Inhibited Freedom

A Digital Endeavour Framed by Randomness

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2019

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Master's Thesis
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Aalto University
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Department of Design
MA degree programme in Contemporary Design

2019

Abstract

For millennia, humans have created objects using a myriad of materials, tools, and more recently, machinery. Each industrial revolution contributes to the enrichment of production techniques and adds to an already vast repertoire of materials and manufacturing methods. The creative industry continues embracing the changes, experimenting with new technology, evolving the practice, and producing novel work. During the last decades, the creative industry has almost entirely shifted, either partially or completely, from analogue to digital.

This study focuses on the creation of objects by applying digital tools across all development faces, from the form finding process to the fabrication. The process utilizes algorithms designed to generate infinite iterations of semi-controlled forms enlivened by the unexpected nature of randomness, producing a collection of objects of similar aesthetic properties while remaining individually unique in form.

Keywords:
algorithm, CNC, computation, design, digital, fabrication, furniture, generative, milling, wood

Acknowledgements

First and foremost, I would like to express my gratitude to the Design Club, a community supporting student projects in order to further develop skills, knowledge, networking, business opportunities, and overall proficiency. Their financial support made possible the development of the project as well as its exhibition at Stockholm Furniture Fair 2019.

The project received also financial support from Aalto University for the purpose of my initial research by attending the RobArch conference in Zurich, Switzerland at the beginning of 2018. The conference included the participation in a workshop titled 3D Printing on Arbitrary Surfaces, followed by presentations of recent projects from students, doctoral researchers, and professionals in the field of robotic fabrication in architecture, art, and design.

The project was mostly created in-house at the new workshops in Väre in Otaniemi, Espoo. CNC machining was guided by NC workshop master Hannu Paajanen, which I thank for his support and advice. My sincere thanks to the metal workshop masters, in special Matti Kauppinen for teaching welding skills in exchange for Spanish language lessons and Ville Arkonkoski for countless advices including metal work advices.

Last but not least, I would like to extend my gratitude to Professor Ville Kokkonen for his guidance and advices during all these years of studies and projects, as well as Lecturer Martin Relander for his support during the preparations for the Stockholm Furniture Fair. I extend my gratitude to Luka Piškorec for his advices on design and digital fabrication.

Content

Introduction

Manufacturing methods have recently encountered a digital overhaul that has shifted production from analogue and mechanical operations into digitally controlled processes. As these technologies are relatively new in comparison to more traditional methods, it requires research, experimentation, and analysis in order to understand their full potential and its possible applications.

Digital manufacturing can be divided into additive and subtractive manufacturing. These fabrication methods do not require molds or templates, therefore product identicality is not a requirement. In other words, the production of replicas does not necessarily bring production costs down; instead, each component fabricated can in theory have its own individual geometry at approximately the same cost per piece. Consequently, the creation of variation is a concept open for exploration and consideration in the design process of the future. As an example, printing one hundred copies of a photograph has the exact same cost as printing one hundred different photographs. This concept is shared by additive manufacturing technologies and might translate partly or entirely to subtractive manufacturing technologies in the near future.

This study explores the creation of objects within a fully digital environment, from the creation of a digital form to the fabrication of a tangible object. The process takes place in a system of rules and boundaries programmed by the designer based on initial aesthetical and technical requirements; a computer then generates solutions considering the established boundaries and rules of interaction. As a result, the human-computer collaboration creates an endless collection of objects that share similar features but remain unique and individual.

Part I

The Research

The Research

As a start, and as a time reference, it is relevant to talk about early human creations. Since the very early times, humans have taken locally available materials and transformed them in order to improve their lives and increase comfort. A 60,000-year-old arrowhead found in modern-day Armenia, chiselled from locally available flint and attached with bone marrow to a wooden shaft, is the oldest arrowhead ever discovered. In order to create such a tool, a complete design process was considered: first, the visualization of a possible solution; next, envisioning the steps required to adequately shape the materials; then, collecting suitable materials from the surroundings and finally, shaping the materials followed by testing and possible changes in the design. After all these steps, a working tool was created from an intangible idea to a purposeful tangible object. This, in basic terms, is the essence of making. The first musical instrument was created 42,000 years ago, the first ceremonial masks 9,000 years ago, and leather shoes where made 5,500 years ago. As makers improved their techniques, developed better tools, and collaborated with other makers, they were able to create objects that ultimately served all human needs such as protection, shelter, food, and clothing. [1]

Computer-Aided Design

Today, some objects are more industrialized than others. A hand-carved bowl passes through

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[1] T. Wujec, The Future of Making: Understanding the Forces Shaping How and What We Create, Autodesk, Melcher Media, 2017, pp. 29-30.

only few people's hands; these objects are commonly seen as authentic and simple, and their craftsmanship is appreciated. Industrialized products require other tools and techniques in order to be manufactured. French engineer Pierre Bezier created the first commercial Computer-Aided Design (CAD) system in 1966. The system could handle simple shapes like lines, arcs, circles, rectangles and basis splines or B-splines. The combination of these elements became complex schematic diagrams of parts, objects, and assemblies. Two decades later a third-dimension was introduced to CAD systems. Two dimensional diagrams became three dimensional representations of physical objects. This led the integration of CAD software to the fields of engineering, architecture, construction, and manufacturing. [2]

Digital Fabrication

John Parson developed during the 1940s – 1950s a device called Numerically Controlled (NC) used for the construction of aircraft wings. NC eventually became CNC once a computer was introduced to the process.[3] By definition, digital fabrication is the manufacturing process controlled by a computer. It can be divided into two key areas: additive manufacturing and subtractive manufacturing. As its name suggests, additive manufacturing is the process of adding material layer by layer, and it is more commonly known as 3D printing. In contrast, subtractive manufacturing removes material from a solid block. A third key area can be called robotic manipulation, where other digital manufacturing methods are included such as bending, stacking, forming, weaving, and others. In essence, these methods are nothing new. In fact, they have existed for millennia. Laying bricks to construct a wall is a form of additive manufacturing; in the other hand, carving and chiselling are a form of subtractive manufacturing. Digital fabrication can be seen as analogue manufacturing controlled by digital means. Control is one key difference between traditional fabrication and digital fabrication, thus the term Computer Numerically Controlled (CNC) is often used to describe digital fabrication. Digital control has greatly improved accuracy and precision in fabrication; other potential benefits include speed, cost, and safety, but these are relative to the context. Installation and programming of digital tools can be time consuming, installing adequate environment surrounding the robot can be expensive, and robots can also cause injuries under certain circumstances. Robots are, by no means, the perfect tool either. [4]

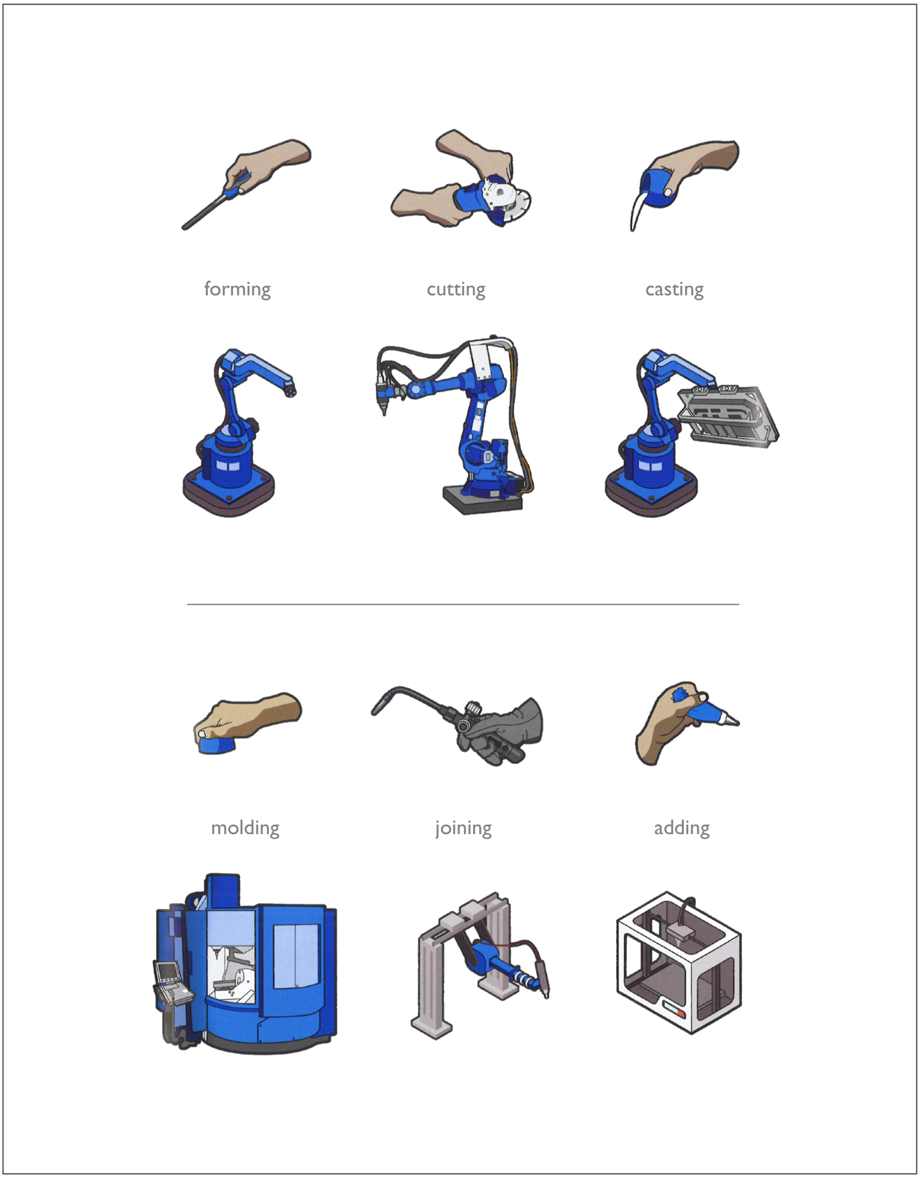

Fig. 1 Six basic ways of material manipulation. Hand tools and power tools find digital counterparts that provide increased accuracy and repeatability.

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[2] Wujec, The Future of Making, p. 91.

[3] P. F. Yuan, A. Menges, N. Leach, Digital Fabrication, Tongji University Press, 2017, p 21.

[4] Yuan, Menges, Leach, Digital Fabrication, pp. 13-14.

Objects are created by a combination of six actions: forming, machining, joining, casting, moulding, and adding. These methods transform and shape materials into objects. Robots have already been adapted to perform these six methods (Fig. 1). The automated machines translate digital data into instructions, and these instructions become machine movements that create physical parts.[5] It is unclear whether the term digital fabrication will be used in the future. When most of the things become digital, digital does not mean much anymore. When Computer Aided Design (CAD) was introduced, the term drawing was still referred to drawings made by hand, and CAD drawings where called computer drawings. As time passed, hand drawings took over computer drawings, this made computer drawings became just drawings while drawings produced by hands became hand drawings. Based on this shift of names and the overtaking of hand-made drawings by computer-made drawings, we might soon refer to digital tools simply as tools, and digital fabrication as fabrication. [6]

Subtractive manufacturing techniques can be as data rich as one wants them to be, but in the absence of a signal, the result is a plain and solid block of material. On the contrary, additive technologies print each voxel individually, and in the absence of a signal, this fabrication method delivers nothing but an empty space. As 3D printing does not involve molds or dies, there is no need nor incentive to make voxel-generated volumes identical to one another regardless of its size. In contrast, mechanical printing technologies are based on matrixes and therefore must be used as many times as possible to lower the costs. In a digital context, we can laser print one hundred different pages or one hundred identical copies of the same page at the same unit cost, and that also translates to 3D printing as we can print any given volume at the same volumetric cost regardless of them being unique in form or identical copies. All these advantages brought by digital design and fabrication have remarkable consequences. For example, in 2013 Michael Hansmeyer and Benjamin Dillenburger created a grotto named *Digital Grotesque* (Fig. 6-7). Commonly, one would believe the structure was created in the subtractive way, that is, removing material from a block. But in reality, it was created by additive manufacturing laying and bonding dust layer by layer. As a result, and as weird as it might sound, the intricately detailed grotto we see was faster and cheaper to make than a plain full block of its size. If a full block was printed, more material would have been consumed and more printing time would have been required resulting in increased costs. The result is counterintuitive as we tend to think that ornament and detail is a synonym of higher spendings, but in the case of the digitally fabricated grotto, ornament and detail is in fact cheaper.[7] In the age of digital design and 3D printing, decoration is no longer an addition and ornament is no longer and added expense.[8]

Mass Customization

During the late 1980s, technologists and economists started discussing the concept of mass customization. At that time, the discussions focused on product differentiation in small batch productions and low volume manufacturing including a multiple choice strategy. As a result, the market would offer a broader choice without abandoning the technical logic of the economy of scale. One decade later, the first generation of digitally intelligent designers proposed that digital design and fabrication should not be utilized to emulate mechanical mass production, instead these tools should be used to do something that industrial assembly lines could not do. As digital fabrication does not use molds, mechanical matrixes, stamps nor dies, there is no need to replicate the object multiple times to amortize the costs. In other words, creating digital copies of the same item will not lower the costs and, the other way around, each digitally fabricated object can be different without increasing the production costs. Consequently, digital design and fabrication is therefore synonym of the mass production of variations. Digital mass customization is one of the most revolutionary ideas ever invented by the design profession and is going to transform, and has already began to transform, the way we design, produce, and consume almost everything.[9] Already in the 1990s, we learned that mass customization in a digital environment could create economies of production without the need for scale.[10]

"Any parametric notation contains by definition an infinite number of variations" [11]

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[5] Wujec, The Future of Making, p. 147.

