large deformations although there is a high creep rate when long term deformations are induced.

In order to collect the deformation data of the specimens, the sticks were clamped (10 mm) and 0.19 m were cantilevering. Subsequently, loads of 0.49 N, 0.98 N, 1.47 N, and 1.96 N were induced sequentially at the tip of the sticks as shown in Fig. 5b and Fig. 5c. Figure 6 shows the load-displacement graph of the aforementioned test. Both double-layered notched sticks indicate a change at the magnitude of their deflection after 1.47 N were induced (blue circle in Fig. 6). At this point, the gaps closed and thus, their cross-sectional height increased. This results in a change of the stiffness of the sticks, which is represented by the inclination of the curves. The stepper the curve is, the stiffer is

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the specimen. Moreover, the specimen c shows a slightly larger deflection than the specimen b. This is due to the longer gaps of specimen c, considering that he bigger gap of specimen c is 3 mm while the one of specimen b is 2 mm (Fig. 4).

For comparison purposes, a solid beam with cross section 5x5 mm was tested (Fig. 5a) as well as the bottom layer of beam c (Fig. 5d). From their load-displacement graphs it is evident that the specimen a is the stiffest while the specimen d is the most flexibl , as expected. However, the curve of the specimen d has initially the same inclination with the specimens b and c. This verifies the fact that the double-layered notched sticks are as flexible as their layers until their embedded shear blocks are activated. Finally, the load-displacement curves of the solid sticks are not completely straight as calculated from the numerical model (red line in Fig. 6). This is possibly due to initial creep of the 3D printed stick. Nevertheless, given the small scale of the specimens and the possible imprecision of the measurements (in a scale of a millimetre) this can be neglected.

In order to receive more precise results, a second experiment with 4 times bigger cross section, made of timber has been conducted. The specimen is a robotically fabricated double-layered lath, with zig-zag joinery detail. The fabrication of the two layers lasted 15 minutes with a kuka robot. The cross section of the double layer is 20x20 mm and its length is 1.9 m (Fig. 7). The used timber is white ash, a wood which has the capacity to elastically deform with minimized creep. Moreover, the white ash was considered appropriate for the milling of small cross sections since it is dense and straight-grained. This results in a nice finishing and thus in a more precise joinery detail.

In order to collect the deformation data of the lath, the latter was clamped in one end (0.1 m) and loads of 4.9 N, 9.8 N, 14.7 N, and 19.6 N were induced sequentially at the other end as shown in Fig. 8a. Zip ties have been placed every 0.3 m in order to keep the layers attached in y direction (perpendicular to the long axis and parallel to the ground). Figure 9a shows the load-displacement curve of the aforementioned test. The change of inclination of the curve (blue circle in Fig. 9) co-incides with the moment that the shear blocks are activated, as shown in figu e 8a. At that specific moment, the specimen acquires an increased stiffness with the enhanced cross section. In order to verify this behaviour, the same test has been conducted for a double-layered lath (each layer has cross section 10x20) without shear blocks (Fig. 8b). As indicated in Fig. 8, and in the corresponding load-displacement curve (b in Fig. 9), the deformation of the specimen b is larger than the one of the notched lath a. This proves that the shear blocks play an important role on the bending behaviour of the lath. Thus, double-layered linear elements with identical cross sections can bend differently according to their internal joinery details.

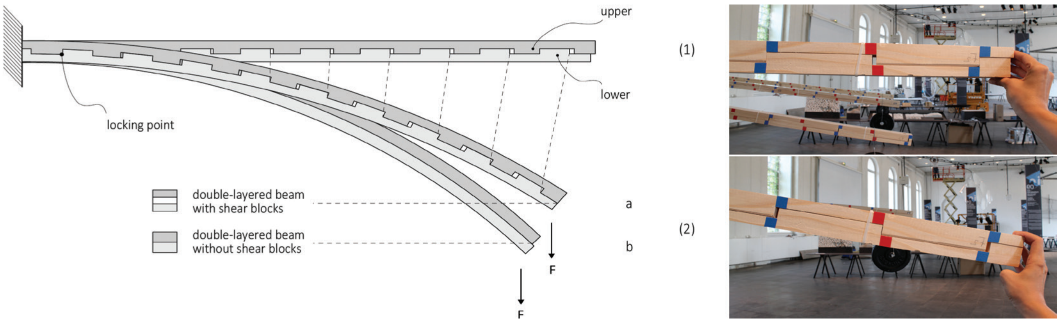

Figure 1.
Cantilevering double-layered linear element with shear blocks: 1) Flat and flexible state without orces, 2) Deformed and stiff state induced by force F (Baseta et al. 2018).

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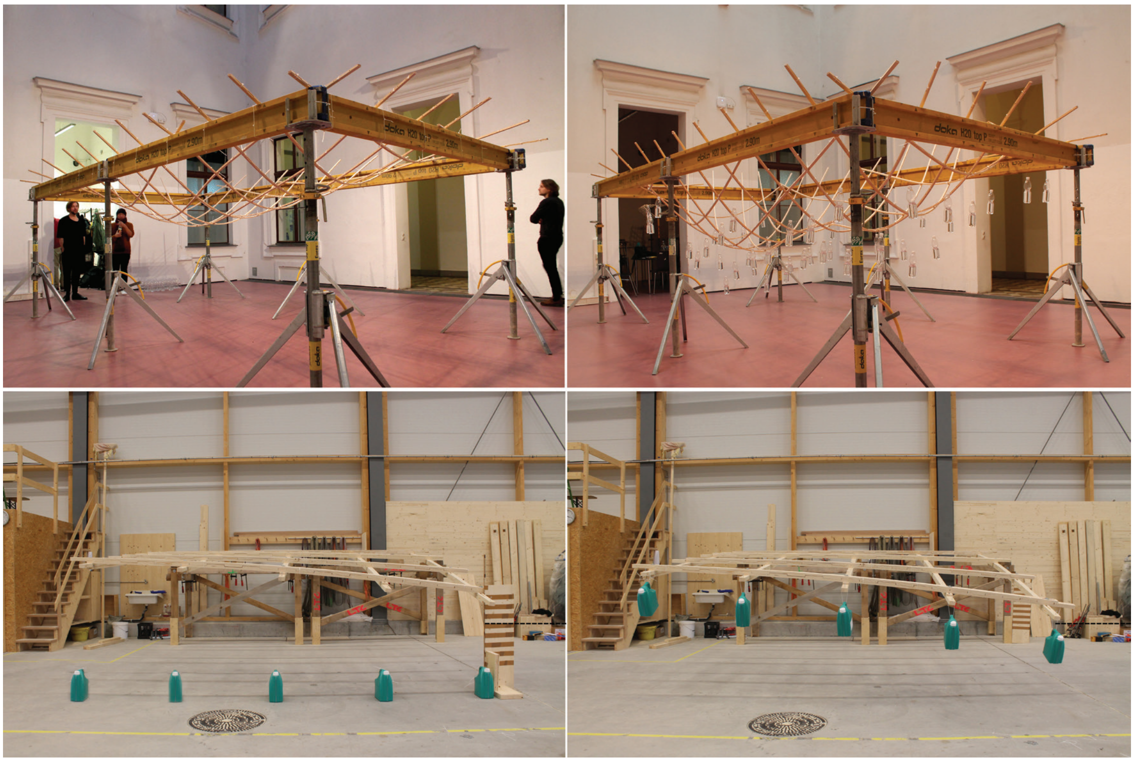

Figure 2.
Self-organized doubly-curved gridshells by gravitational loads (Baseta and Bollinger, 2018).

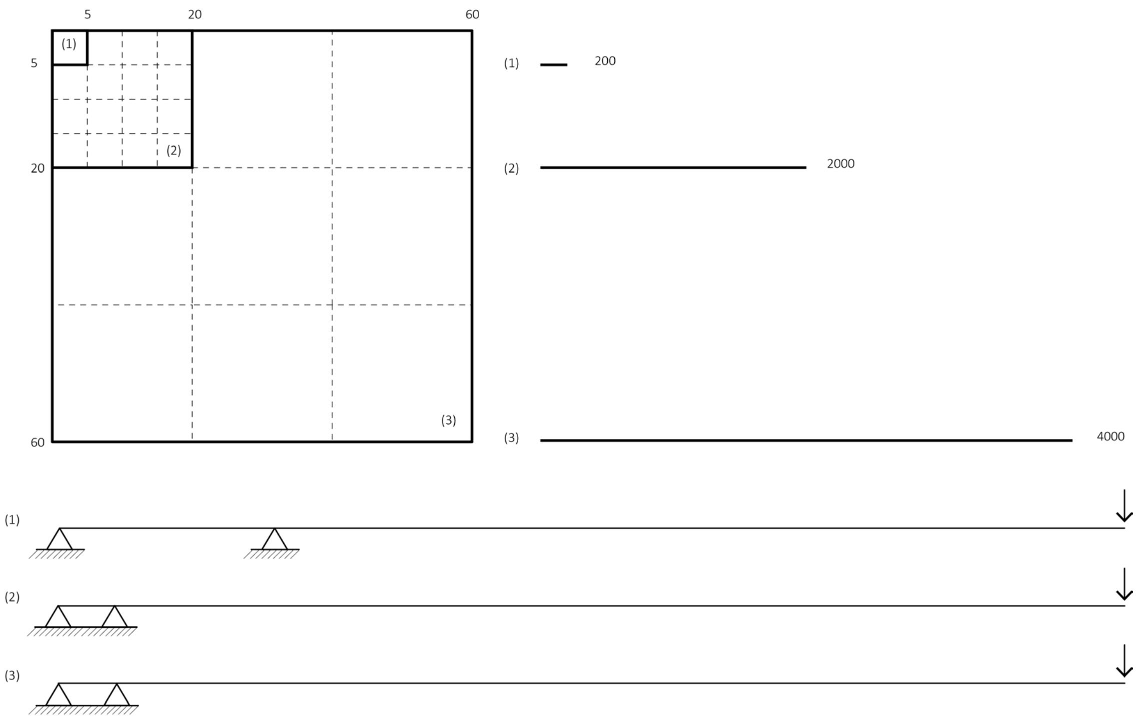

Figure 3.
Comparison of the cross sections and lengths of the specimens for the three experiments.

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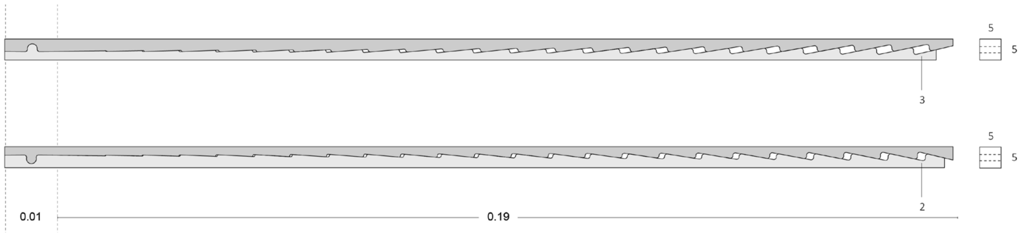

Figure 4.
Specimens for the 1st experiment (cross sections in mm and length in m).

