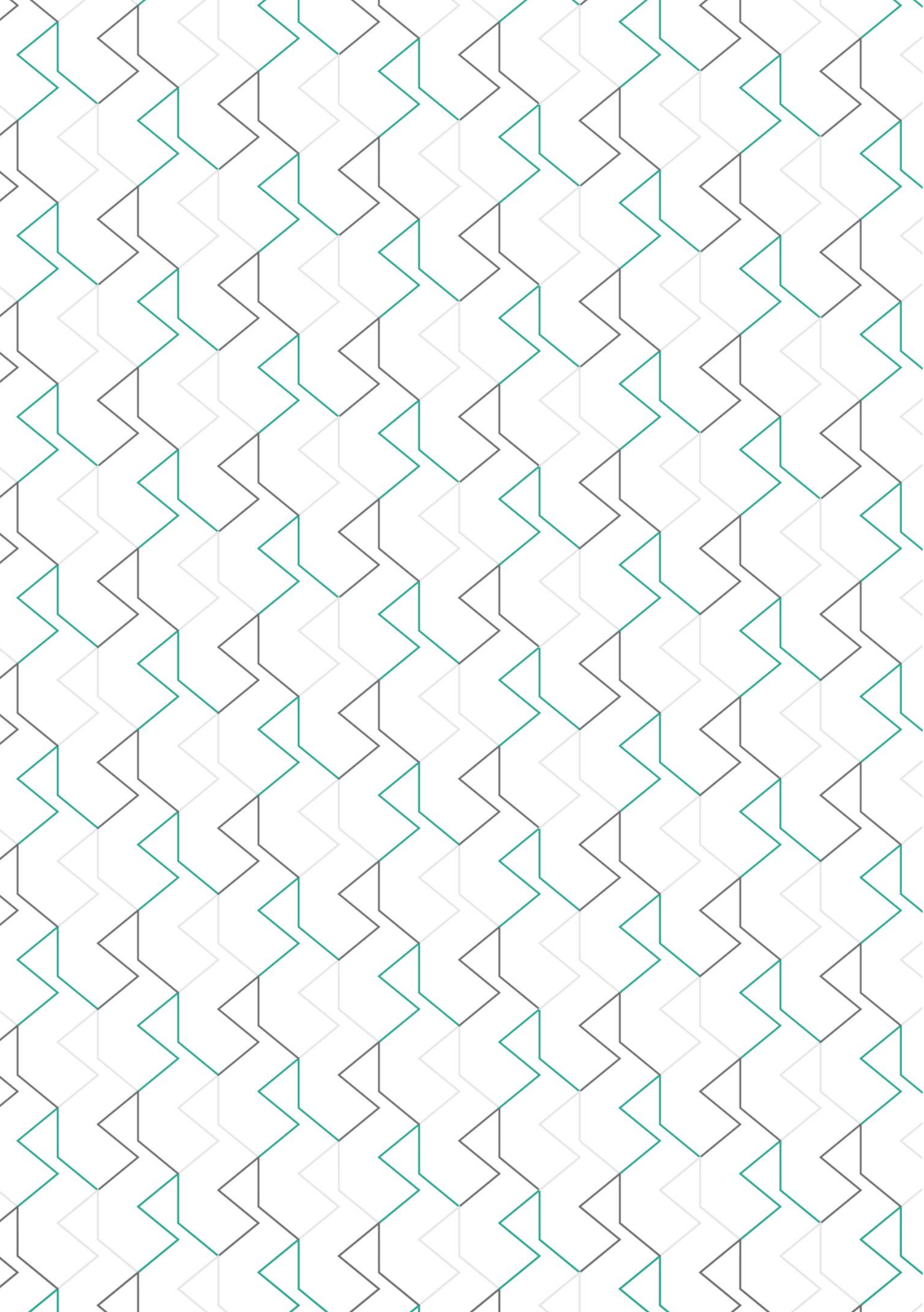
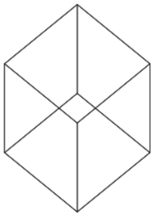
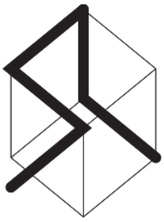
shapes of logic

EVERYTHING
CAN BE
AUTOMATED

MONOGRAPH







SHAPES OF LOGIC

EVERYTHING CAN BE AUTOMATED

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Your task is not to foresee the future, but to enable it.

Antoine de Saint Exupéry

TABLE OF CONTENTS

INTRODUCTION

The idea for the book you are currently exploring was born during the second edition of an international conference of computational design *Shapes of Logic*. It was one of the few Polish conferences addressing the subject of computation in design and architecture.

The first edition of Shapes of Logic took place in 2015 and has become a successful platform for exchanging ideas in the fields of *parametric design methodologies, evolutionary algorithms, digital fabrication and urban structures.*

This year we decided to dive into the world of *automation* and focus on its three vital aspects:

Design Automation - This block shares the knowledge concerning the automation of broadly understood design process. How can computer science improve the way we create ideas and draw plans? What new possibilities are arising thanks to the technological progress?

Digital Fabrication and Robotics - Advancement in fabrication process have opened many new paths during previous years. Are we about to face a new revolution in the way we make things? Can automation reach the realm of physicality in architecture and design industries?

Visions of the Future - Sociology, Political Science, Philosophy, Economy, etc. What is going to be with us? Are we going to reach radical levels of automation in the perceivable future? If so, how will it affect politics, economy, culture? Or maybe it is all just an illusion? Maybe singularity is actually quite far away?

The abundance of exchanged knowledge influenced us to create this monography which introduces a reader to the world of various sides of computational design and its practical applications.

We would like to thank all conference participants, sponsors, partners and supporters for the support which let this book and the conference see the sunlight.

We wish you all the best and hereby invite you to discover this short book,

Shapes of Logic Team

BETWEEN IDEA AND INTERPRETATION - DESIGN PROCESS AUGMENTATION

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The following paper investigates the idea of reducing the human digital intervention to a minimum during the advanced design process. Augmenting the outcome attributes beyond the designer's capabilities by computational design methods, data collection, data computing and digital fabrication, altogether imitating the human design process.

The primary technical goal of the research was verification of restrictions and abilities used in examined hardware and software tools: data collection tools, Machine Learning algorithms and computer-aided manufacturing. The generated effect became the self-interpretation of intentions signalised by the human-designer. The interpretation was possible with Artificial Neural Networks training based on learning sound samples and tracked designer movement in the act of drawing.

Experiments led to design methods, in which primary focus is set on machine interpreting intentions of the user/designer than executing just precise instructions. That approach gives more space for possible solutions, and at the same time leaves the room for whole kinds of form optimisation. Moreover, the process of interpretation may be self-developing in time, as Artificial Neural Network may be trained more for each of the work she will execute.

The following paper presents the workflow for both visual and sound data capturing along with the data processing, creating the methods of the human design process emulation. Additionally, the research presents the possible implementation of machine learning in the design process.

Presented approach reinterprets theoretical roles in the human-machine dialogue during the creative process in the general field of computational design. The research aimed to preserve designers individual preferences, knowledge and skills, to be processed by an advanced, digital entity, resulting in machine-made forms.

Keywords: *machine learning, design augmentation, digitalization of creative process*

1. Introduction

We used to treat the computer as a tool augmenting a designer’s skills the way Computer Aided Design (CAD) programs were doing it since Ivan Sutherland’s Sketchpad (Sutherland, 2003) presentation in 1963. Simplifying, the development of CAD software started from a recreation of the analogue drawing board. Utilitarian requirements forced software development through subsequent phases to include features like saving, copying, making changes, visualisation, making variants of solutions, sharing and processing big data.

Digital tools became the most efficient way to automate the repetitive steps. With growing speed of the hardware (Moore, 1965) - design process demanded shrinking amount of time. One can make the desired amount of digital variants and test them with Computer Aided Engineering (CAE) in a virtually simulated environment before psychical production of the prototype.

Moreover advanced and precise software took the full hardness of maintaining precision and complexity by making the documentation process automated and calculated by the computer. Designers ideas become independent from manual drawing skills and complex calculations.

Broadband and mass availability of the internet with simultaneously increasing miniaturisation of the hardware triggered flooding digitalisation of all kinds of possible information. The information age has begun for good.

Over the last couple years, Information Technology (IT) giants turned their main interests and investments into Artificial Neural Networks (Parloff, 2016). This fact signals increasing demand for managing tremendous and more complex resources of data than humans can process. The paradigm of trust in machines driven by an artificial intelligence has become the reality we live in nowadays.

A time predicted in many science-fiction scenarios, in which machines will replace humans completely, still seems too far off. However, we can already notice the appearance of autonomous programs which can learn and make choices. It may be a gradual end for humankind as the only source of the highest intelligence on earth.

We can only make predictions – but thanks to biotechnological development (Shanahan, 2015) perhaps intelligence will no longer be divided into natural and artificial. Maybe it will become “transcendent” (Kluger, 2007) - flowing through any forms created for its needs. The ability to share any information between organic and non-organic forms may result in an immortal singularity (Vinge, 1993). Intelligence born firstly in the biological body will have its continuum of super-intelligent digital or other living forms.

Although changes bring about many concerns and controversies (Hawking et al., 2014), evolution has always been driven by survival dependent on adaptation skills. That is why the further existence of advanced human civilization might demand the creation of a higher developed entity in the real world - something that will manage tremendous data resources in global scale and stimulate the evolution of human brain. It should not be surprising if we consider that humankind is cybernetics (Arbib, 1987) - was always inventing tools to survive in a changing environment.

As a biologically and mentally limited race we can consider advanced technology as a mirror. Its reflection may reveal a broader image of ourselves than is presently known. It should improve the understanding of processes that are now superficially known or human skills that used to be treated intuitively.

The above-described perspective brings up questions about future changes in the field of art and design.

2. Question - Purpose / main aim / target of research

This research is an exploration of more advanced dialogue between the designer and machine. The human-computer interaction is perceived here as a partnership (Licklider, 1960) of two co-authors. Hypothetically both parties should benefit by learning from each other during the experiment. The main aim of Artificial Intelligence use is to achieve Intelligence Amplification (Asaro, 2008). Machine learns about the designer with every impulse sent by him. The same algorithm corrects mechanism of decisions to interpret any impulses (data) better. The designer communicates with the machine by sending intuitively created signals, instead of making typical precise instruction how to achieve the result. Interpretations may be achieved just from few signals or from the residual amount of information.

Experiments elicit fundamental questions:

- How the described approach affects the design process?
- Will creation process become more open to intuitive, sketchy description of designer's demands?
- Will this change the role of the designer?
- What are the pros and cons of using the program that is continuously learning from the same designer?
- Can it improve human creativity or will remain as just another tool for automation?

3. Methodology

The conducted research was a simplified trial of establishing the workflow for training the intelligent system to autonomously act, imitating user creative process (see fig. 1). Regardless of tools and approach, artistic activity is driven by one’s experience, knowledge, preferences and stimulus in the course of creation. Although the purpose, in other words, called as a topic, might be prearranged and set exactly identical for a set of creators, their vast diversity results in different outcomes. The process of artistic creation is impossible to be programmed as a set of rules, encoding individual abstract decision making. In the place of rigid coding the artists creation algorithm, it is possible to teach the algorithm with a use of Machine Learning approaches (Murphy, 2012) to reproduce the images in the artistic style of a painter (Gatys et al., 2015) or to compose music (Vincent, 2016) based on the stored archives examples, rather predicting the result, without a possibility of being influenced or being used a as creation tool. In the following research, we interpret the creation as a live process, where the artist forms his vision under the influence of the real-time stimulant. The aim of the experiment was to form a tool mimicking the artistic process in the place of the result, which can serve as the art creation augmentation, a co-author, rather than an imitator.

The research investigates the concept of emulating the artist’s decision process with machine learning supervised algorithm - Artificial Neural Network. Machine Learning algorithm is a set of methods to automatically detect data patterns in order to predict future data or to perform decision making under uncertainty. In order to successfully train the supervised learning algorithm, two sets of data need to be created: input and output data, what allows predicting new values based on the given examples. During the conducted experiment data set was formed by digitalizing the creative process - artist’s physical painting under the influence of the sound samples. 3d scanned painter’s movement was stored as an output data set, being the result and music frequencies, triggering the act of creation, as an input data set. Stored samples enabled creating a generative digital tool, real-time mimicking the artist’s painting process in the response to a provided sound sequences (see fig. 2).

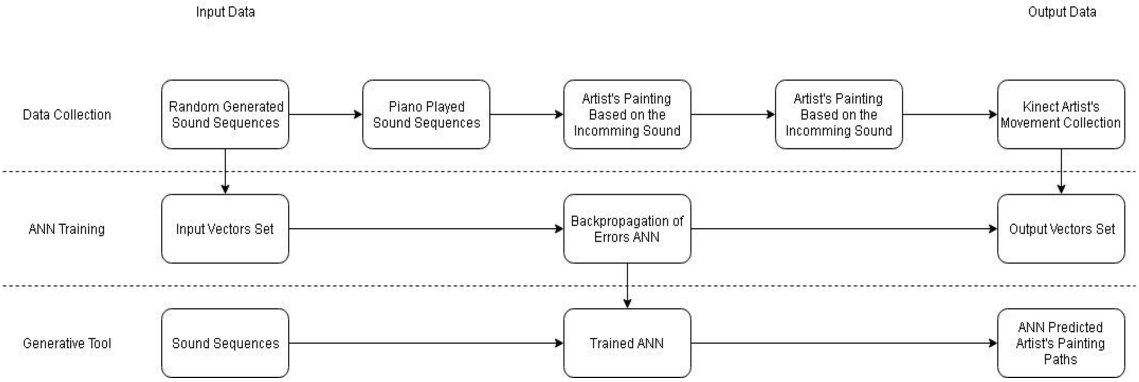

Fig. 1. Research methodology graph

4. Data collection

In order to create set the machine learning supervised learning algorithm, two sets of data samples had to be collected. The input data being the trigger for an artist to act and output data sets representing the following responses. The collected data set consisted of a played piano notes and movement being a direct reaction, resulting in painting track.

4.1. Input Frequencies

The input data set was randomly generated in order to maintain possibly even data distribution. Each of the mapped reactions was a physical response for three played piano notes within one of the selected octaves. Altogether 60 sample sets of 3 notes were stored, which represented 15 samples for each of the octaves from - 1st octave to 2nd octave (between 8.176 Hz and 123.47 Hz). Within the octaves, each of the notes could be played from up to three times for each of the three notes long sample. During the experiment, each of the randomly generated notes sequences was played on the piano separately, where notes within the sequence were played with 0.5 interspaces.

4.2. Movement Tracking

The second phase of the research was focused on digitalization of the artist's painting process. Played generated sound sequences were followed by an immediate response in the form of a brush painting on canvas by the artist. In order to simplify the path left by a painter, each of the movements was simplified to a free-form curves shapes, being one continuous gesture per sample played. The path created on the canvas were managed to store as well geometrical data along with the movement start and end position coordinates, without potential shift. Simple images scanning were impossible due to lack of the data regarding the movement direction, what was important in order to mimic the process itself, rather than the outcome.

The act of painting was stored based on the body movement. The process of storing the accurate painting sequence was conducted with an aid of motion sensing input device - Kinect for Windows (Jungong et al., 2003). The device works based on the system composed of RGB camera, depth sensor and multi-array microphone, what provides the possibility of full-body 3D motion capture, facial and voice recognition. Another feature of the Kinect sensor is its ability to recreate the captured body data in the form of lines and points representing the human joints connectivity. The technology is called skeleton- tracking and is possible of being easily implemented in research projects thanks to released non-commercial Kinect software development kit (SDK) for Microsoft Windows.

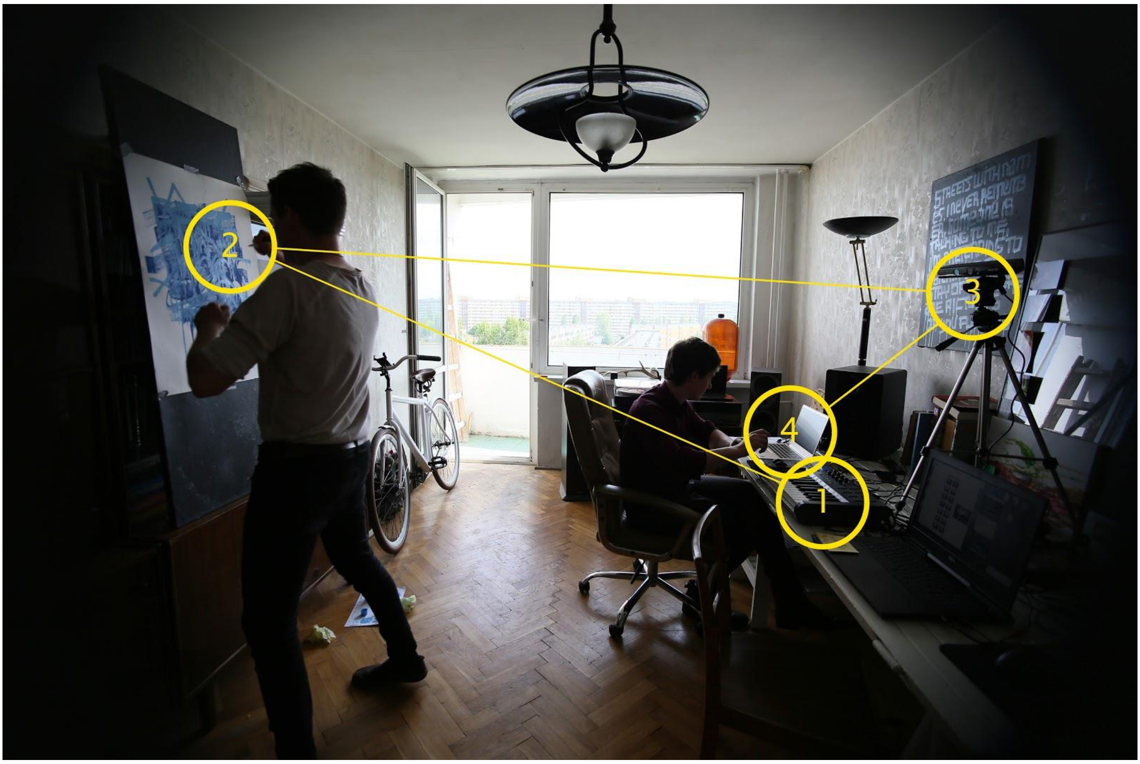

Fig. 2. Data processing flow: (1) Sound Generation, (2) Artists Reaction, (3) Movement Capturing, (4) Data Processing

Movements were stored as the right-hand wrist position mapping which was captured briefly after the corresponding notes sequence were played. The collection of captured points were pre-processed by removing the points in close proximity and duplicate points. Each of the points collection was rewritten in the form of a NURBS curve, which represented the actual painting path with a minor acceptable curvature error (see fig. 4).

Application of machine learning algorithms requires geometry encoding into the vector set. During the experiment recorded movement paths were rewritten as six values vectors, what was sufficient regarding the simple curves to be stored. Each of the NURBS curves was translated into values: two coordinates of the curve start point, three guiding vectors (start, middle, endpoint) and a sixth vector corresponding to the movement path length.

5. Machine learning application

The selected system allows the algorithm to adjust the weights between Artificial Neurons, responsible for computing the data, based on the difference between the current Artificial Neural Networks output value and the value being given as a target- training set output vector. The purpose of the presented system was to learn the correlation between given input vectors and output vectors (see fig. 3).

Both input data (frequencies sequences) and output data sets (painting process movement paths) values were scaled to 0 to 1 domains as a multiple values vectors, what resulted in 60 learning examples set. Due to the structure of the collected data and the task to be performed backpropagation of error artificial neural network algorithm was selected, which requires a sets of learning samples composed previously in order to predict future values based on the given examples. The architecture of the network consisted of 3 input data vectors, 1 hidden layer of 8 artificial neurons and layer of 6 output artificial neurons with a learning rate of 1.0 and 1000 cycles per training. The resulting Mean Square Error was lowered to 0.31, which was far larger than typically accepted, but regarding the experimental nature of the research over the abstract activity and the small amount of learning examples, the error was credit as acceptable.

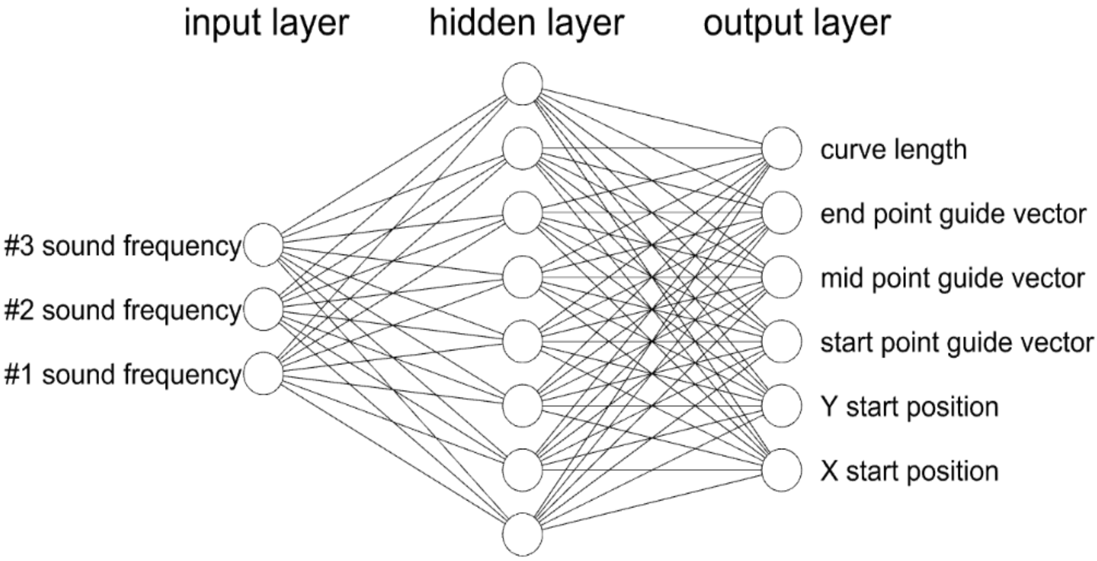

Fig. 3. Artificial Neural Network Architecture

6. Real-time sound based creation and fabrication

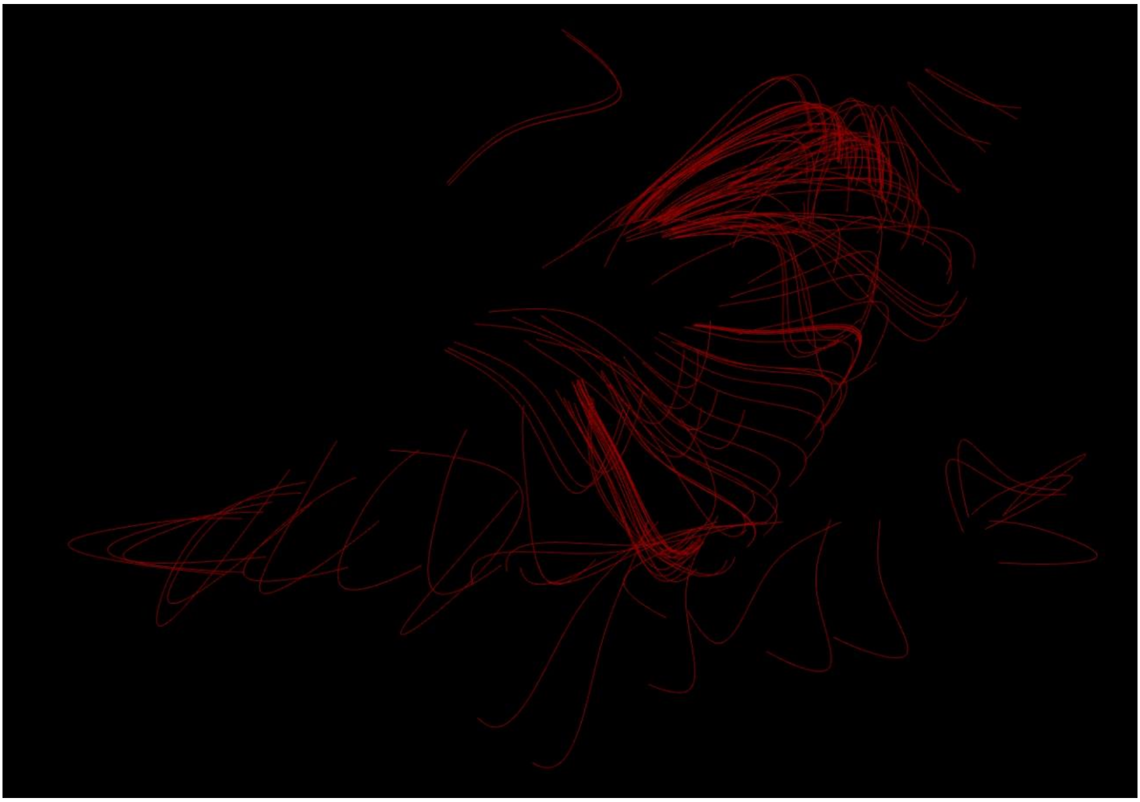

Fig. 4. Sound Generated Graphics

In this phase, signals for the interpretation were made by the same author as previously samples of hand movement. ANN interpreted electronic music pieces modified live in the laboratory during the live-act. Tests were taken with songs having different mood and instruments. There were significant changes in drawn by computer interpretations. Also, every repeated analysis resulted in slightly different effect. The geometry drawn by the computer may be wrapped around the shapes in the same software or used as information how to deform them. As the author used circles for his artworks, few examples were wrapped around it.

Solely digital painting in the form of curves representation doesn't represent the human nature of artistic creation. However, even in that short experiment, there are small signs of a human characteristic in ANN interpretation like for example tracks that the designer was a right-handed person. In order to mimic human painting process, yet automatize it, robotic fabrication was applied. Generated curves paths were used as a movement paths for a 6-axis robotic arm Kuka KR60-HA, which was equipped with a standard painting brush. The painting was created on a canvas of dimensions 500 mm by 700 mm, white on a black background. The designed generative tool along with digital fabrication, creates an automated process imitating the artist's act of creation (see fig. 5).

Fig. 5. Digital Fabrication Process

Fig. 6. First Physical Sound Generated Graphics Painting

7. Conclusion and Discussion

The experiment due to its data sets abstract nature presents a possible future approach for the application of AI in a creative process, rather than a proof of the assumption. It is essential to obtain larger learning data sets to find more accurate networks structure. Although achieved results leave the conclusion that in the future, an idea of the design may be shaped by any means of the expression - like for example piece of text, poem, dance, voice modulation, activity or body statistics etc. Including in the creative process, any information or means of human expression affects the meaning of the term "design" (see fig. 6).

Starting from Italian renaissance, the term "il disegno" was related to the idea, intention of art piece presented with hand drawing. From times of Michelangelo until now, the idea of the project was imprisoned with manual drawing skills. Become related to English term "design" understood as a fancy sketch, frame of the concept closed with contour. With the current state of technology, one may find that way of thinking unnecessary limiting for the creative process. The primary focus should remain on core invention in presented idea than how some idea was visually presented.

The workflow of the experiment may enable intelligence amplification by stimulation of human intuition and creativity or even ability to reveal processes hidden below unspecified artistic visions. A new approach may push imagination much deeper than typical use of traditional tools, or it's digital equivalents. That's another example why our times seems so unique and are signal of fundamental change. Is it a right moment to consider the use of computer algorithm as current successor to drawing as a medium allowing to dive deeper into the structure of the idea?

Perhaps paradox of spending months on the creation of advanced tools using algorithms now will result in design process being more open, intuitive, interactive and sketchy in the future.

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A TANGLE OF LINES

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The article is a consideration of differences between block thinking (blocks, compositions) and line thinking (movement, knots). It is also an attempt to describe the experience of working with a robot as a new project practice in which we ponder: is a robot as a designer's tool closer to the experience of craftsmanship, or to the modern practice of computer-assisted design? It is also a description of our final project "Knotty" involving translating the technique of knitting into the language of a robot, being the practical answer to the questions and theoretical problems stated above.

Keywords: *robot design, line thinking, structure, copper knitting*

The way humans perceive and understand the contemporary world is dominated by block thinking. It is clear when we consider objects, systems and constructions described as modular, composed of prefabricated concrete elements, aluminium profiles, or electronic sub-assemblies. A similar principle applies to constructing objects in 3D modelling software – it features a package of basic components (solids, planes, points) or techniques of drawing two-dimensional images, where often the first draft is composed of basic geometric shapes (squares, triangles, circles). Our entire image of the world consists of building blocks which, in right combinations, form furniture, buildings or machines. This thinking also dominates most humanities, where the human individual is presented as a single element or module that with other elements-modules compose a large structure in the form of society.

A different way of looking at the world, which consists of line thinking, was proposed by Tim Ingold in his book *The Life of Lines* (2015). In order to start thinking in a line (not in a linear way!), one needs to consider entirely different aspects of reality than in block thinking. These include knots, movement, torsion, entanglements, friction, interaction, process, continuity, imprecision. They contradict monumentality and constancy of the block thinking in which every element fits the subsequent one, and has its place and role planned in advance. The essence of line thinking is represented by techniques of knitting and weaving. The line is their material. It goes through the entire process of movement, weaving, twisting and binding to create a permanent structure: imprecise, but adapted to the shape or one that maintains its form. What would happen if the world was woven from lines and knots, instead of built from blocks? We asked ourselves this question at the beginning of the work on our final project *Knotty*[1] which consisted of translating the knitting technique to a language of a robot.

1. Block and linear character

Witold Rybaczyński who states that the beginning of the metaphor of bricks dates back to the mid-nineteenth century. Thanks to the development of housing construction and the possibility of allocating dedicated bedrooms for children, new, even and flat floors of these rooms were finally perfect for playing with building blocks. Rybczyński considers architects to be active promoters and creators of this children's game. Ingold claims that playing with blocks became for us, contemporary people, the way of describing the world, and as we are familiar with this mode from the very early age, we are completely uncritical towards such a universal metaphor (Ingold, 2015).

The system in which we create architecture and understand the world, Ingold called *„hard surfacing"*. It is characterised by the fact that life goes on the surface or below the surface, but never in it. Ingold criticises this concept and proposes that we should think about the ground as a composite woven from various materials, whose surface undergoes constant generation, production and reproduction, in which lives and minds of people and non-people are comprehensively connected. He suggests an approach in which we do not live on the ground or below, but in it, therefore it is crucial that we care for it, think about it and try to use it responsibly, because it is a part of ourselves, just as we are a part of it (Ingold, 2015).

In an interview entitled *Transition from a non-life to life*, published in a quarterly „Autoportret" (2017), Ewa Klekot explains: "[…] what Ingold says about being inside the world. This being inside is connected to the realization that we are entangled, and then there is no theodicy of Christian guilt and punishment, so the responsibility for the world does not result from the fact that we did something bad. The responsibility for the world results from the fact that we are a part of it" (Klekot, 2017). In the same interview, Klekot describes how Ingold perceives the difference between medieval architects-builders and the contemporary understanding of the profession of architect. She evokes the belief that Gothic cathedrals emerged straight from the materials, without project designs and drawings, emphasising the role of builders and their knowledge: "Gothic edifices were not composed of building blocks, like from a set. Blocks are Heidegger's Enframing, i.e. modules." (Klekot, 2017). The author also recalls an anecdote concerning an experimental reconstruction of a late Gothic vault ceiling. The work of conservators-restorers was based on the familiarity with the material, previous studies of existing drawings of the ceiling before its destruction and the general plan of the building, but the ceiling

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[1] *Knotty* is a graduation piece executed in the School of Form in Poznań under the supervision of Ewa Klekot, Maciej Siuda and Oskar Zięta.

had been built as the construction was being erected. “We could venture a statement that before the cathedral was built, it was impossible to draw it. Meanwhile, in the case of contemporary architecture, the drawn design is the fundamental assumption” (Klekot, 2017). It shows that a plan (in the sense of *disegno* – designing on paper, creating a plan before its proper execution) is not essential to create something, and that sciences (mathematics) are not necessary; quite the opposite: one can rely on the process, intuition (embodied knowledge) as well as working with the material.