[6] Yuan, Menges, Leach, Digital Fabrication, p. 21.

[7] M. Carpo, The Second Digital Turn: Design Beyond Intelligence, Cambridge, Massachusetts, MIT Press, 2017, pp. 75-77.

[8] Carpo, The Second Digital Turn, p. 79.

[9] Carpo, The Second Digital Turn, pp. 3-4.

[10] Carpo, The Second Digital Turn, p. 6.

[11] Carpo, The Second Digital Turn, p. 131.

Generative Design

Mass customization require specialized digital tools that enable similarity and variety across a range of digitally fabricated objects. Generative design facilitates the creation of a system that ultimately generates models by following an established procedure resulting in endless number of variations of the same core logic. As explained by Wujec in his book *The Future of Making*, "Generative Design allows computers to explore solutions in creative partnership with designers." He continues, "Generative Design can allow designers to create, and in some cases discover, designs that would never have occurred to them otherwise." Adding "Generative Design gives designers a new workflow for ideas and creation, a workflow that supports the capture, compute, create flow essential to the future of making. A designer begins with the objectives—the goals and rules that guide the computer's work. The solutions produced can be data or a design or model. Algorithms help explore the thousands or millions of solutions for the most promising. The digital model can then be fabricated with tools such as 3D printers." [12]

"Your smartphone contains more computational power than all of NASA had available when it sent astronauts to the moon." [13]

Algorithm

An algorithm is a set of procedures consisting of a finite number of rules, which define a succession of operations for the solution of a given problem.[14] Algorithms have been implemented in architectural design to facilitate space allocation and city planning. Nevertheless, the implementation of algorithms in aesthetics and formal theories has been mostly limited. The logic behind algorithms involves rationality, consistency, coherency, organization, and systematization. The creative fields have maintained an ethos of creative sensibility and intuitive playfulness; in contrast, algorithms are perceived as non-human creations and therefore distant and remote. This perception poses a certain challenge for the application of algorithms in the creative field. Traditionally, architecture has always been based on intuition and talent, where an individual or a group of individuals discuss stylistic ideas and create an executive plan. In contrast, the procedural nature of an algorithm is not necessarily credited to its creator. An algorithm is not about the person who invented it but rather about its efficiency and speed.

Consequently, the application of algorithms is taken with suspicion by some and believed to overlook human sensitivity and creativity. Algorithms are not the end product, bur rather a vehicle for exploration.[15] Algorithmic design makes use of programs to generate space and form from a rule-based logic. By using custom made programs, designers can go beyond the mouse and remove the limitations of commercial software.

"As computation grows more powerful and accessible, algorithms will be trained to participate in every aspect of making." [16]

Identicality vs. Variability

Identicality is a well established practice that we expect to encounter in the products that surround us. The power of identicality arose at the beginning of the Modern Age; identicality was a cultural ambition of the Renaissance humanists. Identicality also became the by-product of mechanical technologies, which still remains nowadays.[17] Three occurrences of identical reproducibility have shaped Western architectural history since the rise of Renaissance humanism at the beginning of the Early Modern Age in the 16th century: the identical translation of design notations into physical buildings; the identical transmission of architectural information through space and time; and the identical fabrication and the pursuit of economies of scale that brought as a consequence mass production and standardization. During the industrial revolution in the nineteenth and twentieth century, mass production grew exponentially and can be seen as a continuation and extension of the cultural and technical trend that started with the printing press, a process that made people used to have everything the same shape.[18]
As an example of identicality and its power in our current society, we can refer to banknotes amongst other examples; a banknote that is not identical to other banknotes of the same series,

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[12] Wujec, The Future of Making, pp. 121-123.

[13] Wujec, The Future of Making, p. 87.

[14] A. Menges, S. Ahlquist, Computational Design Thinking, John Wiley & Sons Ltd, 2011, p. 11.

[15] Menges, Ahlquist, Computational Design Thinking, pp. 94-96.

[16] Wujec, The Future of Making, p. 139.

[17] M. Carpo, The Alphabet and the Algorithm, Cambridge, Massachusetts, MIT Press, 2011, p. 44.

[18] Carpo, The Alphabet and the Algorithm, p. 81.

is considered fake or worthless. We have learned to reject banknotes based on identicality, as they might be counterfeit and therefore worthless. Before the era of banknotes, the same rules of identification were followed. Coins and seals had to be identical, otherwise it was unreliable.[19]

At the same time, some instances follow the exact contrary philosophy; checks for example, their validity rely on a handmade signature of the payer. Like all handmade things, a signature is a visually variable sign, therefore all signatures made by the same person will have slight variations but at the same time they have to be more less similar, otherwise it could not be identified. Recognition in this case is based on similarity, not in sameness. During the handmade era, imitation and visual similarity used to be the norm; during the machine-made era, replication and visual identicality are almost compulsory properties. The digital era is now rapidly overtaking the mechanical era, and visual identicality is starting to become irrelevant. The validity of credit cards, for example, relies almost exclusively by a series of sixteen digits, regardless of the shape, colour, or material of the card. Visual identification is now becoming obsolete. These three monetary examples picture the paradigms of visual identification and their relation to the methods used to create them. When objects are handmade, subtle variations in the production process create differences and similarities amongst copies, therefore the objects are identified by visual resemblance; machine-made objects, or mass-production, generate standardized products, and therefore identification is based on visual identicality. When objects are created by digital means, identification is based on recognition of hidden patterns, computational algorithms, or other similar non visual features. [20]

"The passage from mechanically made identical copies to digitally generated differential variations is happening now." [21]

Mechanical vs. Digital

Industrial mass production commonly relies on mechanical matrices, moulds, or templates of which the upfront cost had to be balanced by reusing them as much as possible. In contrast, digital fabrication can produce variations without any extra costs. As Mario Carpo explains in his book *The Alphabet and the Algorithm*: "In a digital production process, standardization is no longer a money-saver. Likewise, customization is no longer a money-waster."

The vertical integration of digital design and digital manufacturing, and the technical continuity between digital tools for visualization, notation, and fabrication, imply the elimination of most mechanical matrices from the production process. That will spell the end of many basic principles of industrial economics. In the mechanical world, once a matrix is made, its cost must be amortized by using it as many times as possible. The economies of scale resulting from mass production are proportional to the number of identical copies that are obtained from the same mould: in mathematical terms, if the number of identical copies is infinite, the unit cost of the matrix is zero. The more you print, the less you pay per copy. Digital printing, however, does not work that way. A laser printer can print one hundred identical copies of the same page, or one hundred different pages, at the same cost per page.[22]

A non-standard series is defined not by its relation to the visual form of any constituent item, but by the variances, or differentials, between all sequential items in the series. A non-standard series is a set in which each item has something in common with all others. In technical terms, all objects in a non standard series share algorithms, as well as the machines that were used to process those algorithms and to produce the objects themselves. Algorithms, software, hardware, and digital manufacturing tools are the new standards that determine not only the general aspect of all objects in a non-standard series, but also the aspects of each individual product, which may change randomly or by design. [23] All items in a non-standard series hence share the same style. [24]

Most mechanically reproduced objects and forms are unmediated indices of the imprint that made them; most handmade works of the pre-mechanical age, as well as most algorithmically generated items of the digital age, are not. In the new world of algorithmic, or differential, reproducibility, visual sameness is replaced by similarity. [25]

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[19] Carpo, The Alphabet and the Algorithm, pp. 2-3.

[20] Carpo, The Alphabet and the Algorithm, p. 7.

[21] Carpo, The Alphabet and the Algorithm, p. 11.

[22] Carpo, The Alphabet and the Algorithm, pp. 98-99.

[23] Carpo, The Alphabet and the Algorithm, p. 9.

[24] Carpo, The Alphabet and the Algorithm, p. 100.

[25] Carpo, The Alphabet and the Algorithm, p. 101.

“Variability can now become part of an automated design and production chain” [26]

4th Industrial Revolution

A combination of technologies like sensors, robotics, and algorithms are creating the fourth industrial revolution offering high production speed, low cost, broad access, fine precision, and interconnectivity. Technology changes how we make things and who creates them. We are entering this revolution much faster than previous revolutions. It will have an impact in every industry that creates things and touch every person involved in the process. This profound change is due to the proliferation of one thing: the transistor. In 2017, we produced more transistors than grains of rice, and at a lower cost. A smartphone, for example, has around 1.5 billion transistors. Silicon dioxide enables transistors to store and route electrical charge in controlled patterns, enabling the capacity to capture, manipulate, and share data: this translates to the computable world of bits. The fourth industrial revolution is proving to be more disruptive than previous industrial shifts. It has enabled to work on a problem within a digital system in our computers rather than in the physical world. The music industry, for example, was severely disrupted by digitalization. All of a sudden, music became digitized, searchable, and shareable. Vinyl records and Compact Discs became obsolete while online music platforms became the new norm. This same pattern has been seen in different fields: photography, books, advertisement, financial market, and many others. The shift happens slowly at first, but as computer start building faster computers and people get access to more computing power at lower costs, the change start growing exponentially. [27]

RobArch Conference

As part of the initial research as well as to initiate the thesis project, the student participated in the RobArch conference in Zurich in 2018. The annually-held conference focuses on robotic fabrication in the field of architecture, art, and design. Previous to the conference, several workshops are held where participants can get acquainted to different technologies and develop certain skills. In this case, the student took part in a workshop called 3D Printing on Arbitrary Surfaces. The exercise introduced the process of extrusion-based robotic fabrication on curved surfaces. Commonly, deposition or extrusion techniques start with a simple and regular flat surface; in this exercise, an irregular surface was first scanned in order to digitally register the topography, then a previously selected pattern was digitally mapped to the scanned surface, and finally printed on the irregular surface. Each participant had the opportunity to design its own geometry to be printed on a custom substrate. All printed substrates together formed a continuous collection of visually similar and geometrically unique modules.

Existing Projects

Referenced projects have also been studied and analysed to further understand the possible applications of these digital design and fabrication techniques. Some of the projects that heavily inspired this study are:

Digital processes:

- Tables Projectives (2003) by Bernard Cache.

- Breeding Tables (2003) by Clemens Weisshaar and Reed Kram. Structures for tables are generated by a custom algorithm that breeds its geometry according to certain parameters and technical restrictions (Fig. 4).

- Bone Chair (2006) by Joris Laarman.

- Zhang Zhoujie Digital Lab's entire work on digitally made furniture (Fig. 3).

- Aluminum Bench (2015) by Jonathan Olivares. The parametric model enables the instant creation of limitless versions of the same bench.

- Digital Grotesque (2013 and 2017) by Michael Hansmeyer and Benjamin Dillenburger (Fig. 6).

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[26] Carpo, The Alphabet and the Algorithm, p. 7.

[27] Wujec, The Future of Making, pp. 30-32.

Non-digital processes:

- Swiss sculptor Jean Tinguely’s machines. Random movements create singular paintings; all creations from the same machine look similar but remain unique (Fig. 2).

- Dutch furniture designer Maarten Baas. The Clay Furniture collection feature small variations between items of the same series making each piece of furniture unique.

- British sculptor Antony Gormley and his collectively created series of sculptures, for example his work titled Field for the British Isles (Fig. 10).

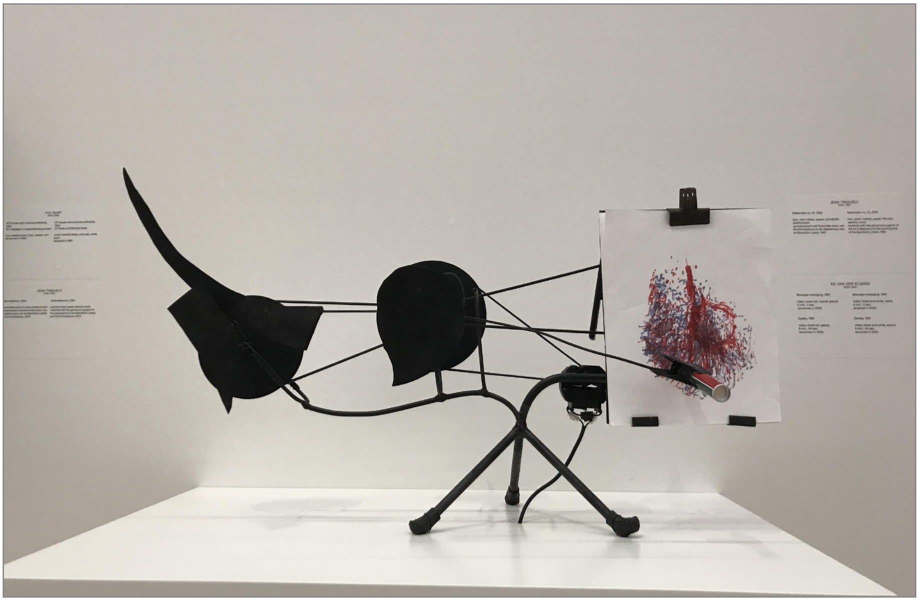

Fig. 2 Stedelijk Museum, Amsterdam, October 2018. Jean Tinguely’s machines create drawings by arbitrary movements. Each creation contributes to a collection of similar but individually unique drawings.