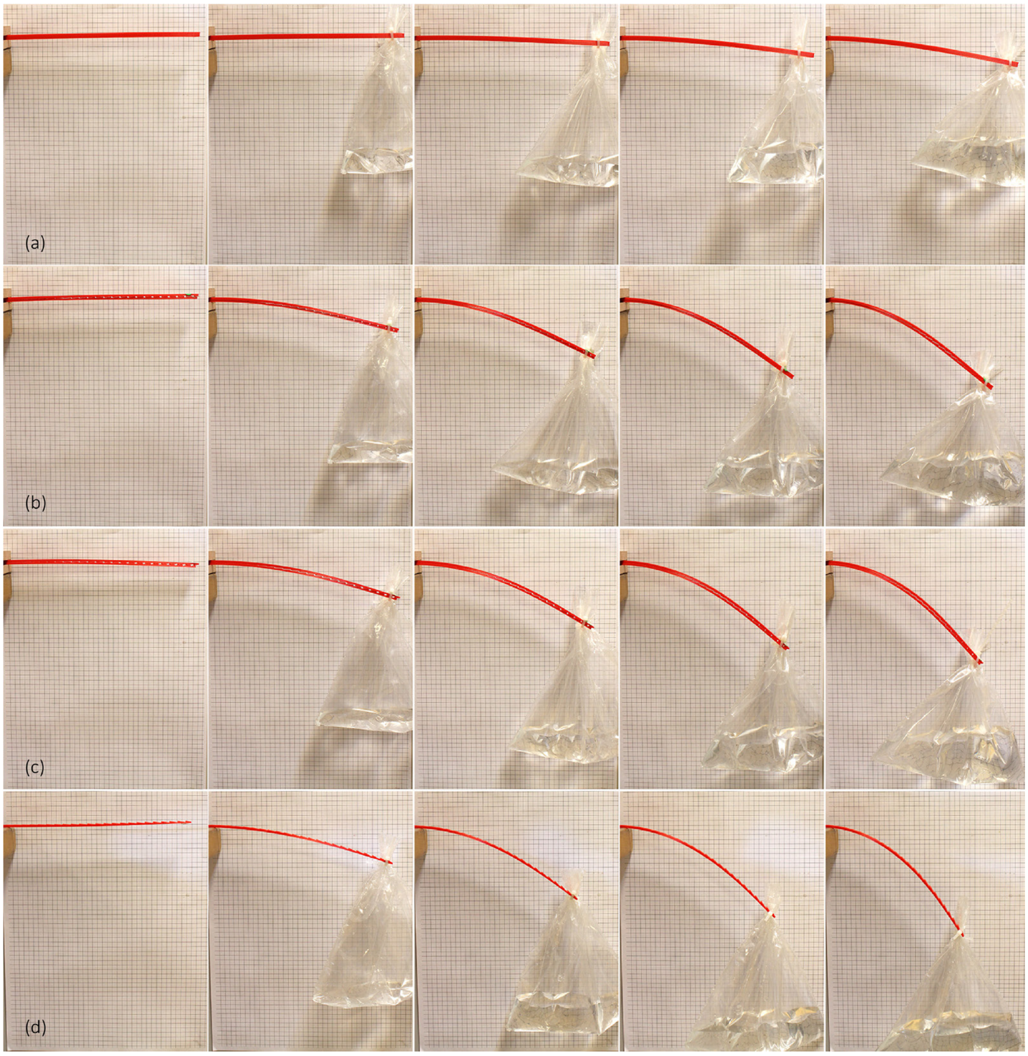

Figure 5.
Setup of the 1st experiment.

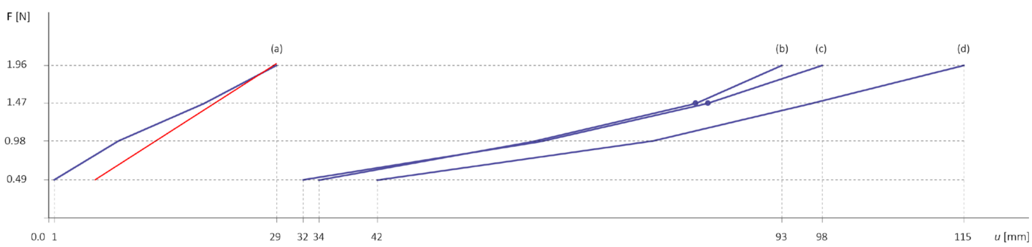

Figure 6.
Results from the 1st experiment.

Novel bending-active system with controllable curvature-stiffness relation

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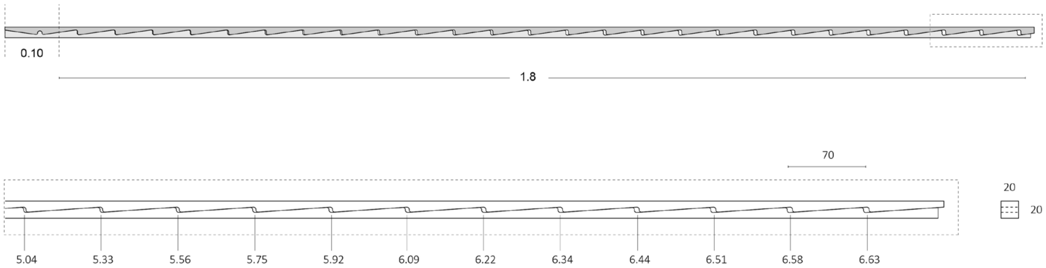

Figure 7.
Specimen for the 2nd experiment (cross sections in mm and length in m).

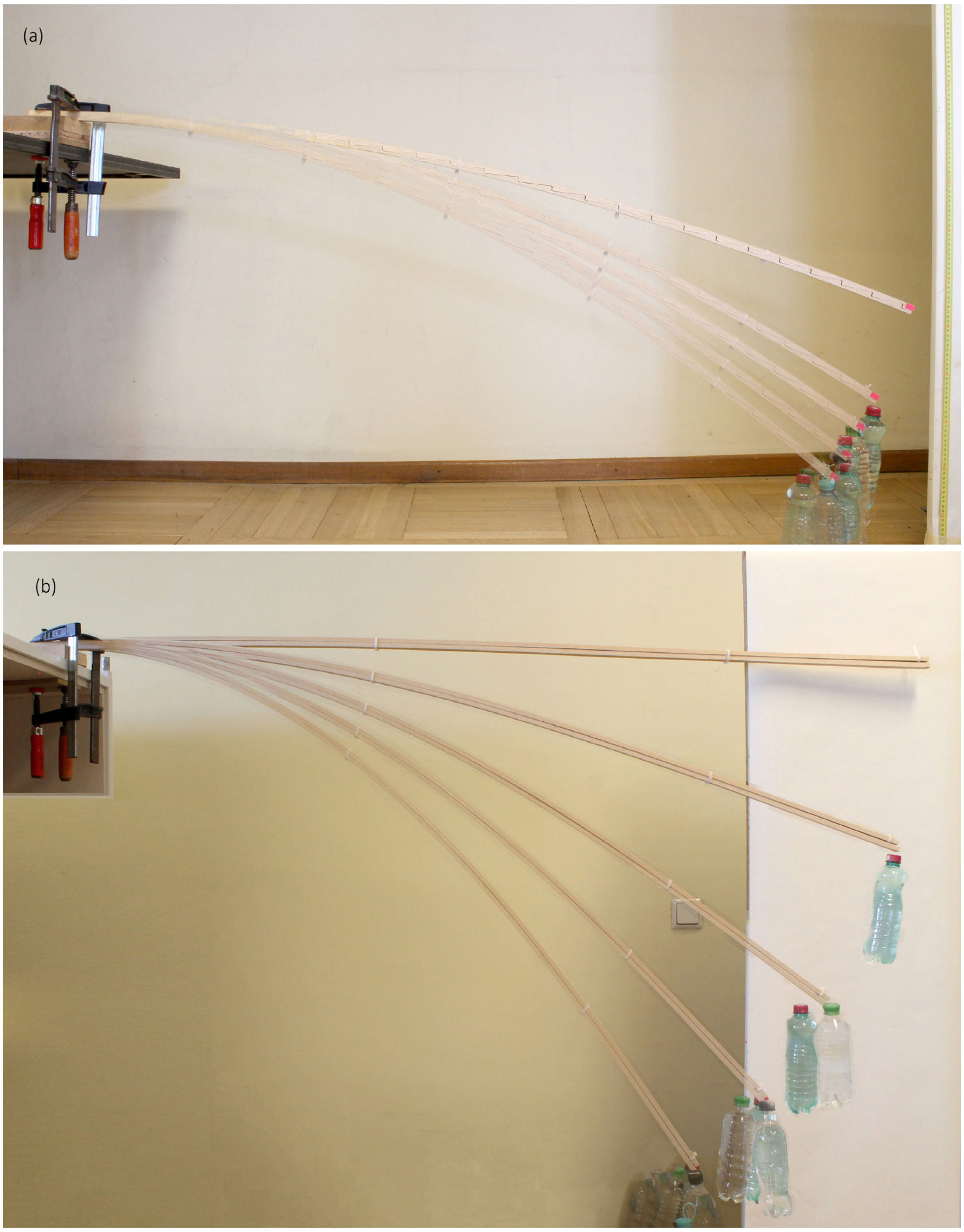

Figure 8.
Setup of the 2nd experiment: a) double-layered notched lath, b) double-layered lath without notches.

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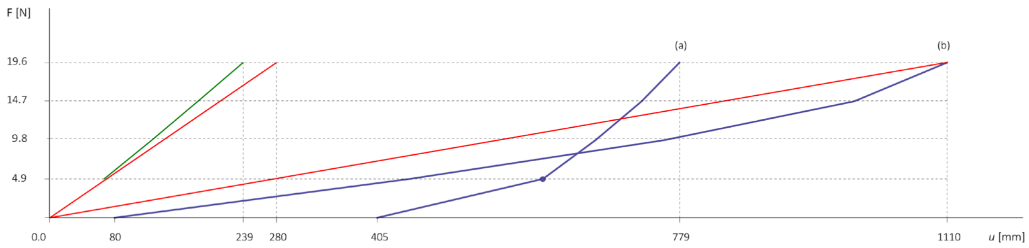

Figure 9.
Results from the 2nd experiment.