2. Knitting

Knit fabric has properties which can be (re-)used to create objects answering both present and future needs. Knitting is characterised by a minimal use of materials – the process always uses only as much material as the creation of a given form requires. In many cases, the material can be reused, it only needs to be unravelled. Furthermore, knitted objects are manufactured as a result of a single process, they do not require additional processing, such as bonding or welding. Knitting is the result of a single line which can be extended indefinitely (new pieces bound together) which allows for creating infinitely large structures and objects. The line which is the material of knitting can be made from almost any matter, which enables obtaining different specifications. These materials can be also combined, or interwoven so that different parts of the created structure behave differently.

Knitted fabric, by nature, is light, penetrable and pliable. Its physical property is a significant resistance to stretching and small resistance to compression. Therefore, it is a perfect technique for creating stretchy clothes, pipe clamps or prosthetic tendons. But these properties are the product of the materials used – flexible and fibrous fabrics in the case of clothes – and the type of applied weave, which nowadays is treated mainly as an ornament. Basket weaving, similarly to knitting based on interwoven lines, enables creating solid objects, resistant both to compression and stretching. All due to the properties of wicker which initially is a flexible, pliable material that with time dries and hardens into an exceptionally rigid structure. The same result can be obtained with a knit fabric, but it requires finding a suitable material or materials as well as a suitable type of weave or combination of weaves.

3. Knotted by a robot

We began the project process by attempting manual work on a knitting loom. In this instance, the Internet turned out to be an exceptionally useful tool. Watching and following instructions helped us to understand how operating the loom works; it also allowed us to explore various methods of knitting. This relationship displays the essence of learning disciplines from the category of embodied knowledge. This type of knowledge can be acquired only through observation, repetition and practice. For us, it was the first signal that knitting can only be understood through physical exploration and watching the “masters”. Further on, we started to familiarize ourselves with a semi-automatic knitting machine. In this case, the situation was similar: pictorial instructions were less helpful than videos from YouTubers who share their knowledge with anyone who is interested.

Even though it was not our first assignment with the use of a robot, only then did we realise that programming is, in fact, translating hand movement into its language (see fig. 1). It really is quite a daunting task. It requires translating not easily measurable gestures into numbers and lines. And when discussing knitting, the task becomes even more complicated, as it involves translating micro-gestures of a hand to the movement of a robotic arm which is achieved either by accident or after numerous attempts and micro-adjustments, in the range of millimetres or even their fractions. Nothing can help in understanding such subtle manoeuvres, except for the observation of one’s own hand at work. Not even sketches provide any assistance since, after several subsequent lines, it becomes impossible to tell where the line begins or where it ends – sequences overlap or duplicate. It is similar to the program: to understand errors or notice things that require improvement, it is necessary to observe what the robot does. There is no way of predicting or planning anything, lines visible in the simulation form an overlapping, abstract tangle. Neither does the simulation inform how would the material shape itself. The work with a robot takes the form of a process puzzle whose solution is based on repeated attempts and drawing conclusions from the mistakes made. After going through such a process, one comes to the realisation that working with a robot is very similar to craftsmanship. It involves working with a material, understanding the process and developing skills.

Our observations (and experience) of students working with a robot indicate that in this instance, a certain limitation of verbal language occurs. Just like other students, we cannot precisely describe what the robot performs, so in many situations, we try to simulate its movement with our own hands. The experience in working with a robot is an experience of working not only with a computer and a machine but also with one’s own body. Gestures constitute a kind of spatial thinking and communication. It forces the designer to change the perspective, provides a new point of reference from which, just like users of the sign language, he or she must perform mental manipulation of the image.

This exceptionally interesting link between the sign language and spatial relationships was studied by Karen Emmorey (2011). Of course, it would be a huge exaggeration to claim that during their work with a robot, students use the sign language; it is rather a pantomime or mimetics. But above all, it points to insufficient resources of the spoken language for the process of understanding and communicating, and this inability to verbalize corresponds with non-verbalized skills of the craft when gestures become the means of transmitting the embodied knowledge.

Emmorey pondered the influence of the knowledge of the sign language on processing non-linguistic spatial information and studied relationships between ASL (American Sign Language) processing and using visual and mental images. In particular, she focused on the ability to rotate objects in one's imagination and creating mental images by deaf and hearing subjects. She presented a hypothesis stating that using the sign language expands the capabilities of imagining objects and rotating or transforming them. In the sign language, the person perceiving (the recipient) must rotate in their mind spatial arrangements performed by the person signing. For instance, space on the right of the signing person (on the left side of the recipient) is understood as a right-hand side in the scene described by the person signing. A similar problem is encountered by users of the spoken language who have to consider left/right directions relative to the position of the speaker (Emmorey, 2011). Results of the study confirmed the hypothesis that using the ASL can enhance the ability to rotate objects in one's mind: both deaf and hearing-signing subjects reacted quicker than non-signing to all levels of shape rotations.

A designer who first engages their own body is forced to translate their knowledge directly to mechanical muscles of the robot. A gesture and movement become the basis of their mental operations; they stop designing out of bricks which are supposed to form a larger structure, and a line becomes the primary building material. These lines, arranged in any way in three-dimensional space, not governed by laws and obligations of projection, are what distinguishes designers using a robotic arm from those who use traditional, block CAD software or programs with mathematic formulas. This is confirmed by Picon's beliefs – he claims that robots force designers to think in full 3D, without any privileged direction of projection. Additionally, he reminds that rotation is an indispensable element of movement. Movements of our own bodies are conditional on rotations of our limbs, and it would seem that we have been forgetting that fact for quite some time (Picon, 2014).

4. Structures

We used enamelled copper wire which is characterized by certain rigidness and flexibility, so the structure made from it has properties which are derived from the original properties of the material. It has certain resistance to compression and significant resistance to stretching, which enables it to maintain its form. But above all, despite its rigidness, it is free to move in all directions. Copper wire is also a conductor of electric current and heat. Since it is enamelled, conducting electricity can be induced only in necessary spots. Thus, it can either be a detector (it knows when it is touched) or emit sounds like a loudspeaker. It is possible to knit it in any desired shape, and the form of the construction can be modified at a later stage. The knitted fabric has its own form but can be altered and re-scaled, which makes it more similar to body of a living organism than a monumental sculpture. It contains

Fig. 1. The process of knitting a copper structure by a robot. Photo: M. Mojsiejuk

apertures, like openwork; it is not hermetic, which can be not just a drawback, but also an advantage, as it makes the structure light and permeable.

We did not want to create a single object, which would be the best possible use of knitting. Because such a solution does not exist. The application of the obtained knitted form is the product of the material or materials used, the knitted form and used weaves, which offer numerous construction combinations and various possibilities of movement. We want future users to be the ones to define objects created with our technology and invent new uses for it. That is why we created a website (knotty.pl) where we uploaded examples of potential uses of our technology, opening the dialogue with users in order to share the knowledge we obtained with others, but also so that they could help us in developing our project. It does not mean that we have no ideas for its use. We imagine that we could knit bridges, create certain types of flexible links, build underground tunnels, and construct a robotic arm out of knitted material. At the very end of the process, an idea emerged in our minds to present this technology in the context of the house of the future. In such a house, walls would react to the inhabitant like a living organism, open for them, eliminating the need to build doors and windows. The house would interact with its user constantly through movement or sound. This is why we created interactive light and sound structures, which provoke interaction and respond to it (see fig. 2).

Fig. 2. Copper structures. Photo: M. Reich

5. Conclusion

In the present article, we presented two ways of understanding the world: block thinking and line thinking. We also described the project process which was the practical consequence of a theoretical analysis of these two issues. The current way of designing is dominated by block and general arrangement thinking. The software we use is also based on this type of thinking. It made us realize that we could not, in fact, think entirely “in lines”, because the tools we use to design or work are not adapted to this mode. Even the way in which we approached solving problems related to the project was strongly influenced by general arrangement and modular. Nevertheless, in many situations block thinking and line thinking are linked. Grasshopper[2] – software we use to program the robot, is based on the principle of connecting functions in blocks and tiles. However, these blocks are connected with lines which make them interact with one another, and their combination forms constructions, structures, movement of the robot – it creates the reality. Thanks to the Grasshopper add-on, we do not program the robot by entering verbal commands, but by organising the trajectory of its movement in three-dimensional space. These functionalities significantly depart from traditional CAD software, such as Auto CAD, or Rhinoceros 3D which operate mainly on projection drawings and cross-sections, creating objects from components-building blocks. In Grasshopper, the user designs movement, which refers to Picon’s observation that the robotic arm is a tool that liberates us from the flat geometry of technical and execution drawings (Picon, 2015).

It created a certain confusion (“entanglement”) which had particular consequences for the work. We solved problems related to the working system with block thinking: the work was divided into given modules and stages, there was a rough division; writing the paper also contained elements of block thinking. Line thinking was visible in the way of handling the knitting technique and solving purely practical problems; it was characterised by process approach to the subject, experimenting – understood rather as learning like a craftsman, exploring with senses (body, working with the material), and not as a lab experiment consisting of controlling the entire course of the experiment – as well as opening the project to the outside. Ingold’s texts reaffirmed our conviction that the work of a designer or creator is connected to the process – which is its intrinsic element. In our case, it was the process that led to the final effect which was its direct consequence – not the product that dictated the process. We had no idea what it would lead to in the

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[2] Add-on to the three-dimensional modelling software Rhinoceros, used for the parametrisation of constructed models (3D geometries), There are additional features created for Grasshopper, which, for instance, enable translating saved geometries or lines to the language and movement of a robot. One of such features is KUKA Prc, enabling operations of the KUKA family robots. We used one of them for this project.

end, or what we are striving for. We do not believe that the process is complete – it simply stopped at a certain stage. (see fig. 3).

Fig. 3. The process of blowing up and expanding the knit structure. Photo: M. Reich

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SURFACE ORNAMENTATION AS BY-PRODUCT OF DIGITAL FABRICATION

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The paper describes series of experiments directed towards devising methodology on utilizing 3D printer as a generative constituent of the design process. A method to manipulate G-code, as an interface between digital and physical, was developed in order to instigate emergence of textural patterning out of fabrication process. The idea of heterogeneous surface ornamentation as a negotiation of internal and external forming forces was translated into a design of controlled production process, in which specific surface topology was informed by printing parameters, such as variated speed of material deposition, tool path and disabled retraction and actualized in the material medium of plastic. Surface ribbing, as a technique to add or subtract mass from a surface, was programmed in G-code, allowing for iterative process and a range of effects to materialize. These effects, while designed, are not entirely uniform or pre-determined, which translates into pattern heterogeneity and unexpected deviation. While spontaneous variation is encouraged, the research seeks to develop a system of control. The value of presented experimentation is seen in the potential applicability of methodology for the enrichment of surface ornamentation apparatus and as a contribution to the work on the integral involvement of manufacturing machines in the design process.

Keywords: *digital fabrication, craft, ornament*

1. Introduction

The objective of this paper is to illustrate textural patterning as the volatile outcome of the organizational material formation with a set of experiments. The overarching theoretical framework of exploration is concerned with studying translations between digital and physical realms, and more specifically, the unstable space of actualization of the 3D digital model through manufacturing machines, such as 3D printers, CNC milling machines and industrial robots. The thesis is that manipulation of manufacturing parameters could lead to various architectural facets being informed by the process of making and material behaviour. The overall intention is to uncover mechanisms of control that could be practised by designers in order to utilize the full potential of existing and developing software and hardware to be constitutive actants in the design process. The work, presented here is specifically aimed at devising ways to instigate controlled yet undetermined surface articulation by manipulating the G-code of a 3D printer, specifically by allowing looping and stringing to occur.

2. The theoretical aspect of the study

The discursive space of this research is a convergence of two lines of thought, namely the concept of surface ornamentation as an indirect material trace of the process of formation and the notion of digital craft. Digital architectural craft is characterized by continuity between conception and production through the tight connection between parametric design and digital fabrication as well as through increasing involvement of designer with manufacturing. (Kolarevic, 2008). Both computer software and digital fabrication tools with their abilities and limitations become organizational models for the formation of matter, simultaneously computer-controlled fabrication machine is a joint between information and its actualization, it serves as a processor of matter through the organizational algorithm. Most importantly, the digital craft is the *workmanship of risk*, because the outcome is not predetermined in its entirety; exercising continuous translation from digital to physical can be employed to discover, not merely represent. (Pye, 2002). Branko Kolarevic is reasoning in *The (risky) Craft of Digital Making* that craft is inseparable from the notions of glitch, error and unexpected results. In the parametric design, process form is a visualization of the underlying generative substrate that is a network of relationships. Often the reaction of form to manipulation of this network is not linear or proportional, therefore digital craft is about learning and training to control the successive translation and transformation of data through an iterative process.

Evolution of digital fabrication tools has initiated a shift in thinking about ornament and revived a concept of ornamental qualities emerging from the process of development and production tightly bound with materiality. Farshid Moussavi introduces an idea of ornament being immanent to object's internal logic behaviour: “Ornament is the figure that emerges from the material substrate, the expression of embedded forces through processes of construction, assembly and growth. It is through ornament that material transmits affects.” (Moussavi, 2008). The interaction between the machine that produces an object and engaged material with its characteristics, such as plasticity, density, directionality, viscosity constitutes “a nexus of external forces and internal structuring.” (Spuybroek, 2016). Fabio Gramazio and Matthias Kohler are arguing for *digital materiality* that is defined by digital logic and material logic mutually informing each other. In order to accomplish this integration, refocusing of the design strategy is required: “We are no longer designing the form that will ultimately be produced, but the design process itself.” (Gramazio & Kohler, 2008). Therefore, manipulation of the parameters of the process leads to indeterminate material effects.

2.1. Precedents

In some of the *objectiles,* Bernard Cache explored consequences of changes in tooling paths for CNC machine. (Cache, 2004). Minute deviation in geometry and sequence drastically affects the way a surface is milled. Change in the process leaves its trace on the surface, reorganizing the matter into a different pattern. Another slight change and a next pattern appear, documenting, like a graph, successive transformation of the shift in milling trajectory into material and formal variation.

Textural patterning as a negotiation of interior and exterior forces as well as the notion of generative imperfection is echoed in Andrew Atwood's *Monolithic Representations*. (Atwood, 2012). His concern is with the limits of an architectural object, seen not as an aggregation of parts, but as a "monolithic" material organization. Atwood stresses the importance of calibrated tension resolution between the heterogeneous architectural system and smooth, homogeneous surface, defining its boundary. The solution is a singular, at least in organizational logic, the process of structuring. Atwood and his team designed their own software and hardware (3D printer). The single material was used for all of the experiments, it was ABS plastic. Continuity of form creation and its fabrication revealed a range of unexpected surface articulations routinely occurring in output objects. These surface tensions between material, geometry and manufacturing process were studied, and as a result, eventually, they fell under a certain degree of control of the designers. Calibrating specific parameters of the printer allowed to create material effects directly linked to the process; in one case, it was apertures, in another - bumps and the third completely subverted to the integrity of surface by turning it into a series of bundling loops.

If Atwood's focus was on creating a continuity of process-affected on a single material, another approach, exemplified by Miguel Fisac's facades constructed through the technique of flexible formwork in the 1970s and inspired by it contemporary P-Wall project by MATSYS, is to link complex formation with physical forces. Flexible formwork for concrete panels is legacy of Miguel Fisac, who felt that the true nature of concrete as a fluid, pliable material was subverted by use of wooden formwork. (West, 2016). A plastic sheet with a set of constraining points as formwork led to rough irregularities like wrinkling, creasing, bulges – non-linear processual traces. MATSYS created a 3D-patterned surface that is a result of precise calibration of a limited set of design and production parameters juxtaposed onto self-organization of two material systems. At the same time, physical forces are treated both as bounding and as constructing. P-Wall is irregular on the surface scale, only the larger pattern is predetermined, similarly to Fisac's work. Imperfection is allowed within the limits of structural stability. Formwork is outlined by a script that tested a set of points within a field to determine a pattern of constraint points based on the distance between them. The minimum and maximum distances were defined by the physical properties of plaster and flexible formwork, allowing gravity and surface tension to have a pronounced influence. (Kudless, 2012).

These examples illustrate the generative potential of fabrication process manipulation in terms of the emergence of surface-scale effects. What usually is treated as “glitch” is an outcome of the interaction between material logic and machine logic during iterative process of making. The ambition of this work is to further the understanding of these effects. What causes them, which parameters are involved and what mechanisms of control can be utilized.

3. Methodology

In order to set a controlled experimental space, it was decided to use single geometry, single printer and single material. Fused plastic filament printer was chosen; for all printed models the digital model is a simple cylinder, the geometry of which is kept stable throughout experimentation. The focus of this series is shedding and accumulation of mass instigated by manipulation of G-code combined with allowing stringing and looping to happen. Usually, stringing and looping are considered undesirable and erroneous, however, it was observed that these effects are systematic, and therefore controllable, as well as generative in terms of surface topology. Centring experimentation on G-code allows keeping attention on the interface between software and hardware, also designing a performative G-code affords a number of potential iterations and therefore is capable of producing continuous variation required to create a substantial range of effects. Addition and subtraction of matter to and from the surface are seen as ornamental manifestations; a particular set of adjusted parameters, such as speed of deposition and tool path, in conjunction with gravity, are treated as forming forces; an undetermined variation that occurs spontaneously is embraced as the emergence of processual and material traces.

4. The model set 1. Accumulating mass through the ribbing

4.1. Ribs

This set represents programming of the speed of deposition with disabled retraction. In G-code lower and upper cylinder bases are subdivided into segments, end points of corresponding segments are connected and then the top base is rotated around the z-axis. At points located on connecting curves, the printer is set to print with speed of 400 mm/min, whereas regular speed is 800 mm/min. Slower speed translates into higher flow rate, so more material is being deposed. Sequential densification of slower deposition points is employed, resulting in the ribbed pattern (see fig. 1, 2, 3). At a certain point, between 12 ribs and 24 ribs, clear boundaries between thicker and thinner surface are blurred and the printer starts to fill the in-between space with fine filaments, producing minute variation throughout (see fig. 3).

Fig. 1. 6 ribs with 30°, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

Fig. 2. 12 ribs with 90°, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

Fig. 3. 24 ribs with 120°, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

4.2. Extruded ribs

The interest in effects produced by stringing, which begin to be perceptible in **set 1.1**, is further explored by extruding ribs 5 mm outwards in G-code. In these experiments the number of ribs is 6, 12 and 18, angles are 30°, 60°, 120° and 180°. Significant variation can be achieved through angle increase (see fig. 5, 6, 7). While the outcome is largely controlled, the 180° model (see fig. 7) approaches the limit of controlled variation. It happens because each printing layer of the cylinder is rotated in relation to the previous one while ribs are perpendicular to each layer. When rotation, and therefore displacement become too severe, each following layer of rib slightly shifts and loses support from below, causing falling of matter downwards. Due to this push towards the untenable, the model's surface can no longer be determined as singular and continuous. If in a model with 120° between lower and upper bases (see fig. 6) there is still a ribbed surface, where ribs are additionally connected to the surface by strings; in a model with 180° (see fig. 7) ribs give out their regularity and linearity. That, combined with less than parallel strings produces a dense space of webbed matter all around the surface of the cylinder.

Fig. 4. 6 ribs with 30°, extrusion 5 mm, V_{rib}: 400mm/min, V_{cyl}: 800 mm/min

Fig. 5. 12 ribs with 60°, extrusion 5 mm, V_{rib}: 400mm/min, V_{cyl}: 800 mm/min

Fig. 6. 18 ribs with 120°, extrusion 5 mm, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

Fig. 7. 18 ribs with 180°, extrusion 5 mm, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

4.3. Intersecting extruded ribs

Further experimentation involved programming of intersecting extruded ribs as an attempt to see what kind of difference might result from the addition of geometric complexity. The orientation of ribs clearly plays a significant role and juxtaposing model with 1-directional ribs (see fig. 6) against a model with 2-directional ribs (see fig. 9) shows that opposite directionality of stringing filaments induces their merging in the centre, which produces branching superstructure. At this point, one more parameter was taken into consideration, namely printing tool path (see fig. 10). All preceding models are produced with default tool paths that amount to printing the rib and cylinder surface continuously, while ribs are treated as secondary geometry and printer “returns” to them. Adjustment of tool path consisted of a topological split of geometry in G-script so that one layer of the cylinder was printed first and then ribs were continuously printed in the same layer (see fig. 10). The space between the ribs is filled with fine, candy-floss like directional filaments.

Fig. 8. 6 ribs with 60° and - 60°, extrusion 5 mm, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

Fig. 9. 12 ribs with 60° and - 60°, extrusion 5 mm, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

Fig. 10. 12 ribs with 60° and - 60°, extrusion 5 mm, V_{rib}: 400 mm/min, V_{cyl}: 800 mm/min

5. The model set 2. Shedding mass through the ribbing

In **model set 1**, the speed of deposition was decreased for ribs, while the surface of the cylinder itself was printed with regular speed. In the following cases (see fig. 11, 12, 13, 14), the speed of deposition for rib areas remained 400 mm/min whereas cylinder surface was printed with 1600 mm/min. As retraction was still disabled, material continued to pour, filling the space between ribs with porous, semi-directional matter. The action of thinning of the cylinder’s surface results in ribs becoming more pronounced as structural elements.

G-code of models, represented by figures 15, 16 and 17 is a diagonal mesh, where solid parts are set to be printed with the regular speed of 800 mm/min and voids with 1600 mm/min. The difference between three models is the length of voids; it is 2, 5, and 10 mm respectively. Similarly to experiments with extruded ribs, the consistent and regulated shift of a certain parameter value indicates the limits of controlled variation. As indicated by figure 17, a model is too structurally unstable even though it exhibits a promising effect, akin to crochet.

Fig. 11. 12 ribs with 60°, V_{rib}: 400 mm/min, V_{cyl}: 1600 mm/min

Fig. 12. 12 ribs with 120°, V_{rib}: 400 mm/min, V_{cyl}: 1600 mm/min

Fig. 13. 18 ribs with 120°, V_{rib}: 400 mm/min, V_{cyl}: 1600 mm/min

Fig. 14. 18 ribs with 240°, V_{rib}: 400 mm/min, V_{cyl}: 1600 mm/min

Fig. 15. V_{rib}: 800 mm/min, V_{cyl}: 1600 mm/min

Fig. 16. V_{rib}: 800 mm/min, V_{cyl}: 1600 mm/min

Fig. 17. V_{rib}: 800 mm/min, V_{cyl}: 1600 mm/min

6. Conclusions

Presented experiments are within the space of manufacturing process design, in particular, they are focused on using the 3D printer as a generative design component. Research is beginning to accumulate data on the relationship between specific parameters, their manipulation and resulting deformation. A clearer understanding is gained regarding the moment when manipulation of G-code leads to structural failure. For example, it occurs if the amount of deposited material exceeds layer height. The experiment with tool path demonstrates that topologically discrete geometry in G-code is translated into an indiscrete printed model, and the topological difference is translated through a change in 3D textural effect.

Geometric parameters, such as a number of ribs, the angle between lower and upper cylinder bases, the amount of extrusion and fabrication parameters, such as speed of deposition, retraction, tool path inform each other. A range of various, semi-controllable effects, which are reproducible, occur as an outcome of this interaction and by-product of fabrication. Studying of making of such effects contributes to an enrichment of apparatus and instrumentality of discourse and practice of digital surface ornament as a processual trace.

Further research will continue to focus on shedding and accumulation of matter through such techniques as tessellation and weaving. Simultaneously, experiments presented in this paper and further ones will be reproduced using different printers and materials in order to study the influence of material composition and behaviour. While most of the produced effects are at surface scale, others begin to broach areas that are deeper than skin. it is expected, that at a certain point the research will have to address structure and form so that ornament can become integrated into the continuous yet heterogeneous system.

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PROGRAMMABLE BENDING A STRATEGY FOR DESIGN, FABRICATION AND ASSEMBLY OF ACTIVE-BENDED WOODEN STRUCTURES

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The project examines a potential of programmable bending - a strategy, which through the use of computational tools achieves the active bent structure of complex geometry out of flat non-customized wooden elements.

The recent development of new computational and fabrication tools brings new potential to the traditional materials such as wood. Being a natural composite, wood has anisotropic qualities, which used to limit its industrial use, yet could become an advantage, when implemented into the design process.

Application of veneer rather than ordinary lumber as a building material allows to include the information of specific fibre structure into the computational process through its scanning. The project develops a workflow, in which a two-dimensional scan of the material is into a mesh. Bending characteristics of the veneer stripe are simulated with a spring system according to its particular fibre layout. The uneven connection of several layers of active-bended veneer allows to accumulate local stresses and therefore pre-program bending characteristics of the structure. As a result active-bended structure forms particular predefined and predesigned shape and possesses locally variable stiffness and flexibility. The project applies this strategy to the design of the pavilion located in the area of Bethlehem Chapel in Prague. Local grain directions of active bent veneer stripes are represented as virtual three-dimensional force fields, which could be overlaid or mapped on the pre-designed geometry, resulting in the optimal organization of the components. The approach was applied to the design and fabrication of a column prototype.

The strategy, examined in the project, can be applied on a bigger scale with a use of both processed and unprocessed wooden elements. The absence of a formwork can be considered as a relevant advantage of the programmable bending, particularly in case of fabrication of non-repeatable complex geometries.

Keywords: *programmable bending, wood, grain, computation, veneer*

1. Introduction

The recent development of computational tools shifted the interest to a new role of materiality and a new role of fabrication processes in the field of architectural design (Menges & Ahlquist, 2011). While initially, the new possibilities brought by the information era meant to increase and more precise control of the complexity of the built structures, recent research is focused on optimization and re-evaluation of the fabrication techniques and re-approaching of the sustainable pre-industrial materials (Menges et al., 2017). A Programmable Bending project aims at defining a computational approach to the design, fabrication and assembly of complex geometries out of mass fabricated non-customized wooden elements. The project considers the anisotropic character of the material and simulates its variable bending characteristic through scanning its grain pattern. The secondary hypothesis of the project is a possibility of using irregular properties of the material as a design driver. Such an approach can result in an architectural structure with predictable free-formed overall geometry and emergent character in the detail level.

2. The theoretical aspect of the study

Contemporary shift from the architecture based purely on notation to the architecture represented by algorithm, which takes into account material characteristics and fabrication processes has been described by Mario Carpo in his works The Alphabet and the Algorithm and Architecture in the Age of Printing as a partial reversal of the opposite process in the Renaissance (Carpo, 2011). Pre-Renaissance and particularly vernacular architecture, for which the indistinguishable processes of design and making are often characteristic, located itself on the verge between the notational and behavioural techniques. The Platonic Eidos of the building might have been present in any human-made structure, yet it was commonplace for the pre-Renaissance master-builders to include the physical interaction with the material to the design process. It is the distinct division of the intellectual and the physical, proposed by Alberti, what pushed the behavioural strategies to the relatively marginal role in architecture (Carpo, 2011).

The introduction of "zero tolerance fabrication" methods, made possible by the rapid development of the fabrication and sensing technology, pursued the aim of reducing material indeterminacy to a marginal level. However, the very same technological development brings the possibilities of re-introduction of behavioural-based design and construction processes (Menges, 2015). The introduction of the system of positive and negative feedbacks allows creating a self-regulating flexible process, something that is being thoroughly explored in the multiple fields of industry and has a potential for a revolutionary impact. The technologies of two-dimensional and three-dimensional scanning and, more importantly, of scan processing allow us to apply specific and irregular characteristics of natural materials to be considered within the design. In particular, these possibilities bring new perspectives to the use of anisotropic materials such as wood in architecture.

Being a natural fibre composite, wood has many unmatched qualities as a building material. Its ability to resist forces in tension along fibre direction, which matches that of a steel of the same weight, its wide availability, its sustainability and ease of processing made wood the most popular construction material in the pre-industrial era. (Cheret & Seidel, 2013) Wooden constructions were widely used in vernacular architecture as well as in churches, palaces and bridges well into the nineteenth century. The approach of industrialization meant that manual processing techniques were substituted by machine mass production.

That led to the increase of use of isotropic materials such as steel and concrete. Wood, being anisotropic material, still was used, however, its use became limited. Another consequence of industrialization was a switch of focus to timber, which represents only one-third of the available wood. While irregular parts of wood were commonly used in the pre-industrialization era, particularly in shipbuilding, new fabrication methods meant, that regular geometries became preferable (Self, 2017).

With the development of computational tools, a new understanding of the material in architecture is beginning to arise (Menges & Ahlquist, 2011). Scanning, scan processing and simulation techniques allow us to take into consideration specific characteristics of the material, while new fabrication tools prove crucial to the reintroduction of traditional craftsmanship into mass production. The potential of this approach lies in particular in the possibility to inform the design process as well as the designed geometry by specific material qualities, thus merging the physical and the digital in one model.

3. Research methodology

The project questions the possibility of informing the design with the particular characteristics of the material structure and of creating complex geometries from non-customized or minimally customizes mass-produced elements.

In order to obtain the information about the material structure, the veneer has been chosen as the main material. Unlike it is in a case of timber, the inner structure of the veneer is virtually similar to the one on its surface, so the necessary information was collected by two-dimensional scanning of the veneer stripes. A custom-made algorithm has been used to transform the raster image into a vector-field, which took into account a particular grain direction of the material.

The simulation of the material bending characteristics was done in consideration with its inner structure using a spring-based system Kangaroo in a visual scripting platform Grasshopper within a 3d-modelling software Rhinoceros 5.0.

As a part of the research, several approaches of informing the design with the data, obtained from grain scan, have been considered. Milling irregular geometries along the grain direction and connecting them with custom-made 3d-printed joints proved promising in creating visually strong design language yet produced a lot of waste material. As the main fabrication method, we chose uneven connection of several layers of active-bended veneer, which allowed to accumulate local stresses and therefore pre-program bending characteristics of the structure.

Another method used to produce the design, informed by anisotropic veneer characteristics, involved local grain directions of active bent veneer stripes being represented as virtual three-dimensional force fields, which could be overlaid or mapped on the pre-designed geometry, resulting in the optimal organization of the components.

Overall, the project examined a potential of uneven and irregular bending as a design driver - a characteristic most fully defined by the veneer fibre structure.

4. The research development

The material-informed design has many precedents in the pre-digital era. One important example present behavioural construction processes, where each construction step is based on visual, tactile or other material evaluation. The behavioural roots of structural processes can be seen in the non-human built structures, such as wasp hives or ant nests, as well as in the ontogenetic processes of the living nature (Hansell, 2008). This approach has also proved essential to the traditional craftsmanship. When working with wood, the craftsman has to consider its structure, its grain pattern and its anisotropic qualities, which he evaluates visually. This approach, optimal in certain areas, has its limits, when implemented in mass production, due to lack of systematic procedure and clear evaluation criteria. Another, entirely different approach is presented by material computation. Known from the work of gothic master-builders, or, more recently, Antonio Gaudi and Frei Otto, material computation searches for the optimal solutions while considering specific material characteristics (Menges, 2015).

The project implements digital parallels to both approaches and tests their feasibility in architectural design. The behavioural construction of non-human built structures or traditional craftsmanship is substituted by scanning, scan-processing and designing based on scan data, in other words automating the evaluation-fabrication loop. The material computation is substituted by digital simulation using established methods within existing visual scripting platform.