Fig. 3 Digitally generated furniture by Zhang Zhoujie Digital Lab. Having the chance to interview the designer during the lectures given at Aalto University by Tongji University in September 2018, he argued that the creation of individuality within his collection is for the sake of diversity; in a fully digital environment, replicating prototypes is an obsolete concept. He also mentioned sketching is not a common practice in his studio as they do not focus on the aesthetics of the objects, but rather on a generative system and fabrication methodologies.

Fig. 4 *Breeding Tables* (2003) by Clemens Weisshaar and Reed Kram. From form finding to fabrication, the seamless digital system creates strictly individual forms across all iterations.

Fig. 5 King Ludwig II Of Bavaria commissioned the interiors of palaces at Linderhof and Herrenchiemsee during the late 1870s and early 1880s. Most of the pieces at Linderhof were designed by Adolf Seder and supplied by the firm Possenbacher in Munich. Large amount of ornament decorate furniture, walls, floor, and ceiling.

Fig. 6 *Digital Grotesque II* (2017) by Michael Hansmeyer and Benjamin Dillenburger. The spatial installation features digitally created ornament. Due to the nature of additive manufacturing, ornamentation does not add additional costs to the fabrication process.

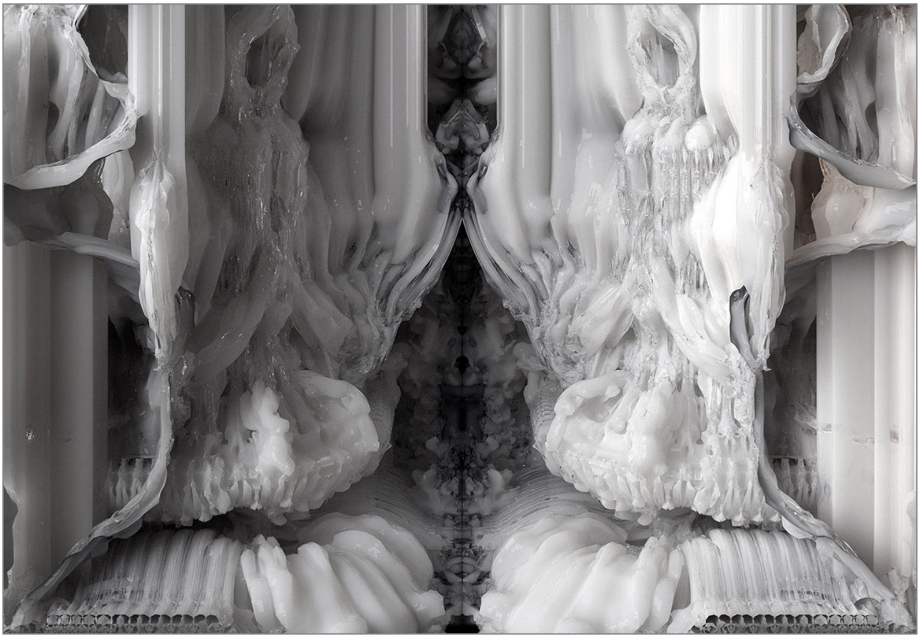

Fig. 7 Detail of *Digital Grotesque I* (2013) showcases the vast amount of ornamentation.

Fig. 8 Illustration by Cesare Leonardi. Each Individual leaf of each individual tree enjoys its own sense of individuality; an endless amount of variation is created by nature.

Fig. 9 *Nias Islanders* by J.P. Kleiweg de Zwaan. Seven and a half billion humans inhabit planet Earth; each individual person is unique. An endless amount of variation is created by nature.

Fig. 10 *Field for the British Isles* by British sculptor Antony Gormley. Thousands of clay sculptures were formed by hand; each sculpture enjoys a sense of individuality and uniqueness. An endless amount of variation can be created by hand-crafting.

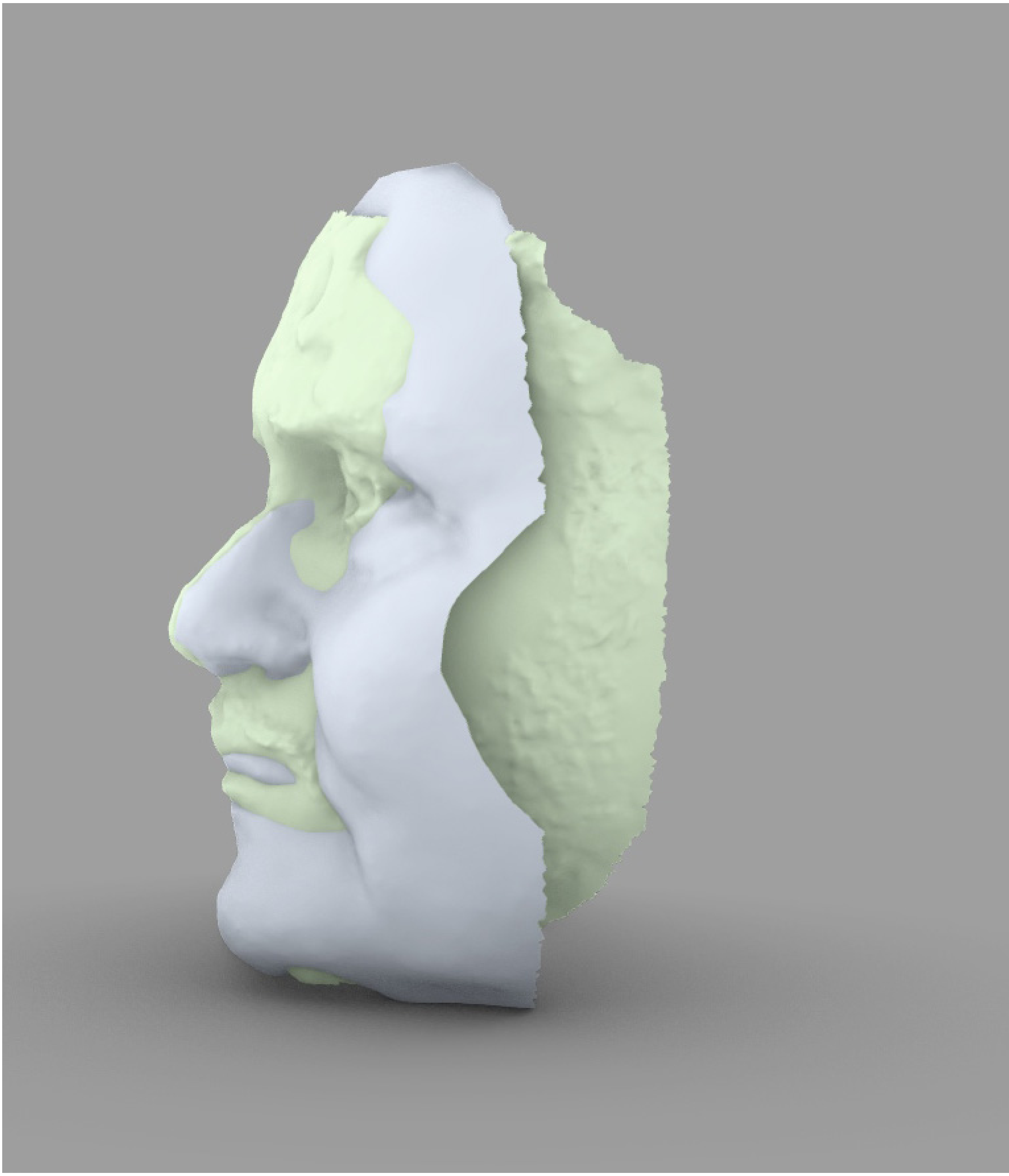

Fig. 11 Even individuals from the same family feature unique characteristics. The image shows a 3D scan of two members of the same biological family.

Fig. 12 Hand-making naturally involves variation and individuality. In most cases, handwriting creates a range of unique hieroglyphs with subtle variations between them.

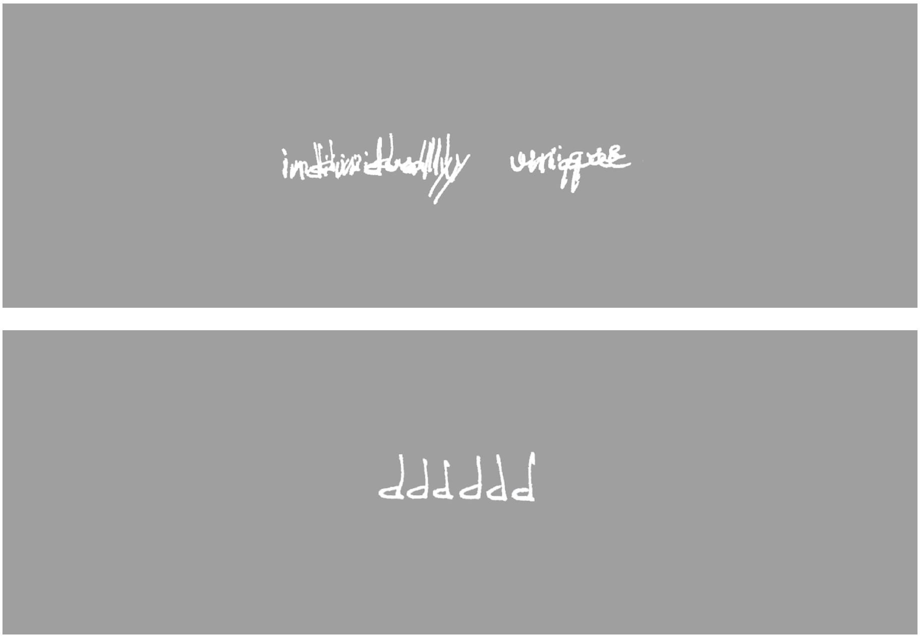

Fig. 13 and 14 Variation between letters written by the same person are clearly visible.

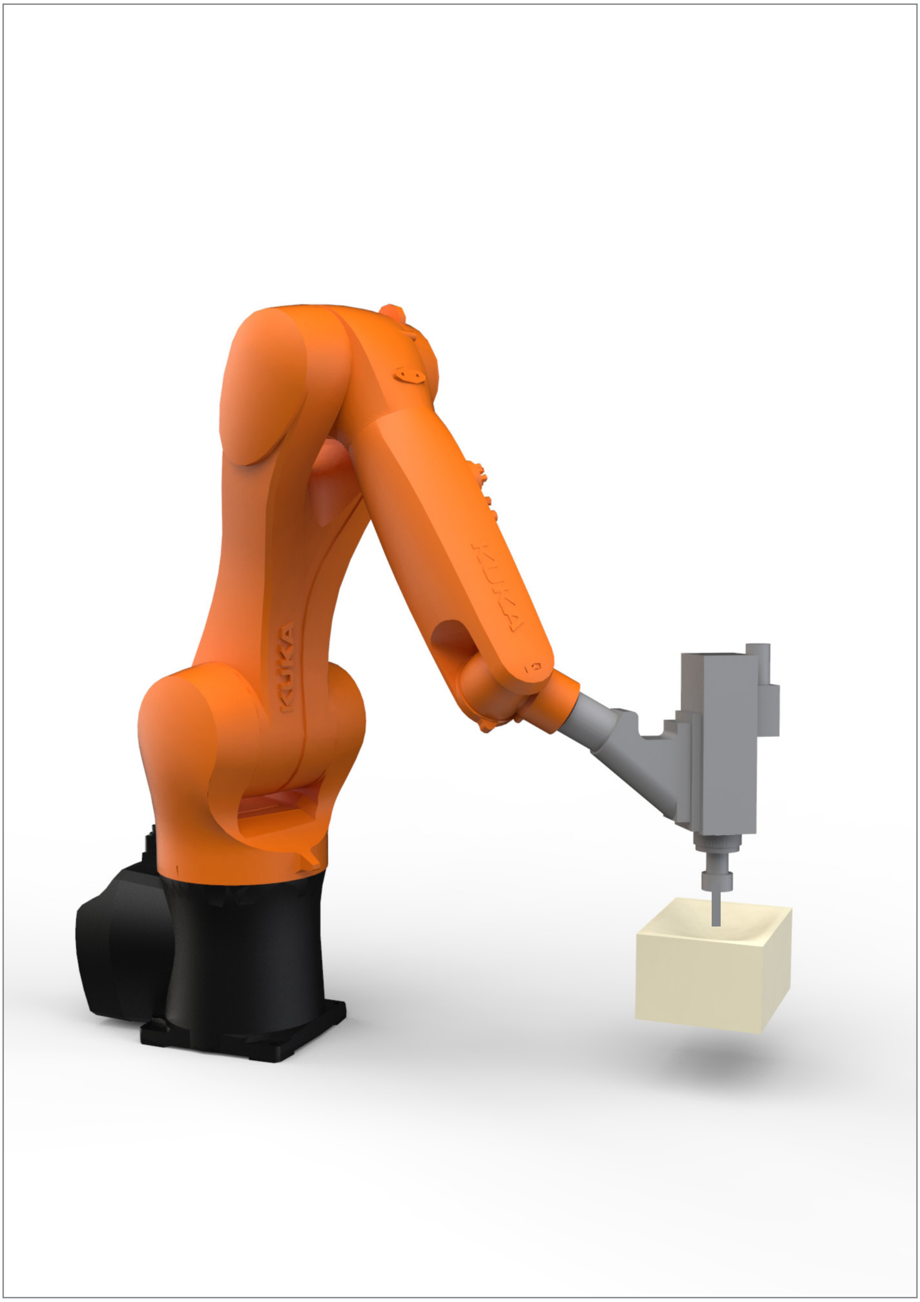

Fig. 15 Machine movement simulation with KUKA|prc plug-in for Grasshopper. Before milling starts, a simulation is usually performed in order to anticipate collisions or unwanted results and avoid possible damages to the material and the machine.