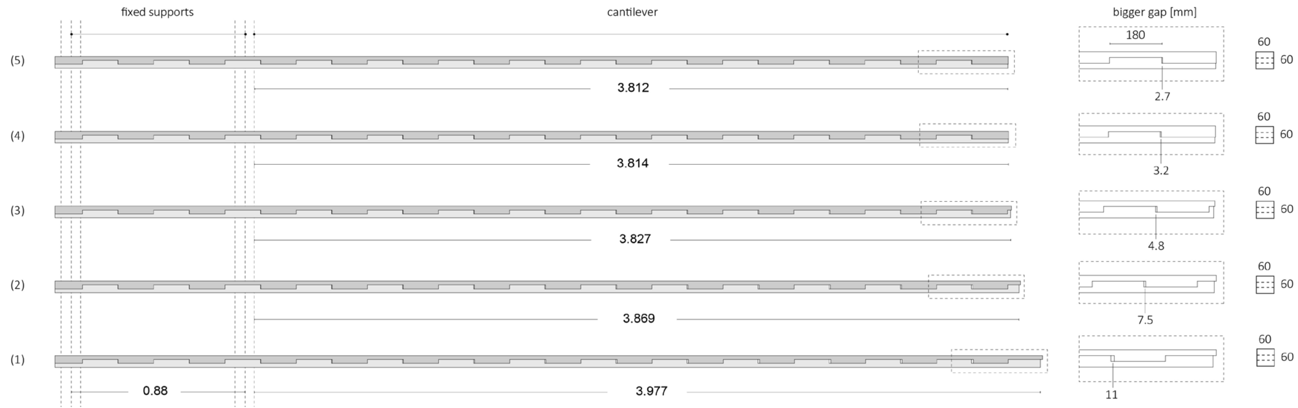

Figure 10.
Specimens for the 3rd experiment (cross sections in mm and lengths in m).

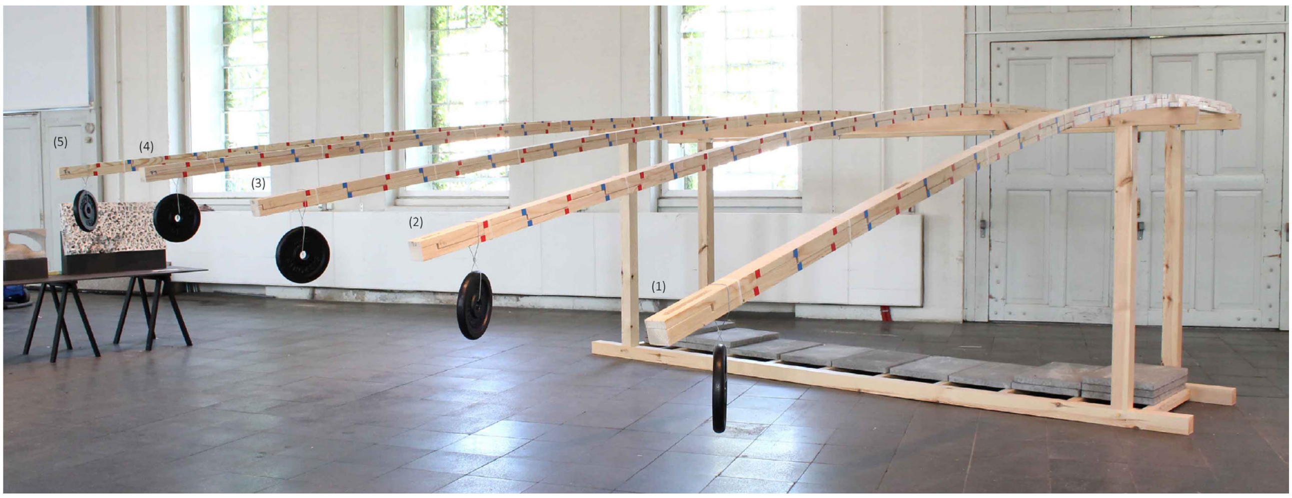

Figure 11.
Predefined deflection of beams 1-5 with 49.05 N of g vitational load.

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In order to show how the length of the internal gaps affects the bending of beams with identical cross section, a third experiment has been conducted. The specimens of this experiment have 3 times bigger cross section than the specimen of the second experiment. Due to the increase of scale, the joinery detail has been improved to a rectangular detail, parallel to the longitudinal axis of the beam. Thus, the cross-sectional height remains constant during the bending of the beam, minimizing the stresses developed at the notches. For this experiment, fi e beams with different gap lengths (Fig. 10) have been industrially fabricated. Their combined double cross section, fi ed with zip ties every 0.6 m, is 60x60 mm and their length is approximately 5 m. The used timber is glue laminated (glulam) spruce (GL24), a low-priced, industrially fabricated glulam which is widely used in construction. The existence of very long (e.g 30 m) glulam beams made of spruce, in combination with large CNC machines like Hundegger K3, enables the rapid fabrication of large double-layered notched beams. The fabrication of each double-layered beam with the aforementioned machine lasted only 19 minutes.

Figure 11 shows the setup of the experiment. The fi e beams are attached to a base at two points, which span 0.88 m, with bolts (diameter 14 mm). This results to the cantilevering of approximately 4 m. The gaps of the beams 1-5 have been designed so as they bend incrementally. More specifical y, beam 1 has been designed to bend at a predefined radius of curvature of 7.6 m, beam 2 at 12.07 m, beam 3 at 21.68 m, beam 4 at 41.8 m, and beam 5 at 60.6 m. The lengths of the beams slightly vary in order to achieve a uniform length in x direction (parallel to the longitudinal axis) when all the beams are bent to their predefined orm (49.05 N) (Fig. 11).

In order to draw the load-deflection curve of the specimens, loads of 49.05 N, 98.1 N, 147.15 N and 196.2 N were applied sequentially at the cantilevering tip of the beams (Fig. 12a). Figure 13 shows the corresponding load-deflection curves (a in Fig. 13). As expected, the fi e beams deform differently under their dead load. Until they reach their predefined form (49.05 N), the beams have different stiffness. Beam 1 is more flexible and incrementally beam 5 appears to be the stiffest. After their predefined form has been reached, the stiffness of all the beams is equalized. However, the change of stiffness is more evident for beam 1 and 2, less for beam 3 and 4 and almost invisible for beam 5. Given that the longest gap of beam 5 is 2.7 mm (Fig. 10) and the fabrication tolerances are 1.5 mm it is clear that there is not a lot of room for it to act as a double-layered notched beam.

For comparison purposes, the deflection of a solid beam with equal cross section has been tested (60x60 mm GL24) (Fig. 12b). Comparing the inclination of its load-deflection curve (b and dashed blue lines in Fig.13) with the ones of the notched beams 1-5, it is evident that the stiffness of the notched beams, after they have reached their predefined curvature, is almost equal to the one of the solid beam. This proves that the gaps have closed and the beams behave as they were made from a solid, stiff cross section.

In addition to the numerical data, data from digital bending simulations have been collected for solid beams. The simulation has been done with Kangaroo2 developed by Daniel Piker and K2Eng by Cecilie Brandt (add-ons for Grasshopper 3D). A polyline divided in small segments represents a bending rod. The length of the segments of the polyline defines the bending stiffness of the 'rod' (a component of K2Eng which represents an elastic rod with bending stiffness only). Each segment of the polyline represents a 'bar', an element with only axial stiffness. The modulus of elasticity and the density of the material as well as the cross section of the beam are given as additional inputs to the definition Moreover, 2 anchor points with high strength are placed at the fi ed end of the polyline and one gravitational point load at the other end. By increasing the point load incrementally,

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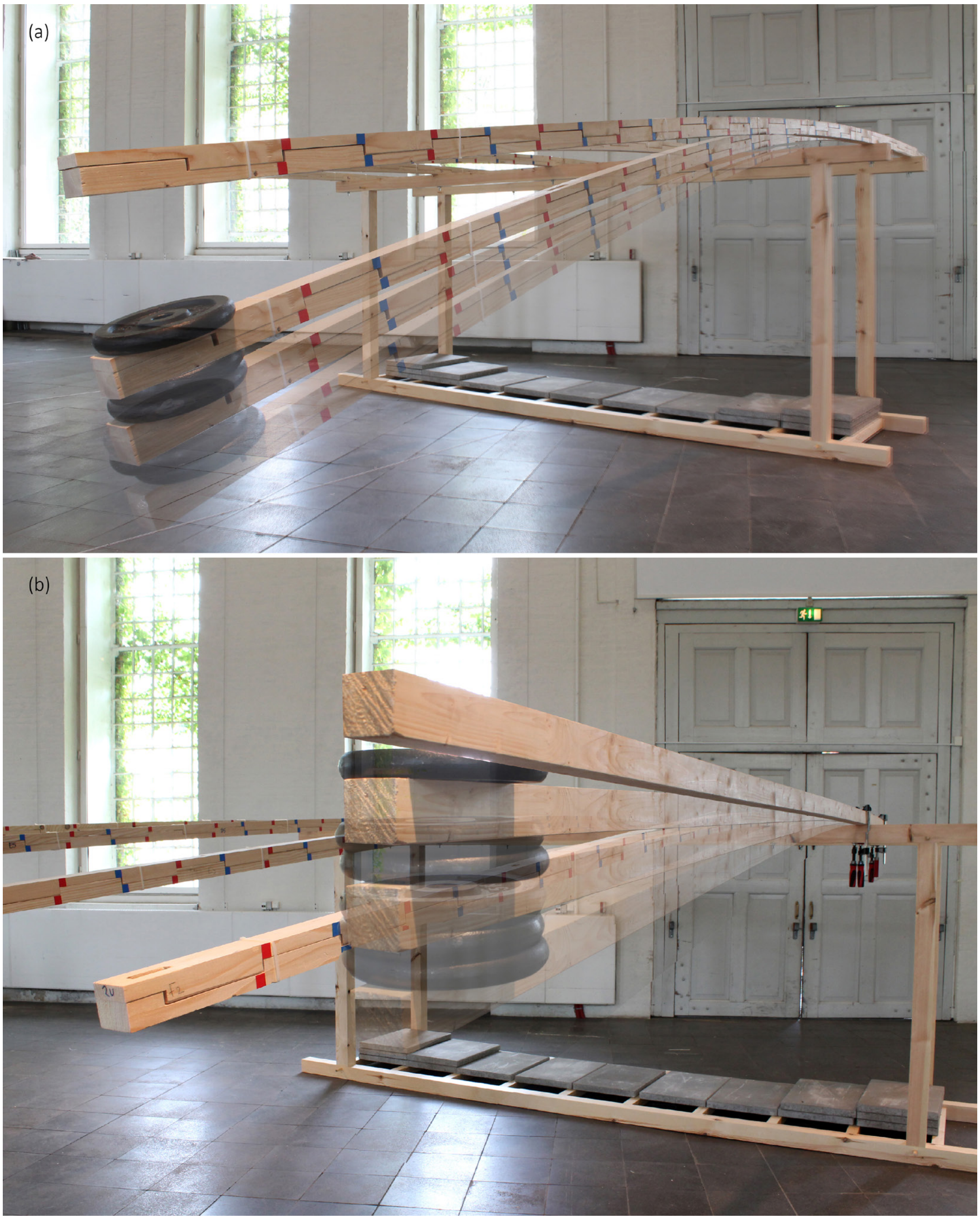

Figure 12.
Setup of the 3rd experiment: a) notched beam 1, b) solid beam.