The advantage of veneer, as scanned material, consists in its two-dimensional character. Unlike timber, which would require complex methods for three-dimensional scanning, such as Computer Tomography, scanning veneer is fast, based on just optical processes, and easily automated. The resulted data are high-resolution black and white raster images, which clearly indicate the grain pattern of the veneer and provide necessary information about its inner structure (see fig. 1). Equally important is processing of this information. While the output of the scan is a raster image, many of the design algorithms, used in the project require a vector-field - a set of vectors with adjusted areas of their effect - in order to operate. A custom-made algorithm divides the image into rectangles three by three or four by four pixels. Within those rectangles, an averages of black pixels position and of the white pixels position are located. A vector cross product between a normal to the scanning plane and a vector connecting those averages presents a vector, which would define fibre direction (see fig. 2). After several iterations of interpolation, a realistic vector-field representation of the grain pattern is achieved. The vector-field representation of the grain pattern has been used in order to achieve precise bending simulation of the veneer, which would take into account its specific structure. As the spring-based engine Kangaroo within Grasshopper visual scripting platform efficiently works with mesh geometries, a mesh with variable stiffness characteristics has been used to represent each veneer element (see fig. 3). The stiffness of each edge within a mesh was calculated basing on an angle between this edge and the relevant vector within a vector-field. That resulted in a realistic simulation, which differentiated bending characteristics along the grain and perpendicular to the grain.

During initial tests, several approaches have been implemented to affect the design with scanning data.

One of this approaches considered transforming through distortion predesigned layouts according to the vector-field grain representation and milling subsequent layouts in the veneer. Resulting shapes had the majority of their borders positioned along the grain direction, which meant more stable surface quality. Additionally, milling speed was optimized based on the angle between the relevant vector within a vector-field and a milling direction. Joints between veneer elements were generated using particle systems, where particles were affected by the vector-fields of each veneer element. Resulting shape was a fluent and continuous connection, fabricated using 3d-printing technology (see fig. 4).

This approach proved to achieve stiff structures with visually strong design language, yet wasteful in its use of material and limited in relation to the mass production and full automation. Additionally, 3d-printing generated joints proved counterproductive, as complex connections are the feature, which requires complex anisotropic inner structure and is widely available in wooden branches (Slater & Ennos, 2015).

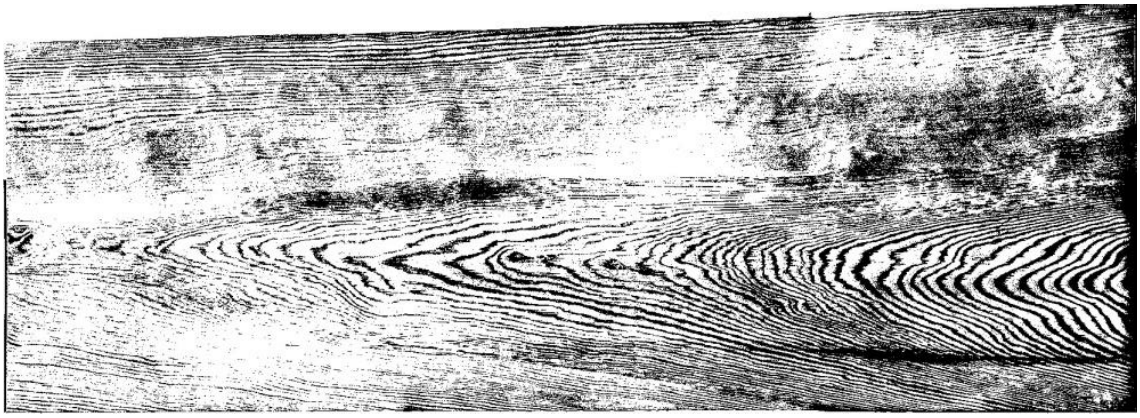

Fig. 1. A scan of the veneer. Source: Tsikoliya (2016)

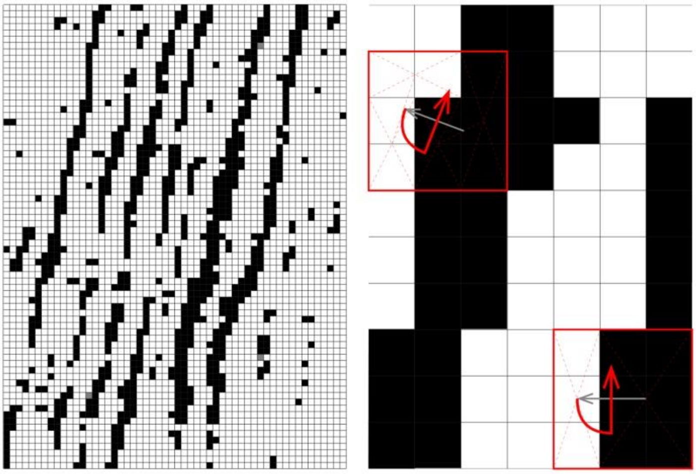

Fig. 2. Transformation of the raster image to the vector field. Source: Tsikoliya (2016)

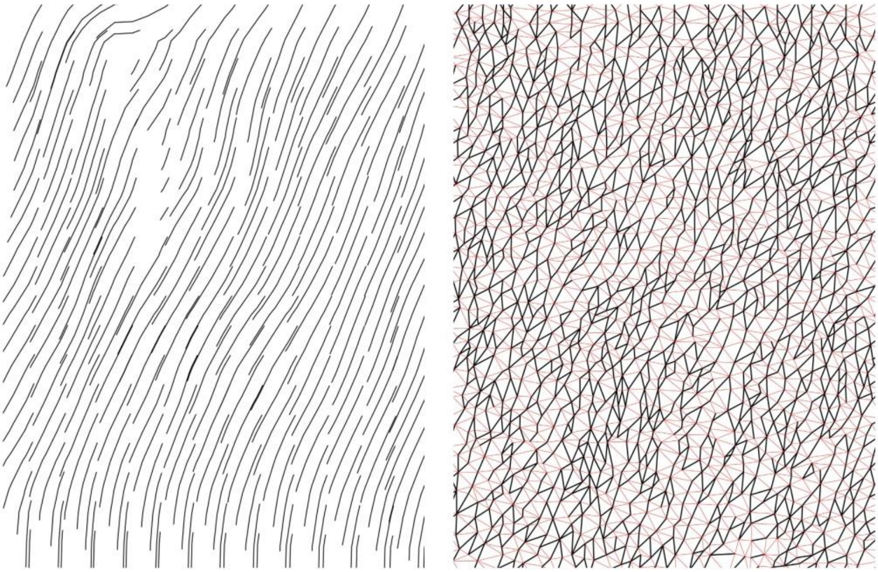

Fig. 3. Vector-field and mesh representation of the grain pattern. Source: Tsikoliya (2016)

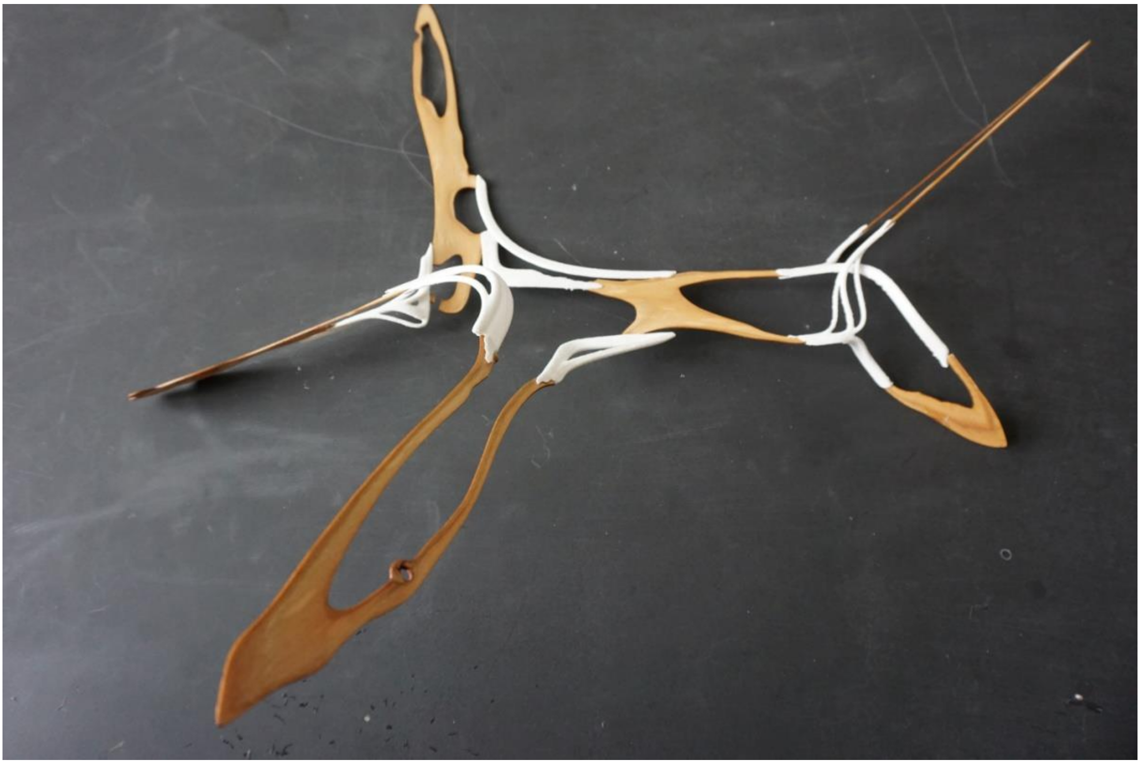

Fig. 4. Custom-milled veneer components and 3d-printed joints. Source: Tsikoliya (2016)

A simpler approach included uneven pre-stressing and layering of the several non-customized veneer elements. The uneven connection of several layers of active-bended veneer allows accumulating local stresses and pre-program bending characteristics of the structure. The anisotropic and irregular character of the veneer meant irregular bending properties. Several iterations of digital and physical simulation allowed to calibrate the digital model and make it precise enough for the design and subsequent fabrication (see fig. 5). While overall geometry was free-formed basing on several external conditions and limitations, the design was affected and optimized using the knowledge of the specific material properties and its bending behaviour. The design procedure went as follows. Initially, the target shape was modelled. This target shape was subsequently subdivided into elastically bent elements with variable bending radiuses. The necessary connection points locations between the layers of the veneer were estimated, in order to achieve such a local stress accumulation for the structure take the required shape through bending. Digital bending simulation tested and if necessary modified the estimated locations according to the irregular grain structure of the veneer. The fabrication process required only the location of connection points in otherwise none-customized elements, therefore being easy to automate.

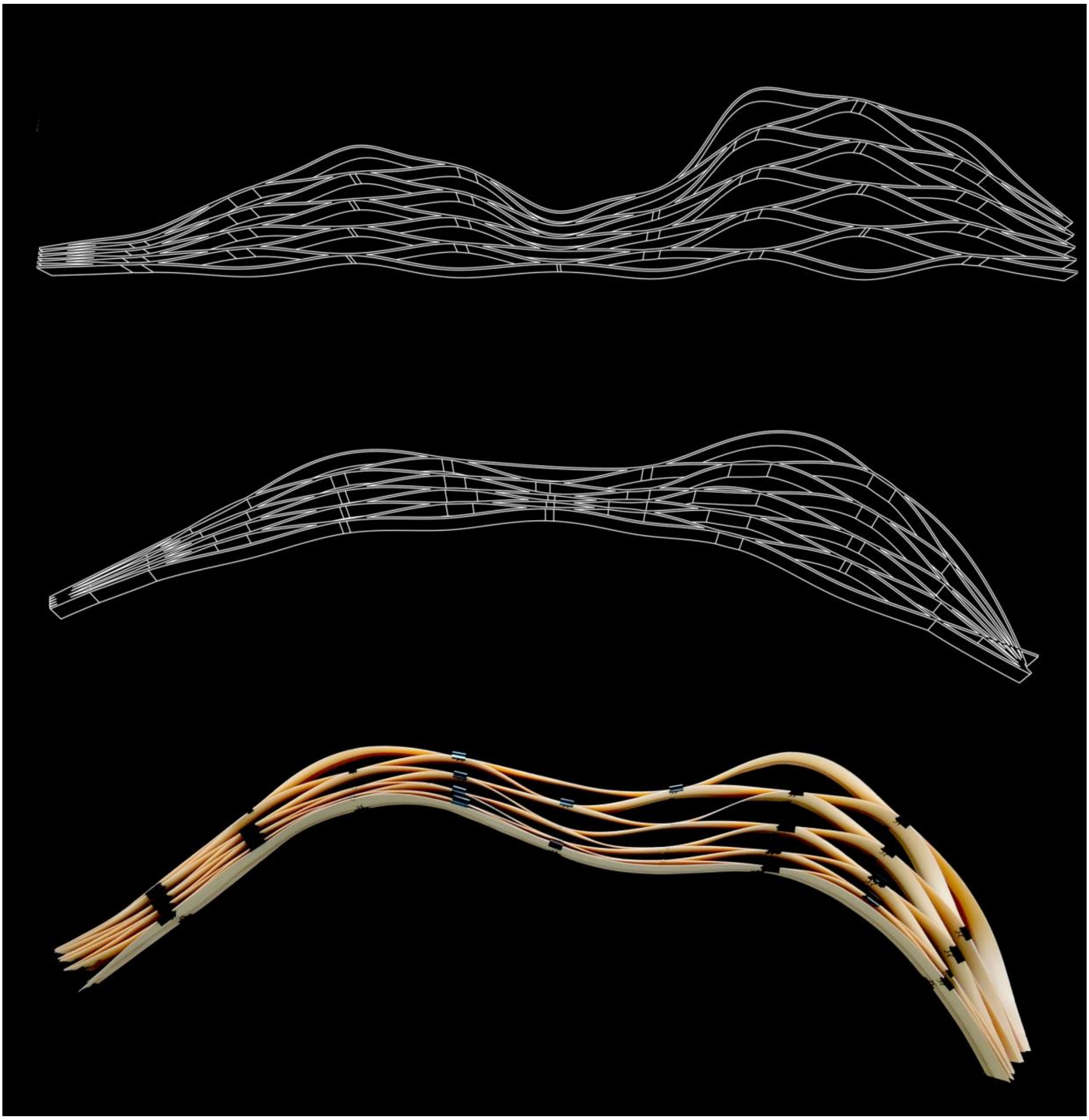

Fig. 5. Programmable bending through uneven layering. Source: Tsikoliya (2016)

Fig. 6. Programmable bending research pavilion. Source: Tsikoliya (2016)

This approach was later developed by creating truly three-dimensional elements by bending the veneer in two directions in order to create u-shaped and 8-shaped loop components. The three-dimensional digital representations of these components were containing the information about their grain pattern and could be overlaid on pre-designed three-dimensional shapes (see fig. 6). The curvature of the components was variable and affected by their size and bending characteristics, therefore complex geometries with various curvatures could be designed and fabricated from non-customized elements.

The uneven layering approach was tested on a design and construction of a pavilion in the courtyard of the Bethlehem Chapel in Prague. The pavilion presented a toroidal shape made out of 25 sections, each built from six unevenly connected layers of veneer.

Fig. 7. Programmable bending research pavilion. Source: Timpow (2016)

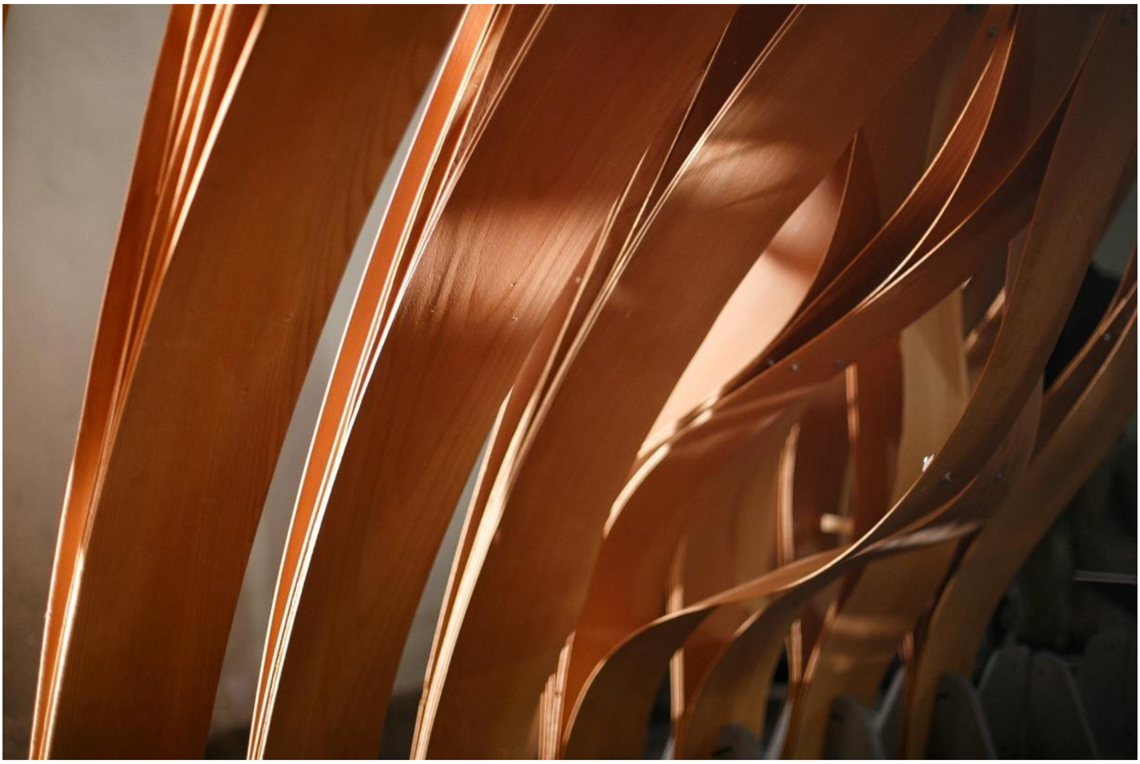

Fig. 8. Programmable bending research pavilion – detail. Source: Straka (2016)

The overall shape of the pavilion was designed basing o the environmental and site constraints, a pavilion being located in the historic architecture (see fig. 7). However, the resulting geometry was strongly affected by the emergent characteristics of the material, particularly in the scale of the detail (see fig. 8). In another test local grain directions of active bent veneer stripes represented as virtual three-dimensional force fields were overlaid and mapped on the pre-designed geometry, resulting in the optimal organization of the components. The approach was applied to the design and fabrication of a column prototype (see fig. 9, 10).

5. Conclusions

As an outlook of the project one can question the significance of the approach in the scale of architectural construction. Unless the process is applicable in those quantities, it will not be relevant for the construction industry. The strategy, examined in the project, can be applied on a bigger scale with a use of both processed and unprocessed wooden elements. Currently, the dominant amount of sophisticated wooden structures is being designed and constructed within an industry of glue-laminated timber fabrication, where complex shapes are created through the extensive use of formwork. This approach, while having many advantages, can bring substantial additional costs, especially in the construction industry, where the use of big series of repeatable elements is limited and small series production or customized geometries are prevalent. The absence of a formwork and minimal amount of custom-milled elements being used in order to achieve highly complex geometries seems to be a major advantage of the approaches used in the project.

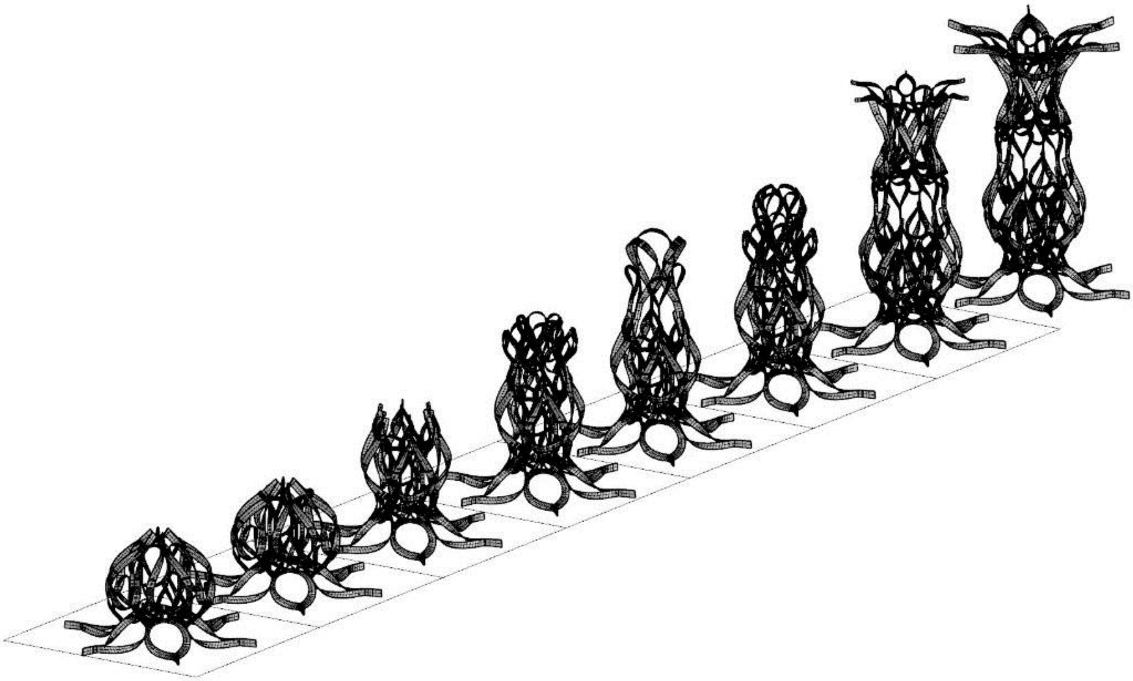

Fig. 9. Column prototype. Source: Tsikoliya, Miskovicova, Olontsev (2016)

Fig. 10. Column prototype. Source: Tsikoliya, Miskovicova, Olontsev (2016)

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GENERATIVE METHODS IN CAR DESIGN

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The paper explores possibilities of utilising generative design methods in automotive design. A description of a typical car design process is provided. Areas with potential for successfully implementing generative design methods are identified. Original works, combining traditional and generative form-finding methods are presented.

Classical car design process, being practised in carmakers' design studios worldwide and honed for the past decades, aims to achieve perfect shape in accordance with technology and industry-specific design requirements. The point being a perfect "car sculpture" ready for successful production, it typically combines the best technology available with traditional techniques, like the very important sketching and clay modelling.

Meanwhile, technologies like additive manufacturing, virtual reality or artificial intelligence are currently expanding the possibilities of what can be done beyond anyone's imagination. Designers need to understand and utilise the emerging opportunities to keep creating relevant designs. Generative methods offer a tool to explore these new possibilities. A generative design method looks different to a conventional one: instead of shaping the final form directly, an algorithm is created to generate it.

Incorporating generative systems to a design process instantly increases the effectiveness of modelling complex or variable structures. Together with digital fabrication, they also allow for design approaches not possible before. Various kinds of data can be used for creating thoroughly personalised products. Optimisation algorithms can be directly integrated into a design process. Designers can truly mimic the nature by applying its principles in form finding.

Possible points of convergence between the two design approaches arise mainly from the specifics of car design and of cars themselves. Data-rich nature of modern cars provides innumerable options for data-driven design development, optimisation or customisability. Proper implementation of generative methods will open new ways of connection between design and engineering. In the paper, a vision for future development is presented.

Keywords: *generative, design, car, automotive, process, method*

1. Introduction

Generative design as a design approach is progressing through different fields of design in various ways and paces, establishing itself as a sub-discipline. In car design, generated parametric structures are now a design trend, although the deeper potential of generative methods is still unexploited. This paper gives an overview of the current situation at the intersection of generative and automotive design. Analysing this narrow field, main challenges are identified and potential ways for meaningful progress are suggested.

The paper starts with a description of a typical car design process, the tools used and the overall situation in the industry. Olah's 2017 habilitation thesis on the topic is the main source of information. Generative design principles are briefly introduced, referencing McCormack et al. Significant examples from the field of interest are listed and described. Analysis and suggested areas of high potential are based on the examples given, and on author's professional experience. The aim is to bring attention to a recently emerged design field and to strengthen its relevance.

2. Car design process overview

Car development is a complex process that typically takes three to five years for a single new model. Car design is one of the disciplines involved in every car model development. Design development starts just after the basic product brief for the new vehicle is defined and usually continues in multiple standardised phases until the whole car is ready for mass production.

Preceding the actual design development are two basic preparatory stages: design brief and design specification. Design brief consists of mega-trends analysis, focusing on four main areas: demographic developments, consumer identification, sustainability and globalisation (Olah, 2017). Aspects like competition, geographic changes, segment development and technological development are taken into account. The design specification is a result of all the pre-development stages, consisting of initial documents from all the departments taking part in the design development process. Concrete requirements necessary for the future product's success are presented here. The design department cooperates with the front-loading department, preparing the first technical package and proportional models.

Based on the target customer group, the model's place in the brand's portfolio, the brand's past and planned future identity and the basic technical package, the first tasks for designers include defining clear design principles, basic proportions and overall emotion for the car. Designers start with creating visual representations of these values that are initially relatively abstract, forming the basis for their future design proposals.

Together with a design brief, designers work with the technical package: a set of "hardpoints" and other physical constraints coming from early engineering development. Some of these can be negotiable, some are not. For a model succeeding a successful predecessor, the constraints would typically be more strict than those of a completely new model.

A car design studio is usually divided into several standard departments: exterior design, interior design, colour & trim (design departments), model building and CAD (modelling departments). Interior and exterior design departments are traditionally separate disciplines with their own specific approaches. The automotive interior design is closer in its nature to regular product design, addressing a variety of functions and materials, detailed ergonomics and HMI (Human-Machine Interface) design. Exterior design is much more specialised, focusing on creating a balanced “stance”, perfect surfaces and a convincing “face” of the car.

The basic designers’ techniques are sketching and 3D modelling, using the benefits of both physical and digital ways of working. Digital drawing tablets have largely replaced sophisticated rendering tools of the past, the reason being mostly versatility and time-effectiveness. Tape-drawing is a technique of “sketching” lines with a special, usually black, sticky tape. This allows quick development of rough designs on a realistic scale, in two or three dimensions. Clay modelling has still not been replaced by digital techniques for the ability to interact directly with the physical form, although the virtual reality is coming close in the domain of representing real-scale design proposals. CAD design surfacing is a precise way to develop a geometrically perfect form, with the final digital 3D model being the main output of the whole design process.

Regarding these creative techniques, car designers themselves are typically the sketching specialists, while both clay and CAD modelling is mostly handled by dedicated workers, guided by designers. Designers and modellers work together in an intensive iterative process, trying to capture the original design intent while satisfying all the functional requirements. Frictionless cooperation and mutual understanding of the respective professionals inside the design department is, obviously, necessary for a good result. If the whole process is successful, the brief is translated into a clear and convincing design vision, which is then materialised in a beautiful “sculpture”, that is set to become a functional car.

There are three major revolutions happening at the same time in the contemporary car industry: electrification, autonomous driving and sharing economy. They are interwoven with the global environmental, technological and social trends. Car design as a standalone discipline, and also as a part of the whole industry, has a unique position in facing the challenges coming with them.

3. Generative design

Generative design is a design approach and a design sub-discipline that synthesises knowledge and methodologies from a number of fields, but prominently design (human-oriented product development), programming (algorithmic, rules- and data-based product development) and biology (natural forms and systems generated by laws of nature and genetic codes). A generative design process utilises a generative system, a set of rules used to generate a partial or final output. These generative systems are relevant to contemporary design practice in a variety of ways. Their integration into the design process allows the development of novel design solutions, difficult or impossible to achieve via other methods. (McCormack et al., 2004)

In a generative design process, a significant amount of creative effort goes to working with - or designing - a generative system. It is usually digital in nature, enabling computational problem-solving, interdisciplinary data exchange, fast feedback loops and precise consequentiality.

4. Examples of generative design applications in car design; trends analysis

Cars offer a number of possibilities for generative design to be used. Ranging from pure engineering optimisation solutions to purely visual, surface-level applications, the generative design is transforming automotive aesthetics, functionality, as well as the whole development process.

An early example is the 2005 Mercedes-Benz Bionic Car concept (see fig. 1). The goal was to achieve unprecedented fuel efficiency; the concept showcased cutting-edge technology, including multiple design techniques to achieve this. The outer shape was inspired by boxfish and designed in a relatively traditional process: Designers, taking clues from a fish that is uniquely hydrodynamic and at the same time boxy and rigid (good source for car design inspiration) try to emulate nature's efficiency using traditional design tools. The generative part came after the outer shape was finished: SKO[1] method was used to generate a basis for the car's body-in-white structure. By applying the SKO method to the entire body-in-white structure, weight is reduced by some 30 percent, while the high levels of stability, crashworthiness and driving dynamics remain unchanged. The reduction in weight thus renders an important contribution to a further improvement in fuel economy. (Daimler AG, 2005)

Renault's 2013 collaboration with Ross Lovegrove, Twin'Z (see fig. 2), obviously used a number of generative methods, but the media communication[2] was mostly focused on the concept's lifelike aesthetics as inspiration for the future Renault's design language. It was one of the industry-first uses of parametric design (tellingly, coming from a cooperation with a product and furniture designer), and probably had a strong impact on the trend that was yet to come.

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[1] Soft Kill Option: bodywork or chassis components are dimensioned by means of computer simulation in that the material is made ever thinner and finally cut away completely in low-load areas, whereas highly stressed areas are reinforced.

[2] Looking at how (if even) the generative aspect is communicated is very important. Most of the more advanced applications nowadays are still concepts, "showcars". These are mostly marketing tools, meant to appeal to customers and stakeholders, maintain or develop brand image, preview future models, or to attract talent. The way anything is communicated is mostly dependent on what the brand wants to communicate to general public, and doesn't necessarily reveal the background.

It is for this reason that the suppliers' concepts are interesting as insights: for example, EDAG's marketing addresses the automotive industry itself, so the Genesis concept is much more openly focused on the design process and manufacturing technology than is usual for carmakers.