Fig. 16 Early testing of KUKA|prc plug-in for Grasshopper at Aalto University Digital Design Laboratory. A robotic arm mills a block of Laminated Veneer Lumber (LVL). A seamless digital process was achieved, from geometry generation to fabrication, all within one software. The exercise proves that the process studied in the thesis is technically viable.

Fig. 17 Robotic arm used during the RobArch workshops in Zurich 2018. The arm was retrofitted with a custom device for controlled clay extrusion.

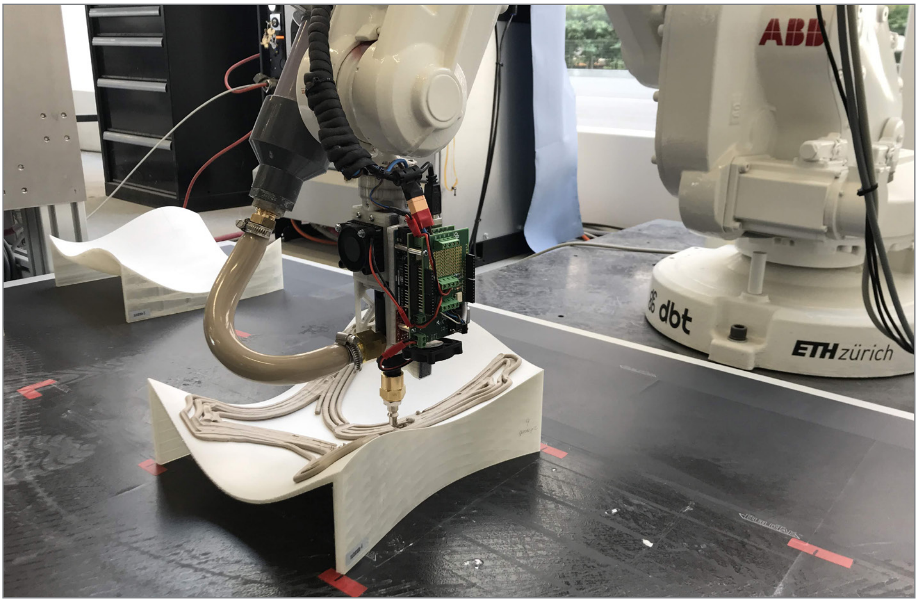

Fig. 18 The modular base consisted of a double curvature surface divided into equally spaced blocks. Each block was the base for a different pattern of material deposition.

Fig. 19 Robotic clay deposition results.

Part II

The Process

The Process

Referring to the digital creation process, Gramazio and Kohler cited in the book *Digital Materiality in Architecture* "the designer is directly involved in programming the algorithm as well as fabricating the object. We are no longer designing the form that will ultimately be produced, but the production process itself. Design and execution are no longer phases in a temporal sequence--design sketches do not need to be converted into execution drawings anymore. The design incorporates the idea and knowledge of its production already at its moment of conception. In turn, the understanding of construction as an integral part of architectural design takes on greater significance". [28]

This thesis project shares the ideology of the previous citation; an algorithm is designed to generate the form rather than designing the final form itself. Additionally, a fabrication method is already selected at the very beginning of the process allowing the seamless transition from intangible digital model to a tangible physical object.

The study applies an all-digital process for the creation of a series of physical objects by developing a core algorithm that breeds objects of similar characteristics while remaining unique in form. The project looks at fully embracing digitality as an active tool in design development.

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[28] F. Gramazio, M. Kohler, Digital Materiality in Architecture, Lars Müller Publishers, 2008, p. 8.

The purpose of this study is not to pursue the creation of a piece of furniture for the current established market. The purpose is rather to study a possible future scenario where objects are created using alternative methods of design and production. Whether this scenario is ever going to be met remains to be seen in the future.

Commonly, a designer would start the creation process by researching necessary background information followed by sketching of initial ideas and the creation of a scale model in order to materialize initial ideas. A full-scale model is possibly created and further design changes considered. The process is by no means a rule, and each individual designer creates objects by its own methods and creative processes.

The process studied in this project suggests the final form not to be dictated by the designer. Instead, the designer sets a list of rules and boundaries that the computer will then follow adding arbitrary values to the formula (see process in Figures 29-36). These arbitrary values will generate variation on each singular iteration. The variation creates a collection of individually unique objects, meaning no replicas would ever exist within the collection regardless of the amount of iterations. Contrary to current industrial-made objects, nature seems to follow a clear form-creation principle: no replicas. Figure 9 shows a clear representation of this fact: 7.4 billion humans inhabit planet earth, none of which are replicas.

In practical terms, the first step in the process required a production method to be chosen before starting the ideation of algorithms. The digital fabrication method was chosen based on availability, costs, and other technical considerations. Additive manufacturing was considered but accessibility and high costs in the scale required in this project restricted their use. Alternatively, subtractive manufacturing would allow the utilization of wood, a material commonly used in the furniture industry due to its suitable properties and natural qualities. Therefore, CNC milling was chosen as the main fabrication technique as it was accessible and suitable for the scale needed and the material chosen. Nevertheless, the project was not able to enjoy full free hands in terms of fully developing the programming of the milling machine. Certain safety and practical protocols have to be followed, limiting the possibility of bypassing the machine's toolpath programming software. For this matter, the study relies on talks and interviews to professionals in the industry, from the perspective of a machinist and from the point of view of an architect specialized in the practice of digitality and algorithm aided design. These opinions are important in order to assess the potential of the project in practical and realistic terms.

Once the machinery was selected, initial algorithm logics where sketched. Growth and movement where important requirements for an initial idea selection. The growth and development of the form shows the philosophy behind the design process and how it seamlessly transforms from an initial volume to a fully grown object. The movement was also considered important as it engages the viewer and increases curiosity towards the project. These aspects of growth, development and movement are inspired by time-lapse videos of plants and flowers growing in what appears to be a fast pace; in reality, the movement is not visible to the naked eye, but when observed in a time-lapse format, the movement is evident, captivating, engaging, and beautiful. These aspects were considered important to include in the project as the nature of the digital generative process studied in this project allowed their seamless inclusion.

Considering that, several algorithms were developed and tested (Figures 20-27). Perhaps ergonomics and usability became secondary at this stage. Priority was given to a visually appealing experience rather than a comfortable seat for extended period of time. During the process, it turned more evident the fact that the design approach prioritized the object as an experiment rather than an object for comfortable seating.

Initial ideas ranged from simple flowing forms to intricate geometries. The visual properties of the forms seen in Figures 20 to 23 do not necessarily show the application of any computational tools. In contrast, Figures 24 to 27 shows an evident application of computation for its form finding process.

The initial concepts seemed to have two clear distinctions; either an aesthetic of evident use of computation or an aesthetic of less visual complexity. In one hand, less complexity would translate to easier fabrication and increased visual neutrality. In the other hand, a more complex form would be directly related to the computational tools utilized in the process. A decision was made based on the nature of the project which goal was to freely experiment, learn, and analyse the process and its possibilities.

Fig. 20 Unadorned flowing forms were initially studied.

Fig. 21 Curved surfaces and simplicity characterised first ideas.

Fig. 22 The form adapts to structural requirements creating a simple and continuous seat.

Fig. 23 Experimentation with different generative systems.

Fig. 24 Explorations on the so-called reaction-diffusion system.

Fig. 25 Form mostly created by arbitrary values.

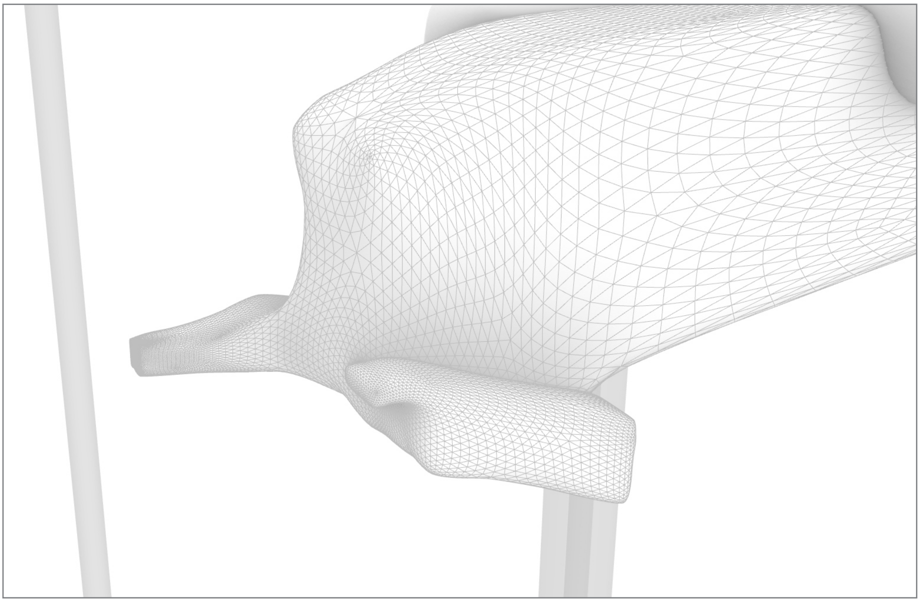


Fig. 26 Study of volumetric ornamentation. The same form behaviour is followed in both the main form and in the details.

Fig. 27 Concept featuring intricate forms and flowing continuity. This concept was selected for further development due to its unusual aesthetics as well as an evident use of computation.

Once an initial concept was selected for further development, the algorithm was improved, debugged, and tested. Each improvement considered the properties and restrictions of the selected material and fabrication technique. For example, the form was optimized for 3-axis machining. This optimization has two purposes: a 3-axis CNC machine costs less than a 5-axis, meaning the machining of the object would have a lower manufacturing cost; and secondly, programming tool paths in 3-axis is less complex than 5-axis reducing the overall time of the technical-intensive tool path programming.

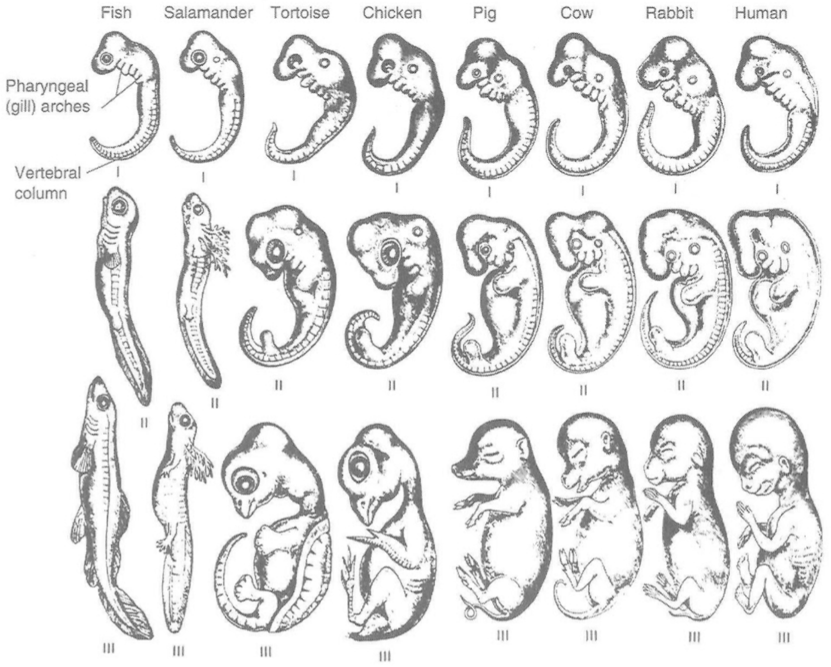


Fig. 28 Fetus development of different living beings. At early stages, very little differences can be seen across the examples. As the fetus develops and grows, differences become more evident.

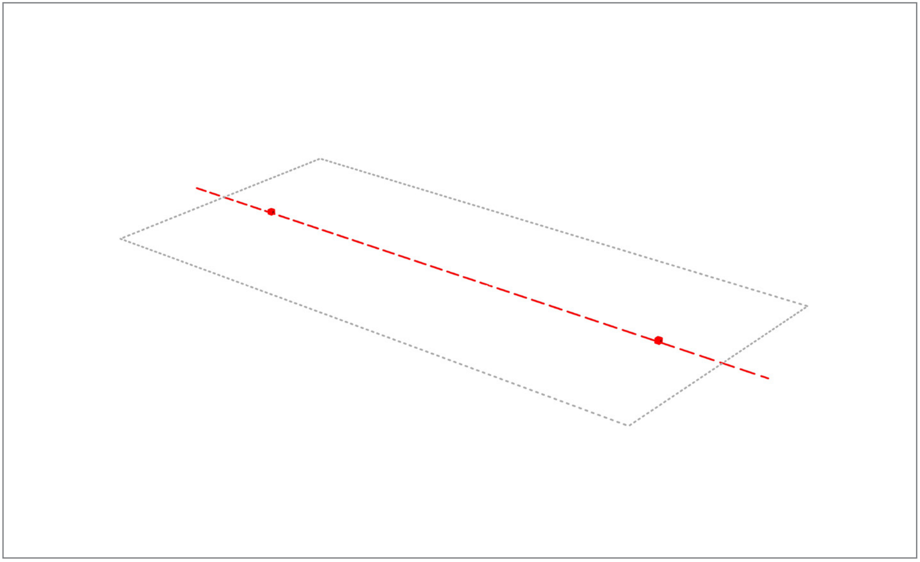


Fig. 29 **Step 1** Certain requirements and constrains are initially programmed. In this case, a boundary rectangle, a cross beam, and two connection points for the structure are the features that remain constant across all iterations.