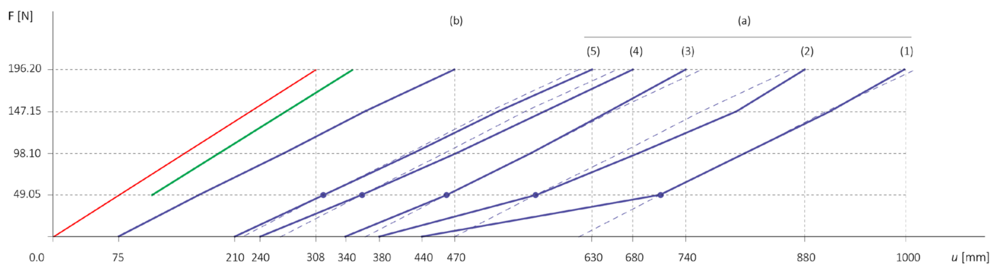

Figure 13.
Results from the 3rd experiment.

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mimicking the loading of the physical tests, the maximum deflection (in z direction) of the polyline is the output of the Kangaroo2 solver (Fig. 14). Apart from the aforementioned data, the solver can output the axial and the shear forces, the bending stresses and moments, as well as the reactions of the supports.

By using the digital simulations, visual understanding of the bending behaviour of various scales and materials can be achieved, reducing the need for physical tests. The load-deflection curve of the solid beam 60x60 mm (green in Fig. 13) has been created from the data extracted from the aforementioned simulation. The fact that the latter curve lies between the curve from the numerical (red in Fig. 13) and the experimental (b blue in Fig. 13) data indicates that the developed digital simulation is a reliable mean to predict the bending behaviour of a solid beam. This is an important step towards the development of a simulation for the double layered notched beams.

In conclusion, similar bending behaviour of the double-layered elements with the shear blocks is observed in the three different scales. This verifies that the developed system is scalable. The desired use of the system and the maximum stresses that it should resist define the material. Materials with high strength and deformability are the most appropriate for active bending systems. Some of the latter materials are wood, bamboo, Glass Fibre Reinforced Polymers (GFRP), Natural Fibre Reinforced Polymers (NFRP) and aluminium (Kotelnikova-Weiler et al., 2013). 3D printing of synthetic composites and CNC milling of natural solid materials are two of the main digital fabrication techniques which can be used to produce the discussed elements.

5. Finite Element Analysis of the joinery detail

As mentioned above, the design of the joinery detail is the most crucial parameter in order to achieve the maximum stiffness and avoid breakages of the discussed system. The zig-zag detail has the disadvantage that during bending the cross-sectional height of the double layered notched element decreases, as the one layer slides into the other in an inclined manner. This fact could be problematic for some applications. Therefore, variations of the rectangular detail have been explored further with Finite Element Method (FEM).

More specifical y, Karamba3D developed by Clemens Preisinger (add-on of Grasshopper3D) has been used for the structural analysis of the detail. A small segment of a double-layered beam has been selected to be analysed. The simplified digital structural model consists of two two-dimensional meshes which represent the two layers as 'shells'. The mesh is more refined only close to the contact points of the two layers in order to get more detailed values in the areas of interest and make the analysis faster. The two shells are independent and connect only through lines defined as 'trusses' (elements with axial and no bending stiffness) with small cross section. The trusses are placed perpendicular to the contact edges of the two shells. Thus, along the contact edge, only axial forces, such as compression can be developed. The bottom shell is fi ed with supports at its bottom edge and the top shell slides towards the bottom with 'prescribed displacements' at its supports at the top edge. (Fig. 15)

The Finite Element Analysis (FEA) of Karamba3D outputs the displacement of the shells as well as their utilization, principal and Van Mieses stresses. Three different angles of the contact edge have been analysed, 0o (perpendicular to the long axis), - 45 o and 45 o. In Figure 15 the colours represent the principal stresses induced when the two shells are forced to contact. The red represents

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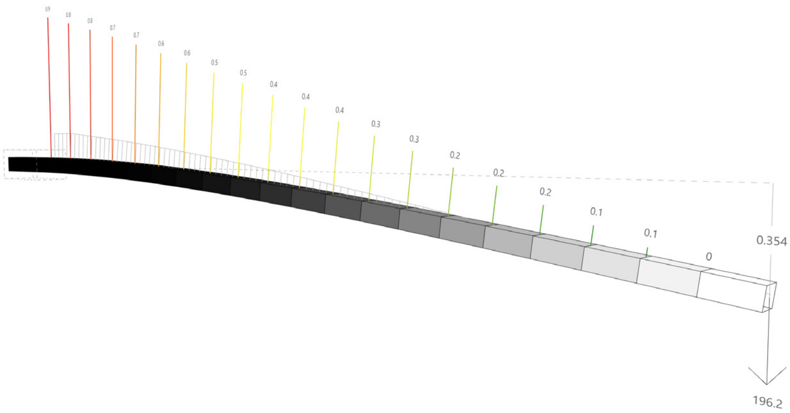

Figure 14.
Maximum deflection of the solid beam f om the 3rd experiment extracted from digital experiment. The moments, for each segment of the original polyline, appear with different colours.

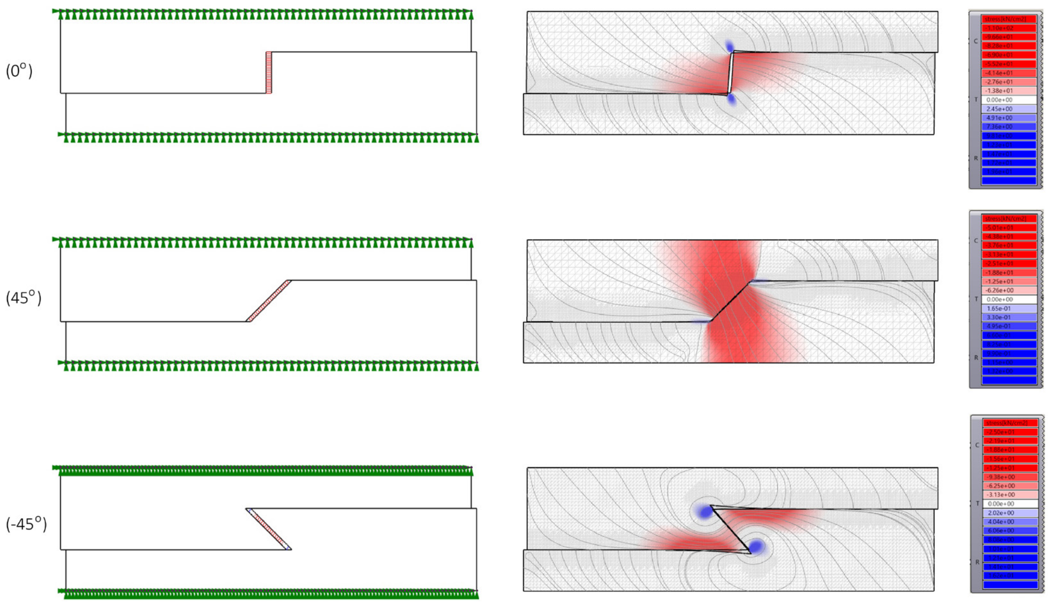

Figure 15.
Setup and results from the FEA of 3 different joinery details.

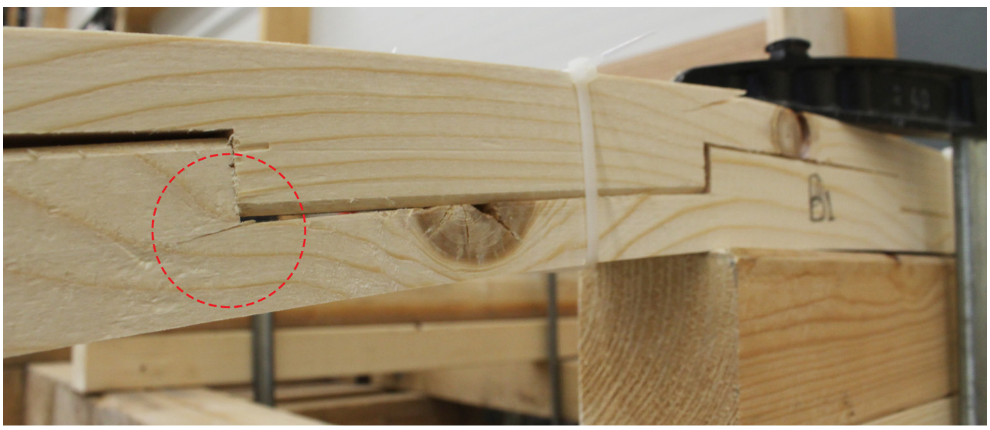

Figure 15.
Setup and results from the FEA of 3 different joinery details.

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the compressive stresses and the blue the tensile stresses. From this FEA it is evident that the problematic areas are the blue areas at the ends of the contact edges, which is verified by a physical strength test (Fig. 16). Looking at the values of the stresses, the bigger areas with tensile stresses are developed at the - 45 o angle specimen. As a result, this joinery detail is more susceptible to breakages. On the contrary, the 45 o angle specimen shows the smaller tensile stresses and the maximum compressive stresses, which makes the specimen the optimal shear block in comparison with the other two specimens.

6. Conclusion

This paper proposed an alternative way to produce curved structural elements, with both big curvature and high stiffness, in various scales. The developed system relies on multi-layered elements which can be formed easily into a predefined geometry when they bend. The discussed research focuses on 1D linear elements which can form planar curves. However, there is potential to extend it to 2D elements. The method to prove the structural performance of the developed system was the physical experiment. In the conducted experiments, the deflection of the discussed elements was measured under various loads. The extracted experimental data proved that the elements increase their stiffness when they reach their predefined form, relying exclusively on geometrical configurations and material properties. Thus, curved elements can be easily produced with digital fabrication techniques and rapidly construct free-form geometries, considering that their construction manual is embedded in their joinery details. The optimization of the latter details can improve the performance of the elements, therefore FEA has been employed. Future goal of the research is to develop a digital simulation of the kinetic and structural behaviour of the proposed elements, so as the designer can predict their performance, eliminating the need for physical prototypes. Finally, case studies for the application of the system in three different scales (small products, furniture, and architecture) are yet to be developed.

Acknowledgments

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Using Materially Computed Geometry in a Man-Machine Collaborative Environment

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Abstract

In this research, we interweaved real-world geometry with computational tools for a man-machine collaborative assembly process. Current research for robotics in architecture aims to bridge the gap between digital design and fabrication, but rarely considers manipulation of real-world geometry by human actors. In contrast, we utilized material computed geometry as a physical interface. 3D scanned wooden lamellas served as input for computational tools to finalize a design and create toolpaths for the robotic placement of rods.The research combines methods of machine vision, physical interfaces and man-machine collaboration to restructure workflows in the process of design and construction. Consequently, real-world geometry was used as input to start the design process. The designer engaged with wooden lamellas and a computational tool to build a demonstrator, illustrating a clear division of tasks in a man-machine collaboration. Moving from parametric design tools directly to physical interfaces using real-world geometry, our research proposes a stronger participation of human actors within digital fabrication environments.