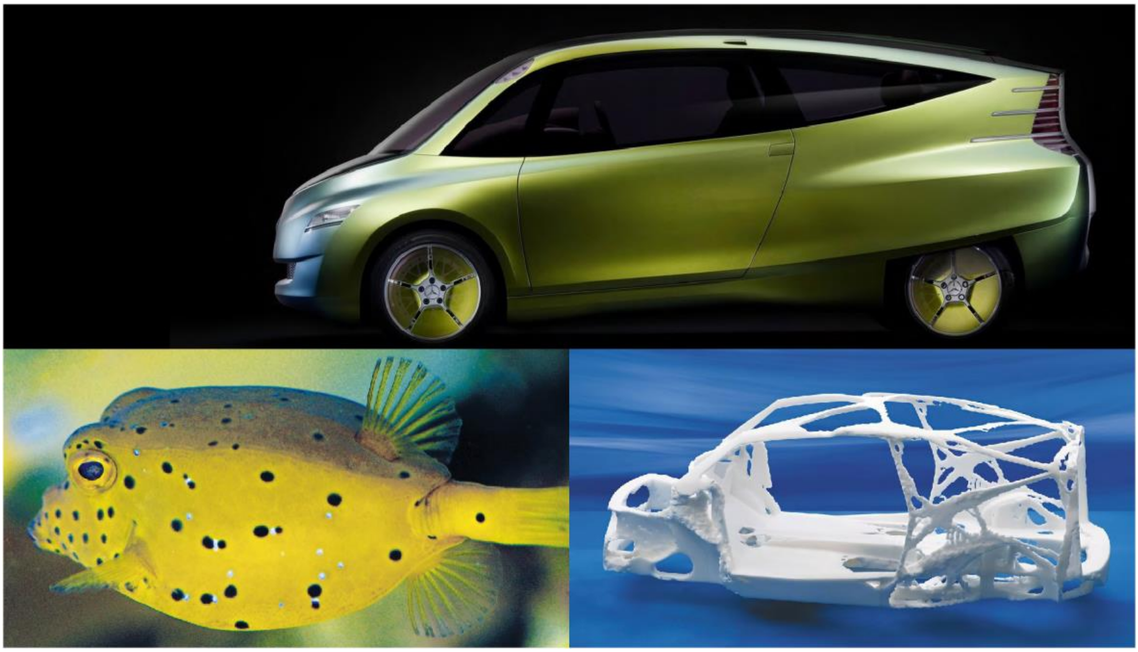

Fig. 1. Mercedes-Benz Bionic Car. Source: Daimler AG (2005)

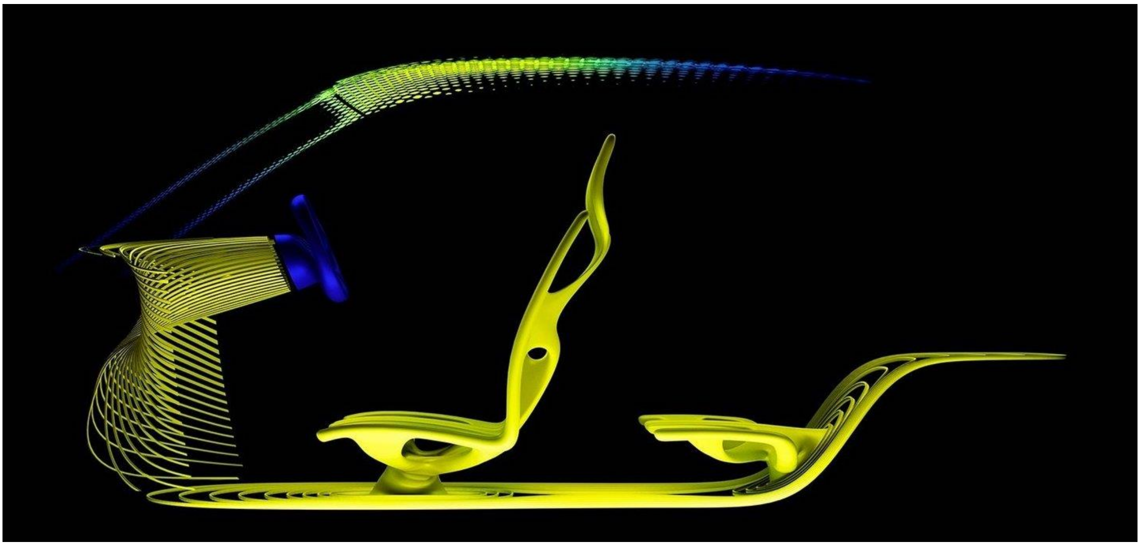

Fig. 2. Renault Twin'Z: organic shapes and parametric structures. Source: Groupe Renault (2013)

There has been an influx of parametric structures to the car design world in the recent years. Applied to both exterior and interior elements, they are one of the prominent visual design trends, mostly in showcars. The most straight-forward applications are the grids that cover air intakes, air conditioning and speakers. These grids are being parameterised as a styling element. Parametric structures, flat or 3-dimensional, frequently cover much of the interior surfaces. Only occasionally a functional reason for them is communicated. Peugeot Fractal concept's sound-absorbing (see fig. 3), 3D printed door and floor surfaces is an example. In the exterior, traditional clean-cut DLOs[3] are being replaced by pattern gradients (see fig. 4, 5), thus transforming one of the traditional brand- or model-identifiers. Lighting modules, also influenced by the trend (and a signature element as well) are becoming increasingly intricate (see fig. 6), aided by miniaturisation and progress of lighting technology. It is yet to be seen what effect the trend of parametric patterns will have on serial production cars. It certainly has already enriched the car designers' visual vocabulary.

Fig. 3. Peugeot Fractal: sound-absorbing structures, generatively. Source: Peugeot (2015)

The aesthetics that designers are trying to achieve with these patterns are meant to project technological advancement and sophistication. They look animated and soft, in contrast to the clean and rigid solutions that were a necessity in the past. In fact, they are often used as a bridge between the physical form and animated digital elements, often a part of Human-Machine Interface. In BMW VISION NEXT 100 (see fig. 4), such a pattern (a simple triangular grid) got a name: "Alive Geometry", and became one of the main design elements. As the company writes on the concept's website, *"The Alive Geometry of the BMW VISION NEXT 100 performs two main functions. On the one hand, it serves as an analogue display system on the dashboard, alerting the driver to incidents and objects ahead. From the exterior,*

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[3] Day Light Opening: a term for the side window contour in car design.

the Alive Geometry is visible in the form of movable wheelhouse covers for optimal aerodynamics.” (BMW Group, 2016)

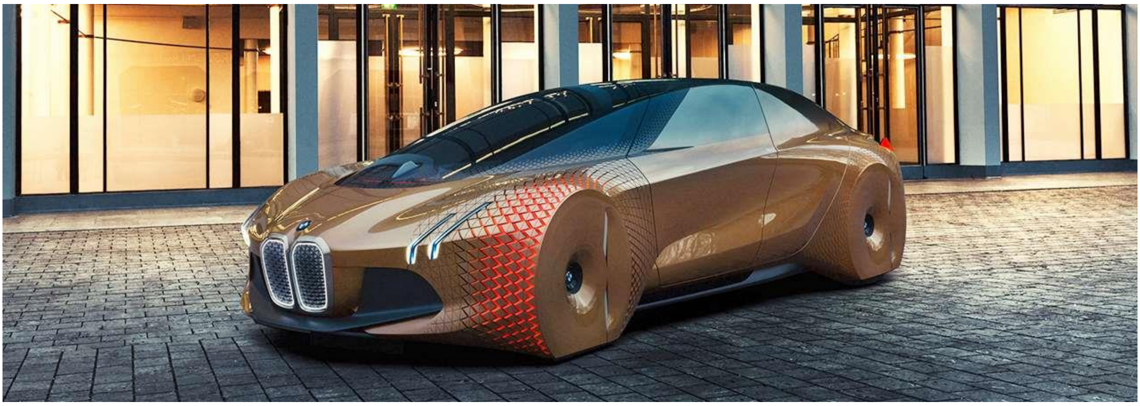

Fig. 4. BMW VISION NEXT 100: Alive Geometry. Source: BMW Group (2016)

Parametric patterns in the exterior can also be associated with autonomous driving concepts. With the car driving itself, the DLO wouldn’t be so restricted by the driver visibility, thus creating a new space for design creativity. Combined with the trend of air intake grids being transformed to exterior HMI[4], parametric structures used in exterior design might become a signature visual clue for autonomous mobility in the future.

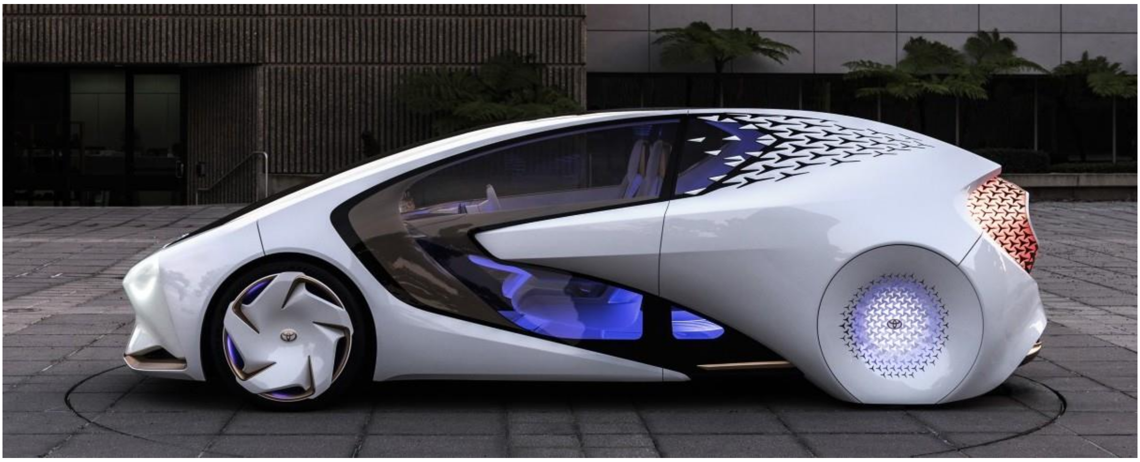

Fig. 5. Toyota Concept-i, an autonomous car concept covered in and filled with parametric patterns. Source: Toyota (2017)

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[4] Exterior Human-Machine Interface: visual communication between a self-driving car and it’s outer environment. An emerging design field with enormous role in future mobility.

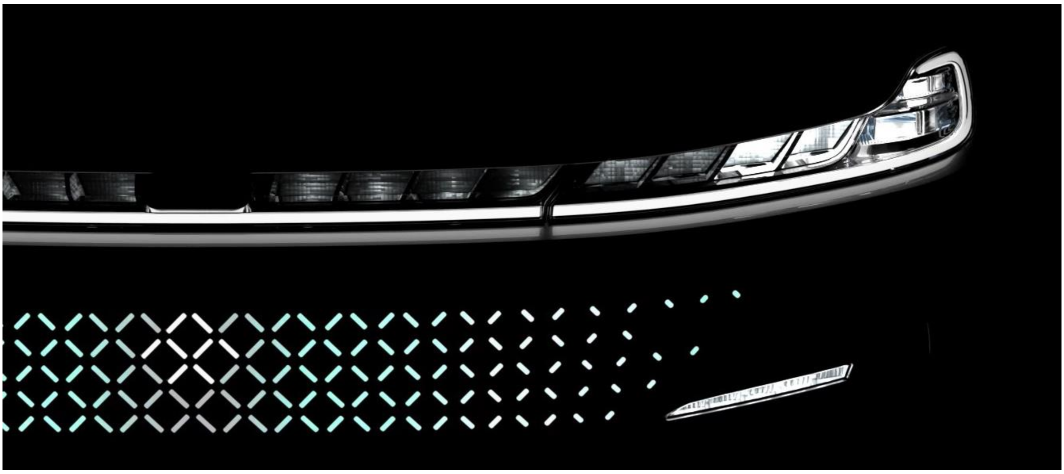

Fig. 6. Faraday Future FF91: exterior lighting features the company’s logo on a grid. Source: Faraday Future (2017)

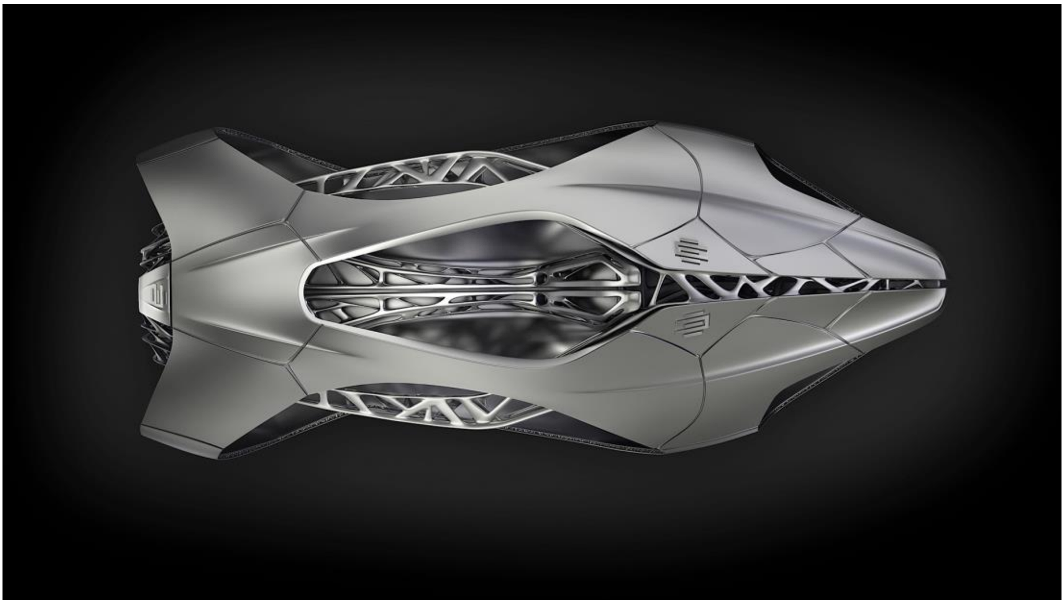

Fig. 7. EDAG Genesis - top view. Source: EDAG (2014)

EDAG’s Genesis concept (see fig. 7) is a showcase of combining traditional and generative design methods in a novel form-finding process, while also using the possibilities of additive manufacturing. This concept doesn’t try to look like a pre-production prototype but is rather focused on presenting the potential of novel technology in design and production. Additive manufacturing and generative design are shown as complementary technologies that are meant to bring about more efficiency and new aesthetics. As shown in the Genesis concept, designers can use generative methods to produce complex, load-specific geometries, virtually impossible without some specialised software's help. They can also be materialised using 3D printing technology, now approaching quality needed for mass production.

There are several ways to dissect the approaches that can be observed in the recent spread of generative design tools and methods in the automotive design world. One of them is comparing aesthetical and functional aspects of implementing them, and the relationship between them. Any of these aspects could be virtually invisible, with thoroughly all-around (both aesthetics and function enhanced by implementing generative design) examples being scarce. The boxfish-inspired Mercedes-Benz Bionic Car featured a generative optimisation method as a revolutionary computer-generated basis for engineering work, while not affecting the final car's appearance at all. On the other side of the spectrum, we are trying to lay out, many designs use generative methods purely for visual novelty or even just trend catching. Examples like BMW VISION NEXT 100 or EDAG Genesis show a more holistic way to innovate using generative methods; one that advances both function and aesthetics, and explores new ways to design cars in the process.

5. Generative methods in a car design process

As shown in the examples above, knowledgeable designers can implement generative methods into their workflows at multiple different stages (see fig. 8). Generated functional elements can be used as design inspiration, or they can be used directly, with more traditionally designed elements complementing generated structures. Blending the two approaches into a single form-finding process that would use the strengths of both traditional design vision and of optimisation software, rather than compromising on them is still a challenge for the future. Integrating generative methods into the established intense iterative design process, while educating the designers and executives about the possibilities, is probably the best way forward.

Another option is to apply generated structures to an already (traditionally) designed geometry. This seems to be the most feasible workflow scenario for now, as observed at contemporary car shows. There are clear risks with the current trend of ubiquitous "sticker-like" parametric patterns, for example, potential sensory fatigue caused by the unnecessary ornamental complexity, and considerable genericness. Clear added value is often missing, which could be a sign that this really is a sweeping trend. The patterns will probably only survive in those brands and studios, which can find a good reason to use them while integrating them tastefully into their design language.

There is arguably significant potential for a more worthwhile approach to generative design: data-based design. Moving from purely aesthetical, designer-defined pattern gradients (an obviously strong design element) towards structures based on relevant data would mean moving beyond shallow trend catching. It could establish a deeper reason for generative design methods to stay. The types of data could range from structural stress through ergonomics geometry to customer preferences. They could be sourced from simulations, sensor-recorded, or chosen by a human. Carmakers are already very rich with data and have no problem with access to the technology needed to obtain or generate them.

Aesthetically, generative methods have a potential to bring substantial innovation. The challenge here could be the emergent nature of the generated outcome, which might be hard to accept for the car designers and customers alike. The automotive design world is relatively narrowly oriented on bringing beautiful, functional sculptures designed by talented teams to the streets. Concepts like emergent beauty are basically non-existent in the discourse. However, the aesthetic potential of such data-based cognitive layer of design is clear, looking at the much more developed world of parametric architecture.

Perhaps the most convincing reasons for generative methods implementation come from their complementarity with digital fabrication technologies. As mentioned above, generative design process could truly exploit the benefits of additive manufacturing. Designing and producing previously impossible forms is now possible. The unprecedented customisation is also enabled by this combination. Using generative methods, designers can design parametric designs rather than rigid, one-size-fits-all solutions. Products can be customised based on customer's biometric data, personal needs and preferences, or based on consultation with a designer. There would be a continuous, multi-dimensional spectrum of possibilities, instead of today's combinatorics of several colour & trim options[5]. Progressively better quality and cost-effective digital fabrication then make it possible to produce each piece unique. This way, carmakers will not only appeal to their luxury customers but could also make individual mobility more accessible for people with special needs, previously excluded due to the necessary cost-effectiveness of serial production.

The role of the designers themselves obviously changes in a "real" generative design. The key relationship between designer and artefact is a direct one (even if mediated via some third-party or medium). There is a direct relationship between the designer's intentions and that of the designed artefact. In contrast, design using generative methods involves the creation and modification of rules or systems that interact to generate the finished design autonomously. Hence, the designer does not directly manipulate the produced artefact, rather the rules and systems involved in the artefact's production. The design process becomes one of meta-design where a finished design is the result of the emergent properties of the interacting system (McCormack & Dorin 2001). The 'art' of designing in this mode is in

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[5] Automotive industry has been pioneering mass customisation for decades, making the possibility of further advancement even more feasible.

mastering the relation between process specification, environment, and generated artefact. (McCormack et al., 2004) Such a drastic change from the traditional "surfacing genius" designer might take a long time to be accepted by future generations of car designers.

This workflow transformation could also prove to be a challenge for car design studios[6], but at the same time, the generative design is a part of larger digitalisation process, and as such can be used to enable more seamless interdisciplinarity. Visual programming in software like McNeel Grasshopper 3D, or Autodesk Dynamo proved to be especially beneficial in popularising programming among architects and designers. Today's engineers already get a lot of visual output from the simulation software. A sweet spot at the intersection of precise, data-based workflow required by engineers and visual approach preferred by designers certainly exists.

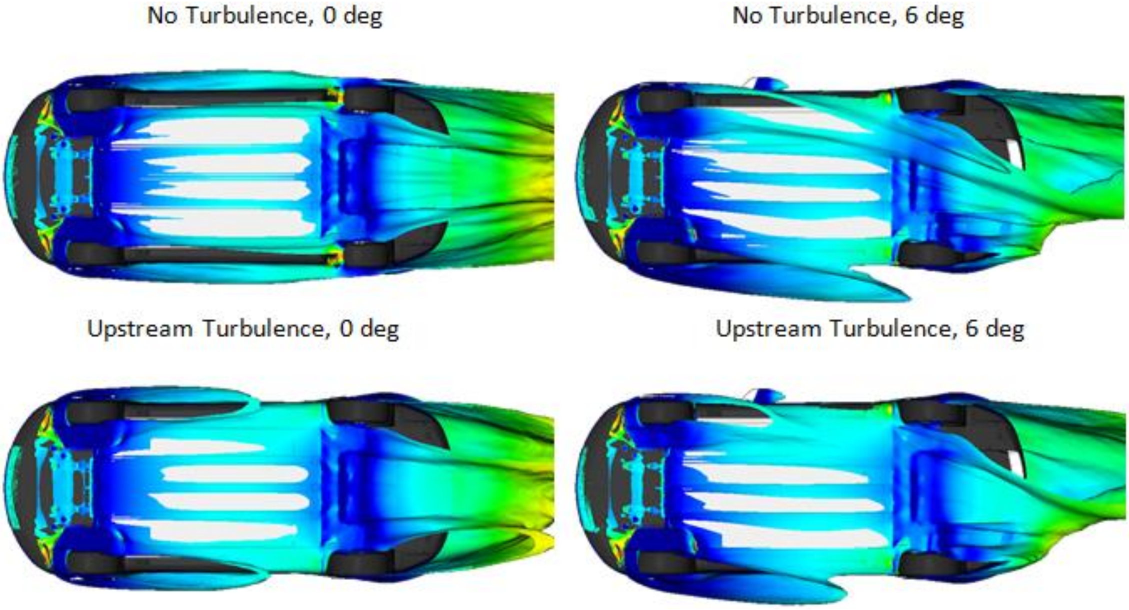

Fig. 8. Tesla's aerodynamicists' visual output.
Source: D'Hooge, A., Rebbeck, L., Palin, R., Murphy, Q. et al., (2015)

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[6] It would require a thoroughly interdisciplinary approach, namely intense horizontal engineer - designer contact, which is relatively uncommon in most large corporations.

6. Conclusions

The potential for generative methods to influence car industry lays mostly in combination with digital fabrication, and in incorporating relevant data input. Automotive design's specific rules and affiliation to a massive, mostly conservative industry makes it challenging to implement significant changes to the design process. At the present time, the field values mostly the novel aesthetics coming from generative methods, with more substantial applications appearing only in concept cars. At the same time, current revolutionary developments (electrification, autonomous drive, shared economy) might prove to stimulate novel approaches, including generative design.

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ELISI, EVOLUTIONARY ARCHITECTURAL AIDED DESIGN TOOL - ANALYTICAL METHODOLOGY OF ARCHITECTURAL DESIGN GUIDELINES

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The article discusses new approach for possible theoretical solution for the support of architectural design of floor plans in a computational way, presents theoretical design guidelines regarding the application supporting the architectural design process and briefly describes specification for the first implementation of the application prototype from the perspective of an architect supporting the architectural design process by accelerating the initial conceptual design phase via the computational creation of architectural floor layouts. First, the description of application features - main functionalities and workflow with the description of the input user data and applied design canons is presented. Furthermore, description of the evaluation functions and their effects is discussed. The paper concludes with conceptual usage scenarios of the proposed tool, discussion and further work paragraph.

Keywords: *architectural design, computer-aided design, computer-supported design, design automation, design tools*

1. Introduction

It is hard to imagine an architect working without a tool. Current technological capabilities offer more advanced solutions than basic drawing tools. Computational design, using computer power, significantly improve design processes, liberating the human mind from carrying out complex calculations, making the whole process much faster. The recent technological breakthrough has broadened functionalities of architectural software, which today take a vital role in the architectural design optimization, both geometrically and qualitatively. Is it possible, however, for the machine to reach beyond the programmed paradigm? In other words, can the computer be perceived as a creative partner in the architectural design process?

Finding the answers to above questions is important because access to high-end computing solutions is growing, their capabilities are increasing, while in the architectural industry, still, the most popular digital tool is software imitating work with the drawing board.

The author thinks the answers to the questions are affirmative and it is an appropriate time to find the right solution for working with the computer creatively. The solution that will make the computer a tool to aid the creativity of the architect by suggesting interesting and meaningful design solutions.

Evolutionary programming has a great potential to be suitable for this role. In the author's opinion, this method has the potential to significantly accelerate and streamline the design act. In addition, supplementing the imagination of the architect by the unpredictability embedded in the way these methods work. As a result, evolutionary design broadens the spectrum of results meeting design goals, still allowing for solving common architectural design problems. In this light, the user appears as a breeder, the person responsible for supervising the breeding process, creating the populations of design solutions.

With this in mind, in this paper, the author presents a theoretical proposal for a digital tool that supports the creative design process by applying these evolutionary methods to the design of architectural floor layouts.

Computing power is still not fully utilised creatively, despite years of research and diversity of approach to the problem of computational design of architectural objects. The best evidence of this state is a lack of a fully functional solution for the computational design of architectural objects which is widely used in architectural studios.

The study conducted in the article (Nisztuk & Myszkowski, 2017) shows that current research is still focused on the finding correct and efficient computational methods for the computational floor plan generation. The author also notes the lack of cooperation with architects in the prototypes research and development process, resulting in lack of consideration of their needs and omitting the tool usability aspects. The author believes that the deep connection between parametric community, architects, researchers and the businesses developing commercial architectural software will produce good results. This combination will streamline the flow of information and technical solutions, dramatically accelerate product testing, and will better determine the actual demand of the architectural community for computational tools for floor plan generation.

The future development of computational tools for architectural design must be inseparably connected with the architectural practice. based on the specific nature of the design process. The study of design methods preferred by architects should be a very important guideline for the development of computational tools (Meniru, Rivard, & Bédard, 2003). As suggested by research study (Bernal, Haymaker, & Eastman, 2015) many phases of the design process can be perceived as the mechanical processing of certain datasets. These solutions should primarily support architectural creative work specifically by accelerating the analysis of available, quantifiable data (ergonomics, legal conditions, user's functional preferences, etc.) leaving the most important design decisions to the architect.

Particular emphasis in the proposed application will be given to usability, acceptable design outcomes of generated architectural plans, determinants of architectural design work, modularity (modules of multiple optimization criteria, generative modules of various design aspects, etc.), cloud computing, access to existing digital datasets useful in architectural design and usage of BIM philosophy, resulting in a complete and functional supporting tool of the architectural design process - intuitive, interactive, customizable and above all scalable. The application operating on the principle of suggestions system of meaningful design solutions in a given urban and legal context. The tool taking into account a set of individual design requirements and flexible enough to adapt to individual design style, while not limiting possible creative solutions. A consulting tool, which can complement the technical architectural knowledge being particularly useful at the conceptual stage of the design process (Meniru et al., 2003). The connection of computing power with architect creativity will produce entirely new design quality.

Based on the analysis, conclusions and the survey conducted on the professional architects presented in the article (Nisztuk & Myszkowski, 2017) the author defined the set of expected features and functionalities that the proposed application should fulfil: an intuitive, interactive and fast program, suggesting optimum ideas rather than generating ready-to-use solutions, where the user has full control over the computational design process. Use of the software should proceed deductively, resembling as closely as possible stages of architectural design. In addition, the tool must use widely available online resources, such as weather data and maps. The software should take as an input multi-faceted dataset: the detailed design requirements, local spatial management plan guidelines, etc. Finally, it must work with BIM software and operate on both most common PS operation systems (macOS, Windows).

An important aspect of the proposed software should be a modular design, allowing seamless development and modification of individual parts and easy extension implementation such as new functionalities or new evaluation criteria. The proposed application should be able to imitate the way the architectural design process works allowing the main users (architects) natural work with the application. An additional criterion the author emphasizes when designing proposed tool is the software functionality and usability while maintaining the user possibility of full control over the majority of the technical aspects of the application.

The proposed application must include a multi-faceted input data set such as client design guidelines, local spatial management plan guidelines, widely accepted design canons (resulting from generally accepted architectural knowledge), the ability to create custom design canons, etc.

The application should also allow smooth work for multi-level users: from beginners (through a series of step-by-step wizards) to advanced users (giving the full control over the properties of the design process).

In addition, the tool should have a friendly interface allowing easy work with the program, intuitive system of input data management, possibility to interactively correct or modify in real time software-generated floor plans, data CAD/BIM exchange system (export to SVG, DWG and other common architectural software file formats).

The paper is organised as follows. The paragraph 2 presents the research main design goals and the methodology. The section 3 describes the initial and detailed design guidelines for the proposed tool and the application logic, followed by the section 4 describing application conceptual structure. Paragraph 5 describes possible prototypes where presented logic can be applied. The article concludes with the discussion in paragraph 6 and the future work section presented in paragraph 7.

2. Design goals and selected methodology

The general assumptions presented in the previous paragraph was used to develop design guidelines for software that will support the architectural design process through the creative use of computing power. The development of design guidelines for the proposed software became an ongoing research project, focusing on an application supporting the design process of a single family houses based on: legal guidelines (local spatial management plan guidelines, Regulations of the Polish Ministry of Infrastructure No. 75 of April 12, 2002 (Ministerstwo Infrastruktury i Rozwoju RP, 2015), Polish construction law, etc.), urban context, customer requirements, analysis of environmental conditions (sunlight, ventilation, viewing axes, shading), designer evaluation and the cost-estimate analysis.

2.1. Aims and assumptions

The main objectives that underlie author research work can be summed up in the following points:

- Broadening of the solutions spectrum meeting the design goals
- Acceleration and streamline of the architectural design process.
- Introduction of computer computing power into the creative design process.
- Improvement of architectural design with the introduction of multicriteria optimization of design solutions.
- The assistance of the designer creativity by generating non-obvious and surprising solutions.

The main assumption made by the author is computational design can significantly streamline and improve the architectural design process if only computing power is used in a creative way. By harnessing the computing power into the design process, following benefits can be achieved:

- Expanding the spectrum of solutions that meet the design principles.
- Accelerate and streamline the design process.

- Acceleration through the integration of computers into the creative process.
- Improvement through optimization of design solutions.
- The assistance of designer creativity by generating non-obvious and surprising design solutions.

2.2. Methodology

As the main way to creatively facilitate the computing power author suggests the use of evolutionary algorithms as a tool for solving typical problems in architectural design. Evolutionary algorithms are an IT tool used to search for sets of solutions through an algorithm based on biological evolution, used for optimization and modelling tasks. By using this tool, the designer becomes a kind of breeder directing the evolution of architectural projects. Author philosophically refers to R. Dawkins (Dawkins, 1996, 2006) theory of cultural evolution in which memes are an ideological extension of the gene. In the philosophical sense, the author perceives architectural layouts as memes and the research project as a digital implementation of this theory. The fundaments of this point of view the author described in the article (Nisztuk, 2016).

3. Application design guidelines

The following paragraph presents detailed usage requirements specified by the author, which should be included in the implementation of the prototype. An outline of the main requirements presented in the article (Nisztuk & Myszkowski, 2017) is further elaborated here. The main functionalities were determined on the basis of existing scientific studies and software analysis and the study of preferences among the architects presented in the survey (Nisztuk & Myszkowski, 2017).

The tool being developed should mimic architectural design process in order to be intuitive for target users, the architects. The section 4.1 outlines briefly the initial stages of the architectural design process and the brief functional diagram of the proposed tool. Section 4.2 presents the concept of the architectural design brief, which according to the author's conviction should be included in the proposed tool in order to facilitate the input data collection.

3.1. Architectural design process

The architectural design process is a strictly phased process that begins with the general set of client's design guidelines and concludes with the construction of the designed architectural object. The classic sequence of architectural process stages can be defined as follows:

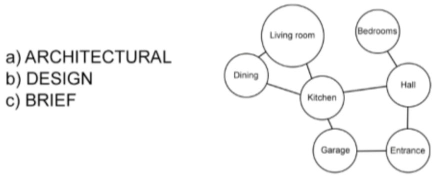
A. Collection of project guidelines from the client.

B. Analysis of the collected design guidelines and conditions of the urban context
C. Development of the overall concept of the building, its leitmotif and ideas, conceptual formal sketches.
D. Functional diagrams of the building's topology, the zonal layout of the building in the context of the plot (bubble diagrams)
E. The architectural concept of the building in the form of simplified building plans, schematic elevations and building volume.
F. The preliminary phase for the preparation of building construction drawings.
G. Preparation of building technical drawings, taking into account all available design data.
H. The preparation of detailed architectural drawings of the building.
I. Building construction.

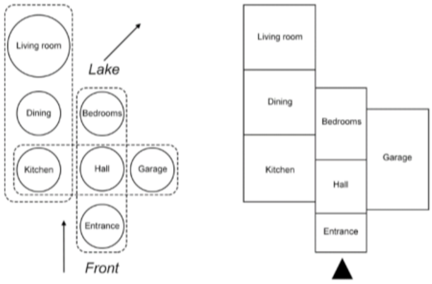
At stages D, E, F, G, H and I the architect cooperates with construction, installation and other specialists who introduce their own corrections and influence the final shape of the building. The entire process iterative in nature.

The proposed tool focuses on the support of the initial stages of architectural design: the collection of design information and requirements from the customer, their proper processing and confrontation with the existing legal requirements for the site and the support of the conceptual phase of the architectural project. In the conceptual phase, the main functional and spatial layout of the building is determined, as well as its overall shape, arrangement on the urban context, the general location of architectural openings (doors and windows) and communication divisions.

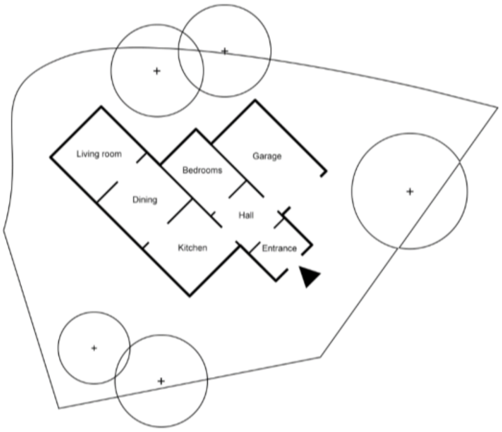
A conceptual schematic diagram presenting the actions of the proposed tool can be found in the illustration (see fig. 1). The illustration shows initial stage from conceptual bubble diagram to the simplified architectural layout.