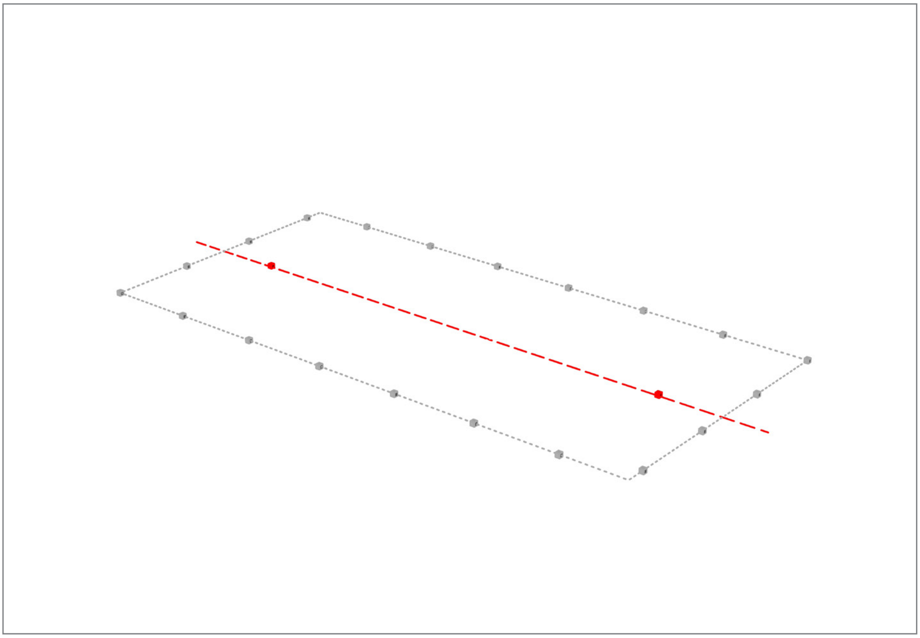


Fig. 30 **Step 2** The boundary rectangle is divided into equally spaced sections.

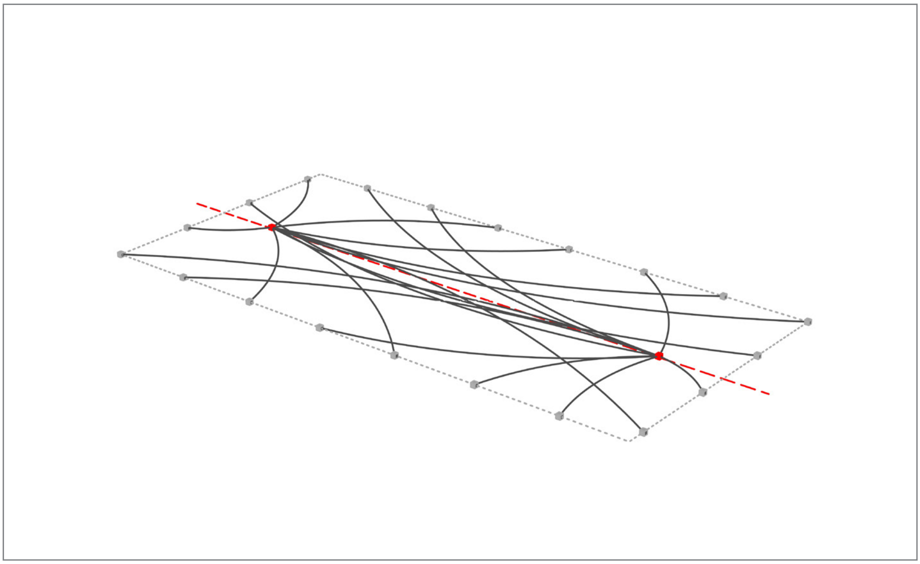


Fig. 31 **Step 3** Curves are created starting from the structural connection points and ending at the divisions of the boundary rectangle. This feature is randomized and creates the main visual characteristics of each individual iteration.

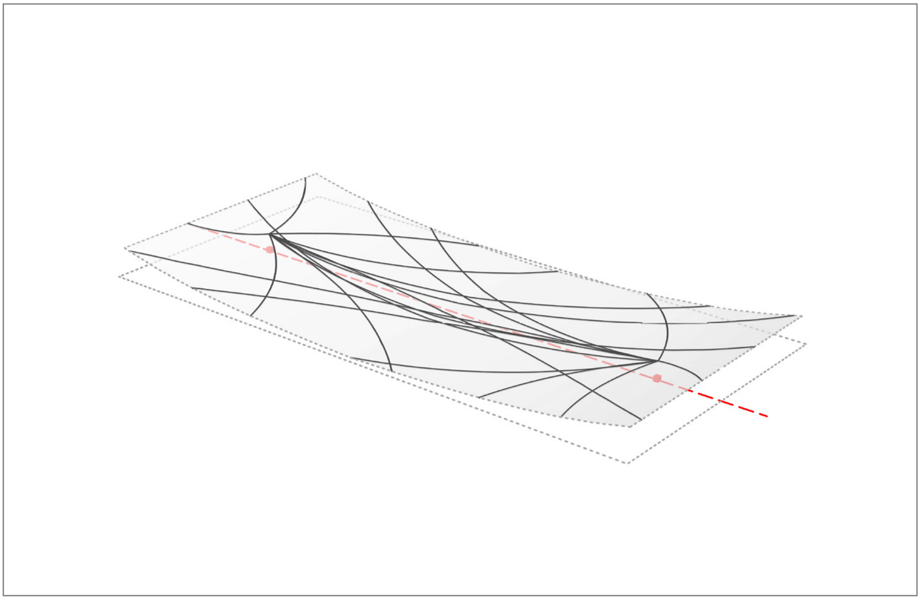


Fig. 32 **Step 4** The generated curves are projected into a curved surface in order to add another layer of three-dimensionality.

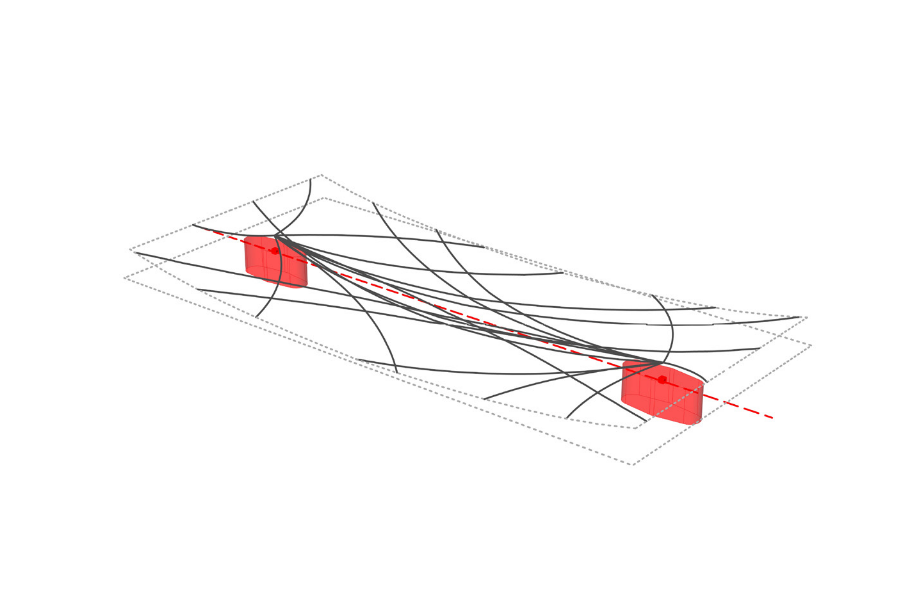


Fig. 33 **Step 5** Requirements for a strong joint are added to the system. Increased volume at the joints create a robust connection between seat and structure.

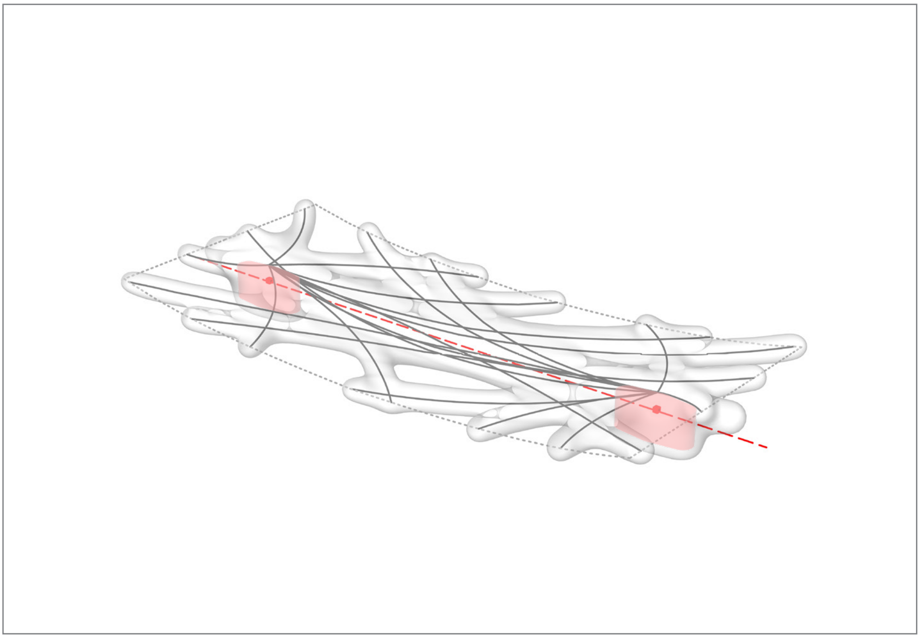


Fig. 34 **Step 6** A volume is created around all previous elements forming the main geometry.

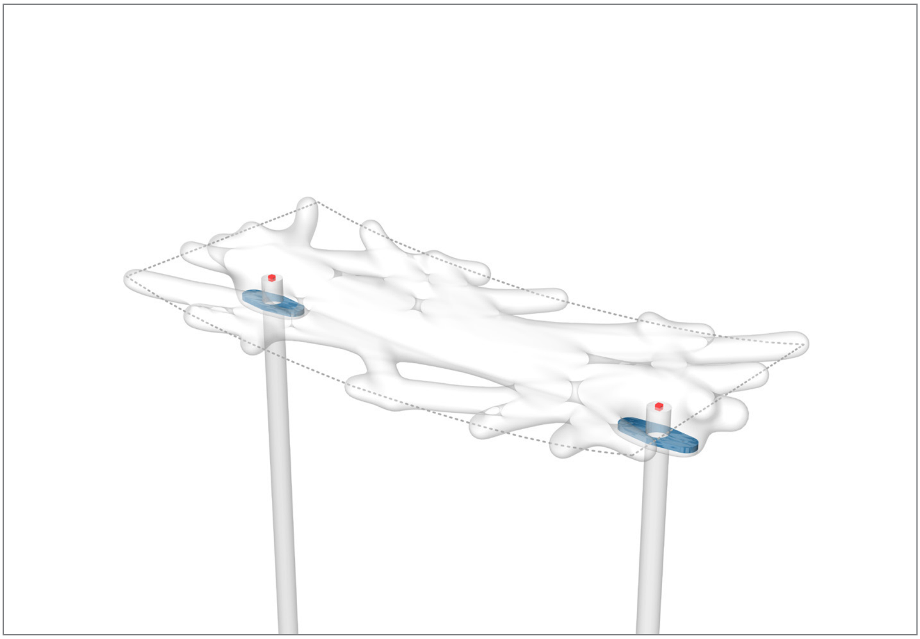


Fig. 35 **Step 7** Connection plates are added and a boolean operation is introduced.