Keywords

Construction/Robotics; Machine Vision; Man-Machine-Collaboration; Real-World Geometry; Physical Interface

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1. Introduction

In this article, we present a physical design interface that uses manipulated wooden lamellas as an input for a man-machine collaborative process. The significant contributions of the ork are:

- A physical design interface as part of a built structure
- Real-world geometries that serve as input for an algorithm, which automatically creates data for robotic fabrication
- A collaborative man-machine building process that is augmented using projection mapping

Architecture research in robotics creates a link between digital data and the material world and allows for new concepts of materialization. Moreover, these orchestrated systems show a high degree of automation that allow for thousands of repetitions of a similar yet variable task without human interference.

In contrast to most research, we focus on the question of how humans can collaborate within digital robotic construction processes through real-world geometries. Therefore, we develop a user interface with a 3D scanning device to merge the real-world into the digital. Questioning the clear separation of the two worlds, we demonstrate how they can inform each other.
Certainly, the division of tasks between users and robots will become more relevant due to growing advancements of autonomous robotic operations in architecture.

This paper is divided into four parts. The first explains the framework and background of this research by naming the main fields of interest: material systems, physical interfaces, machine vision, and man-machine collaboration. The second part describes the method with all its relevant parts that were used to build a demonstrator, which illustrates the proposed framework. In the third part, we evaluate our findings on physical interfaces, machine perception, and man-machine collaboration and explain challenges within such a framework. Finally, we review the contribution that material-based modeling environments can make in architecture through man-machine collaboration and offer some suggestions for future research to implement our proposed framework.

This research explores if real-world geometry - as physical interfaces for a man-machine collaborative process - can be part of a built structure to challenge the common division of planning and construction.

2. Background

In order to begin defining novel architectural production strategies that can integrate user intentions and robotic fabrication strategies, it is necessary to bridge a series of related research fields We reviewed physical interfaces, machine vision and man-machine collaboration to create a foundation for the presented research.

2.1 Geometry Computed by Material
Material properties and their integration into design systems and construction processes have been researched within the last decades. Frei Otto showed how analog large-scale models were used for form-finding Although digital simulation techniques already existed in 1975 for anticlastic surfaces, they were in their early stages. Hence their design interface and the geometrical representations were relatively basic. Thus, as structural properties are scalable, models served as design interfac-

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es by taking measurements manually or via precision cameras and photogrammetry (Otto et al., 1975). Overall, those models are geometric representations of physical form-finding processes for a specific material system

Materials have the capacity to compute and thus inform the design process with their physical properties. (Menges, 2012). Here the question is how to combine the advantages of both the digital and material computation. Cyber-physical systems combine digital computational logic with the dynamics and uncertainties of the physical world through actuators and sensors (Rajkumar et al., 2010). Recent research on robotic systems in architecture shows possible real-time actualization of production data. Based on the feedback of the measurements, the error margin encountered within the fabrication is reduced. This consequently forms a stronger connection between the digital model and material system.

Our research looks at how a material system can be informed through human interaction with real-world-geometry.

2.2 Physical Interfaces
The conventional design interface to generate geometry in architecture is the computer. In contrast, we propose using real-world geometries as tangible user interfaces that stay part of the built structure.

Thus far, several studies have shown that tangible user interfaces allow the change of physical objects as an input device for design tasks (Herr et al., 2011); Balakrishnan et al., 1999; Grossman, Balakrishnan and Singh, 2003). Moreover, augmented physical interfaces offer the possibility to project digital information onto an existing structure to visualize properties like load failing probabilities or stress distribution (Savov, Tessmann and Nielsen, 2016; Johns, Kilian and Foley, 2014).

2.3 Machine Vision
Machine vision frames the field that enables machines to extract visual features of the real world. In the building industry, machine vision is used to create as-built Building Information Models (BIM) using 3D point clouds captured via laser scanners from the construction site. Many studies have demonstrated that scan-to-BIM is a sufficient way of comparing the actual building with the planned model (Macher, Landes and Grussenmeyer, 2017). So far, little attention has been paid to integrating object recognition for manipulated components and to merge them back into the digital design model.

In robotic construction research, one commonly used sensor is the Microsoft Kinect depth sensor that allows visual feedback in the form of 3D point clouds from built structures (Brugnaro et al., 2016). Moreover, Bard has shown that machine vision can be used to embed real-world objects or human gestures into human-robot collaboration processes. Physical making and generative computer models simultaneously inform design processes through those hybrid workfl ws (Bard et al., 2014).

However, the implementations in architectural production are still limited due to insufficient computational tools to interpret or segment the data from visual sensors. We are aiming to extract geometric features according to their relevance for design tasks.

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2.4 Man-Machine Collaboration

Task-shaping is an emerging research area in the field of robotic fabrication in architecture. As an aspect of man-machine interaction, it describes how new technology, like robotics, effects the way human tasks change within an automated fabrication environment (Goodrich and Schultz, 2007). A clear division of tasks and skills is delineated by several researches in the field of robotics fabrication in architecture (Nguyen et al., 2016; Helm, 2014). Moreover new process chains indicate a stronger connection between physical and digital construction systems, allowing users to interact and command during robotic assembly processes (Rossi & Tessmann, 2017). Likewise, human gestures can link the human body with the digital fabrication environment (Johns, 2013). Our research seeks to identify a division of tasks that highlight robotic qualities in a collaborative assembly process.

3. Method

Man-machine collaboration in design and construction processes is a rapidly growing field as robotics bridge the gap between the physical and digital world. We explored modes of collaboration through a demonstrator made from bendable lamellas, fixated by wooden rods, that yields its temporary configur tion through a process that coalesces design and construction into a fluid process of man-machine interaction (Figure 1).

We sought to identify the most effective way to share tasks among all parties involved to benefit from the abilities of both humans and machines. While robots effortlessly position elements in planes in space regardless of inclination and orientation, humans can coordinate complex assembly sequences through senses, experiences, and intuition (Figure 2). Finally, computational design software generates large numbers of gradually diversified building elements. These different capabilities were exploited in our research through the following steps:

We built a demonstrator based on the notion of a material system (Menges, 2012) that acts as an input for the computational design tool that is actuated by human shaping and robotic vision via 3d scanning (18 wood lamellas, Kinect 2, Grasshopper, Firefly)

We implemented a way to extract specific features of a 3d point cloud that serves as an input for an algorithmic design tool (Grasshopper, Volvox).

We developed a collaborative placement process of wooden lamellas for humans and robots, with a clear separation of tasks. Its features are visual guidance for humans through projection, precise placement of rods and a friction based assembly method.

The process began with the manual design and placement of two wooden lamellas at the left and right edge of the foam board (Figure 3). Their curvatures, inclinations, and shape were designed through direct engagement with the physical object (Figure 4). The designers negotiated forces, design intention, and material behavior into one geometrical configuration while avoiding breaking the lamellas. The desired shape was fi ed by wooden rods punched into the foam board.

The 3d depth sensor (Microsoft Kinect 2) was mounted to the six-axis robot (UR10, Universal Robots) to fully scan the physical set up. Based on the robot's position the point clouds were combined into one digital model (Figure 5).

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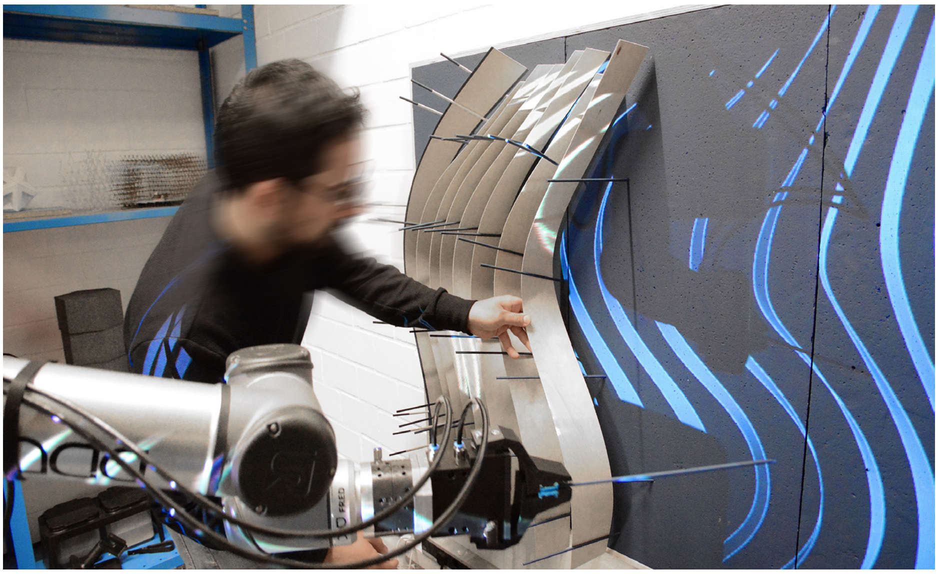

Figure 1.
The demonstrator for the man machine collaboration illustrates a division of construction tasks.

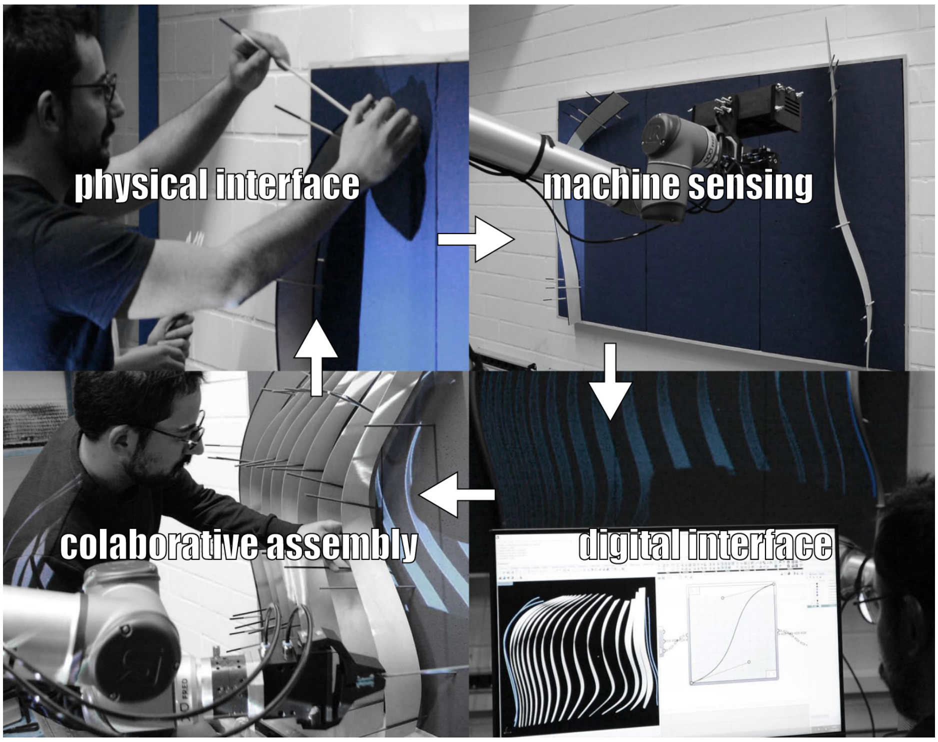

Figure 2.
The research links physical design, machine vision, computational design and man-machine fabrication.