A. Design brief information B. Bubble diagrams



C. Zoning, general area relationship diagrams D. Layout geometrical concept



E. Layout draft in the urban context

CONSTRUCTION DRAWINGS

F. Construction drawings and further
design technical phases

Fig. 1. The conceptual design flow of the proposed tool which mimics the general idea of architectural design process steps. The tool focuses on the support of the concept stage of architectural layout design which universally can be simplified to following stages: gathering the design data and client requirements (A), creation of general functional and topological layout conception (B), establishment of areas and zones geometrical and topological relations (C), concepts of architectural floor layouts (D), first architectural drafts within urban context (E), preliminary phase for the preparation of building construction drawings and further technical design steps (F)

3.2. Architectural Brief

Design brief is the initial stage and one of the most important stages of the proposed tool, where the input data from the client are collected. Design brief contains descriptive questions which facilitate retrieval of specific architectural data.

The architectural brief is an efficient way to gather customer design requirements. The brief provides a starting point for further architectural design work containing all the information and requirements that should be included or taken into account when developing the architectural object. The form of the architectural brief is arbitrary, but a set of open questions, to which the client gives descriptive answers is the most popular. The questions cover a wide set of utility criteria, customer lifestyle and aesthetic preferences. The brief contains also specific questions about the investment area, functional, geometrical, topological requirements as well as available budget, urban context and legal design requirements.

The development of a good architectural brief usually involves several stages of collecting design information, as customers usually have a vague idea about their design preferences.

4. Specification of the proposed application

This paragraph outlines the main aspects that will be included in the specification of the proposed tool for architectural design support.

4.1. Input design datasets

The proposed application is a tool to support the initial, conceptual design phase by analysing the changeable clients and legal design guidelines delivered as software input information in combination with universal law and design constraints. Some of the design conditions are a group of immutable data (through their universal, legally defined nature) becoming the set of constraints for the searchable by the software design solution spaces:

- The matrix of minimum and maximum limits for architectural spaces resulting from legal conditions (such as room area, dimensions, etc.)
- The matrix of limitations for plot elements resulting from urban legal requirements.

The remaining design conditions are a group of variable design canons resulting from the widely accepted architectural design practice, collected in architectural design textbooks such as (Neufert & Neufert, 2012):

- A matrix of design canons for rooms resulting from design practice and design manuals such as topological relations, dimensions, areas, room proportions, space locations regarding the cardinal directions, etc.

- A matrix of design canons for the location, dimensions and areas of urban elements resulting from design practice and design manuals.

The proposed application envisages the possibility of introducing a wide range of input data, from information on legal and urban conditions, through customer preferences, to lifestyle information that is essentially a set of legal and client design guidelines. These data are used to determine customer design expectations and provide an information base for the application to determine the best possible (within the framework of Construction Law) design solutions that meet customer expectations.

The first group is a set of legal guidelines which include information from the Local Spatial Management Plans or (interchangeably) Planning Permission (in the absence of both datasets the information is not taken into account) regarding the building structure:

- Building foundation line, build up the line.
- Permitted building area in relation to the plot area.
- The width of the front elevation.
- The height of the top edge of the front elevation, its cornice or attic.
- Roof geometry (inclination angle, ridge height, roofing system).

The second group of input data are any information relating to the plot:

- Location
- Contour
- Existing infrastructure (installations, etc.)
- Urban Context
- Expected technical installations (such as a septic tank, heat pump, etc.)
- Important elements of the plot that could affect the building's structure (tree, view axes, slopes, etc.)

The third data group consists of customer functional and utility requirements:

- Required cumulative house area.
- Functional program:
    - Types of rooms.
    - Room preferred area.
    - Room preferred a location in relation to cardinal directions.
    - Preferred functional relations of rooms with point scale evaluation (0 - not important to 3 - very important).
    - Expected technical home installations.
- A number of floors.

The fourth group of input data is information about the client's lifestyle. Analyse of this data allows to customize and adapt the architectural layout space distribution to the individual needs and habits. Preferences cannot be enclosed in a rigid frame, so the proposed software provides a lot of flexibility on this subject:

- Non-standard type of spaces (orangery, painting studio) including requirements for area, location and topological connectivity.
- A number of cars.

- Hours at home (example use of this information is the appropriate placement of window openings based on information from the interior solar analysis for the indicated hours).
- Other.

The last group of input information can be the aesthetic style selection based on the choice of predefined proposals implement in the proposed tool. The software implementation of individual styles according to the author can be done in two ways:

- By introducing the averaged parameters characterizing a particular aesthetic style such as the functional connectivity scheme, room proportions, spatial arrangement etc.
- Through the software learning systems (such as neural networks) based on the analysis of the appropriately described database of architectural layouts. The second way seems particularly interesting given the automated process of finding averaged dependencies in a specified set of data. The software could generate the aesthetic style template based on the available material, grouping individual design properties, functional and topological links. Subsequently, the program could use the averaged stylistic rules when computing architectural layouts.

4.2. Set of criteria for selecting a good architectural layout (evaluation functions)

Every tool for architectural computational design should have a set of criteria for finding architecturally feasible results. For the computational layout generation, the author proposes the use of genetic algorithms, which uses evaluation functions for estimating the given criterion. The proposed application contains multiple of these functions. Each of the specified functions evaluates the numerical value of architectural layout for a given criterion. The result of the partial evaluation function is then summed in the total evaluation function. In the proposed application, the process of selecting architectural projections is, in fact, a multi-criterion optimization. The set of proposed evaluation functions specified for the application is as follows:

Evaluation of room connectivity (F_p) – topology of the architectural layout

The rooms should be connected in accordance with the client's design guidelines and in accordance with the design practice. Each combination has a numeric value (also negative) that determines the preference of the functional connection between the rooms. The sum of the connection values gives the value of the evaluation function F_p. Connection values can be determined by the adjacency matrix between rooms. Negative values define extremely undesired connections. Adjacency matrix can be based on design canons (design rules resulting from architectural design practice) but can be changed at the request of the designer according to customer requirements.

Layout boundary evaluation (F_o):

Assessment of the architectural layout circumference. The function measures the irregularity of outer wall configuration by comparing the current value of layout total circumference and surface with respect to the circumference and surface of the boundary rectangle (a rectangle depicting in a simplified way the smallest space in which all objects fit in). Evaluation criteria can be connected with the legal requirements or design guidelines.

Evaluation of room dimensions and area (F_w):

Validation of the dimensions and the area of the given space. The function simplifies the room dimensions to its maximum width and length. The given value is compared with the values from the legal and design guidelines (design canons). If the value of the area or dimensions of the room bounding box (simplification of the irregular shape of the room to the rectangular shape) exceeds the value of the design canon, the value of the evaluation function is lowered. The penalties (reduction of the value of the evaluation function) are related to the difference between the values of a given room and the relevant limit (minimal or maximal) values from the design canon matrix.

Location evaluation of the rooms in the building (F_l):

Evaluation of the room location in the architectural layout according to cardinal directions. The values provided by client requirements or design canons values.

Evaluation of view axis of rooms

Evaluation of rooms in terms of viewing qualities. The evaluation ensures optimal distribution of rooms and window openings allowing for visibility of valuable landscape elements (dominants, panoramas, view axis).

Evaluation of the sunshine time inside the rooms

A function evaluating the amount of sunlight inside rooms in the building. The evaluation ensures optimum distribution of rooms and window openings based on expected time of sunlight in each space. Sunlight time can be determined based on health and safety conditions, user preferences or data resulting from design standards.

Energy evaluation of building structure and form

Fitness function evaluating house volume based it energetic efficiency. Using simplified estimators of heat radiation, it shapes the building shape to be as energetic optimal as possible. The values for this function can be provided by Construction law, client preferences, energy efficiency EU norms, etc.

Evaluation of layout circulation

Inner space flow evaluator. The function measures total time and access distance between most common house rooms based on space syntax theory (Hillier, 2007).

Evaluation of door and window openings

Evaluation function for proper window and door alignment and size. Interconnections between rooms are evaluated at minimum width, taking care of the minimum size of the door opening. The window's location is rated for viewing, lighting and energy requirements. The size of window openings is assessed based on legal requirements and customer preferences.

Additional possible evaluation functions

The author believes the set of possible evaluation functions can be widened by additional assessment formulated along with the development of the application.

Total evaluation function

The sum of results of the partial evaluation functions gives the value of the total evaluation function. The value of the total evaluation function indicates how well a given architectural layout meets the requirements defined by the designer, design practice and legal conditions, formulated and expressed in the values of the partial evaluation functions.

$$F_c = F_p + F_o + F_w + F_l + \dots$$

4.3. Additional features

The centimetre is the basic metric unit used in European architectural documentation. The proposed tool will use it as a fundament of its metric system. The proposed tool should be build based on modular structure. This structural approach allows the flawless implementation of the first tool version and development by adding further functionalities without changing them without changing the core of the program.

The described functional framework of the proposed tool translates into the logic and mechanics of the proposed application presented in the following paragraph. The author presents two conceptual prototypes showing possible usage scenarios.

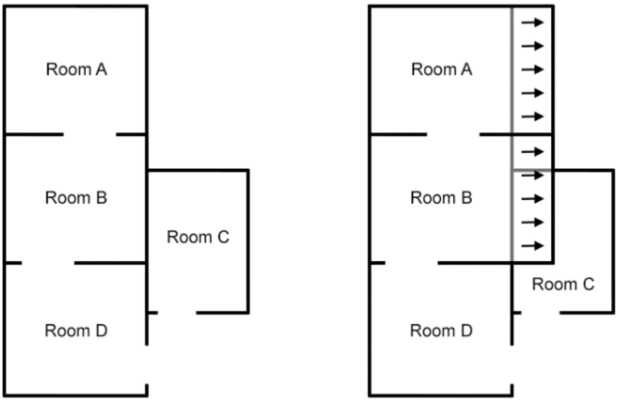
5. Conceptual scenarios for the tool for computational floor plan generation of single-family houses

Based on the developed prototype specification and design guidelines, the author presents two conceptual usage scenarios of the proposed tool. The first scenario involves the creation of new architectural layouts by compiling the client's design guidelines with design properties derived from legal restrictions and design guidelines (design canons) being the reference point for design specification (by creating the domain for the numerical design values or delivering the preferred values). The second scenario is an algorithm proposal for the tool evaluating existing architectural layouts using the methodology from prototype A.

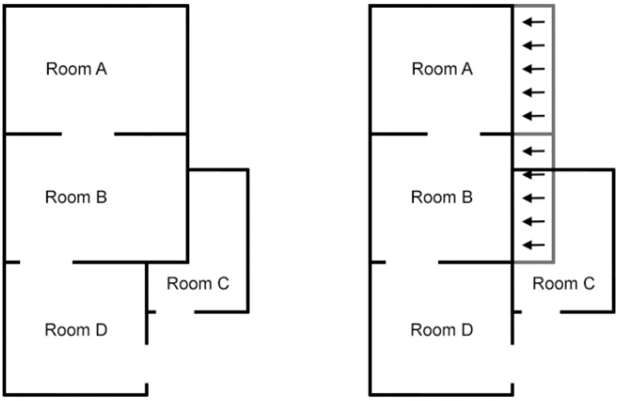
5.1. A usage concept scenario for the prototype generating architectural layouts based on the widely accepted architectural design guidelines based on Neufert (Neufert & Neufert, 2012) design guidelines case scenario and customer requirements (A):

1. Load of input data: preferred total building area, number of storeys, number of rooms, type of rooms, number of floor layouts to generate, number of optimization iterations (iterations in which each layout will be subjected to the optimization set from section 7A or 7B in relation to the evaluation function from section 8).
2. Load the preferred topology of the layout: Topology based on the Neufert design requirements in the form of adjacency matrix table. The stage for establishing functional connections of spaces. 2D drawing of each layout floor, with marked strong or preferred functional connections between rooms.
3. Create a population of individuals: In each iteration, architectural layouts are optimized and evaluated for mutations and geometrical transformations from point 7A (or 7B) against the requirements of the assessment function of point 8.
4. Draw a rectangle depicting the floor outline with the area specified by the user. The rectangle area is the layout surface preferred by the user. In case of multiple floors, draw each floor separately, which the number of squares corresponding the number of floors with the specified area.
5. Divide the rectangle(s) into the appropriate number of parts specified as the preferred quantity of rooms in section 1. Floor assignment based on (Neufert & Neufert, 2012) design guidelines or user requirements. The divisions should have equal areas.
6. Assign the function of rooms to divided squares. The function assignment is accidental.

7. The stage of layout generation and distinction. For this phase, the author proposes two possible approaches for the mechanics of layout geometrical modifications:
   - Draw the building floor boundary, divide the outline into rooms of equal area, assign the rooms function randomly, transform each rectangle separately by moving the wall segments by perpendicular vector (wall segments treated as any edge of the room distinguished by the rectangle corners or nodes. Similar system was proposed in (Merrell, Schkufza, & Koltun, 2010)), ensuring that the width of connections between rooms (those that are to be connected) is minimally the width of the door opening (at least 100 cm) aiming for specific area and room dimensions specified by the client requirements and design guidelines (evaluated by fitness functions specified in section 8). Mutation can be a random change in the function of given room within a floor or accidental shifts of selected edges (see fig. 2).
   - Clustering method – functional topological diagram translated to the clustering zones which create floor plan through „magnetic-alike” relations in the adjacency matrix.
8. Rate generated layouts according to the fitness functions values. Each evaluation function has weight point value assigned by the user based on its architectural importance:
   - Evaluation of room connectivity (F_p), numerical values should be maximized. Rooms must be connected in accordance with functional requirements. Each connection has a numeric value (also negative) which determines the weight of the functional connection. The sum of connection values determines the value of the rating function. Connection values are specified using the room adjacency matrix determined on the basis of architectural or customer design guidelines. Negative values determine extremely unwanted connections.
   - Layout boundary evaluation (F_o). The values of subtraction of area and circumference of boundary rectangle and current layout keeping the layout boundary compact. Additional penalty when the total area or cardinal layout dimensions exceeds the limits of legal or design requirements.
   - Evaluation of individual room dimensions and area (F_w). The surface value and cardinal dimensions should be kept within the limits of customer, design or legal requirements. The assessment value is related to the difference between the limit values of cardinal dimensions and area of the required canon and the current layout.



Room edge segment offset



Room edge segment snap

Fig. 2. The first proposed approach of layout geometrical modifications. The arbitrarily selected room segments can be offset perpendicularly to a random vector, creating new wall edges or can be snapped to adjacent room edges

- Evaluation of the room location in the building according to world sides (F_l). The assessment of the position wherein the layout a given room should be placed according to customer or design requirements. Possible measurements of the location relative to the world sides could be an angle between the line connecting the centre of the building (the bounding box of all rooms) with the centre of the room and the line defining the side of the world. The closer to zero the value of the angle, the higher the value assessment.
- The total evaluation function is a sum of the values of sub-evaluation functions giving the final rating of the generated layout. Importance of each sub value is measured by the weighted factor established by the user (w): $F_c = w_p*F_p + w_o*F_o + w_w*F_w + w_l*F_l + ...$

9. Based on the quantity of desired layouts (specified in the point 1), go through step 4, 5, 6, 7, 8, save the best layout in the current iteration and collect a database of optimized floor plans.
10. Crossover the layouts (genetic algorithm implementation) collected in step 9:
    - Mix the layouts by copying entire functional zones in between.
    - Copy the characteristics of a given room between layouts (location, dimensions, area).
11. Present the results to the user in the form of a set of layouts with the highest value of the total evaluation function.

5.2. A usage concept scenario for the prototype evaluating existing architectural layout against widely accepted Neufert design guidelines (Neufert & Neufert, 2012) case scenario (B)

1. Load the layout geometrical properties, e.g. in the form of a table with the design numerical values such as room name, room function, cardinal dimensions, area, location relative to the world sides, floor.
2. Load the layout topological properties such as room connectivity, e.g. in the form of a weighted graph.
3. Load design guidelines data from Neufert (preferred topology, layout boundary dimensions, boundary surfaces, preferred room location in relation to world sides, etc.).
4. Evaluate the layout based the proposed methodology described in section 8 of prototype A.

6. Discussion

Based on collected in the article (Nisztuk & Myszkowski, 2017) information, the author proposes a new approach for the tool supporting the architectural design process. The selected approach focuses on the concept stage of architectural layout design. The proposed methodology is based on the classical and generalised representation of architectural design process. The author believes that in order to create a truly functional and useful computational tool for architects, software use should complement the way architects used to work, becoming an important part of the design process and embed as much as possible to the architectural workshop.

The presented in this paper methodology attempts to describe the principles governing the architectural design by the language of mathematics and algorithmics. At first glance, this may seem to contradict the creational spirit of architecture, in which the designer's experience and intuition play an important role. If, however, one will carefully study the architectural textbooks such as (Ching, 2014; Neufert & Neufert, 2012), (Alexander, Ishikawa, & Silverstein, 1977) being the spectacular example, it will turn out they are full of such algorithms. Nevertheless, these sources are an invaluable help in architectural design and for years are highly appreciated by architects, becoming the basis for many creatively elaborated ideas.

The approach chosen by the author focuses on collecting and translating architectural design principles to a form readable by the computer. Based on gathered data, the author intended to create a responsive and consulting architectural tool helping to analyse basic architectural design requirements and to create the most suitable design solution. The author believes that this goal can be achieved by a combination of the designer experience with the creative use of computing power in the process of analysis and selection.

The paper outlines design guidelines for the further computational tool assisting the architectural project with the use of genetics algorithmic multicriterial optimisation process. In order to achieve truly functional state, the proposed methodology needs to be further elaborated and verified, in the series of prototypes and their tests.

7. Future works

Future works will focus on the codification of the detailed design guidelines for the application described in the article and on the preparation of technical documentation being the basis for the creation of the proposed tool initial prototype. The prototype will be the basis for the first stage of tests focusing not only on the computational efficiency but also on the usability and productivity from the architectural point of view. The author predicts that the further progress model for the selected approach will be “development through testing” founded on iterative tests and batch implementation of their conclusions.

In the long term, the author plans extensive trials of the proposed methodology through cooperation with architects in the verification and development of the tool.

The author believes this approach will allow the creation of the first truly functional and useful tool for computational architectural design.

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FINDING THE OUTLINE OF A SET OF BIDIMENSIONAL POINTS EMBEDDED IN A THREE-DIMENSIONAL SPACE

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This article presents a tool for finding the outline of a set of bidimensional points embedded in a three-dimensional space. In Grasshopper, the current option for extracting a mesh out of a set of bidimensional points is the Delaunay mesh tool, and the option for extracting a grid out of a set of points is the Delaunay edges tool. These tools provide a convex hull of a set of points. However, usually, the outline of a compact set of points which covers a region of the surface, can be cognitively perceived as a polygon with convex and concave portions, that describes a characteristic shape. The proposed algorithm sets out from the convex hull, finding the outline of a set of points, that is the exterior edges, as well as the interior edges, and then it moulds in an iterative manner in order to fit the shape of the region of the surface covered by points. This provides an interactive tool for the architect to adjust the outline of a planar shape, embedded in 2d or 3d space.

The algorithm can be used for creating various regions on a surface with different outlines, that can be treated differently, separating areas of lower density from areas of higher density. As well, the iteration parameter can be used to control the area according to area specifications.

Keywords: *outline, characteristic shape, iterative moulding*

1. Introduction

The problem of finding the outline of a set of points that describe a flat or curved region of surface often arises in architectural design situations. In computational geometry, finding a convex boundary of a given set of points is a well-known problem. The "convex hull" of a set of points *P* is the smallest convex polygon which contains all the points in *P*. However, in architectural situations, in most frequent cases, the distribution of points foresee shapes with convex and concave contour portions, or "star" like shapes, that is compact regions(with no holes), with pronounced extremities. In these cases, the convex hull does not capture the "characteristic" areas of the region. Therefore the convex hull doesn't describe accurately the shape of the region covered by points.

The current option for finding the outline of the convex boundary by architectural computational software such as Rhino/ Grasshopper is to first find either the convex mesh, or the convex grid that goes through all the given points, and then separate the exterior edges from the interior edges. Here, we propose an implementation of the *"chi"* algorithm (Duckham et al., 2008), or the *"characteristic shape"* algorithm, that sets out from the Delaunay triangulation, reducing the initial area. The proposed algorithm generates simple polygons (that don't self-intersect) with convex and concave polygon portions, that describe the region of the surface covered by the given points.

2. The theoretical aspect of the study

In the context of architectural practice, oriented towards dynamical computational processes that yield complex geometries, the present research focuses on developing a tool for geometrical interpretation of a set of data acquired from a previous dynamical process. The data obtained from “growing” algorithms, that set out from a seed and evolve into an elaborate structure, sometimes need geometrical additional tools, for reorganizing the relationships within the data structure in order to generate an architectural feasible outcome.

This algorithm is meant for situations where a highly irregular outline of given set of points from a certain data set is requested. The proposed architectural challenge is to create a surface with variable properties: structure, texture and material consistency. In some cases, this can be achieved by separating different areas on an initial reference surface. The boundary between the regions can act as a strong boundary, or conversely, as a transitional space between two kinds of surface consistency. For our purpose, we create two kinds of the area: the first kind of area consists of several “islands” delimited around points of maximum or minimum height, and another kind of area, that surrounds the given islands. The sets of points that approximate the inferred islands are generated by an *up-hill* algorithm, meaning that the grouping of the original points depends upon the oscillation of level of the referenced surface, influencing the shape of the boundary. The up-hill algorithm provides an irregular shape of the islands (see fig. 1).

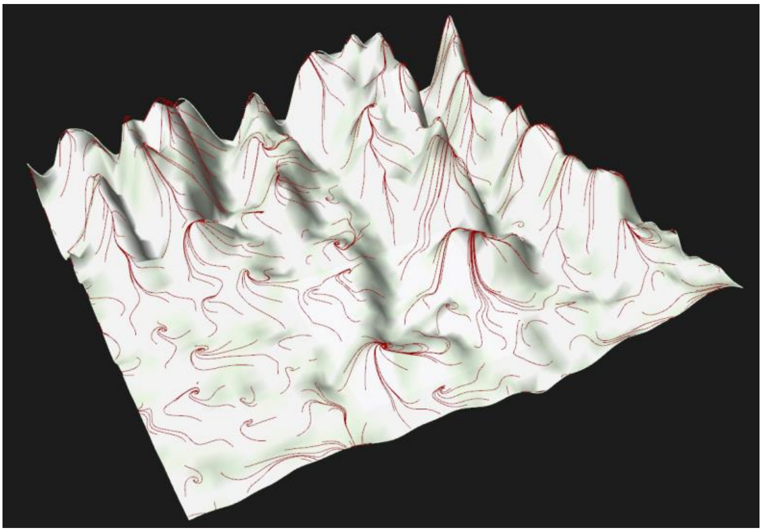


Fig. 1. Reference surface with trajectories of the up-hill algorithm

3. Research methodology

The algorithm is implemented in Grasshopper, a visual programming software. The algorithm uses the half-edge data structure, implemented in Topologizer plug-in for Grasshopper. Topologyzer (Piker, 2012) plug-in takes as input a set of lines at it out-puts a *directed graph*. A graph, in graph theory, is a set of vertices connected by edges, where the edges have a direction associated with them. The half-edge data structure is used to store the mesh entities (items) vertices, edges, faces, and their connectivity information. The half-edge data structure was originally presented by Muller and Preparata (Muller & Preparata, 1978).

4. The algorithm

Given a finite set of points P (minimum three points) distributed on the Cartesian plane (a flat surface), or a curved surface embedded in three-dimensional space, the characteristic shape algorithm provides a shape that might not be convex, depending on the distribution of points on the plane. The polygon produced by the algorithm is a simple polygon (it doesn’t self-intersect), it contains all the points of P and it bounds an area contains within the convex hull and possibly is equal to the convex hull.

The algorithm sets out form the Delaunay triangulation, for which Guibas and Stolfi provide pseudo-code, (Guibas & Stolfi, 1985), that is we first compute Delaunay grid that covers all points (see fig. 2). Then, the algorithm applies *peeling*

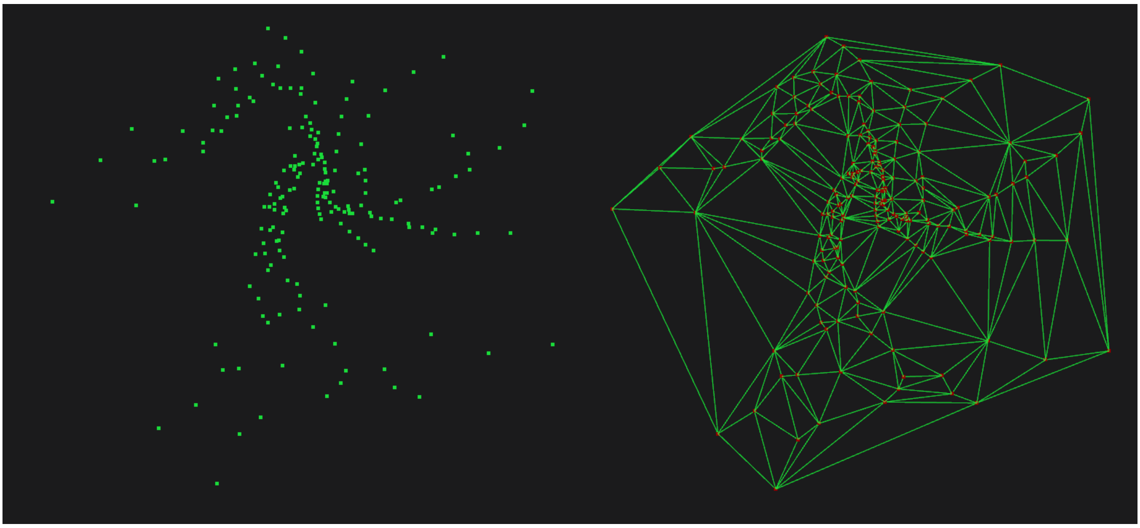


Fig. 2. The initial set of points and the Delaunay triangulation

operation, that decimates the outer-most segments, according to a length parameter. The proposed algorithm can be applied repeatedly, thus generating solutions that range between the convex-hull at one end and a characteristic shape with concave and convex perimeter portions at the other end. The shape of the polygon depends upon the length parameter that controls the number of segments to be decimated and replaced. The length parameter decides the length of the segments to be decimated and replaced.

Once the Delaunay triangulation is achieved, we need to find the boundary of the of the triangular Delaunay grid. For this, we compose a combinatorial map M (P, θ_0, θ_1). The combinatorial map is made up of three components:

1. P - a half-edge data structure (The Delaunay triangular grid contains a data structure, that provides for each point (or vertex) the indexes of its neighbour's indexes. Each point is associated with an index or an address. For each point address, the Delaunay triangulation provides its topological neighbours. In order to find the exterior edges, and the interior edges, we need to create a dataset of half-edges or darts. A half edge is represented by an origin vertex and a direction. This means that each edge of the Delaunay triangulation is associated with two half edges, with origin at each end of the edge, and oriented in opposite directions. That way, the triangles of the grid can be oriented (facing up, or down) and the rotation can be set on the clock or counter-clockwise (see fig. 3, 4).
2. θ_0 - an operation that associates each dart with the opposite dart. This separates the combinatorial map in two sets.
3. θ_1 - an operation that finds for each dart, the next dart with same origin (in cyclic notation (clock-wise or counter-clock-wise notation).

In a triangle, if we apply the sequence of operations $\theta_0 \theta_1$ three times, that is $\theta_0 \theta_1 \theta_0 \theta_1 \theta_0 \theta_1$, each half edge returns to its initial position. The interior half edges of a triangular grid have the property that by applying the operation sequence $\theta_0 \theta_1 \theta_0 \theta_1 \theta_0 \theta_1$, they return to their original position. For the half-edges corresponding to the boundary edges, when applying the operation sequence $\theta_0 \theta_1 \theta_0 \theta_1 \theta_0 \theta_1$, one of the half-edge covers a triangle and it returns to its initial position, and the other half-edge reaches another position. We identify the exterior edges by identifying the half-edges that don’t return to their original position. Then we apply o procedure for identifying the other set of half edges corresponding to the outer edges, that return to the original position. This way, we complete the separation of the half-edge data sets corresponding to the interior and exterior edges.

Once we find the exterior edges, we introduce a parameter for determining the segments to be kept versus the segments to be replaced (see fig. 5). Each exterior line is going to be replaced with two lines, adjacent to the line being replaced. Two separate operations are necessary for finding the half adjacent left and right edge of the replaced edge. Once the new edges are found, the remaining edges and the new, replacement edges are merged to form the new boundary. The boundary edges are subjected to the sequence of operations of traversing a triangle in order to identify the other set of half edges lying on the boundary. The new boundary half-edges are removed from the list of interior half-edges. This way, we obtain two new lists: the new boundary edges, and the new interior edges. This completes the first iteration of the algorithm.