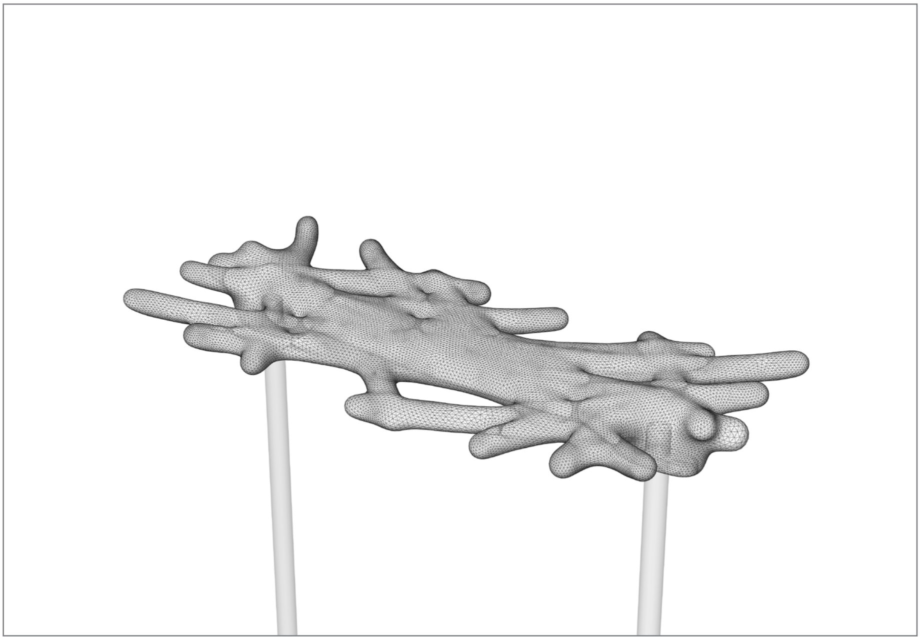


Fig. 36 **Step 8** All steps are finalized and iterations can now be generated.

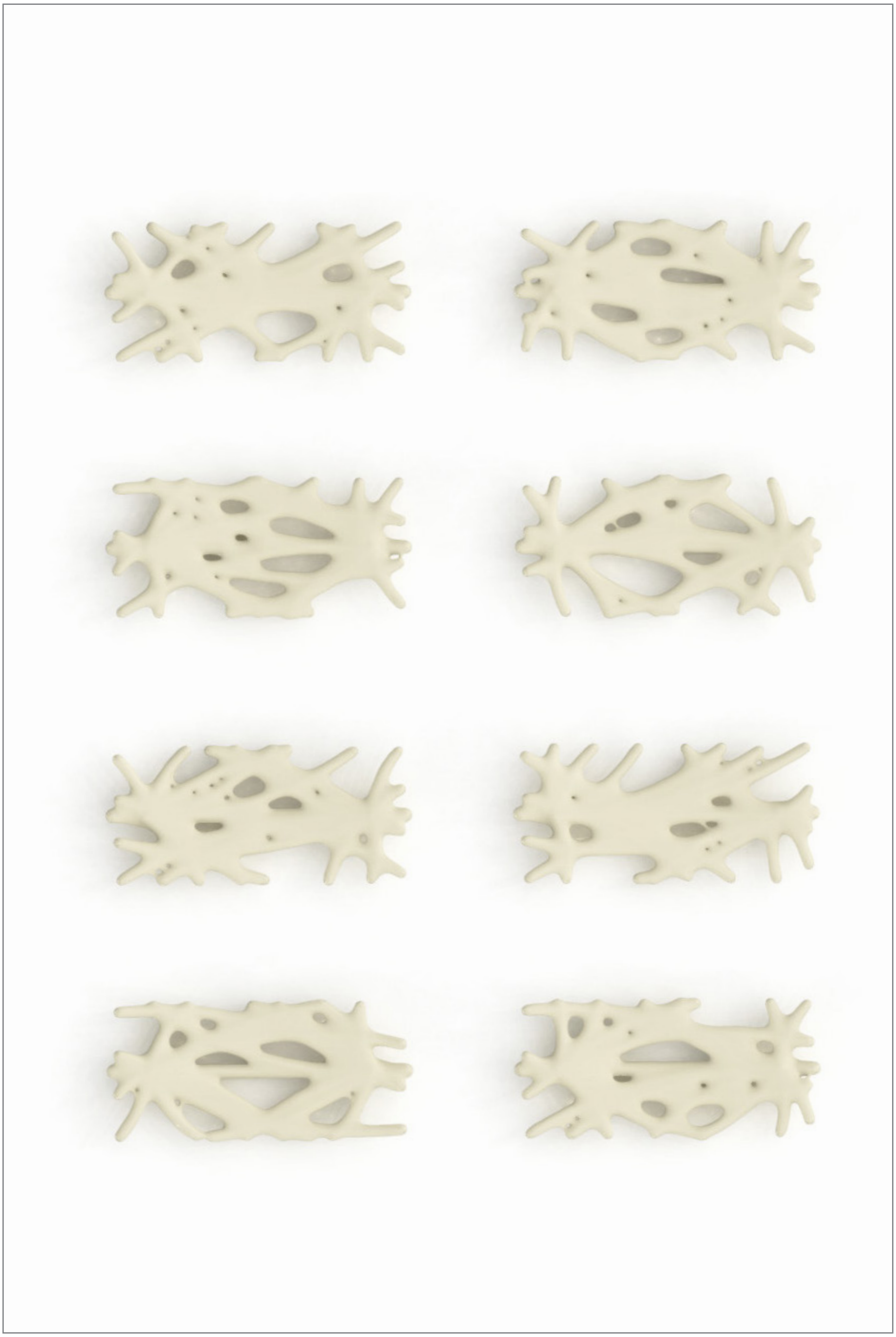


Fig. 37 An endless collection of forms are generated based one common algorithm.

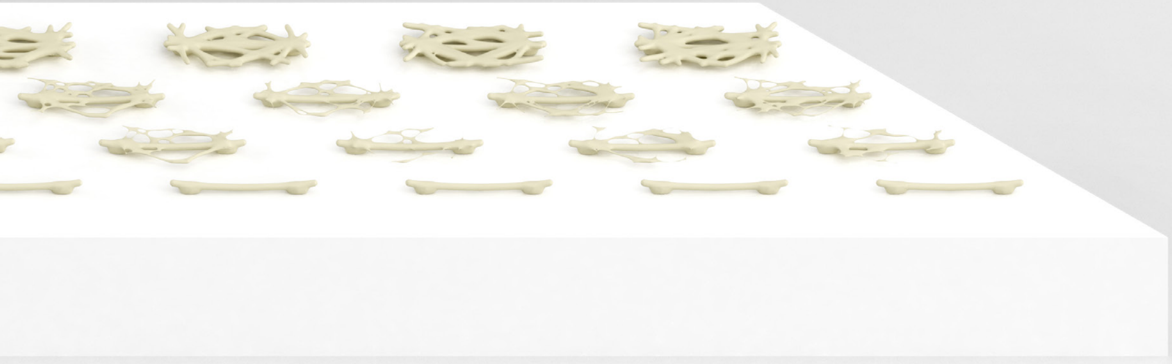
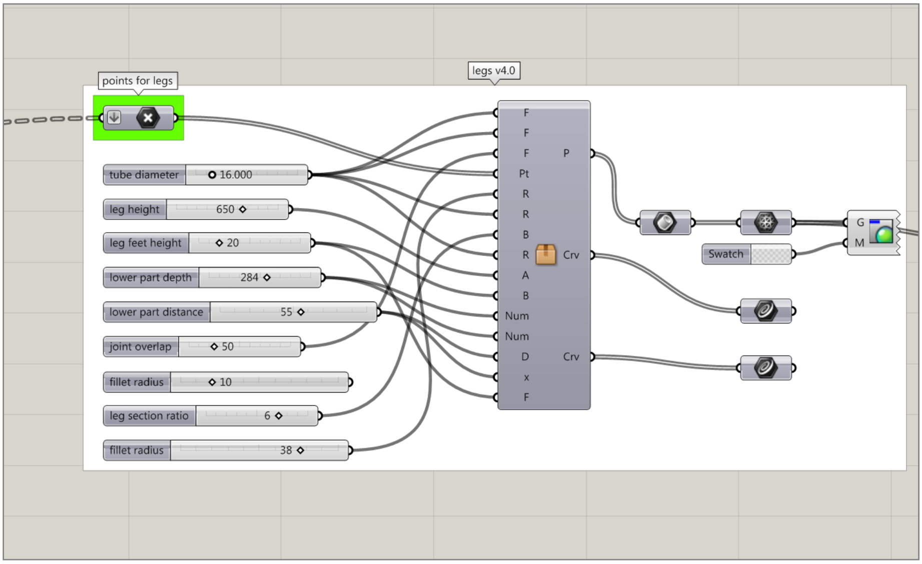


Fig. 38 Growth stages of iterations 38, 40, 55, 56, 90, 94, 95, and 98. As in Figure 28, the more developed the form is, the more visual differences there are between them. The first stage is equal across all iterations.

Fig. 39 Iteration 38 was selected to continue to the fabrication process.



tube diameter 16.000

leg height 650

leg feet height 20

lower part depth 284

lower part distance 55

joint overlap 50

fillet radius 10

leg section ratio 6

fillet radius 38

Fig. 40 Parametric Grasshopper definition of the leg structure design. By parametrising the model, changes in proportion and dimension can be done fast and easy. When numeric values are changed, the model updates in real time.

In terms of aesthetics and composition, the logic behind the two-part stool lays on hierarchy. The seat was considered to require a strong visual appeal as it is the character of the entire object. The seat is the part that exhibits the digital process and therefore it required to be raised to an adequate height by a simple and neutral structure. It was considered that only two connection points between the seat and the structure were the simplest and cleanest solution to hold the result in the appropriate height. The merging of these two elements together create an evident distinction of material, hierarchy, and perhaps style. At this point, the solution was so evident and powerful that other solutions were left aside. Even if form continuity was not achieved in this solution and a somewhat uncommon visual composition was created, the logic behind the solution was sufficiently justified in order to be selected and implemented for the purpose of this study.

Several options were considered for the design of the lower structure. Aluminium casting was considered as it would enable the creating of a flowing form that would extend the aesthetics of the seat to the lower structure. Due to the complexity and time limits amongst other complexities, a standard steel tube structure was considered to be a suitable option. A structural test was built to investigate the strength and also the dimensions and proportions (Figure 42). The *Officina Stool* by Ronan & Erwan Bouroullec (2016) was initially referenced to adequately dimension the stool. The structural test proved to be strong enough for its purpose; nevertheless, the leg angle opened too wide resulting on a very visually disproportioned object. Adequate changes were considered in the design and tested digitally in the form of renders. It is worth mentioning that the structure was parametrically modelled allowing changes to be made fast and easy (Figure 40).

The structure is made from four tubes of which two are straight and two are bent. Due to technical restrictions of the tube bending machine available at Aalto's premises, the required bent tubes had to be made of 3 parts and therefore some additional welding had to be done (Figure 44). Ideally, the bent tubes would be transformed to the required shape from one long continuous tube. Maybe unnecessary but for the sake of testing, water jet cutting was used for the connection plates between the structure and the seat resulting in a very precise joint. The structure was powder coated in matt white for a uniform and strong coating of the steel parts.

At the same time, the algorithm was being fine-tuned and improved. Various small scale models

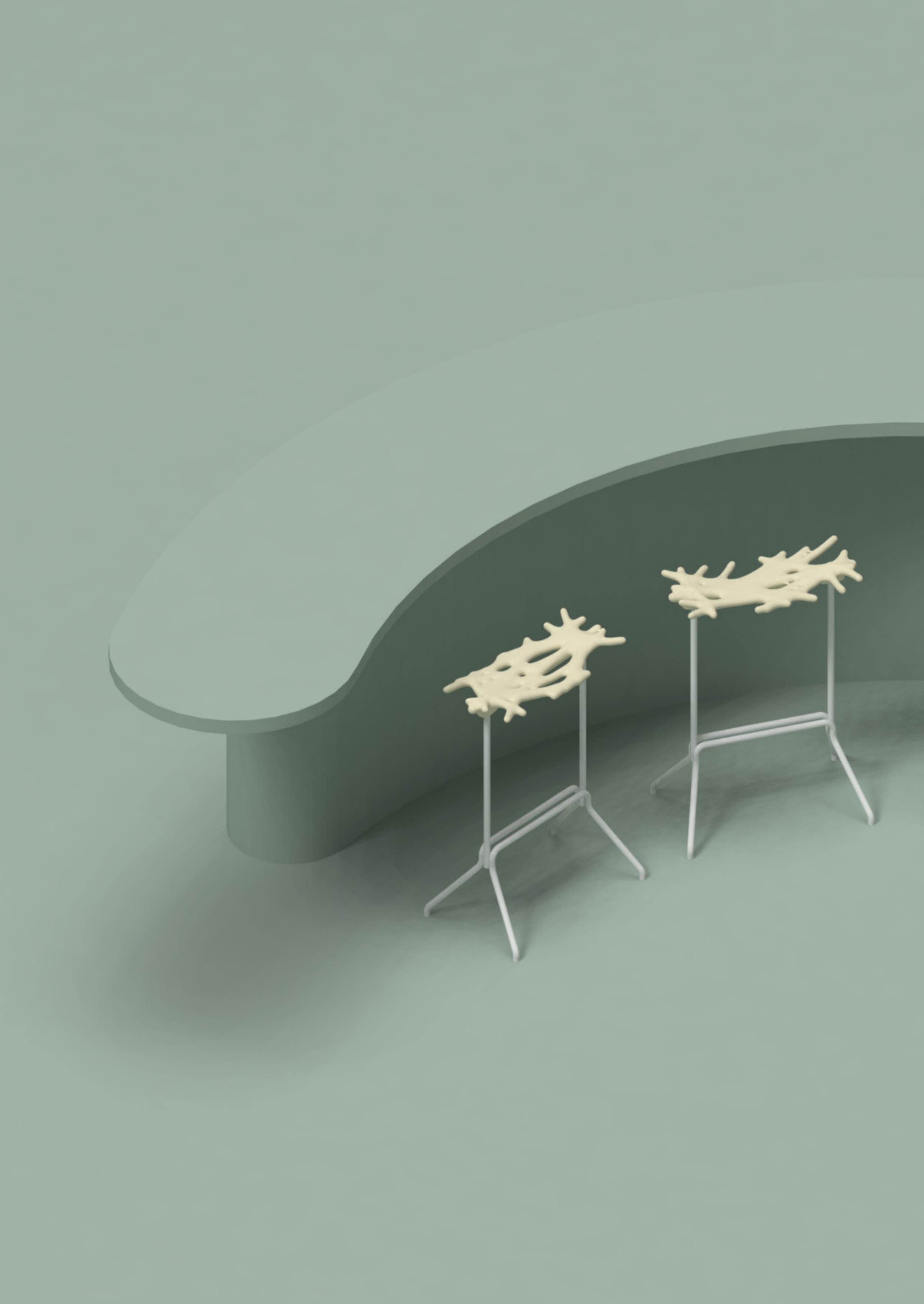


Fig. 41 Rendered image of four different iterations.