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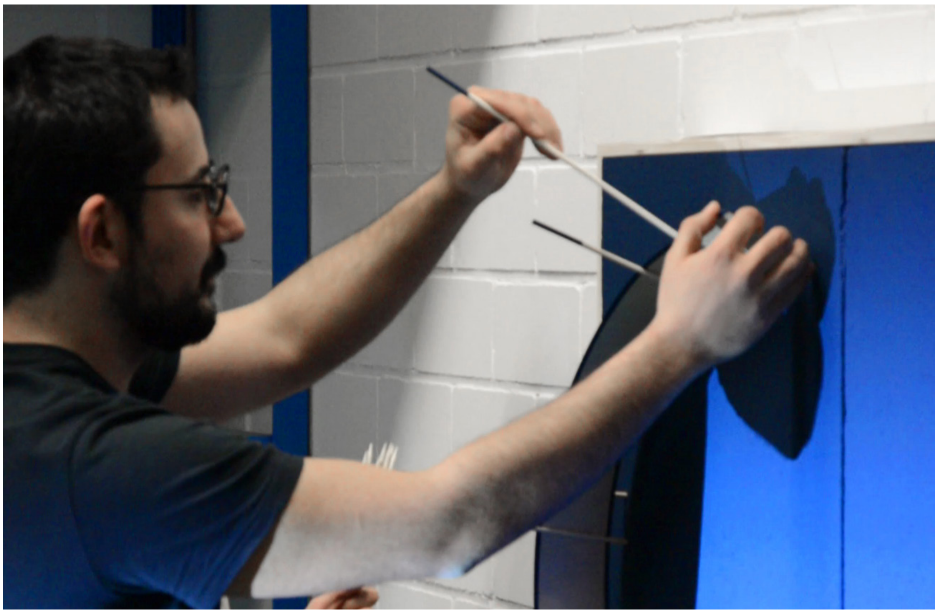

Figure 3.
The designer shaping the input lamellas and placing rods for their fixation

Figure 4.
Lamellas placed.

Figure 5.
Robot arm with mounted Kinect 2 scanning the input lamellas from different positions.

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The point clouds were processed and separated for each lamella using the Volvox plugin for Grasshopper. A Grasshopper script extracted the design features from the point clouds. A mesh is generated from the point clouds, and the top and bottom edge of the lamellas were computed as curves, and represented in the digital model (Figure 6). The extracted curves served as input for the parametric design algorithm. Showing the advantage of digital computation, we implemented an interpolation strategy to create differentiated geometries based on the inputs. The extracted features were interpreted by the algorithm to construct a series of lamellas. The distance between the top edges and bottom edges of the input lamellas was measured and equally divided to draw the digital lamellas. Graph mappers integrated into the interpolation design tool allowed the user to control the positioning, orientation and rotation of the interpolated lamellas through a numerical differentiation based on visual input (Figure 7).

The lamellas follow the definition of ruled geometries. As such, they can be described through a series of straight lines, which are called generators (Figure 8) (Pottmann et al., 2007). Already, the physical input lamellas follow this logic through the placed rods. For the robotic construction, the rod positions, directions, and associated planes were extracted from the digital lamella model based on the surfaces generators (Figure 9). Those were simulated with the Grasshopper-Plugin Robots and then sent to the robot for precise arrangement (Figure 10).

The assembly process was divided into the positioning of the rods and the lamellas. The rods require a precise placement as their position and orientation controls the bending of the lamellas, which was achieved by the use of the six-axis robot. The lamellas friction based assembly logic calls for a more complex process sequence; therefore this part is done by humans, based on vision and touch. The assembly is supported by a projection mapping of the digital model onto the physical, and serves as guidance during the manual assembly of the lamella distribution between the rods.

The material system of rods, lamellas, foam board, and robot allows for a reconfiguration of the model. Therefore, the whole model is scanned, and the actual position of the rods is extracted from the point cloud. The design algorithm can be fed with new inputs generating a new lamella config -ration. The physical and digital configurations are compared by measuring the distance between the physical and digital rod positions. The comparison results fl w back into the previously described process. While there are no new lamellas added the robot pulls out existing rods from the foam board and places them in new positions. The lamellas stay within the model during the process and are transformed by the robotically moved rods.

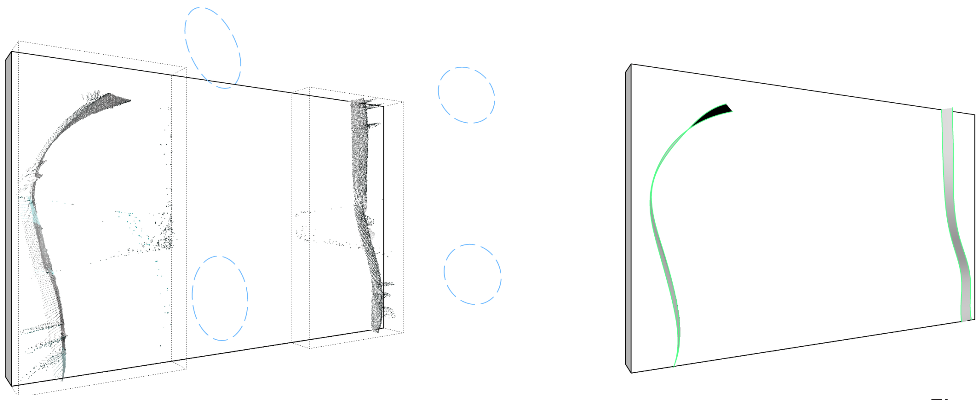

Figure 6.
The dashed circles represent the scanning positions of the robot. The lamellas edges are extracted from the point clouds.

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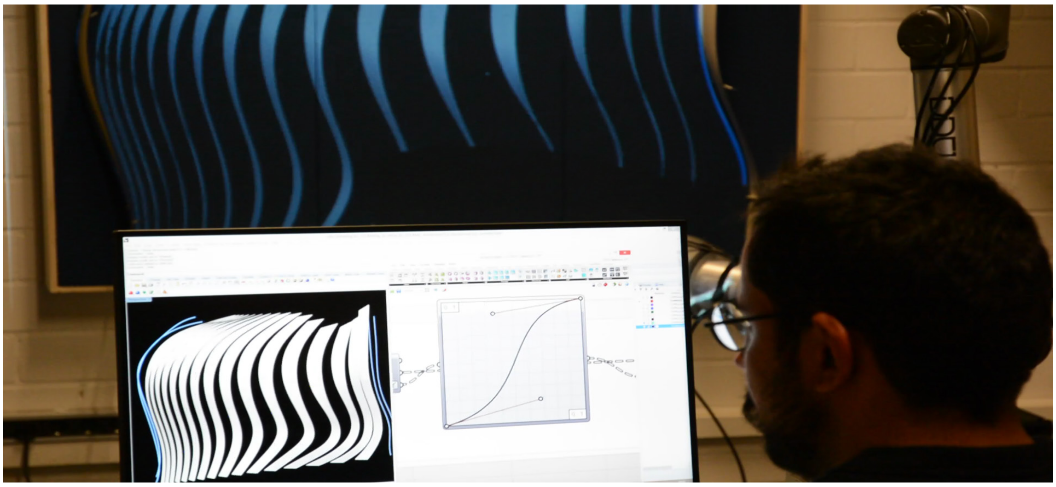

Figure 7.
Design tool interpolating the lamella positions.

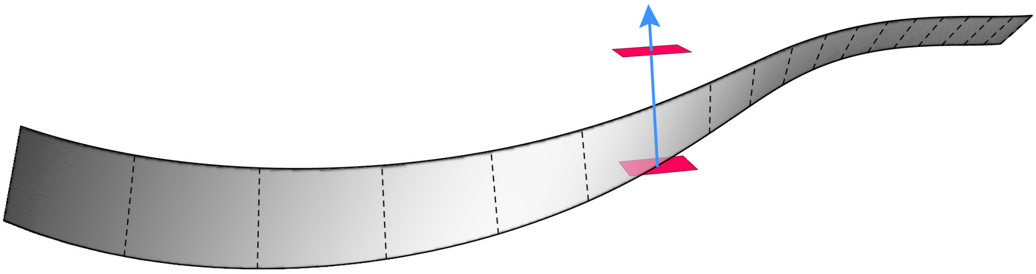

Figure 8.
Ruled surface with its generators as dashed lines and two planes extracted from the generators vector for the robotic path planning.

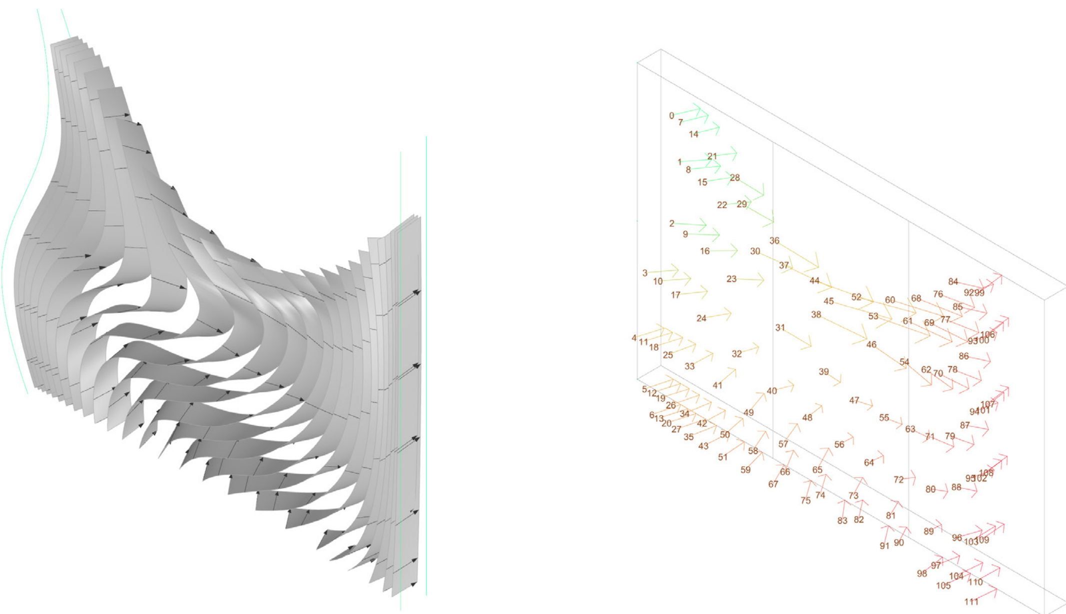

Figure 9.
Planes and Vectors for the robotic process extracted from the digital surface model.