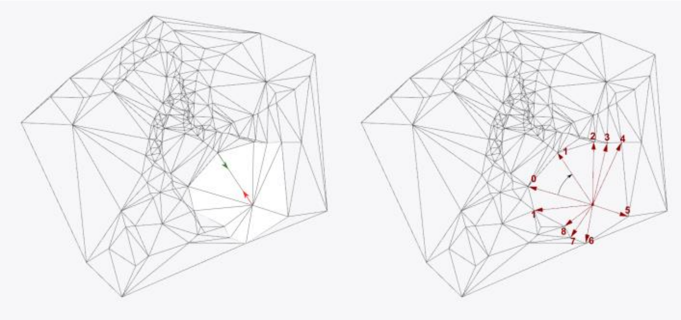


Fig. 3. Operation of finding the opposite half edge and the next rotated half-edge

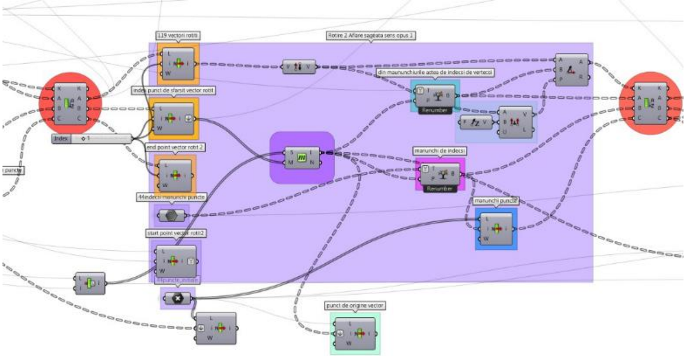


Fig. 4. Operation of finding the opposite half edge and the next rotated half-edge (*Grasshopper* graph)

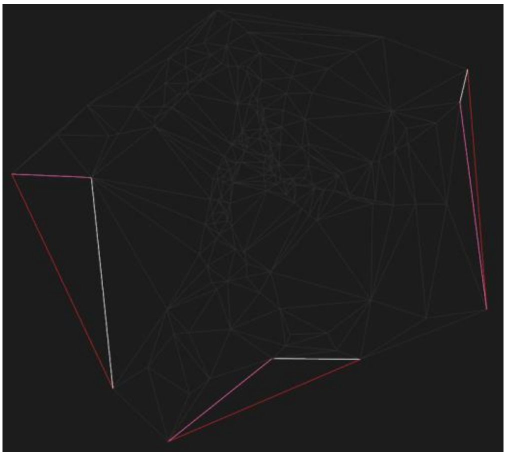


Fig. 5. Replaced edges (red) and replacement edges (white, pink)

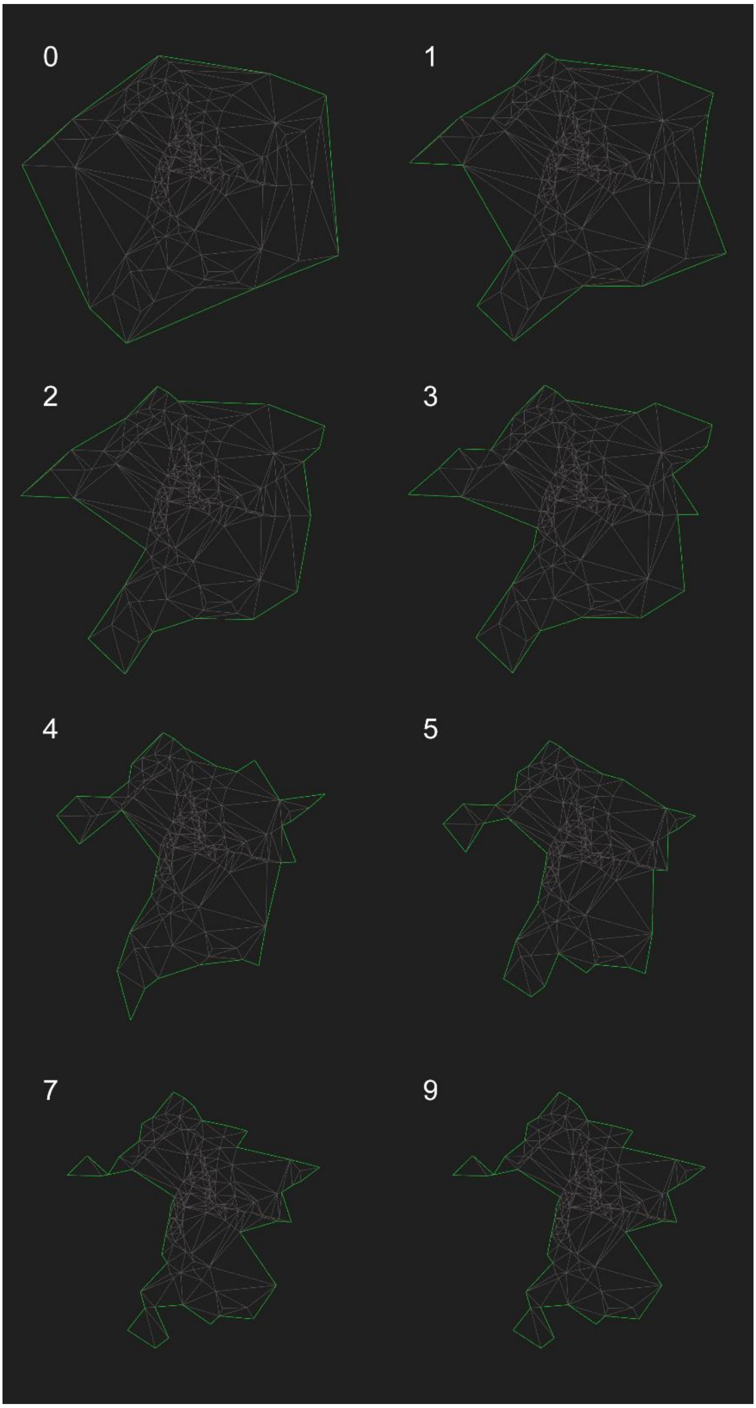
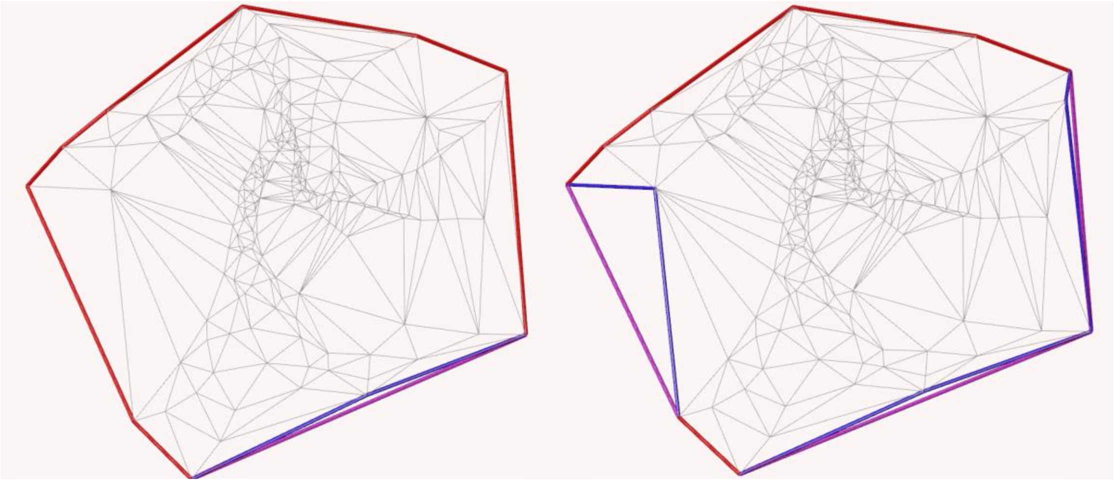


Fig. 6. Progressive iterations of the characteristic shape algorithm

The algorithm for finding the characteristic shape not only finds the outer boundary, that means the edges that are on the boundary, but also the interior grid of edges. The two sets are updated at each iteration, enabling the creation of various shapes with a different boundary but with the same core (see fig. 6).

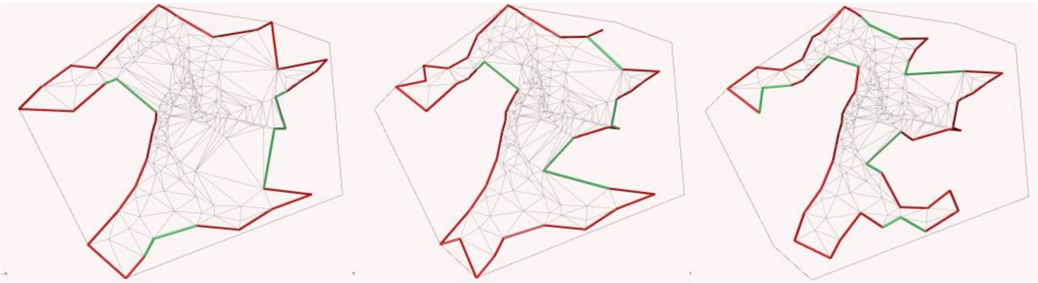
The parametrization of the number of lines to be replaced controls the shape of the polygonal boundary (see fig. 7). Setting the number of lines to be replaced according to their length decides how many edges are to be replaced at once. When applied repeatedly, the algorithm yields various unique shapes, bounded by the convex hull, that are carved with different ratios. By specifying a higher proportion of outer boundary edges to be replaced, leads to solutions where the outer-most edges are replaced with priority, yielding a more robust, “rounded” shape. By specifying a smaller proportion of outer boundary edges to be replaced, yields more slender solutions, with a thinner body and more pronounced extremities or ”limbs” (see fig. 8). In our case, we look for the most slender solutions possible, keeping at the same time the extremities of the shape. Through experimentation, for the present study case, we realized that a small ratio for replacing the boundary edges at each iteration yields more accurate results, and the final shape is tighter to the set of points distributed in the more dense areas. Also, the set of points defining a region is recommended to be evenly distributed and with a much higher density than the areas which are going to be carved.



7/8 from the number lines to be maintained

2/3 from the number lines to be maintained

Fig. 7. Percent of a number of lines to be replaced. First iteration



4/5 from the number of lines to be maintained 15 iteration

6/7 from the number of lines to be maintained 15 iterations

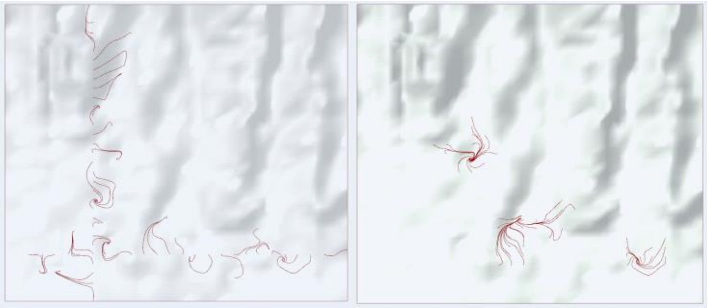
7/8 from the number of lines to be maintained 15 iterations

Fig. 8. Comparison of resulting characteristic shapes with different replacement parameter ratios

5. Application of the characteristic shape algorithm

The presented algorithm finds the boundary of a set of points, in an iterative manner, thus providing a wide range of possible outlines. From these, the shape with the most convenient area can be chosen to best fit the architectural constraints, like maximum illumination area. The algorithm can be used for the fine adjustment of a highly irregular boundary without the need of manual modelling. The algorithm adjusts not only the boundary but also updates the interior grid bounded by the new outline.

In order to test the algorithm, we chose a predefined surface with a complex geometry on which we had applied an up-hill algorithm. The up-hill algorithm provided a set of curves clustered on rows and columns (see fig. 9). The curve data-structure is reorganized in order to create certain regions on the surface, that become regions of the variable, different treatment than the “negative”, or the remaining, bounding area. The future regions are meant to have a different structure and material consistency than the rest of the surface.



Initial organization of curves on the surface on columns and rows

Clustering the curves according to a common point

Fig. 9. The original dataset of the curves is reconfigured to create the „islands”

The new clusters of curves organized around a central common points infer certain regions, which we wish to delimit. In order to find the initial boundaries of the clusters, we replace the curves with points laying on the curves, and then, for the resulting set of points, we apply the Delaunay triangulation (see fig. 2). This provides the initial convex hull. From here, we want to refine the boundary, in order to bound tighter the extremities of the initial curves. In order to achieve this, we apply the characteristic shape algorithm repeatedly, but separately for each cluster. The operation is applied individually for each cluster because each group supports a maximum number of iterations that differ from cluster to cluster. The iterations performed on the groups vary between 2 and 4 (see fig. 10, 11).

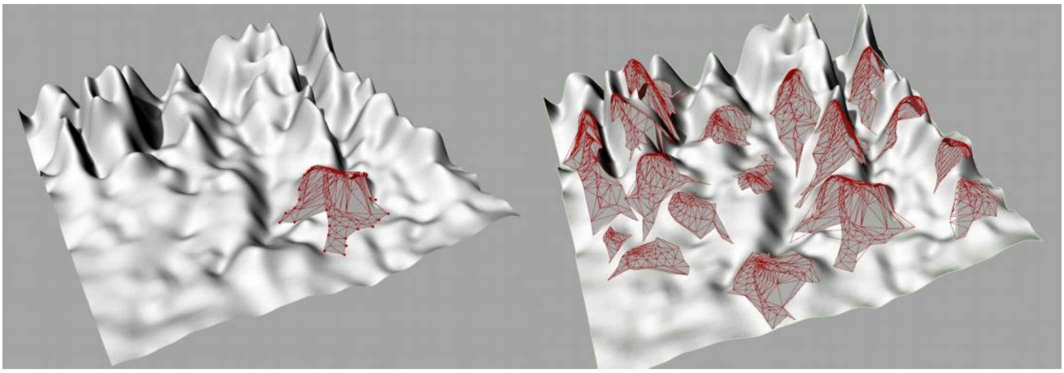


Fig. 10. The boundary of islands before and after applying the characteristic shape algorithm

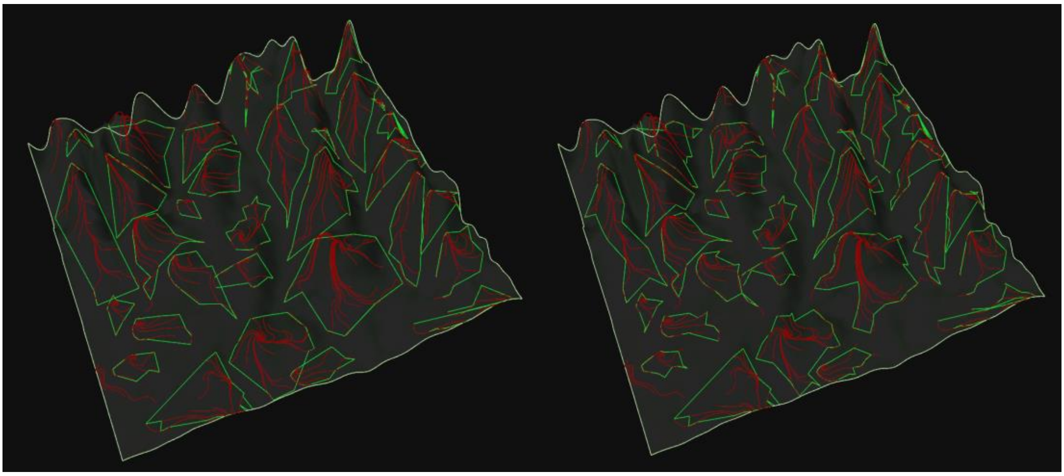


Fig. 11. Reticulated areas surrounded by a continuous surface area

The initial reference surface represents a facade, and the “islands” are the less dense, glazed areas. We wish to reach a certain value of the total glazing area but allowing at the same time local variations of each island. Thus, we propose an optimization algorithm, with one objective, in order to achieve a final target area. For each island constraints are set, that is a minimum and maximum area, between which the boundary can vary. The constraints are imposed by setting the number of iterations to vary between 2 and 4 for each region. The range is limited because of computational calculation time. However, the optimization process allows the exploration of various possible solutions, keeping in mind a certain final glazing area (see fig. 12, 13).

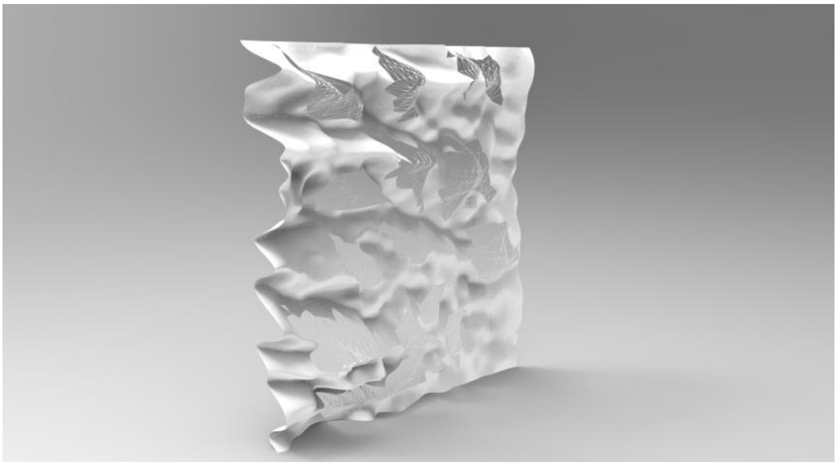


Fig. 12. Optimized facade based on total glazed area

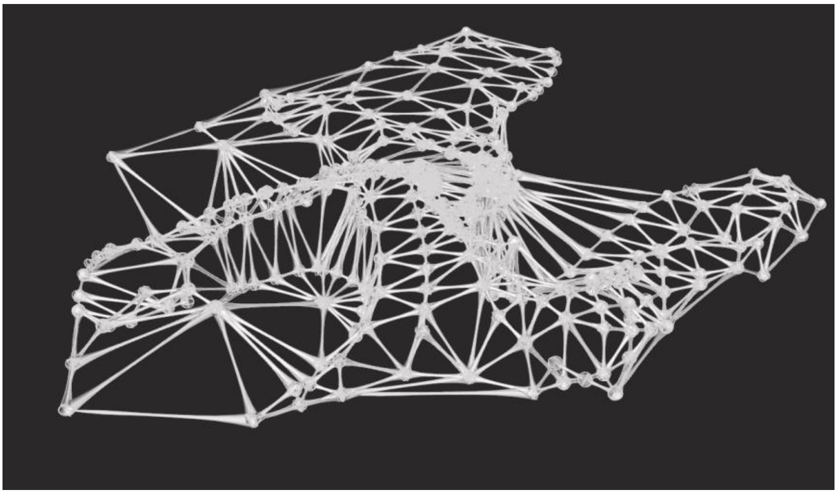


Fig. 13. Optimized facade based on total glazed area

6. Conclusions

We have implemented in Grasshopper an algorithm for reducing the convex-hull boundary of a Delaunay triangulation. The algorithm provides the convex-hull boundary at one end, and a unique shape of the minimal area at the other end. The algorithm provides a range of possible unique shapes, controlled by a boundary replacement parameter. We have shown the architectural possible applications of the implemented algorithm, by employing it in a dynamic manner in order to obtain a performant facade. The algorithm can be applied for sets of points situated on a planar or curved surface, that are already known through a “shaving procedure”. Further research can adopt a converse approach in interpreting a set of points, that is to progressively cover the set of points instead of removing the boundaries, thus enabling the expansion of the created mesh parallel to the expansion of the point set.

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DESIGN INSPIRED BY MATH AND MUSIC - THE BUILDING MADE OF LISSAJOUS CURVES

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Mathematical inspirations join the world of music and architecture showing how logic and geometric rules could be used by artist and designers. The article presents examples of mathematical patterns in music and architecture in European cultural circle, when they appear in history and how important they were. The thesis presents methods of creation, which appear in composing area and can be implemented in architecture. These models include intuition and scientific influence and show how important is gathering pieces of information and creating new ideas on already known facts and how they could be used as a design method. The design method is presented on the example of the project - Music Center of Creation, located on the bank of the Vistula river. The form of the object is inspired by a three-dimensional representation of a resonance curve, called Lissajous figure. Topologically transformed enabled to create the object joining the Vistula boulevard and the central street which are parallelly situated on the other side of the building. During the design process, in a conscious way, a model of the creative process, based on the Graham Walles one, was implemented. This thesis is an example of the idea that effective creation of new ideas should be based on an extension of the existing state of knowledge.

Keywords: *musical inspirations, mathematical inspirations, intuition and scientific, creating a process, lissajous curves, topological transformations*

1. Introduction

Creating a beautiful, harmonious, parametric architecture based on scientific and mathematical rules is a tempting idea, but can be difficult to implement directly in a project. This thesis contains reflection about relations between Music, Architecture and Math and how they can inspire the design process joining intuitive and scientific influences.

2. Mathematical patterns in music and architecture

Historically, there is a strong connection between Math, Music and Architecture. In ancient Greece, the Pythagoreans believed that the world could be described by *numberskor* (Kordos, 2010). As one of the examples, they have given the fact, that we can find harmonized sounds in music by mechanically dividing strings in proportion to fractions of small natural numbers. Their search for pairs of harmonics on a monochrome instrument with a single string has led to the creation of the first Greek tonal system. Despite using very simple methods, they managed to invent a very good approximation of the modern harmonics, which differs roughly by 0.5%.

Another example of fractions usage is rhythm and bar divisions, affecting how are the accents unfolding on an appropriate note in musical compositions. Both whiles composing and in the world of architecture, rhythmic relationships play an important role in shaping the final work.

Geometry was another pillar of ancient mathematics developed in the Mediterranean. Usage of scaling allowed Europeans to create precise maps and develop structures from technical drawings. It was possible thanks to the Tales' theorem, based on unchanging relations between corresponding sections of scaled objects. That gave them a huge technological advantage over their rivals - in Asia, for example, instead of using blueprints, the full-size examples were transported to target location and then copied piece by piece, which made distributing designs difficult (Kordos, 2010).

The musical application of the Tales' theorem might be found in the design of a guitar that emerged in the European cultural circle. The unequal distribution of the frets on the griff allows a quick and easy retuning of the instrument using the guitar capo.

Interestingly, geometric relationships can also be found in the structure of musical compositions. Transformations based on the usage of geometric relations in the musical notation are called counterpoint techniques. When symmetry is used with respect to the horizontal axis it is called an inversion. Symmetry with respect to the vertical axis - retrograde, in which part of the melody is repeated backwards. Examples of those can be found in Beethoven's compositions (Chorościan, 2014).

Over the centuries, mathematicians began to develop new branches, like probability theory and calculus, including solving higher-order equations. Musical compositions were inspired by the world of a randomness and mathematical algorithms. One of the eighteenth-century composer's games was using randomness in the process of creation. According to historical reports, the composers (among them were celebrities like Haydn or Mozart) were working on 12 versions of the bar, and then, using two dice, they have been deciding on the order in which bars would appear in the final composition. But that was only a prelude to what comes in the 20th century. Mathematical inspirations really flourished during that period, thanks to both advancements in mathematics and invention of computers.

There were many composers fascinated in science and mathematics who used them as an inspiration in their music. Stockhausen, the composer famous for his works during the second half of the 20th century, has used structures like the arithmetic and geometric sequences, the Fibonacci series, combinatorics and the proportions principles (Humięcka-Jakubowska, 2013).

Even more complex mathematical formulas can be found in works of Xenakis. He was a composer and an architect, fascinated by mathematics. While composing, he used various probability distributions, geometric patterns, proportions, and graphics. One of his most famous compositions is the Metastaseis. The Composer invented his own musical notation for its purpose, allowing capturing unconventional sounds. His work was inspired by a kinetic gas theory as well as geometrical relations from the world of architecture. Graphic notation of the Metastaseis, composed in 1954, influenced the Philips Pavilion, designed by Xenakis and Le Corbusier for the World EXPO in 1958.

3. Methods of creation, including intuition and scientistic influence

Scientific patterns that can be found in both musical and architectural creations are either introduced by the artists consciously choosing particular structures and adding to their work - which is called a scientific approach, or they have emerged from the subconsciousness and are intuitively incorporated into the design.

In this thesis we will be using a definition of the scientism formulated by the professor Justyna Hamięcka-Jabłkowska in her book “Intuition or scientism” (2013):

> *“Scientism (...) will be treated as a specific philosophical orientation, (...) of which an important factor is a well-defined relation with science and scientificity. It is about the situation in which a distinguished position of science within the culture is a consequence of the science delivering special cognitive qualities (truthfulness and rationality) of the articulated idea.”*

As for the intuitive approach - it has its roots in the cognitive psychology and in general, it is based on the logical reasoning processes that are often completely unconscious. Looking for a theory of creating process there could be found an example of two models of creation that are taking both intuitive and scientific motives into consideration.

The first is the associative theory of the creative process. It says that every creation is based on associations between some facts or experience, sometimes even very far from each other. As Sperarman said in 1931, “nothing is created ex nihilo, new works are only an original combination of well-known elements” (Sołojew, 1997).

The second theory that could be useful is The Graham Walles' Model of the Four Stages of Creativity, which defines four stages: preparation, incubation, illumination and verification. Preparation stage is a time to gather information. During second step - incubation, we do not work on the main topic. Instead, consciously focus on a different activity and let our subconscious to process the main problem in the background. After some time, and we never know how long it could take, illumination comes. We finally create a new idea, which needs to be vitrificated and checked if our solution really solves the problem. If not, the process may be repeated iteratively until the result is satisfactory for us. In new iteration, we can go back to the incubation or preparation stage.

Both theories show how important is the process of gathering knowledge and experience, as well as preparing a phase in which new ideas are created in a subconscious way on the basis of information previously acquired. In Mathematical mind (Brożek, Hohol, 2013) it could be found out the thesis that civilization could exist thanks to improving global knowledge extension/ over-building of the existing state by new generations.

Based on the analogy to the creative processes of composing, it was possible to develop a design method that was both intuitive and scientific. For parametric design methods it is possible to distinguish six basic design steps inspired by Graham Walles Model of creation:

1. **Preparation.** It is a phase which bases on gathering knowledge and facts from the given field, a program of the building and conditions of the environment. Taking into consideration usage of parametric design it could be useful to focus especially on mathematics and physics areas.
2. **Incubation.** After research phase, when the designer consciously engages in a non-project activity, unconscious processes generate ideas and solutions for the main project.
3. **Illumination.** After research and phase of incubation, during which can be found both scientific and intuitive parts, there is a moment to choose one or more mathematical structures which would create the main core of building construction and a general design expression.
4. **Implementation.** Create a 3D object using a mathematical structure in programming with parametric tools, which can easily create architecture structures - like elevations, plans and construction systems, integrated with a visual expression.
5. **Fitting by parameters.** A designer can choose a way and main parameters of the structure to fit them to a program of the building and conditions of the environment. This part can be mainly connected with the intuitive part of the creation process, but also determined by external conditions.
6. **Topological fitting.** Further transformations, which help match the form and structure of the building to external conditions and assumptions. Usage of topological transformations allows changing the shape of an object without changing the structure itself, retaining the mathematical order. The transformation can be applied directly by the designer, or their form may be the result of optimization algorithms.

4. Implementation of the Project

The design method was implemented in the project of Music Centre of Creation, located on the bank of the Vistula river. The form of the object was inspired by a three-dimensional representation of a resonance curve, called Lissajous figure. Topologically transformed enabled to create the object joining the Vistula boulevard and the central street which are parallelly situated on the other side of the building. The project was developed under the supervision of professor Jerzy Wojtowicz.

During the ***preparation step (1***), firstly information about localization, conditions of the environment and program of the building were collected. Next, during the data gathering, I have collected the above mentioned historical relationships of music, mathematics and architecture. I have also gathered information about musical notation system and wave nature of sound, which was important for the final project.

Based on the theoretical information it was possible to complete a set of projects based on scientific and intuitive inspiration from music field. (Dąbrowska-Żółtak, K., 2016) As a scientific approach, I mean the theory of sound waves, musical notation system and mathematical patterns used in music.

Another part of research step was connected to acoustic, as a knowledge of shaping space and choosing materials to receive the best architectural solution. During this part, I have gathered information how to design good static and flexible acoustic space (Kulowski, 2011). The research was based on both classical and modern, mechatronical solution. As classical, I mean static solutions, based on volume and of the space, shape of the space and used materials. Modern solution based on the contemporary technology, like a moving system of reflecting and absorbing panels, active acoustic cancellation, using active sound source and intelligent materials, can change acoustic parameter dynamically.

After gathering information and mathematical patterns comes time for ***incubation (2)*** part in which subconscious processes takes place. Then comes ***illumination (3)*** that inspiration for the final project could be Lissajous curves (Weisstein, E. W., 2017).

Lissajous curves are a graphical representation of a motion path, drawn by an object that is set in motion by two simultaneous harmonic oscillations. Soundwave is perpendicularly directed and there are no other forces, even gravity.

These curves were first described at the end of the 18th century. The mathematical description of the figures is understandably based on sinusoidal relationships and can be represented by two equations.

Despite the difficulty in performing mechanical experiments, Lissajous curves have successfully been extended by mathematicians to the third dimension. The rule for three-dimensional curves assumes the existence of a third sound source - an acoustic wave generator propagated along a vertical axis (see fig. 1).

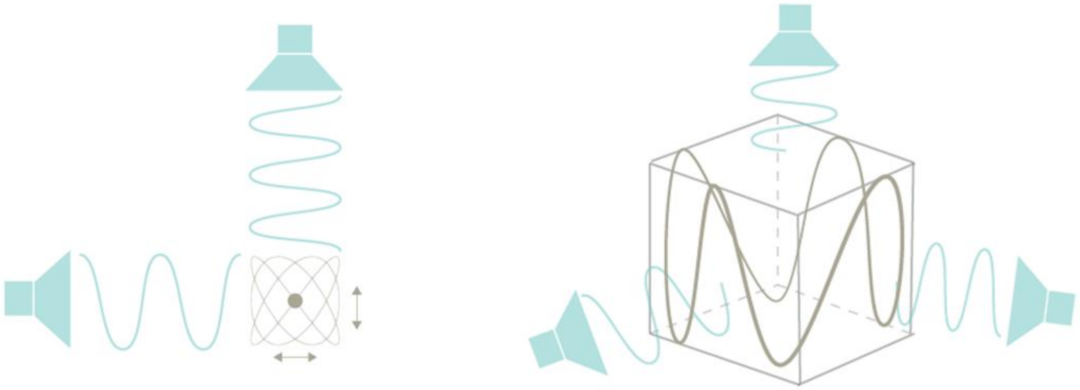

Fig. 1. a) (left) Schema of 2D Lissajous curve, b) (right) schema of the 3D Lissajous curve

The first step of ***implementation (4)*** was to generate Lissajous curves in the Grasshopper. During the step of ***fitting by parameters (5),*** based on the conditions associated with the location and function of the object, there were selected the parameters of the curve forming functions. Some examples of receiving 3D curve based on mathematical formula were shown in figure 2.

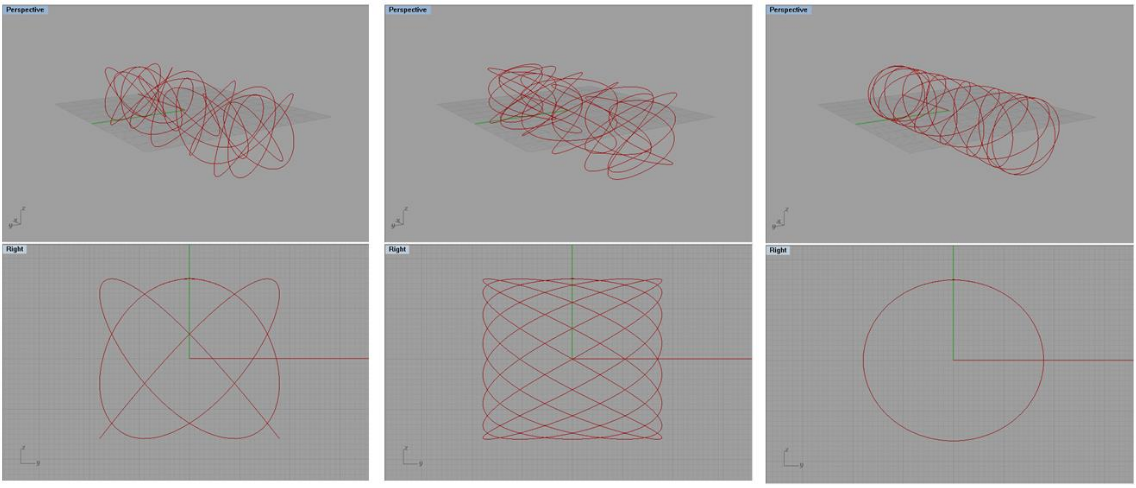

Fig. 2. Example of receiving an object from the Lissajous curves mathematical formula

For the final solution, there was chosen a double sinusoidal barrel vault (see fig. 3). It allows to include the functional program of the building in the object and create space connecting city street and the river.

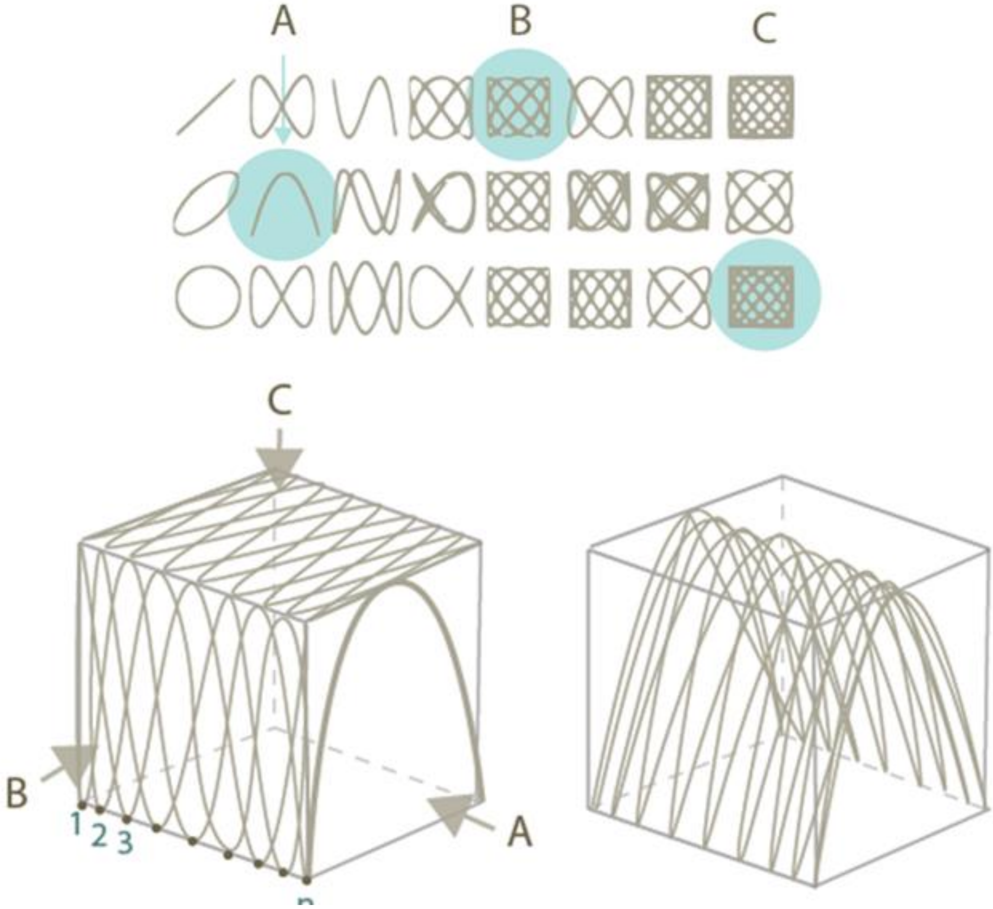

Fig. 3. Sinusoidal barrel vault – as a final project form

The project was set between the Vistula river and the city street. In the part of ***topological fitting (6)*** the structure the elevation from the side of the city street was approximated to a rectangle. At the same time, the part of the facility on the riverside was raised and tilted towards the Vistula River (see fig. 4).