Fig. 42 Structural test of an initial structure design. The connections showed enough strength to withstand the average weight of a user. The leg angle was considered too wide; the next iteration featured tighter angles resulting in improved proportions while maintaining the required structural rigidity and stability.

Fig. 43 After several technical and visual improvements, the design moved to the fabrication face.

were 3D printed in order to physically analyse the design. Once the algorithm was programmed and bugs were fixed, one of the infinite number of variations was selected (iteration 38) and a digital mesh model was exported.

The material choice for the seat was based on the fabrication method used for its creation. An obvious material choice for milling was wood. A light-colored, easy-to-mill, locally available type of wood was required, and birch wood was a natural choice. A block of sufficient size was made ready for the CNC milling machine to subtract material. For tool path generation, a specialized software is required. In this case, Hannu Paajanen, in charge of NC workshop at Aalto University, guided this process applying SurfCam for G-code generation. Due to the nature of the geometry and the process, tool path generation was time consuming as the mesh exported contained hundreds of thousands of mesh faces. The block of wood was first milled with a so-called rough pass, eliminating most of the material not required for the seat. The second pass defines more the shape while a last pass cleans most of the tool path grooves that remained from the second pass. Once one side was finished, the block was flipped and milling continued. After all three passes, the block was removed from the bed and post-milling work begins. The seat was still attached to the block by strategically placed pins. After the seat was detached from the block, sanding was required to achieve a smooth surface. Due to the complexity of the surface, hand sanding was the only option to smoothen the grain. For the surface treatment of the seat, a mix of clear and white Osmo Color Wax (ratio 8:2) was applied in one layer. This ratio was selected after several tests were made; the desired result was a matt, slightly white surface that kept the grain underneath visible.

The seat part was used as a template for welding the water jet-cut steel connection plates to the legs, assuring an adequate placement and an optimal connection. The welding caused some burning to the wood at the inside of the joint; nevertheless, the burn mark remains hidden by the connection of the steel and the wood rendering it invisible. The seat and leg structure was attached together by standard screws and left visible. The aesthetic decision of visible screws was made on the basis of simplicity and practicality. The elegancy of the joint is appreciated by the fact that the screws themselves can become a requirement considered in the algorithm and become a feature rather than an issue. This extra volume required by the screws becomes an aesthetic property of the form, and is also one of the constants across all iterations.

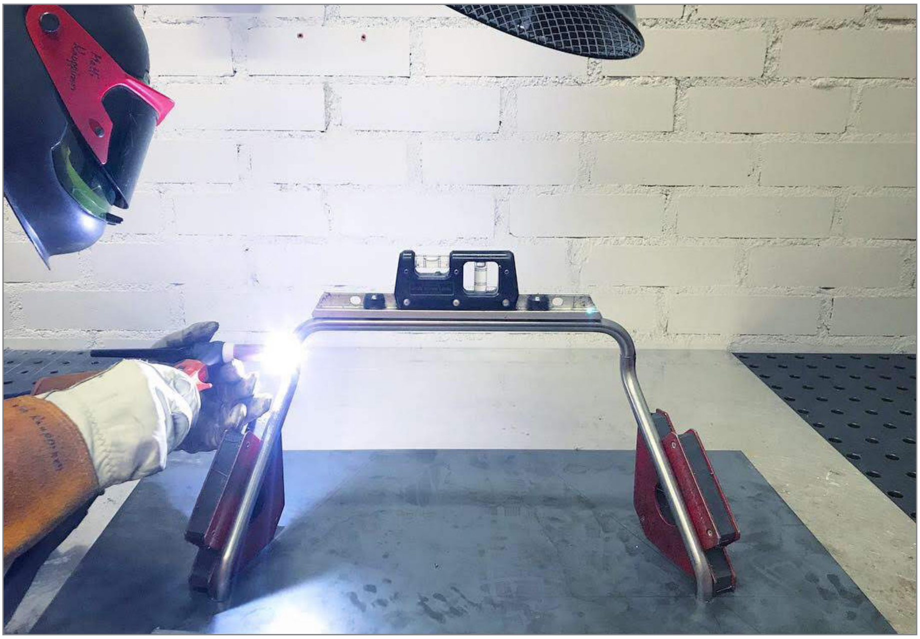


Fig. 44 Metal workshop master Matti Kauppinen performing one of his preferred activities.

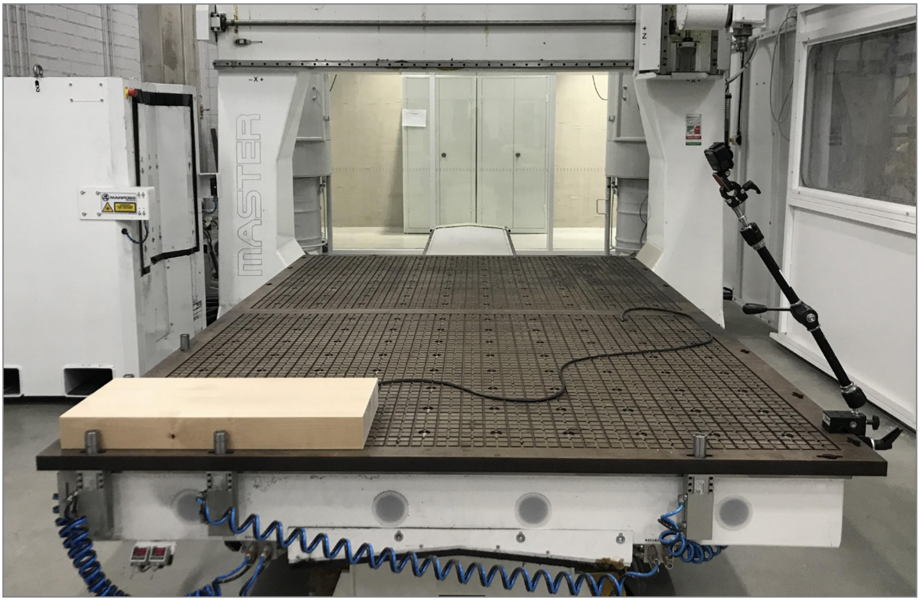


Fig. 45 BACC 5-axis milling machine at Väre's NC Workshop. The wooden block is securely attached to the bed with suction and is ready to be milled. A camera mounted in one side documents the process.

Fig. 46 CNC milling process. A rough pass first removes most of the unnecessary material followed by medium and fine passes that gradually form the seat.

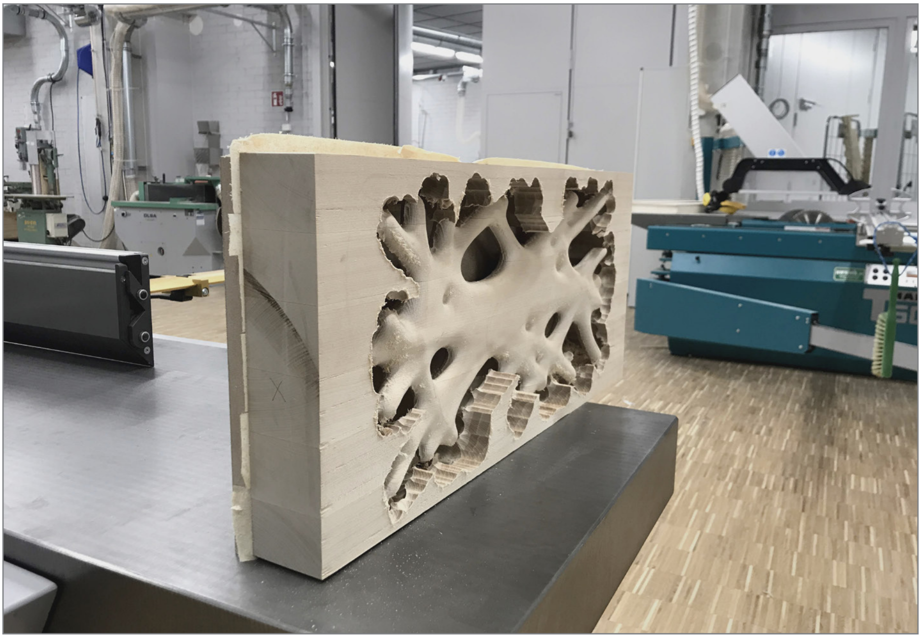


Fig. 47 As the milling is complete, the seat has to be detached from the block.

Fig. 48 Bottom side milling complete.

Fig. 49 Seat before manual sanding. Tool paths can still be seen on the surface.

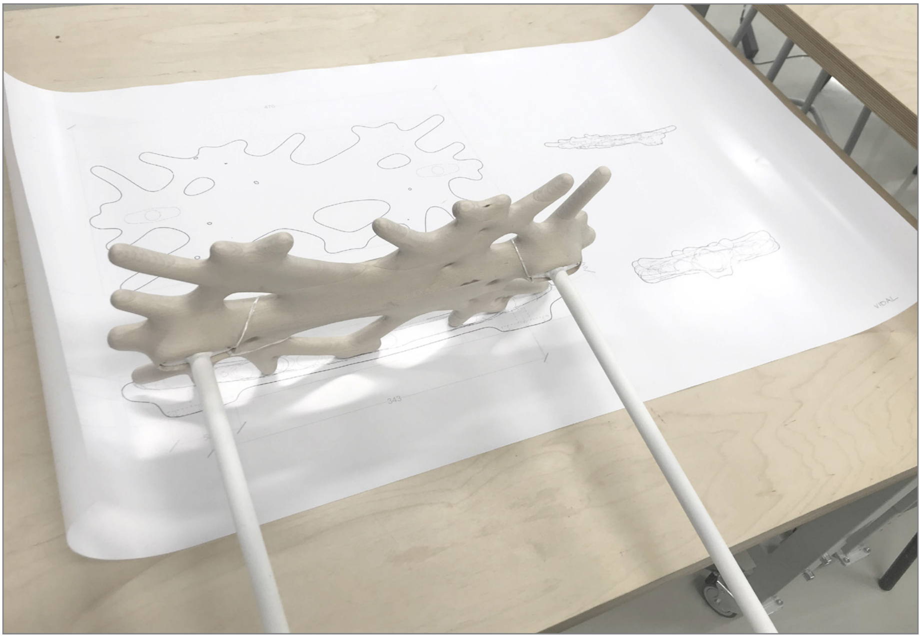


Fig. 50 1:1 seat blueprints and CNC milled birch wood seat attached to the test structure.

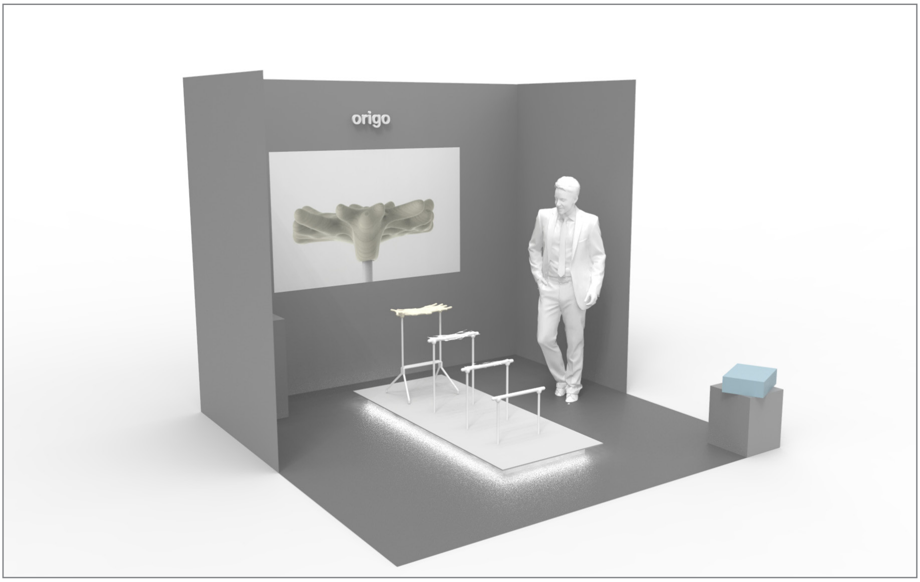


Fig. 51 Visualization of stand for Stockholm Furniture Fair 2019. A projector (in blue) shoots animations and images to the white foam board attached to the back wall.