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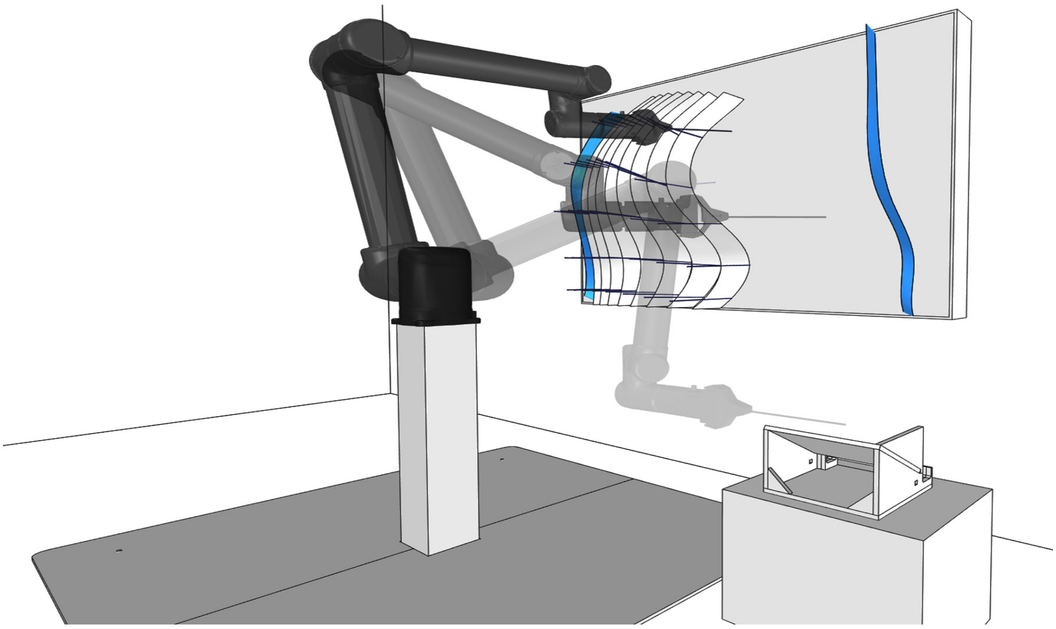

Figure 10.
Simulation of the robot paths with the main tasks: pick-up, positioning and placement.

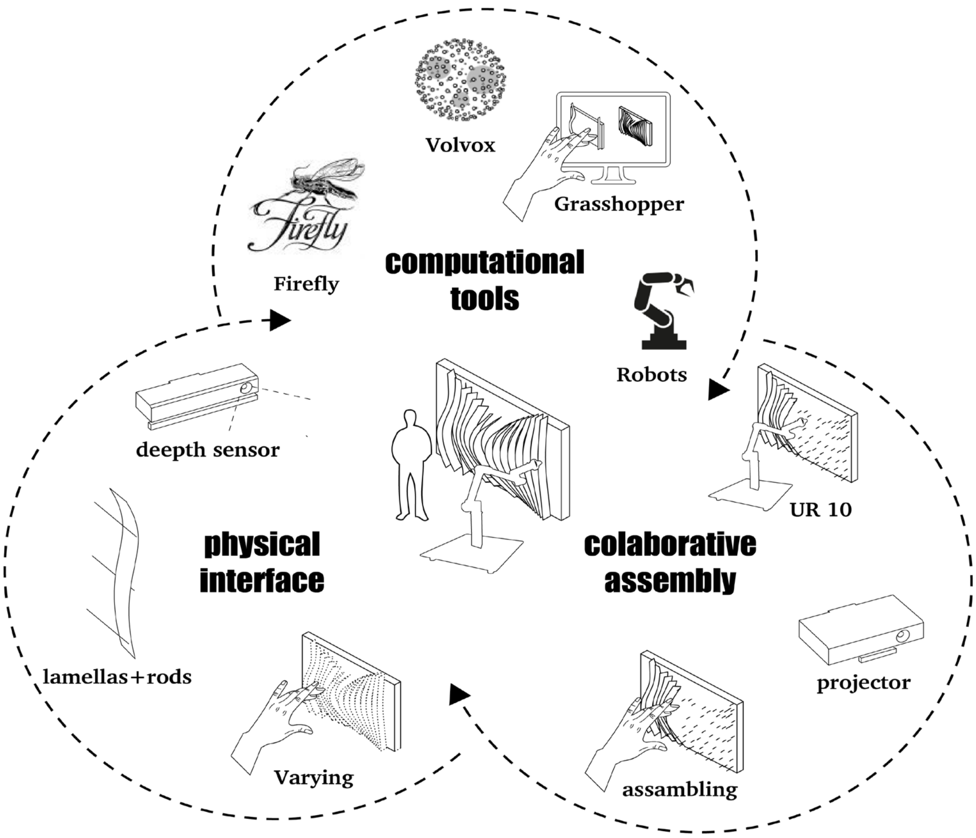

Figure 11.
Human represented by a hand within the process.

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4. Results

The project challenges the sequence and tool use of conventional design to production workfl ws and carefully intertwines human design interventions with machine vision for a robotic construction process. Moreover, it uses a physical interface within the architectural process of design and construction to generate materially computed geometries (Figure 11).

Material Interface
The material properties and constraints of the wooden lamellas gave rise to a certain geometric configuration The placement of the lamellas served as input for the parametric design tool. This interface was used to enable users to interact with real-world geometries while taking into account material properties and constraints like bending behavior and friction between rods and lamellas. Moreover, users without prior knowledge of the design interface were able to configu e lamella designs sufficient y.

Digitalization of Design Intend
The 3d scanning was precise enough to generate the necessary data for the digital representation of the manually shaped lamellas. The captured point clouds had a maximum distance between the points of 2mm. The density was high enough to create meshes from which the edges of the lamellas were extracted. The used plugin Firefly for Grasshopper caused minor problems, showing unnecessary points that were assumed to be a result of the plugins interpolation algorithms between infrared depth sensor data and image data. Those points were avoided by a coloring the edges of the lamellas which allowed to cull the points by color. Subsequently, the physical set up was 3d scanned and translated into a digital geometry.

Computational Differentiation
The computational design tool used the input curves from the physical lamellas for its interpolation algorithm. The operator of the algorithm interpolated 16 lamellas between the input lamellas. The material constraints were embedded in the parametric design tool through the scanned geometries set by the operator. The final design was found after several iterations of tweaking the design parameters. The goal for the design was to achieve an appropriate differentiation of the inclination and distribution for the lamellas. From this digital surface model, the rod positions and inclinations were extracted as vectors to fix and hold the lamellas and generate the obot tool paths.

Collaborative Process
The collaborative construction process took 45 minutes. The projection enabled for the correct placement and alignment of the rods (Figure 12). Manual placement of the lamellas was synchronous with the robotic rods placement (Figure 13). The robotic rods placement illustrated the high precision of the six-axis robot and the digital model. The reconfiguration of the demonstrator was tested in a smaller model (Figure 14). Rods were identified using visual sensing capabilities. The repositioning of rods with lamellas in place needs to take into account the constraint of the lamellas bending behavior.

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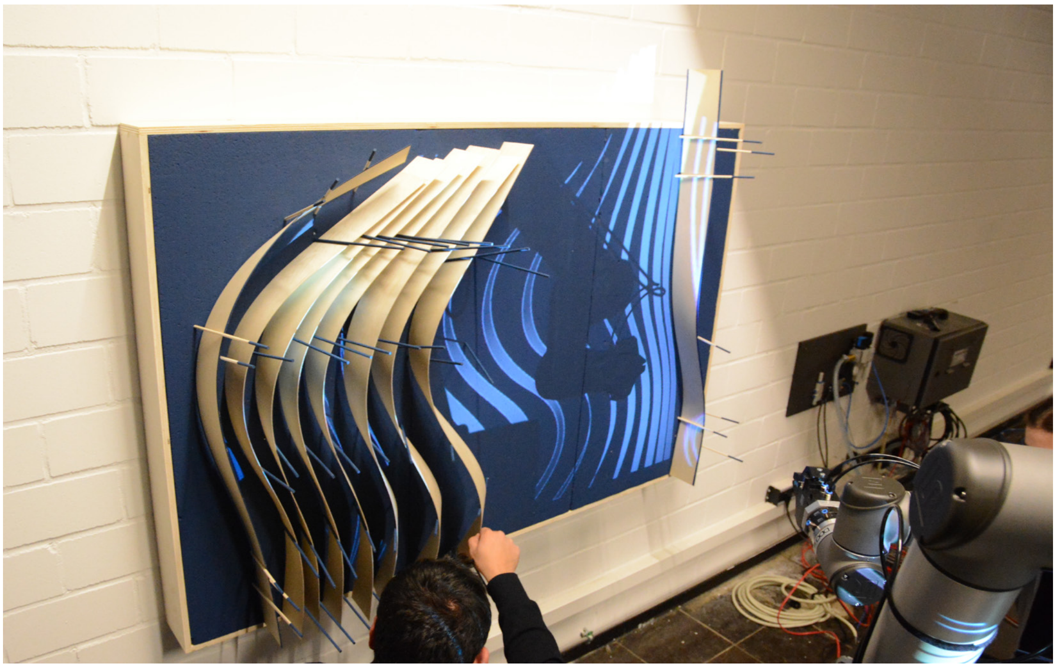

Figure 12.
Projection guiding the human during the collaborative assembly process.

Figure 13.
Projection of lamella alignment and curvatures

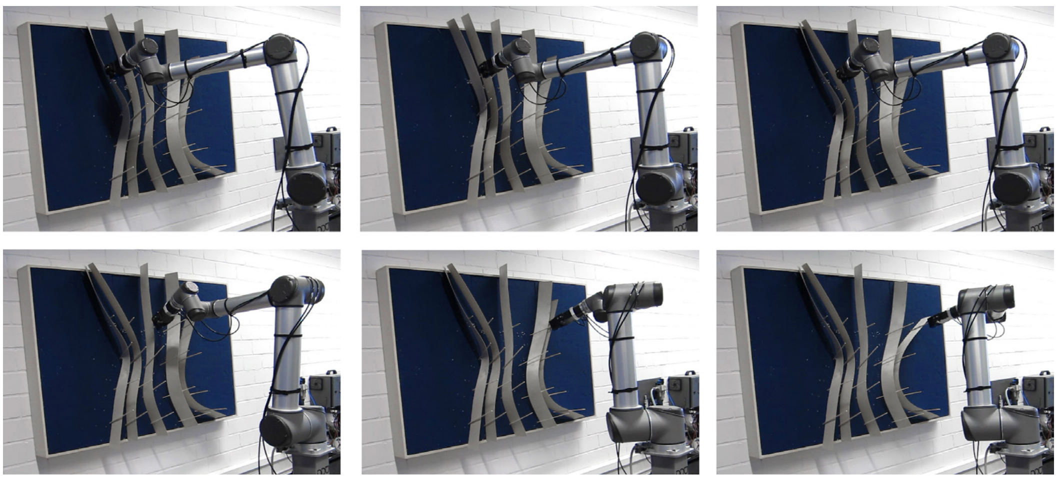

Figure 14.
Robot changing the position and orientation of lamellas.