Based on the final curve there was generated both a uniform cross-sectional building structure and elevation system. The cross-section of facade elements was getting smaller from the city side towards the river in order to emphasize the opening of the object towards the `Vistula (see fig. 5).

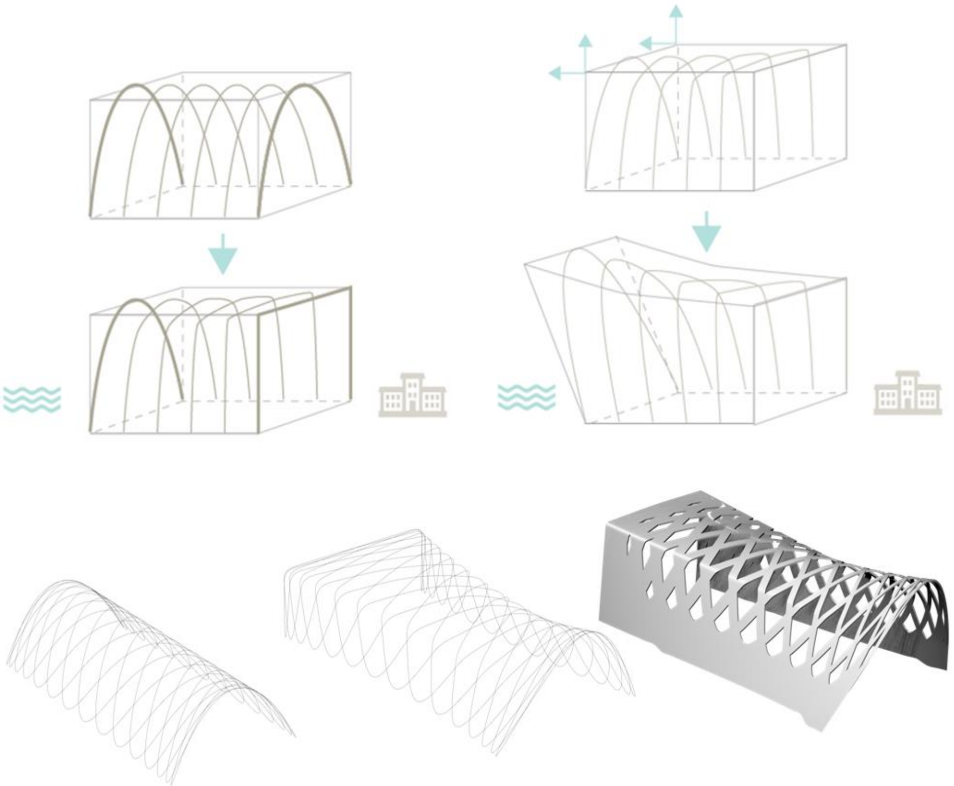

Fig. 4. Topological transformations of the external sinusoidal barrel vault

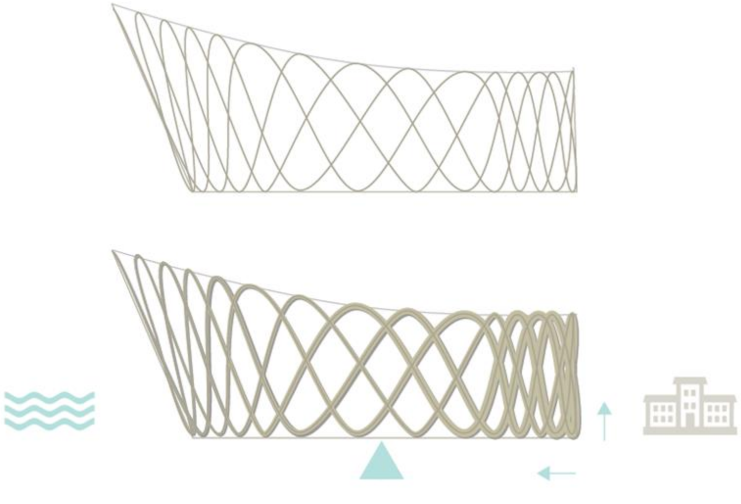

Fig. 5. Elevation of the Music Centre of Creation

The internal sinusoidal barrel vault geometry was changed by nonlinear scaling transformation along the building (see fig. 6). In the part where the concert hall was located, the inner vault was enlarged (see fig. 6. 1). Further downstream, the barrel vault's centre has been narrowed to increase space for audio-library and rehearsal rooms (see fig. 6. 2). The hall of the building was softly expanding towards the river (see fig. 6. 3).

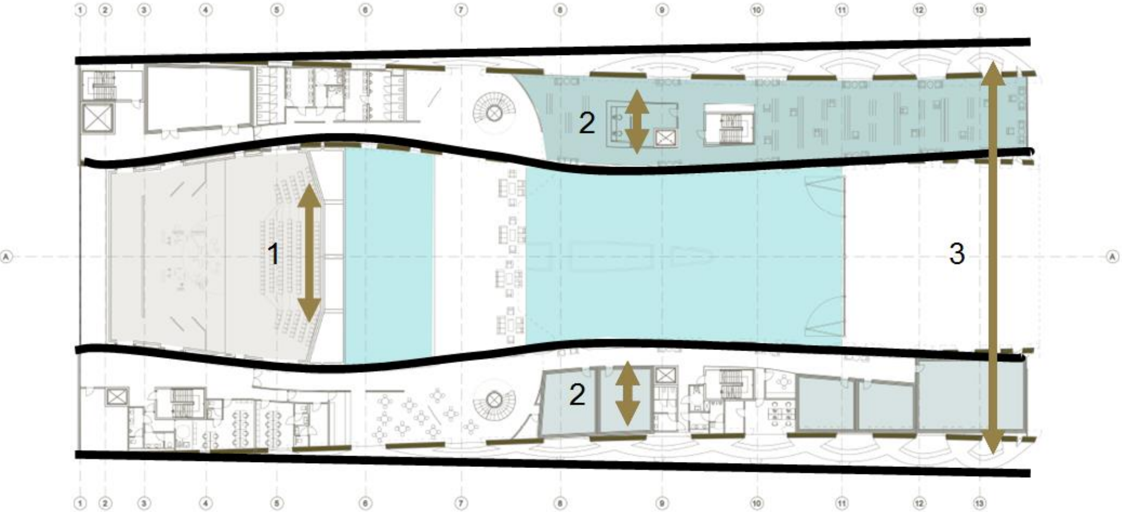

Fig. 6. Plan of the first floor of the Musical Centre of Creation, showing non-linear scaling transformation along the building

Transformation of an inner barrel vault, besides function, was dictated by acoustic roles. The cycloidal shape of a ceiling allows for a favourable distribution of the first reflection of the sound wave. In the concert hall area, sinusoidal barrel vault was transformed and approximated to cycloidal shape in cross-section view, by using further topological transformation (see fig. 7. a). Changing in the concert hall plan was dictated both by enlarged audience area and how sound waves propagate. Fan-shaped audience allows for a proper propagation of the direct sound wave and its first reflection (Kulowski, 2011) (see fig. 7. b).

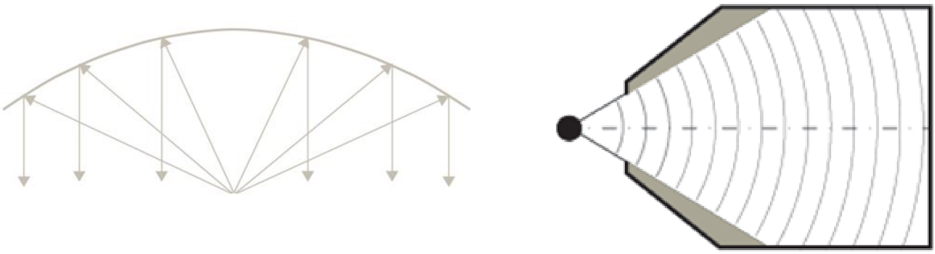

Fig. 7. a) (left) The cycloidal shape of cross section helps in the uniform propagation of the sound wave. b) (right) The fan-shaped audience shape. (Kulowski, 2011)

Other solutions affecting the acoustic parameters of the rooms used in the project are:

- for the concert hall - suspended panels and reverberating chambers,
- in the rehearsal rooms - sound insulation,
- in the system box in the box,
- in the audio-library - active acoustic cancellation system, which allows separating acoustically independent zones in the audio-library, without placing a physical barrier in its area and in the main hall controlled panels (see fig. 8),

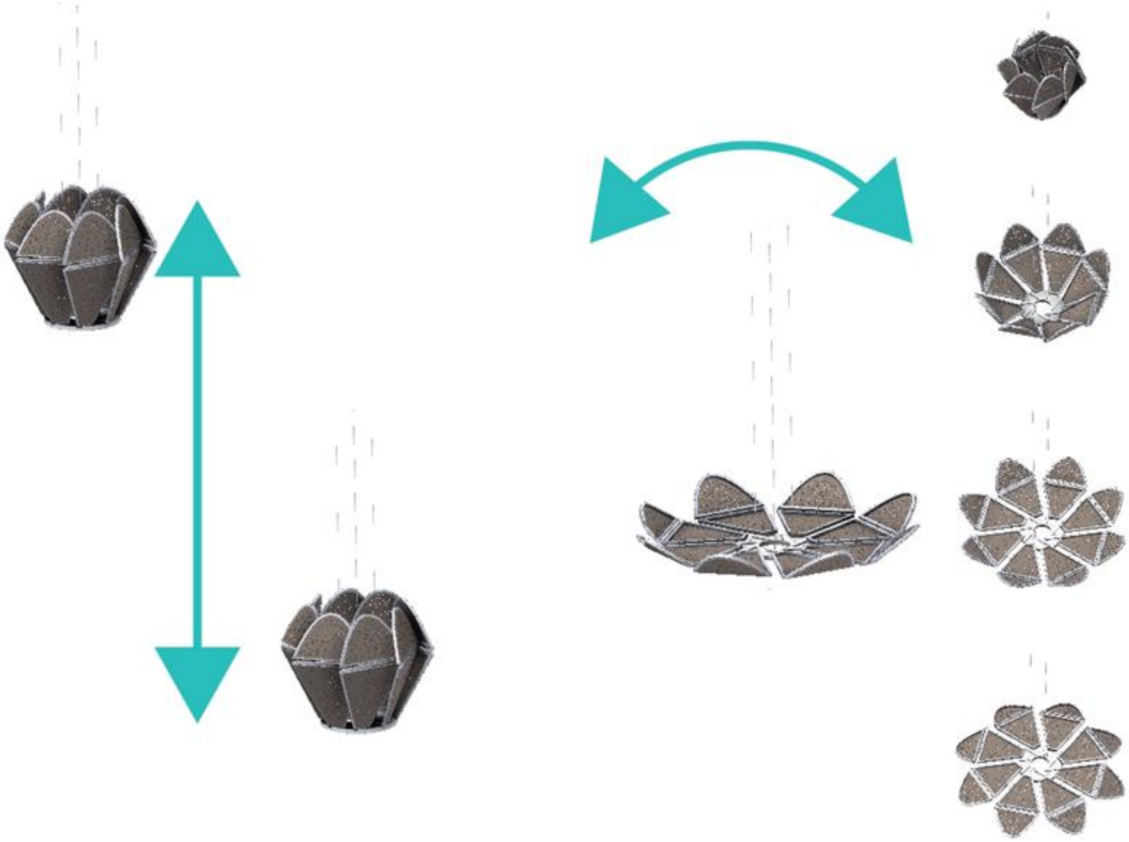

Fig. 8. Controlled acoustic panels

The final form of the Music Centre of Creation building was created as a result of the collection of materials such as mathematical patterns in the music area, physical nature of the sound wave and acoustic roles which should be applied during the process of creation of acoustically flexible spaces. Using mathematical language to communicate with parametric tools allow creation in a conscious way, a consistent form of a multifunctional utility building.

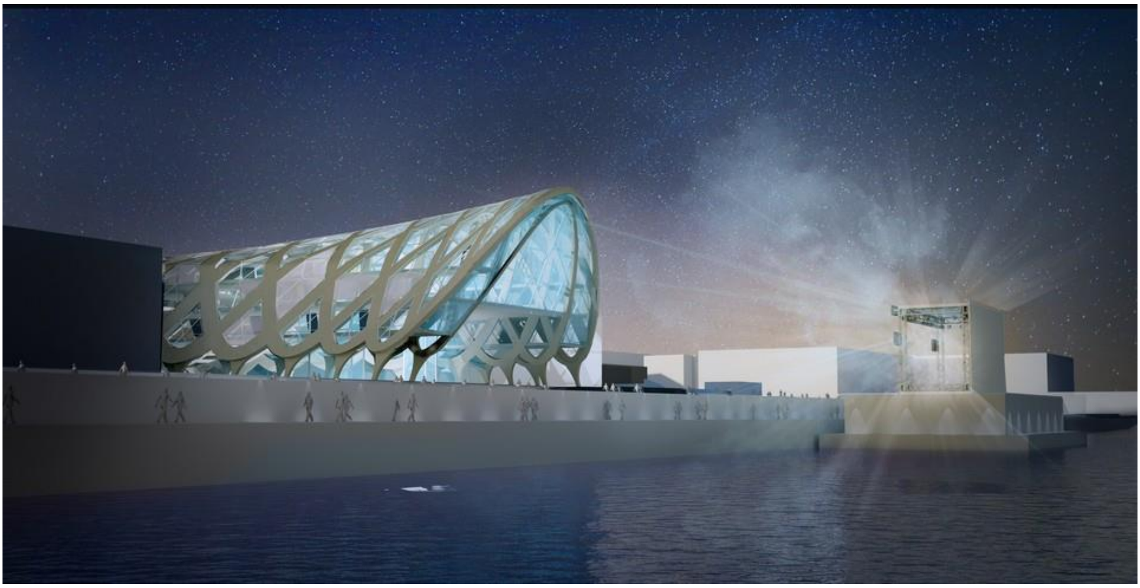

Fig. 9. Visualisation of the Music Centre of creation project, inspired by music and math

5. Conclusions

The process of creation, both in the world of music and architecture, can be based on gathering information and subconscious joining together the already known facts. The mathematical patterns could be especially useful in implementing the final protect into the digital environment and for further transformation.

Using the ready-made mathematical formulas and mathematical description of physical phenomena presented in the world of music and architecture and can be seen in architectural designs more frequently, because of development of computing and modern fabrication methods. Perhaps through the conscious use of creative process models which take into account intuitive and scientific approach, it could be easier to use structures already described mathematically.

An effective creation of new ideas should be based on over-building of the existing state of knowledge. Ready-optimized models derived by mathematicians can simplify calculations, and their direct usage can be an alternative to search for a form directly in the environment of generative tools or the usage of randomness as a design method. The designer can create a project based on his knowledge and intuition using computer programs as tools to implement and verify the developed solutions.

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MANDALA AS THE EXAMPLE OF VISUAL CODE BASED ON CULTURE. CASE STUDY OF FRACTAL GEOMETRY IN PRACTICE

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What is mandala doing at a conference for architects?
My presentation will be a practical interpretation of the idea of the conference "shapes of logic." The mandala is an ideal rationale for experiments on the borderline of parametric and generative design and it is also anchored in culture. In the broadest sense mandalas are diagrams that show how chaos takes on a harmonious form. Therefore, they bring the symbolic and humanistic world closer to the parametric one.
Why do I find this topic so interesting? Because I see my future in generative design for the space industry. The technical know-how and the skills to apply it in design are essential to design tools, but still, only tools to help people further develop. I consider combining humanistic values with technology to the greatest advantage of being a designer.
Who, if not designers, are supposed to deal with the visualization of a hypothesis?
In the section on the technical workshop, I will present examples of fractal geometry and its application. Fractal geometry is most commonly known from examples presented two-dimensionally. One of the points of the paper will be the presentation of the effects of a visual experiment on fractals in three dimensions and the possibility of applying them in practice.
Mandala is an example of man-made fractal geometry. Created from simple elements, the complex structure is also culture-related geolocalized information.
Discoveries are hard to come by without trials and experiments in an interdisciplinary environment, not to mention ground-breaking ones. I treat my paper as a record of a continuing experiment, to which I invite everyone interested.

Keywords: *culture code, glocality, hologram, mandala, symbols, meaning, anthropology, 3D printing, coding*

1. Introduction

As an introduction to this article, allow me to relate a scene that I was witness to at a discussion which took place a month after the “Shapes of Logic” conference; “DESIGN the Language of BUSINESS” took place during Gdynia Design Days 2017, one of the most important design festivals in Poland.

During his presentation, a certain journalist who claims to be a trendspotter showed a picture from an international design exhibition with three chairs.

The context of what he said indicated that he felt he was an expert on design. For that reason, it was alarming when he said that “the first was designed by a human and the third by a computer.”

It clearly seems that the journalist, who I would not want to provide with disreputable publicity, did not realize that the project concerned software showcased by AutoDesk already in 2014. This was the Dreamcatcher project that had been in the pipeline for seven years before we were able to see the famous picture with the three chairs (see fig. 1). Sure, we can see the caption which says that the first was designed in a “traditional” way and weighs 10.3 kg, the second already takes into account a reduction of material with the use of lattice fitted to the Active Material Library and weighs only 4.1 kg, the third model shows one of the versions obtained with generative tools called “evolutionary design with AML” and weighs 2.9 kg. (Baklitskaya, 2016)

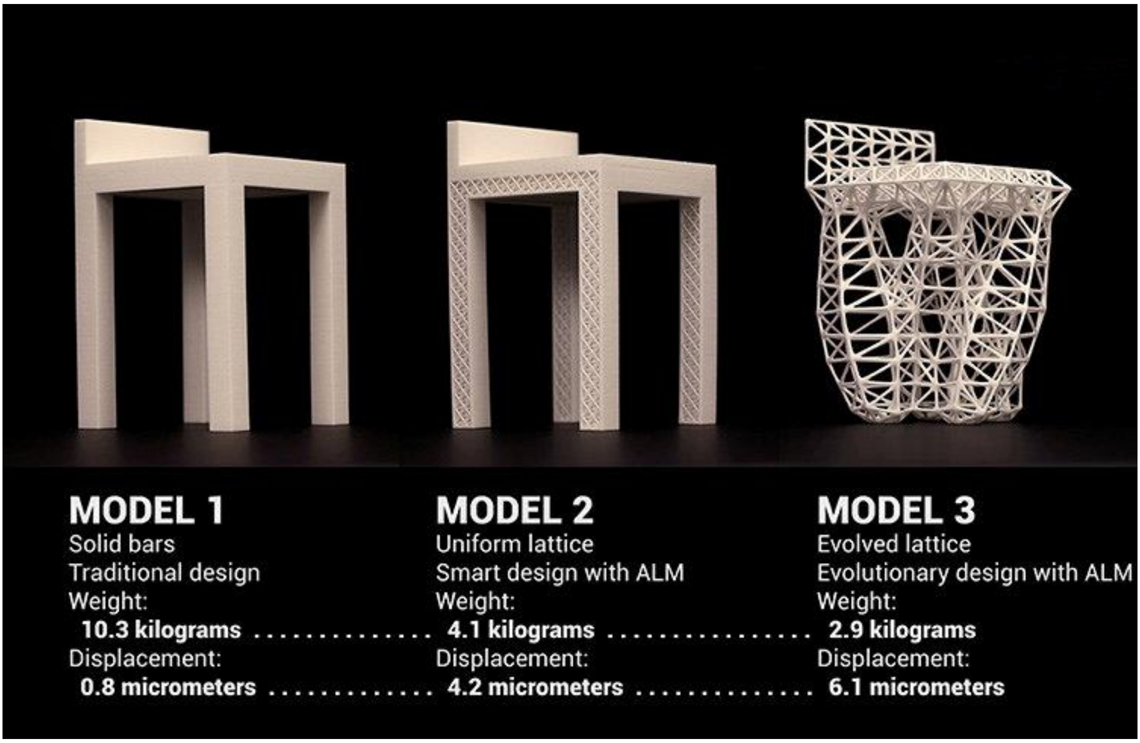

Fig.1. Autodesk Dreamcatcher example designs for a chair (Baklitskaya, 2016)

The audience of 300 were not necessarily people with close ties to design, but rather enthusiasts and businesspeople for who any set of notions with the word *design* still sounds like a password to a magical world, with a steep price of entry.

The eyes fixed on the speakers did not exhibit the slightest bit of knowledge about design or any critical thought; everyone listened in rapt admiration.

“It is not a human being but a computer that designs.” Is this a mental shortcut? Perhaps the journalist’s superficial knowledge? Most likely. The speaker’s idea of the designer’s work had stalled in the 20th century; he did not see that today’s designer uses more than just a chisel and pencil (if designers had ever been limited to just these tools at all). Why is this alarming? Because it is easier to accept and comprehend. Therefore, a seemingly innocent oversight or slip of the tongue can have its consequences in how the designer's profession is construed in the future.

For example, a phrase that always hurts and irritates Polish people is "Polish concentration camps," instead of "Nazi German concentration camp" (in Poland): the historically correct term that has been adopted by UNESCO (UNESCO, 2007). In spite of UNESCO's authority, it is easier to say "Polish concentration camps." Of course, these two cases of abuse are incomparable, but they show the scale of the problem of ill-conceived mental shortcuts. In spite of this, when we talk about tendencies and trends, we should take note of what is easier for people to accept and remember because it is the message that is easy to remember that becomes information more often than the facts do.

I realize that the very question of "what does a designer do" is very broad and that many a conference ended with disputes about this matter. However, I still feel that there should be at least attempts to take up this matter given the speed of the changes that are taking place.

"Design, Language of Business" took place after the Shapes of the Logic conference. However, it is because of such situation that I would like to introduce a discourse related to the designer's role in the generative design and about the humanist values that irrevocably accompany this field.

If we designers fail to take a stand, there will be others who will do it instead: persons who know nothing about design and interpret our work superficially. And we cannot blame them if we ourselves failed to clearly express ourselves on the subject.

The central theme of my article is to show that generative tools are tools that are completely different and require a different way of thinking when designing than the tools we used before. However, they still remain tools in human hands. We have a tendency to completely fall for new capabilities. Nevertheless, every experiment requires reflection if it is to lead to progress rather than to just be a one-off pleasure.

2. The theoretical aspect of the study

In the spirit of the Shapes of Logic conference, I wanted to take up the shapes that result from logic, but which do not lack a cultural context. It is the latter that becomes the true code, the geolocalizer, clear and understood in a given area. The cultural context nonverbally conveys complex information that is often abridged when translated into another language.

I feel that combining humanist and technical values is the greatest virtue of being a designer. The ability to create a visual message using new tools is becoming a new language: the visual code.

I focus in my deliberations on social and anthropological aspects, using to this end a visual language obtained with parametric and generative tools.

I look for contact points and boundaries, the human and software, and the differences and similarities that come from a culture and with which we achieve greater social awareness and develop our civilization.

Cultural and anthropological observation translated into the language of generative design can become a basis for AI researchers.

This is already taking place because the original inspiration for the structure of neural networks was the structure of natural neurons, the synapses that link them together and the nervous systems, especially the brain. (Kurzweil, 2005)

Based on a mandala-inspired design I will present both the symbolic and visual context, as well as the context related to parametric and generative design.

3. Research methodology

This article uses material from my own research under the “Futurology in Design Practice” project sponsored by the Faculty of Architecture and Design at the Academy of Fine Arts in Gdańsk. The project’s study component was carried out with the Kathmandu University School of Arts Center for Art and Design).

The result was presented at the Parallel Reality exhibition at the City of Gdynia Museum 9 June – 5 July 2017. The exhibition had the support of the Marshal of the Pomorskie Voivodship.

This section is the background of the subject matter and the context of its research.

I would like to compare and contrast this with a very practical and tangible project that I carried out together with Prof. S. Fijałkowski from the Experimental Design Studio at the Faculty of Architecture and Design, Academy of Fine Arts in Gdańsk, the result of which was the monograph Trend Book 2017, published in collaboration with the Polish Chamber of Amber Commerce and the City of Gdańsk. In this section, I especially want to refer to a trend that is actually called “Mandala.” (Fijałkowski et al., 2017).

The final thing is an original interpretation of the mandala. A materialization of the principles of futurology in design practice. A strong symbol of culture known as a two-dimensional form. The mandala is a perfect rationale for experiments on the borderline between parametric and generative design. The result is a hologram, which because of its lack of physicality in a strict material form. On the other hand, it represents what constitutes an undeniably communicated piece of cultural information that is not recorded in the form of a traditional code/message.

In summary, the Research Methodology to: discuss the cultural context on the basis of my own research and the collected information, compare and contrast the practical implementation of the ethnographic inspirations in product design with an experimental recording of a three-dimensional mandala as a hologram that represents cultural and symbolic values translated into the visual language of generative geometry.

Finally, I will present some conclusions on the contemporary use of generative tools.

4. The culture code

According to Clotaire Rapaille, a culture code is the meaning we subconsciously attribute to a given thing. How a given phenomenon or object is perceived in a given culture.

In his book, Clotaire Rapaille lists examples such as these:

- In America, a car signifies IDENTITY, whereas in Germany ENGINEERING.
- For Americans, health means MOVEMENT, for the Chinese BEING IN HARMONY WITH NATURE.

Culture codes are incredibly important because they are superimposed on the target's personal experience and determine the personal meaning of, for instance, a product. (Rapaille, 2007)

I described the example of the KitKat candy bar that is a good illustration of when local cultural habits impact a global product in my monograph *Design in Glocal Culture*.

In 1988 Nestlé took over the Rowntree company, the originator of KitKat candy bars. KitKats are available all over the world, but the contents of the package may differ. The product on sale was researched and developed by teams of market analysts in order to suit the product to the needs of the target consumer. Depending on the market where the candy bar is sold, local flavours, habits and cultural differences are utilized in its production. This way the candy bars become a mass project with a local touch (see fig. 2). This is one of the faces of glocality (Ritzer, 2014).

The use of such data in marketing and social engineering is by now common practice and nothing new. However, the scale and diversity of information and the ability to process it will only begin to yield results in the future.

The place where we are born and where we reside, our environment and reality, are a starting point. Each new experience will be compared to our first ones.

Geographical conditions, history and access to knowledge are all factors that influence cultural differences. We all have the same needs, are cut from the same cloth, but we differ locally and in detail.

Knowing only our own environment, we automatically accept it as a model and an interpretation.

“Parallel” does not mean “the same.”

Fig. 2. KitKat in wasabi coating. Snack Dengan Rasa Unik Yang Tidak Ada Di Indonesia, Senin, 29,08, 2016

A distant culture means different traditions, rituals, language and mentality. It may deem as important matters which we do not notice at all.

How can we learn something new about ourselves? How can we advance civilization?

By changing our perspective, we notice and, consequently, understand more.

Idioms and expressions do not just exist in words; their multitudes of them and it is thanks to them and the differences that we learn more about the world. They are what often constitute, as it were, the markers of reality in an encoded world. This reality often seems to be parallel.

Here, I would like to again refer to the origin of the Parallel Reality exhibition and to two of the twelve selected pictures that represent the issue at hand.

The first picture shows a manhole labelled with the year 2052. Asking what year it is may not have such an obvious answer. Nepal has an interesting and peculiar calendar of its own. It is called Bikram Sambat. The New Year begins in mid-April and so every month also begins more or less in the middle of “our” month. Now they have the year 2073. If you want to point to a certain date when talking to the locals, it is better to say “five days ago” or “in two weeks” etc. Our “March 20” or “July 1” would not tell them much. (Nepali Calendar 2074, 2017)

“Back to the Future” indeed!

The Gregorian calendar (i.e. the Julian calendar reformed by Pope Gregory XIII) is the one we know best; it is the one which regulates the principles of our Western way of thinking and how we function socially. And it is rather hard for us to wrap our heads around the fact that it is now 2073 in Nepal, 1438 according to the Muslim Calendar and 2561 in the Buddhist one (see fig. 3).

Fig. 3. Manhole in Katmandu, Nepal. M. Flisykowksa 2016

Fig. 4. Hand-made swastika at the Tihar Festival of Lights in Nepal. M. Flisykowksa 2016

Another striking example is the picture of the swastika made by hand on the street during the stunning Tihar Festival of Lights (see fig. 4).

The swastika is a religious symbol that is present in most of the world's cultures and religions. As such it is also used in Europe and the Americas by neo-pagan movements and indigenous religions. However, it also still functions as a neo-fascist symbol, due to which it keeps being commonly associated with Adolf Hitler and Nazism, whereas in Asia it is a common symbol of auspiciousness and good luck.

Perhaps this example is tediously familiar, but in this case, it was not supposed to be innovative but was rather meant to emphasize how much culture codes can change how we interpret them. (Tresidder, 2000)

When setting out to work on a three-dimensional interpretation of the mandala, I was keen to approach it in a new and contemporary way, which would obviously be processed through the filter of a European designer.

5. The Mandala

The mandala is an ideal rationale for experiments on the borderline of parametric and generative design. In the broadest sense, mandalas are diagrams that show how chaos turns into harmony.

People try to tame chaos with the geometric division. Mandalas can also be called a kind of binary system because they are built of two simple shapes: the circle and the square.

The Buddhist mandala is a harmonious combination of these shapes, where the circle is the symbol of the heavens, transcendence, externality and infinity, while the square represents the sphere of the internal, that which relates to humankind and the Earth. Both shapes share a central point, which is both the beginning and the end of the entire pattern. (Tresidder, 2000)

Just as with coding, where we get a line, a sentence, but not construed as a poem but as a command, so in making a mandala, apart from its construction and shape, the entire dimension of creation, as well as the final result, have a symbolic meaning.

As a digression, which I intend to treat somewhat jokingly by comparing the intricate art of pouring coloured grains of sand with incredible precision and accuracy to the situation of artists working with a computer. Wiping out the completed pattern is an intrinsic part of creating mandalas is Tantric Buddhist art. I think that not only readers who are designers using generative and parametric software found themselves in situations where the software did not save the changes and a message about an unidentified error appeared on the screen, which meant that their many hours of work was drastically laid to waste. The moment when we discover that the backup version was saved right before we made our day’s biggest headway is especially painful. Some of us may then wonder if the experience is more traumatic or tantric. Of course, there is a radical difference when this is a result of a random occurrence and not part of a planned process. Nevertheless, it can sometimes be refreshing for the piece.

Let this digression be an introduction to present two separate projects that were the outcome of the above deliberations.

Trend Book 2017 contains a collection of mandalas designed by fifth-semester full-time students. Most of them are printed in titanium, with a few exceptions where they are printed in white ABS. DMLS (Direct Metal Laser Sintering) technology is used for the additive manufacturing of metal components and has been developing for over 20 years now. The most popular materials used in DMLS technology include tool steels, titanium alloys and others.

Fig. 5. Mandalas made by the students of the Academy of Fine Arts in Gdańsk for Trend Book 2017. Titanium and ABS printing. Trend Book 2017

In this case, the mandala became an impetus for stylistic experimentation which was to result in the designed objects (exhibition prototypes) made with advanced technologies.

The mandala was one of the five subjects presented in Trend Book 2017; it did not entail any close attachment to the origin of the symbolic pattern (see fig. 5). It was to be a call to present possibilities, experiment with the material and technology with only a hint of the cultural context. This context has also been noticed and diagnosed in the products and exhibits showcased in Trend Book. Their context is closely related to the commercial world, which in turn, as mentioned above, has long since found values in culture codes, not least of them economic.