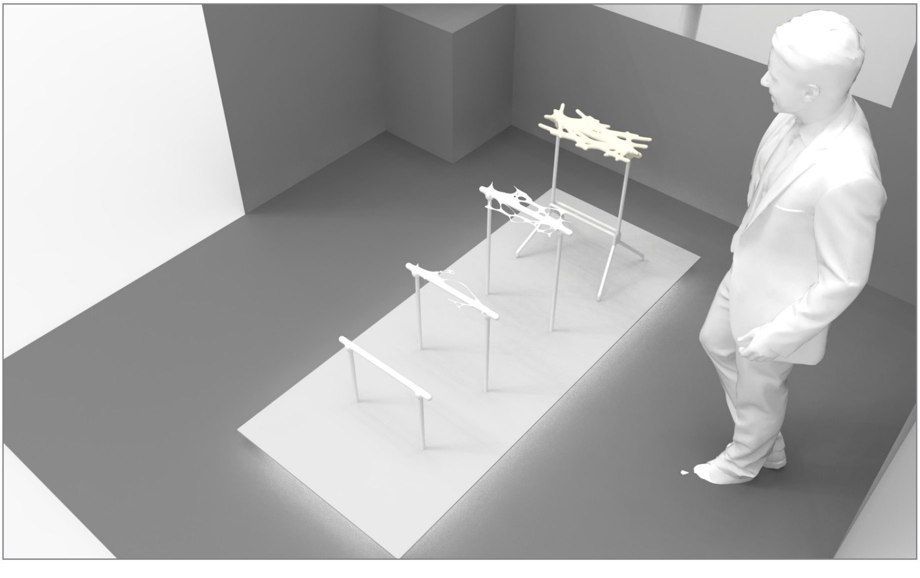


Fig. 52 White LEDs illuminate the bottom of the platform creating a centre of focus in the stand. The growth stages are arranged in steps in order to show the chronological order and hierarchy. The box at the left corner serves as a shipping box as well as a side table during the fair.

Part III

The Results

The Results

The outcome of the algorithm is now fully materialized; birch wood has been CNC milled, sanded, surface-treated, and assembled to the powder-coated steel structure. The stool awaits its exhibition at the Stockholm Furniture Fair and its ready to gather feedback from the industry.

Once assembled, the stool acquires its sense of purpose and its properties become ready for analysis and evaluation. At first glance, the two main elements of the stool, the seat and the structure, might perhaps have different visual personalities and might lack certain understanding and compatibility between them. As the creative process made emphasis on the generative system rather than on the visual aspects of the object, this seemingly unusual aesthetic combination becomes supported by the reasoning behind the process, and therefore accepted by the author.

The generative process was prioritized, and the semi-autonomous result was computationally developed following the rules created by the designer. In other words, the designer framed the requirements while a computer created the form. The result of the semi-controlled form were not judged on the basis of pleasing aesthetics nor maximum functionality or ergonomics, but judged rather by the holistic approach to an alternative form generation and fabrication system.

The project required good visual documentation in order to effectively communicate the idea behind the project as well as attract the audience's attention and raise curiosity. Animations were considered a great tool to show the development of the form, and quickly became an important requirement to include in the coming exhibition stand. Photographs were another important visual tool of communication; photographer Chikako Harada composed and shot pictures appropriately displaying the final result and its details.

For the Stockholm Furniture Fair, the exhibition stand required to be simple and neutral in order to adequately display the project and engage the viewer. Other considerations were cost efficiency, easy to transport, and easy to install and disassemble by one person. With those features in mind, the stand was designed, built, and ultimately shipped to Stockholm.

The stool was packed and shipped together with other furnishings for the stand at the fair. Being the most important design fairs in Scandinavia, the event attracted a great amount of visitors and the project was successfully exhibited. Feedback and comments from professionals and fellow designers helped gather points of view and provided direction for future development.

Fig. 53 A simple flushed connection between the seat and the structure securely joins the two elements together using simple standard screws.

Fig. 54 Form development stages. The initial form contains all elements that remain constant across all iterations; it includes a transversal beam for structural rigidity, pockets for leg structure placement, and added mass for screw connections.

Fig. 55

Fig. 56

Fig. 57

Fig. 58

Fig. 59

Fig. 60

Fig. 61 Stand C17:41 at Stockholm Furniture Fair 2019

Fig. 62 The bottom-lit white platform displayed the growth stages of the selected iteration. The first three stages were 3D-printed from PETG. The last stage was represented by the stool itself.

Part IV

The Reflection

The Reflection

Hand-made objects have a natural charm to them. Often, and perhaps just a matter of sensibility, computationally-created objects lack a certain "human touch" that hand-made objects naturally have. We can effortlessly draw a perfectly round circle using CAD software, but in certain cases, the geometrical perfection might seem to lack the "human touch". By programming a generative system that creates each time an irregular and unique circle, that "human touch" can partly be reintroduced. In my work, I intend to digitally create objects that have those irregularities or individualities that could ultimately add certain value to the object. In my opinion, the inclusion of arbitrary values in generative systems are a very important tool for achieving that effect.

One of the benefits of creating a generative system are the countless iterations that can be generated from one common algorithm. This process can naturally deliver infinite variation and individuality without any extra effort. This system paired with digital fabrication technologies enable entirely new and exciting possibilities for designers to explore.

Based on my assessment, I will argue that the process suggested in this thesis is technically viable; nevertheless, it comes with high monetary costs in the current state of the study. The increased costs are perhaps counterbalanced by the added value integrated to the object's intellectual and visual properties. The process will be studied further and applied in future projects.

Digitality is here to stay, the fourth industrial revolution will keep evolving and digital tools will be increasingly important for our practice.

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Images

Images are taken and/or produced by the author unless otherwise stated.

Figure 1
Evolution of production techniques. Wujec, T., *The Future of Making: Understanding the Forces Shaping How and What We Create.* Autodesk, Melcher Media, 2017, pp. 150-151.

Figure 3
Furniture by Zhang Zhoujie Digital Lab. Retrieved 22.04.2019 from: https://www.ciff.furniture/chinese-trends/designers-and-young-creatives/66-zhang-zhoujie-digital-lab-formation-in-action-the-sensor-chair-and-design-auto-gen

Figure 4
Breeding Tables by Clemens Weisshaar and Reed Kram. Retrieved 22.04.2019 from: http://www.kramweisshaar.com/projects/breeding-tables

Figure 5
Linderhof Palace interior. Partington, S. W., *The History of Furniture*, Orbis Publishing Limited, London, 1976, p. 203.

Figure 6
Digital Grotesque II by Michael Hansmeyer and Benjamin Dillenburger. Retrieved 22.04.2019 from: http://www.michael-hansmeyer.com/digital-grotesque-II

Figure 7

Digital Grotesque I by Michael Hansmeyer and Benjamin Dillenburger. Retrieved 22.04.2019 from: http://www.michael-hansmeyer.com/digital-grotesque-I

Figure 8

Illustration from the book *The Architecure of Trees* by Cesare Leonardi and Franca Stagi. Retrieved 22.04.2019 from http://www.startribune.com/new-book-is-tree-tome-like-few-others-part-science-part-art-marvel/507788702/

Figure 9

Nias Islanders by J.P. Kleiweg de Zwaan. Retrieved 22.04.2019 from: https://commons.wikimedia.org/wiki/File:Plaster_face_casts_of_Nias_islanders_by_J.P._Kleiweg_de_Zwaan_circa1910.jpg

Figure 10

Fields for the British Isles by Antony Gormley. Retrieved 22.04.2019 from: https://mymodernmet.com/antony-gormley-field/

Figure 28

Fetus development illustration. Menges, A., Ahlquist, S., *Computational Design Thinking*, John Wiley & Sons Ltd, 2011, p. 189.

Figures 55-60

by Chikako Harada, Helsinki, 2018.

Human 3D model

Downloaded from https://renderpeople.com/free-3d-people/

Appendix

Interview

Luka Piškorec

Lecturer at Aalto University
Computational Design and Digital Fabrication

March 2019

1. The programming of algorithms is becoming increasingly familiar to architects; also, digital fabrication is being implemented in the building industry. Why is their application in other creative fields (involving the creation of a physical object) like furniture design not being adopted at the same extend?

Architecture projects involve more people, major complexity, and usually are one-offs projects. Mass standardization never really took off in architecture, meaning each building is completely customized. Due to the size of architectural projects, research and development can be buffered out in the budget of the project; this can result in a more efficient building and the R&D cost would pay off in the long run. In smaller scales that additional price cannot be justified. Architectural projects can have a great amount of complexity; manual work can be avoided when computational models are applied, bringing an evident benefit to the process, one being cost efficiency.

2. In your lecture at ETH Zurich in 2018 as part of the Digital Fabrication Lecture Series, you mention three paradigms in digital design:

-Manual drawing / modelling
-Generation through instructions
-Generation through examples

In the field of industrial design, and including furniture design, the first paradigm manual drawing / modelling is the norm. What is holding the industry from jumping to the second or third paradigm?

If each piece is different, someone has to still be behind production and planning. There are *some services online where you can customize at certain extent your own product. For example, custom sneakers by Nike, you get a tailored design but it involves more time as the product is not on the shelf and it has to be produced to custom specifications, so the customer does not get the product right away. Having visited a Mercedes factory, the customization factor is already there and integrated to the factory; certain parts can be chosen by the customer, and each car assembly is consequently different from one another. That brings to think that the application in other fields or products is in fact possible. The other question is why would you want customization at all? Why customization when you can have standardization.*

4. Do you think an object's value and/or desirability diminishes if it was created by an algorithm rather than crafted by a human?

This is based on the mentality of people and what does the society place value on. Mario Carpo, author of The Alphabet and the Algorithm, said at one moment that in the 20's and 30's bakeries in Italy would be called "the modern bakery" and it was a desirable concept, get your bread from "the modern bakery". Today, we have the opposite situation; modern is associated with industrial production, and what is valued today is "hand-made bread", or "rustic", or "craft". Hand-made things became more valuable. To answer the question, it really depends on the current trend and the culture. For example, when I was growing up my parents would tell me how now we are watching so much TV and when they were kids they could only watch TV once a week; what happens today, we don't watch TV but we are on our phones all the time. There was just a shift on the method but we continue to consume content. And now, perhaps being off-the-grid is actually quite desirable, a new trend, and people might not want to get the latest phone anymore but instead get just a phone to make phone calls. Back to the craft beer example, a "craft" beer is usually more expensive than a regular one, but people still buy them. Currently also "sustainable production" or "rainforest alliance" are selling not only a product but also a lifestyle; when you have so much choice, so many product out there, you choose by the lifestyle. A pair of shoes that are produced locally sells the idea of supporting the local economy and so on.

5. Commonly, the designer dictates the final shape of the object. Do you think generative methods will become more popular in the future?

My previous boss and professor Fabio Gramazio at ETH, he was naming three reasons why differentiation or diversity or customization is better than standardization. In history we always *had customization; if you look at production of artefacts, there is a high differentiation between cultures, climates, etc. This idea of standardization came with industrial revolution and rather late, and it was related to technology. Now technology is sort of freeing us from that. Somehow, we might be reverting back to differentiation.*

Another argument. The reason there was also a lot of customization in the past is because optimal performance, local conditions, and optimization. The houses looked different because they have to accommodate to different things, cold climates or hot climates. In furniture it was the same; access to different materials and access to different production methods affected how these objects looked like. Neri Oxman from MIT mentioned in one of her lectures that if you look how nature works, it seems like for nature material is expensive but material is cheap, so nature optimizes as much as possible the shape and uses as little material as possible. The way we humans build for now is kind of the opposite; the shape is expensive and the material is cheap. If we do a structural analysis of a concrete slab, we would see that only part of this material is being utilized but somehow we have to poor the whole slab. With 3D printers, this might be closer to how nature designs. In 3D printers the shape is cheap, you can put in any shape and the printer doe snot care, it just builds. The materials matters, as we have to pay for material. For certain types of printers, the less material it is used, the faster it is to print so the cost comes down. So this concepts brings us closer to how nature builds.

Another argument is that everybody likes to feel special and we like things tailored to us. This might also be one of the drivers why in the past objects were more customised. Ornaments would be unique from object to object and therefore the value is greater as it is a unique object. You see it often in architecture where the client wants a house to look different, customized to its personal needs. In the other hand, architect Adolf Loos believed that we are all different but we should all dress the same and that is the idea of the business suit, making people looks the same and having only few elements that can make people differentiate from each other. That was the mentality then, and mentality changes with time.

6. In my thesis I explore the possibility of creating an object of similar qualities but individually unique in form through an all-digital process. In this case, I applied subtractive manufacturing techniques (CNC milling) but additive manufacturing techniques (3D printing) are an alternative as well. Does this process have potential in the industry?

People could value having unique objects. Production price is expensive, but in change the piece you get is unique. The customer could buy this or choose the standardized one, but *there has to be the choice. The way you can extend this project is through a web browser; not everybody can use Rhino and Grasshopper but everybody can use a web browser. The argument is that there is value in uniqueness, and the technology can create this variation in objects. And that becomes the idea of selling a lifestyle that we previously talk at the beginning. In the luxury market, the customer is already paying a very high price for a design object that is mass produced and all being equal, so this could be the next level; having a product with similar aesthetics but each one is a little bit different.*

Animations

Animations communicate to the reader the concepts of form development and growth. The animations can be accessed by scanning the QR code or by accessing the web address.

www.vimeo.com/313207376