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5. Discussion

The project reorders and repurposes well-known elements of the architectural design to production processes. While interaction with physical objects is a normal process for humans, operating digital design interfaces requires a mental acquisition of certain skill set. Therefore, parametric modeling software was removed from the front end of the design process and wooden lamellas served as design interface.

The design of the lamellas as geometric input for the parametric design tool interweaved material sensitive design with computational materialization processes. The computational tool used the sensed input lamellas and derived a series of gradually differentiated lamellas by interpolating the two extreme ends for the robotically fabricated demonstrator. Moreover, the robotically placed rods can be understood as the generators within the ruled surface of the lamellas, connecting digital and real-world geometries with the same principles. Thereby, connecting the computational logic with the material realization possibilities enabled by a robot (Gramazio and Kohler, 2008).

The 3d scanned lamellas at the front together with the robotic fabrication process allow for a responsive design and fabrication process which is a process described by Felix Raspall through sensing, controlling and actuation to address uncertainties within construction processes (Raspall, 2015). In addition to that, we look at how design intentions can be shared between man and machine through real-world geometry.

The assembly process was divided by identifying abilities of the two involved actors, human and robot. Contemplating the complexity of architectural fabrication realities which are often so elaborate that though, we might not fully automate them, we get assistance at decisive moments (Helm 2014). The demonstrator shows these moments and illustrates a clear division of tasks while integrating them into one collaborative process (Figure 15).

In 2014 Mahesh Daas presented a taxonomy of a broad range of robotic applications in architecture. One framework defines different modes of interaction between man and machine. It states it as a field of research in which one refines the modes of human-robot interactions (Daas, 2014). Our research explores those modes and emphasizes the importance of man-machine collaboration in architecture.

The collaborative assembly showed a successful implementation of task-shaping between man and machine (Figure 16). However, the synchronous collaboration between man and machine may become even more relevant with a real-time implementation to enable updates of the manufacturing data based on subsequently placed lamellas.

In the field of robotics in architecture much research focuses on integrating machines via real-time feedback and agent-based systems into materialization processes. Achim Menges describes the concept of cyber-physical systems in which "[…] the behavioral machine may not even remain external to what is made, but become fully embedded and absorbed in the system to be constructed" (Menges, 2015). Our research makes a contribution by reordering the roles of the different actors within such a system. Additionally, we developed a methodology for digitization of materially computed geometries for correlating construction and design environment.

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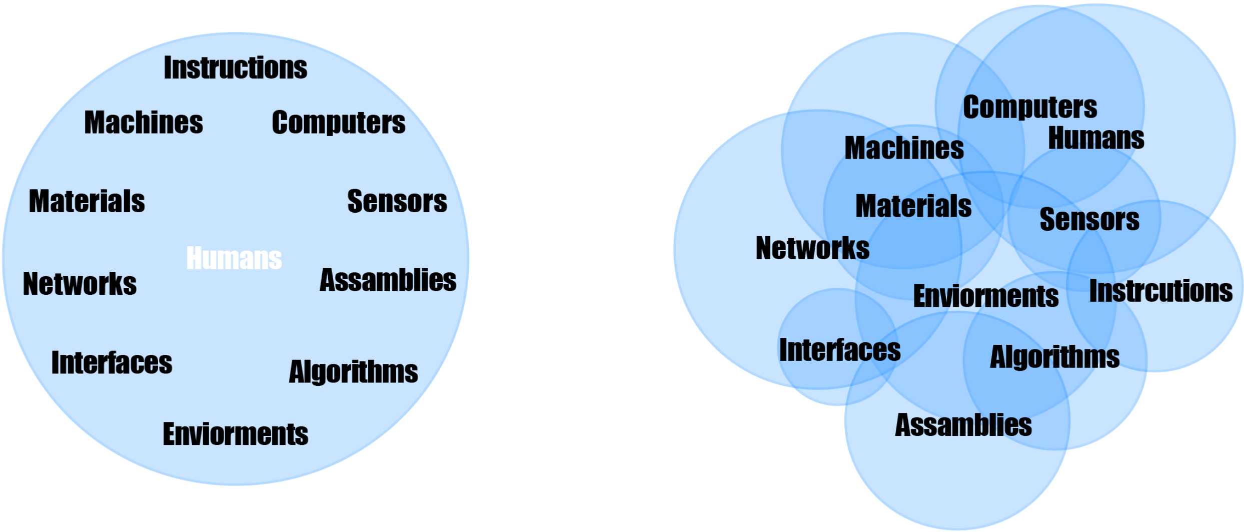

Figure 15.
Different models positioning humans within the architectural production framework. Left: All objects are oriented towards human operation from the background. Right: The humans is an equal participant within an agglomeration of actors.

Figure 16.
Placement of the last lamella.

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6. Conclusion and Future Work

This paper has presented a method for using real-world geometry that stays within the actual built construction as a design interface to start a man-machine collaborative process.

The 3d depth sensor was a first step of integrating sensing tools within the research, and can be continued for more complex feature extraction. Future research might apply more sensory data like force sensing and embed it as real-time feedback. The integration of such sensors in a collaborative processes would allow faster updates and interactions (Dörfle , Rist and Rust, 2013).

The collaborative construction illustrates possibilities of task-shaping due to the agents' capabilities. Our research suggests, that collaborative coexistence between man and machines does not have to end with the construction of one possible configuration but can rather be an ongoing process of continuous temporality. Thereby humans are becoming the key environmental factor within the materialization process and participation in a Behavioral Model as suggested by Theodor Spyropoulos (Spyropoulos 2016).

The demonstrator places the human as a participant within computational design and materialization systems. We were able to show a novel sensibility between the humans, real-world geometry, the computational design system and the robotic assembly process. The material components together with machine vision form a design interface that could be available not only for architects. It pushes the concept of cyber-physical systems towards stronger participation of the human factor through real-world geometry (Figure 14).

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Constantin Spiridonidis is Architect (Aristotle University of Thessaloniki) Urban Planner (Univ. Paris VIII), Dr. in Architecture and Urban Design (Aristotle University of Thessaloniki). He is actually Professor in School of Architecture of the Canadian University of Dubai. His research interests are cantered on design theory, architecture and urban design, architectural education and design pedagogy. He has a long experience in the management of academic educational programs investigating different educational environments as to their priorities, values and principles and the ways all these are expressed and represented in educational strategies, pedagogical approaches and teaching methodologies. He has an extended participation in and contribution to inter¬national organizations in Europe and USA, decision-making institutions, policy-making bodies and capacity building mechanisms to enhance the quality of architectural education and assure learning outcomes corresponding to the contemporary profile of an architect in a fast-changing world. He is a distinguished scholar with a broad record of publications aiming to disseminate innovative views on architectural education, to encourage and support changes in curricula structures and contents, to reconsider educational objectives, pedagogical methods and teaching strategies, to inspire new logics, new conceptions and new practices in design education respecting local identities and attitudes without losing touch with the international trends and dynamics.

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scientific assistant and visiting professor at the International Hellenic University of Greece, and has previously taught as Adjunct Lecturer at the Department of Architecture of the Aristotle University of Thessaloniki, and the Architecture School of Graz University of Technology in Austria. She is the author of more than 35 papers, published in scientific journals, books and conference proceedings, and has participated in research projects in Greece and abroad.

Bastian Wibranek joined the Digital Design Unit at the Faculty of Architecture at TU Darmstadt in 2015, where he is currently a PhD candidate and a research assistant, teaching in the area of computational design and robotic fabrication. He holds a Diploma in Architecture from the University of Applied Sciences and Arts Dortmund and a Master in Advanced Architectural Design from the Städelschule, Frankfurt am Main. Bastian's research focuses on how we will share our future buildings with intelligent machines. He proposes that the practise of architecture must define modes of co-existence and man-machine collaborations for design and production. This requires architects to bridge research fields such as machine learning, machine perception and task-shaping for architectural purposes. His latest passion is a collaboration with computer scientists to implement machine learning and sensing for robots in architectural production. His professional experience includes working on architectural projects for 2BXL, OSD and Schneider + Schumacher. He has collaborated on exhibition design and large-scale sculptures with internationally renowned artists Tobias Rehberger and Thomas Bayrle. He taught computer-based architectural design and robotic fabrication techniques at the ITE at TU Braunschweig (2012-2015) and tutored digital tooling at the Städelschule Architecture Class.

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FORCES

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Forces

Guest editor: Dr Odysseas Kontovourkis

Assistant Professor, Department of Architecture, University of Cyprus, Cyprus

The 13th issue of ArchiDOCT e-journal revolves around the notion of 'forces'. 'Forces' have been revived, for their key role, in contemporary contemplations of architecture conceived as a complex and speculative process of dynamic interactions amongst agents involved in an ecology.

'Forces' are met in both deterministic, top-down processes of form generation and they can be generative in bottom-up, emergent form generating scenarios and narratives. Literally or metaphorically, consciously or unconsciously, the notion of 'forces' lies at the heart of decision-making, simulation, control and physical realization of urban, architectural, structural and material systems in the built environment. Most importantly, however, it is their ability to trigger changes of existing situations, to reformulate, to revive, to regenerate and to renew existing material or immaterial systems in a way that their optimization and renewal, in virtual and physical space, can be achieved. They drive, shape and influence design decisions on both theoretical and practical levels and at various scales.

'Forces' can become activation principles, as they may be determined by aesthetic, sociological, economic, ecological, geopolitical, constructional, media, networks, data or other influences They may span from 'social forces' used to explore interactive relationships between humans and/or machines, to 'topology optimization' methods whereby the best distribution of material in a system based on force distribution can maximize structural performance. The importance of 'forces' can be found in exploring architectural and structural systems' structural efficienc , buildability, virtual simulation, interactive attraction or repulsion and so on, always aiming to redefine and renew an existing state towards a new improved form of existence. This can be done by any means, analogue or digital, allowing users to activate such forces, through which the results can be interpreted, revisited and implemented.

The 13th issue of ArchiDOCT invites researchers, PhD students that explore the concept of 'forces' in theoretical and practical terms and highlight the breadth and scope of the results their implementation can bring about.

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Important dates
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ArchiDOCT is published twice a year, in July and January. The official language of the journal is English. Submitted manuscripts for review should not exceed 4500 words, including abstracts, references and image captions. The referring system will be the Harvard System. Text should be saved in a Microsoft Word or RTF fil , while the supporting visual material (images, diagrams, sketches, tables and so on) should be sent as TIFF files with a resolution of at least 300 dpi. All visual material should be clearly indicated and numbered in the text, along with the respective image captions and credits. Additionally, all manuscripts should be submitted in A4 "camera-ready" .pdf format that gives an idea of how a finalised ersion looks.

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The peer reviewers are all confirmed educators of architecture coming from different educational backgrounds, with different specialisations and expertise that share the common interest of their doctoral students: to encourage them to publish their work while improving their thinking processes towards academic research writings. Each submitted article is reviewed by two members of the journal's Scientific Committee anonymously.

Copyright policy

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