Interpreting the mandala as a hologram was also to involve the use of digital tools. The equivalent of the mandala’s fleeting nature is its graphic representation as a projection, which is to set it free from the material world but remain a materialized three-dimensional result.

In this case, the interpretation of the digital language went a step further. Instead of using a circle and square as in a traditional Buddhist mandala structure, I focused on combining a “Mobius” solid with a “Voronoi” surface, which I feel are the ABC of generative style in objects.

I will explain these notions in a very laconic and simplified manner, as a practitioner and a user of Rhinoceros and Grasshopper software, not an academic mathematician. A “Mobius” solid, based on the strip discovered by German mathematician August Möbius, is presented in a three-dimensional rather than two-dimensional version. We obtain the features of a Mobius strip when we connect two ends of a strip where one is turned to the other by 180 degrees. Variations on the theme form a complex geometry (see fig. 6, 7). Similarly, a Voronoi Diagram forms a surface which we can illustrate by comparing it to the structure of the cellular tissue. The Voronoi Diagram concerns the division of a surface into a visually organic systematized way.

The hologram was also presented in the designed structure printed in PLA in pearl colour. The small print was made up of four supports and a field to project it; the entirety was also part of the exhibition at the City of Gdynia Museum (see fig. 8, 9). The visitors interpreted it as “temples for the hologram.” Even though this was not my aim, the instilled context in the form of the mandala said the rest. This is yet another example of encoding information via cultural context.

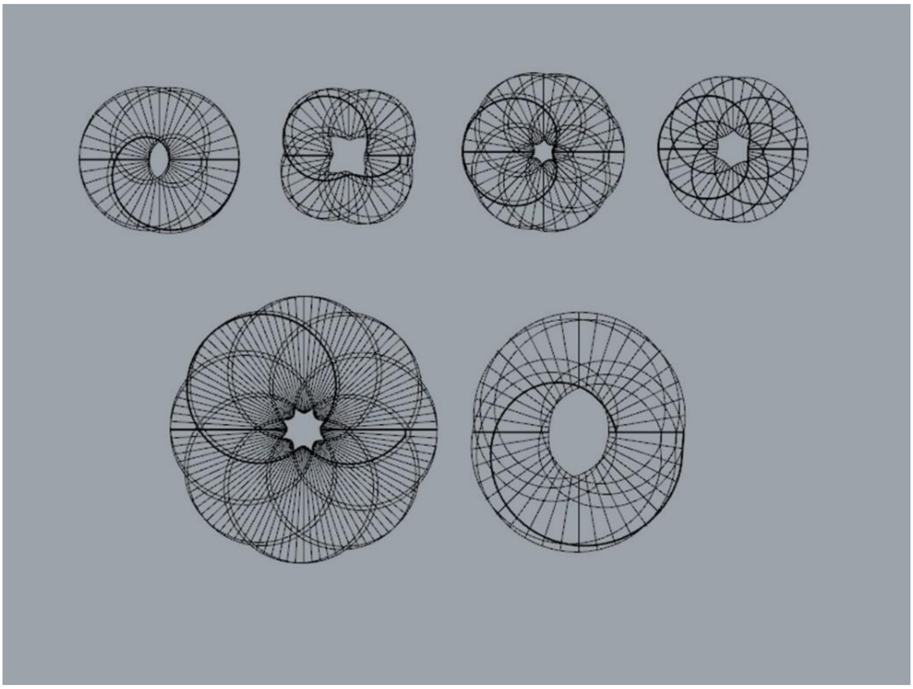

Fig. 6. Projections from above, wireframe view of Mobius solids Marta Flisykowska 2017

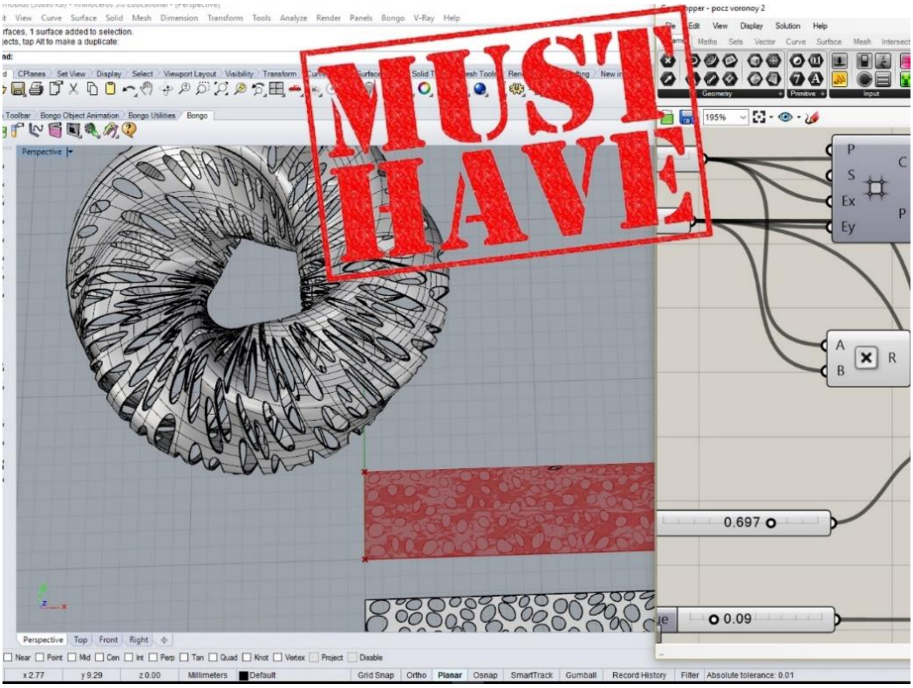

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Fig. 7. Screenshot with a view of a forming hologram solid using a Voronoi diagram and a Mobius solid. Marta Flisykowska 2017

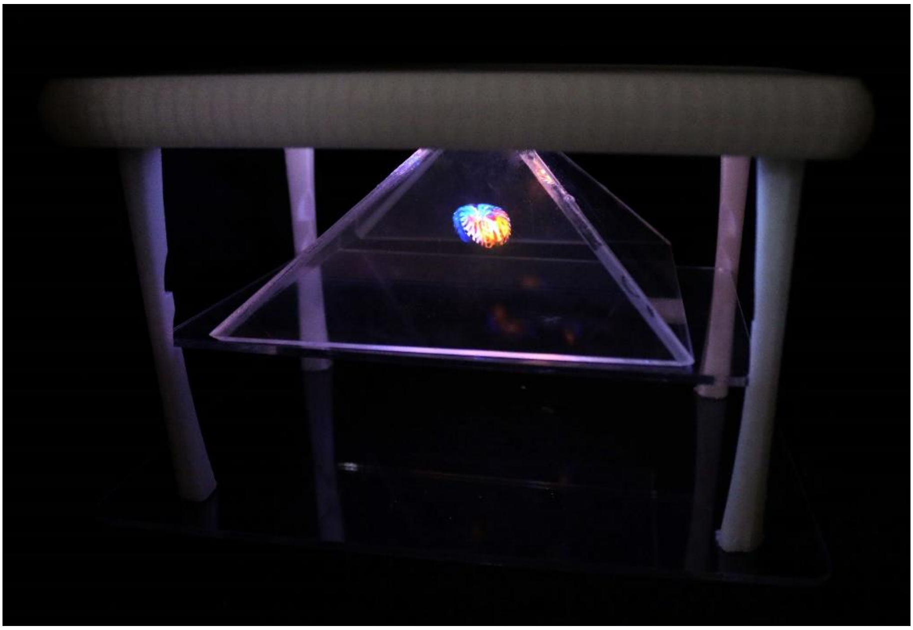

Fig. 8. Hologram from the Parallel Reality exhibition at the City of Gdynia Museum Marta Flisykowska 2017

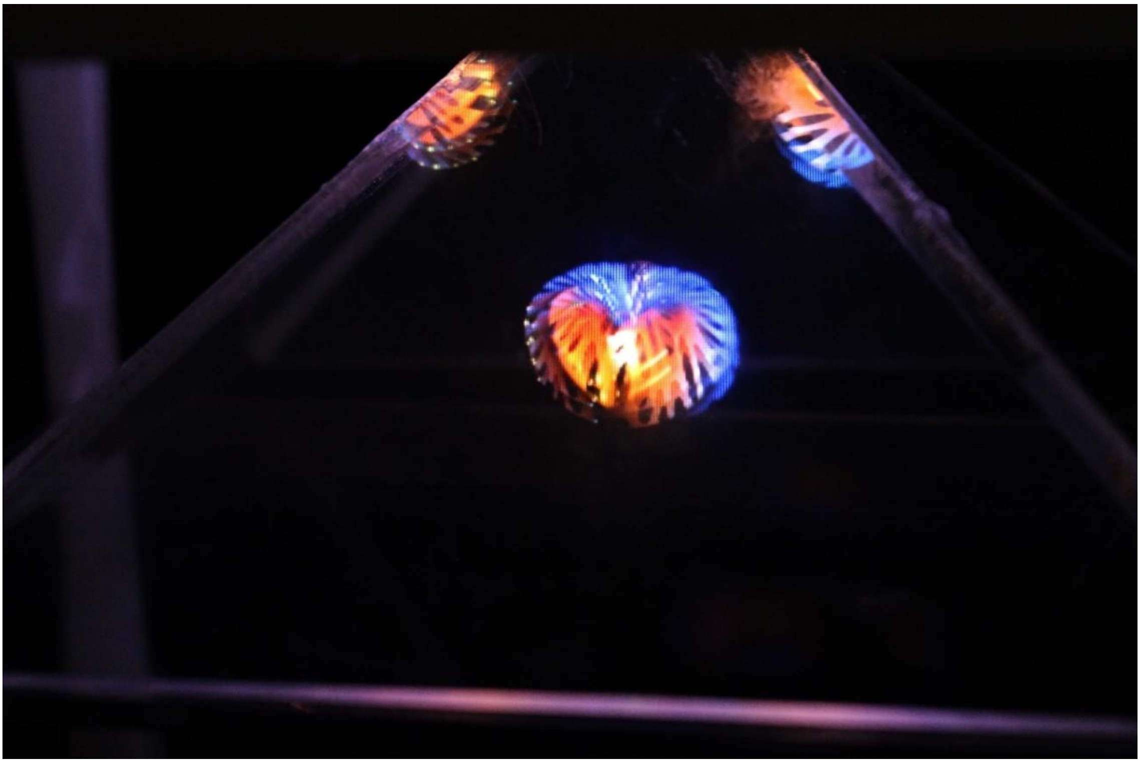

Fig. 9. Hologram from the Parallel Reality exhibition at the City of Gdynia Museum. Marta Flisykowska 2017

6. Summary

An important question hung over the Shapes of Logic conference that was left unsaid.

Will the future of design be about optimization or creativity?

However, I asked the question which is the gist of this article: what is the opposite of optimization? Does designing by an architect or designer mean just looking for optimal solutions or, perhaps, using generative capabilities to experiment and create new things?

Both, in my opinion. However, it is the latter that takes courage and risk, whereas just looking for the best solution means that we know how to take care of a certain challenge or project, i.e. it is already made and in this sense optimization is just an act of improving what is, not generating an actually new solution and more play-safe in the scientific sense.

Between 2013 and 2015 more data has been generated than in the entire previous history of the human race. Their segmentation raises many doubts (Marr, 2017)

Access to the tools which a designer or architect can use today has changed very much in recent years. The number of parameters which we can simultaneously enter into a computer and the time required to get an answer is incomparable to that from before the age of computers. This unquestionably impacts the project.

For now, the cultural context and its understanding cannot be noted down in a binary way. Even though computation capabilities are growing all the time and Big Data science is becoming an increasingly strong field of science, we still have information recorded as a culture code, which does not exist as a recorded message without the participation of the human designer and the receiver.

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AUTOMATION OF DESIGNERS' DAILY LIFE

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Use it wisely
„Buildings provide us with physical shelter and allow us to use it in specific way, but not only. As a haven for our fragile bodies, host minds, memories, desires and dreams. "[1]

Keywords: *design automation, generative design, parametric design, 3D scanning, 3D printing, coding*

1. Introduction

A few years ago, at the last year of my studies at the Faculty of Architecture, my friend asked me for help in working on a project of the sport hall with the commercial gallery – competitive project. The conceptual stage of the project was already behind the team – they needed only help in computer drafting. The project was carried out under the guidance of the renowned architect in Wrocław – Edward Lach. My task was to draw Mr Lach „sketches" in AutoCAD. I called it „sketches" because the drawing I got was by Mr Lach on the B1 format. On paper, on the ground floor, where over 220 rooms and dependencies between functions were perfect. There was only one correction in the entire format.

The rooms were marked with the axes of the walls - I had to add appropriate thickness. After that, I had to check the compatibility of rooms' sizes with those described in the competition guidelines. Differences were very small – 39 m^2 in the project, 40 m^2 in guidelines, 54 m^2 in the project, 53 m^2 in guidelines. Almost surprisingly identical compatibility considering the fact that I received „sketch" drawn in axes on the fairly strange scale – because of 1:400.

I remember how once, during the work, Mr Lach pointed out that we, as a generation, which started our creativity in kindergarten with pencil and paper, today we design in a virtual reality with lack of sense of scale, proportion and function.

2. The new design tools usage examples

Being at the end of my architectural education, with several years of work experience in the office, I began to wonder if I would ever be able to take

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[1] *W stronę neurobiologii architektury – umysł ucieleśniony i wyobraźnia, in*: *Miasto-Zdrój. Architektura i programowanie zmysłów*, red. J. Kusiak, B. Świątkowska, Fundacja Bęc Zmiana, Warszawa 2013, pp. 29-44. Trans. M. Pakowska

responsibility for a project I do not feel. Next generations use the keyboard, mouse or even joystick more and more efficiently. Even the Finnish authorities decided to give up to teach handwriting in schools[2]. With young people in the same age, I found myself on the borderline of tradition and future. So how to deal with it? Below I would like to present projects well known by me. All of them use parametric tools in different ways, but it's only complementing the largest tool available to the designer – imagination.

2.1. The G-table

The object on an interior design scale, one, on which I had the opportunity to work, is G-table designed in Zieta Prozessdesign – Wroclaw design studio. Design of this table is based on FiDU technology (see fig. 1). The process of creating this table with very smooth „legs" is extremely interesting from my point of view. Not only its shapes but also the work of designers, technologists and algorithms are seamlessly penetrated each other here. The G-table countertop is always supported by „legs" which shape is based on „V" letter. There are several different versions of this „legs". However, this is not a table leg in the classic sense of meaning. The contact point of „leg" and top is not the point of support of its weight. Here comes the first problem – how to combine interesting shape and object stability. First attempts made by designers to set up „legs" in software manually ended in fact that prototypes printed in FDM turned over because of their own weight very often. Another important parameter that should be taken into account during formation process is the number of people and their placement at the table. The shape of „legs" not only affects its stability but also very clearly designate places where people can sit down around. The parameter that also has to be mentioned is shape

Fig. 1. G-table designed by the Zieta Prozessdesign Studio (photo: courtesy of Zieta Prozessdesign)

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[2] https://www.telegraph.co.uk/news/worldnews/europe/finland/11391999/Finland-to-teach-typing-rather-than-handwriting-in-schools.html, [access: 03.01.2018]

of the top. It must be adapted to the material, but more significant is its function and space in which it will be used.

The designers of Zieta's studio decided to reverse the situation and develop an algorithm that will determine the position of „legs" depending on the purpose of the table, size and shape of its top and number of people who will sit around it. Of course, all of this with maintaining the stability of table. So what is the role of the designer? In Zieta Studio designers like to teach and see the shape. In addition to developing many technical details, such as the method of joining legs with top their have to take care about aesthetics. Not every leg setting is visually correct, especially when it is made of INOX steel, which reflects the entire environment and changes its perception. To get feel with the real shape of the table, several versions are prototyped. Next step is to print it in 3D. Designer's ability to see the prototype of the table is, in fact, an extremely valuable experience, which allows you to assess the aesthetic aspect of the final set. Designer ultimately decides which of the options generated by the algorithm is aesthetic and adequate to the material form which it will be created. After all, how to save this kind of information into the parameter…?

2.2. The Pavilion

Not always and not every project requires prototyping because of its shapes. The first real project in architectural scale done by students' research group – LabDigiFab[3] took place in June 2012. At the last day of workshops organized by *projektowanieparametryczne.pl,* all participants, organizers and members of LabDigiFab built a wooden pavilion (see fig. 2, 3). Because of the lack of time to fabricate elements during the workshops, Jawor Design Studio with the cooperation of LabDigiFab members prepared project previously. I must admit that this is one of only a few examples of implementation of parametric design tools from concept stage to the final, in which I was allowed to participate.

Pavilion shell was generated using dynamic relaxation in Processing[4]. Then, the algorithm was determined to generate on the shell a structural system that will be durable with wooden plywood (20 mm thick) which we chose as a material. Any additional work related to the development of node detail, preparing for fabrication, and, what become the most important for this project, the numbering system was made in the Generative Components[5] software. Because project consisted of over

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[3] LabDigiFab - (Laboratory of Digital Fabrication) student research group founded in 2010 at the Faculty of Architecture of the Wrocław University of Technology, Poland by Przemek Jaworski, Marcin Kosicki, Mateusz Olczyk, Piotr Halczuk and Marta Pakowsk. The group's activity was focused on the promotion of parametric design tools

[4] A programming language based on Java, which was created in 1991 by Ben Fry and Casey Reas. Its purpose was to facilitate the work of graphic designers and utility designers

[5] Free program published by Bentley Systems. The plugin is installed as an addition to the Mircostation program, and its main function is the possibility of using dependent functions based on

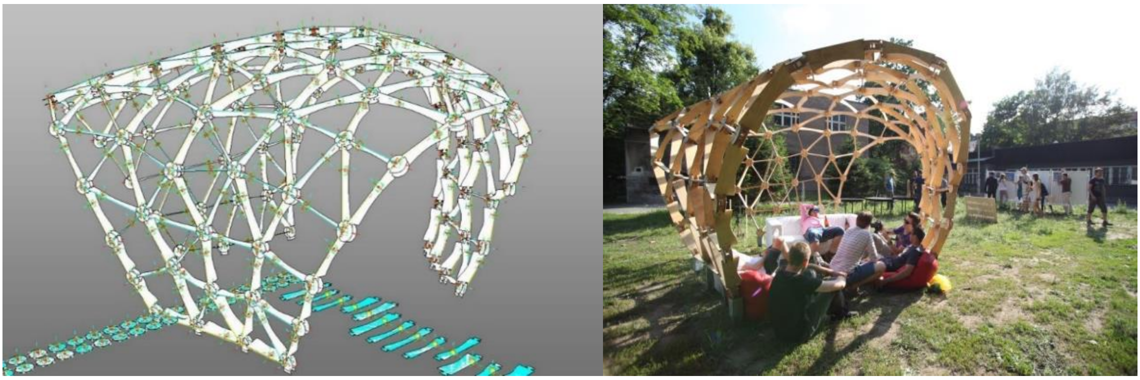

Fig. 2. (Left) View from the Generative Components program showing the preparation of the model for fabrication. (author: Przemysław Jaworski). (Right) The wooden pavilion was built in the courtyard of the architecture faculty of the Wrocław University of Technology (author: LabDigiFab)

Fig. 3. (Left) Connectors and nodes before quick impregnation (photo author: Mateusz Olczyk). (Right) Detail of node in 1:5 scale prototype (photo author: Mateusz Olczyk)

250 connectors, 100 nodes, and each element was unique and had its own specific place, we decided to test the numbering system in reality. Comprehensible numbering system opened the door for trouble-free assembly. For this purpose, a prototype was cut out in the scale of 1:5. Out of the blue, it turned out that it took 3 days for 5 people to assemble the prototype. To improve our system we decided to put additional information to the surface of the connector. We added numbers of the nodes to which it will be attached at both ends of the connectors. We also put similar information on nodes. It took 4 days to cut out the entire pavilion using CNC milling machine and… 6 hours to fold it. The new numbering system, supported by a virtual model which we could check and control assembly process in real team solved all problems.

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parameters. The program allows scripting. Due to the problems in the system department it was supplanted by the Grasshopper additive

Embarrassed by the complex geometry of the pavilion and problems arising during the assembly of the prototype, we have forgotten about material properties that was used to build the pavilion – we forgot about impregnation. All we could do at this stage was to immerse each of the elements for a few minutes, a day before assembly, in impregnate. This procedure brought surprising results. Changing external weather conditions weakened the materials and in places most exposed to shell bending forces connectors began to bend and twist – but it took two years to dismantle this structure and during this time no additional maintenance was carried out.

The team's proficiency in the use of parametric design tools made it possible to generate the entire model in virtual space. The final shapes corresponded to the initial design intentions. In the matter of assembly, we decided to trust the physical model – because the final model was designed to assemble by the workshop participants, preparing simulation of assembling pavilion in the computer was pointless.

As it turned out, using virtual tools for designing architectural objects in our research group has become more and more common. One of the members of LabDigiFab started his master's project by using a traditional tool in Revit. However, he soon realized that this BIM-kind software was a set of developed rules written by its creators and in large extent limited his creativity. He decided to change the software and this time he tried to use Grasshopper plug-in with Rhinoceros. After a short time, this also turned out to be insufficient. It did not take a few months, and young designer graduated Faculty of Architecture with a project implemented using C++. For him, it was the only tool, an alphabet of pre-used functions, that gave him enough freedom in creation. He could freely release creativity and realize his idea without any restrictions.

2.3. The didactic struggles

On the third year of doctoral studies, I conducted classes on the subject of "parametric modelling" at my home university. The group whose history I am presenting is memorable because of the high commitment and high level of creativity. The time of classes conducted with Kangaroo has come. Classes went quite well, so to check the message the group was asked to do an additional exercise. After a few minutes, I was asked to consult one of the students. A Grasshopper graph of 7-8 elements appeared to my eyes, and each of these functions in the parameter had a "random"[6] function. The effect of this treatment was totally uncontrolled. Although spectacular was incomprehensible to the author. "Machines can do everything. The law does not apply to them, and they cannot give

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[6] Function in the Grasshopper program, which allows for random generation of solutions within a given domain

shape to themselves. The form of products - through the will of the designer - is given to a person (...).

However, regardless of the environment in which we work, we should use the available options wisely. On the third year of my doctoral studies, I lead classes on the subject of parametric modelling at my home university. The group, whose history I am presenting, is memorable because of the high commitment and high level of creativity. More or less, in the middle of the semester, the time of classes with Kangaroo has come. On this day classes went quite well, so to check the knowledge the group was asked to do an additional exercise. After a few minutes, I was asked by one of the students to consult his project. His Grasshopper graph of 7-8 elements appeared to my eyes, and each of these functions in the parameter had a "random" function. The effect of this treatment was totally uncontrolled. Although the result was spectacular it was incomprehensible to the author. "Machines can do everything. The law does not apply to them, and they cannot give shape to themselves. The form of products - through the will of the designer - is given to a person (...). [7] But none of our projects would be successful if designers were not prepared to start work properly. Using parametric tools requires too precise its basic parameters. This, in turn, forces designers to collect a robust output information.

2.4. The music instrument reconstruction

Almost at the beginning of the doctoral thesis, I was asked to consult on the possibility of 3D printing of musical instruments reconstructed by musicologists from the Institute of Musicology at the University of Warsaw under the National Centre for Science (NCN)[8] grant (see fig. 4).

The main goal of the research work was to reconstruct damaged instruments, mostly wind. Musicologists would like to recreate its shapes and in the next stage sound.

One of the tested instruments is a pipe made of goose bones dated back to the 16th century. Only a fragment of the pipe, with two openings for fingers, has survived. It is not known, however, what the other part looked like. The size of the pipe can only suggest that it was a shepherd's instrument, and the identification of such instruments thanks to iconography is very difficult. The collection of the Department of Archaeology of the University of Warsaw managed to find an exemplary goose bone. The members of the research group decided to compare the shape of the pipe and the shape of the bone. It could determine the fragment from which the pipe was made. However, it turned out, that the curvature of both bones and pipe which slightly broken, it is so similar that it is not possible to visually

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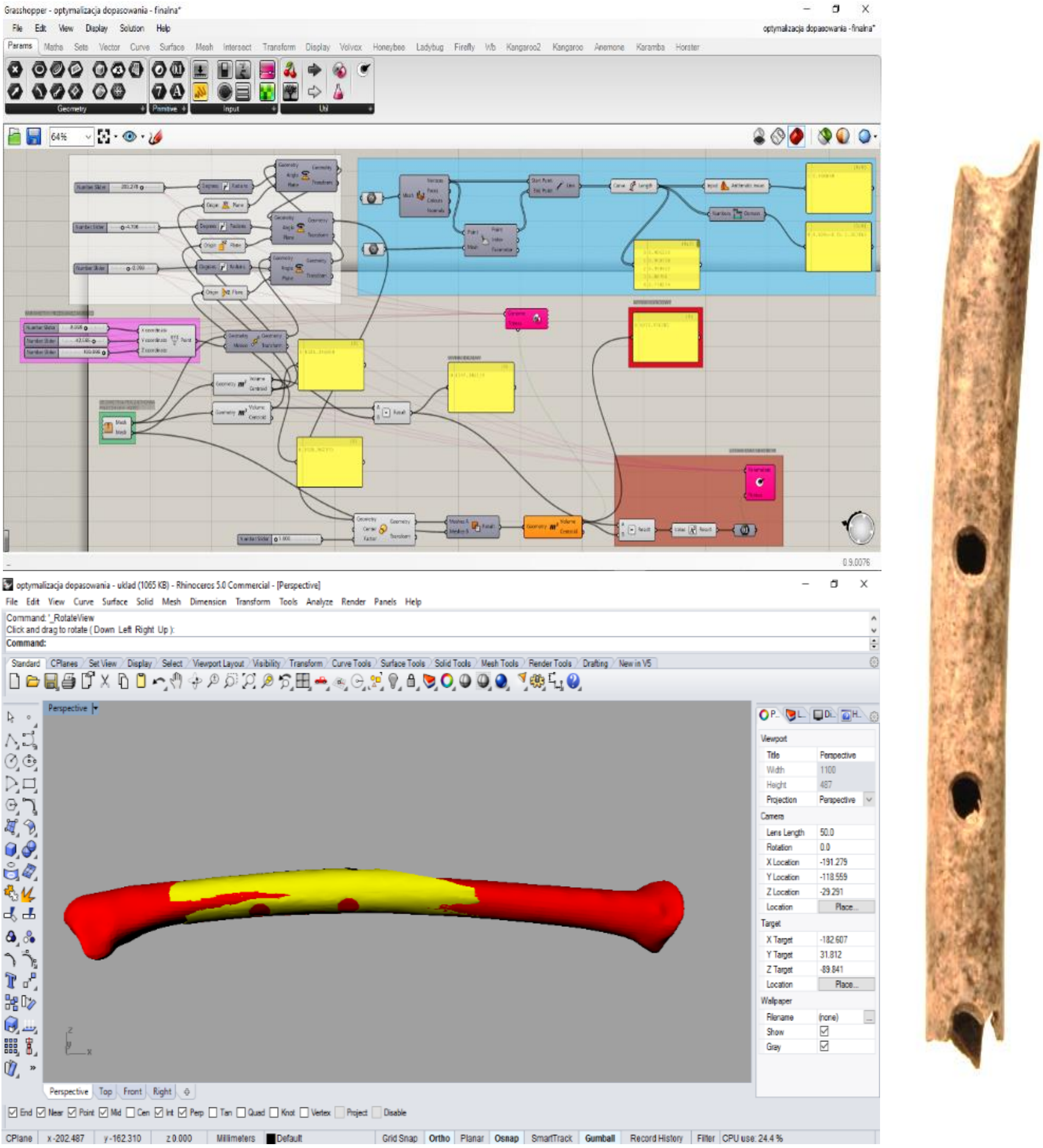
[7] Tschichold J., *Wiara i rzeczywistość*, in: *Wybór najważniejszych tekstów o dizajnie. Widzieć. Wiedzieć*, red. P. Dębowski, J. Mrowczyk, Karakter 2015

[8] Grant "Archeological musical instruments in Polish museum collections" conducted by dr hab. Anna Gruszczyńska-Ziółkowska at the Institute of Musicology at the University of Warsaw

adjust their shapes. There was no choice but to approach the reconstruction in a purely technical way.



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Viewport

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Width	1100
Height	487
Projection	Perspective

Camera

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X Location	-191.279
Y Location	-118.559
Z Location	-29.291
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Target

X Target	-182.607
Y Target	31.812
Z Target	-89.841
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Fig. 4. (Top) Graph from the Grasshopper program showing the operation of the algorithm (author: Marta Pakowska). (Down) Results for matching the surface of the pipe (yellow) and goose bones (red) (author: Marta Pakowska). (Right) A fragment of an analysed instrument made of goose bones (photo: dr hab. Anna Gruszczynska-Ziółkowska)

The 6.5 cm long pipe is too small to properly scan its surface in three dimensions using the optical scanner. That is why we have started cooperation with the Faculty of Civil Engineering at the Wrocław University of Science and Technology. Here we manage to obtain a 3D model of a pipe after scanning made by a computer microtomography. The bone itself did not contain any details or openings, which is why its surfaces were easily scanned by a NextEngine - optical scanner. Both surfaces[9] were imported into the Rhinoceros software, and next to Grasshopper. An algorithm was developed in this plugin, by examining the distance between the outer surface of the pipe and surface of the bone. Using optimization engine, software tried to move and rotate pipe surface in space to make the distance of one surface from the other was as small as possible. The SilverEye engine was used to optimize the position, which, during almost 5 hours of work, analysed about 70,000 different settings by selecting one in which the average deviation of both surfaces is 0.21 mm.

The obtained data was returned to musicologists, who are currently in the process of reconstructing the shape of the pipe, based on the obtained fit.

The close cooperation of both disciplines, more precisely modelling, scanning and 3D printing with musicologists was very important in the whole research process. Continuous exchange of information and a precise description of each operation provided both sides with data for the interpretation of results and the development of subsequent steps to the research. The knowledge provided by musicologists allowed for the appropriate selection of research technologies, the determination of initial parameters and the scope of their fields.

The second important element of this process is the use of the computing power of the computer to perform as many analyses as possible. Operation on such a small scale for humans is extremely difficult, but in the case of the algorithm, the size does not matter.

3. Summary

All these stories show that only the conscious use of parametric design tools bring positive effects and self-development. As designers, we must remember a number of other things that happen outside the computer screen - a project is not just what on paper. Parametric design, like any tool available so far, force on designers the possibility of conscious design. We are able to interfere in the project at every stage of its creation.

Maria Helenowska-Peschke in the last, but an extremely remarkable chapter of her publication "Parametric-algorithmic design of architecture", although objectively, presents a critical image of the use of a parametric design tool by contemporary designers. This chapter presents all the mistakes that parametric

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[9] The scanned surfaces have been prepared and cleaned in programs dedicated to the operation of individual scanners

designers can make. It seems, however, that the presented criticism is based only on the analysis of cases without practical participation in the design process. As a result, presented criticism is based primarily on designers' failures and aspect of the positive side with using parametric tools in a rational manner.

The author claims, inter alia, that "The parametric system for the designing of housing remains a challenge for designers". The parameter as the basis for design is one of many available tools for designers. Using it in the design process should be aware and adequate both to the skilful use of it by the designer, but also to the project itself. After all, you cannot cut the bread with a spoon.

For centuries, the experience and intuition of architects gave prestige to this profession. So let us not blindly trust in the logical connections of parameters that arouse anxiety in us. "Every creative visual work is a manifestation of the creator's character." Let's use the effective computing power of the tools available to support our creativity. "Architecture as a scientific discipline is a kind of hybrid, science contaminated with elements from different worlds. It combines opposing elements, often incompatible with each other, for example, material technology with desires resulting from human mentality (...) ". If you believe in the infallibility of algorithms, any future designer will create the same projects that will be used in the same way. So let's try to make our own choices. It will define our style and our work. It will define us, designers.

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