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Diplomarbeit

Robotic Timber Construction

Study on Robotic Fabrication Methods of Computational Designed

Timber Structures

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs unter der Leitung

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Abstrakt

Diese Diplomarbeit untersucht die Bedeutung der digitalen Fabrikation und robotische Holzkonstruktionen anhand des historischen Hintergrunds der digitalen Fabrikation. Verschiedene Methoden der digitalen Fertigung werden erforscht, analysiert und aufgrund ihrer Vor- und Nachteile bewertet. Denn seit langer Zeit-CNC-Fräsen oder -Schneiden war bereits in der Industrie im Einsatz und fand seinen Weg in die Architektur. Auch in der Automobilindustrie wurden Roboterarme eingesetzt, die jedoch darauf programmiert waren, ein Leben lang einen Job zu erledigen. Das rechnergestützte Design ermöglichte die Verwendung dieser flexiblen und präzisen Werkzeuge zur Herstellung von Freiformkörpern. Roboterarme haben eine Vielzahl von Vorteilen, wie beispielsweise die Flexibilität in ihrer Bewegung, da sie nicht in einem kubischen Arbeitsraum arbeiten. Neben der Tatsache, dass sie nicht nur an einem Werkzeug befestigt sind, kann der Endeffektor jede Art von Arbeitswerkzeug sein. Der Roboterarm kann jede digitale Fertigungsmethode ausführen, angefangen von der additiven Methode bis zur subtraktiven Methode. Dies hängt vom Endeffektor ab, der am Roboter angebracht ist. Das rechnerische Design ist ein großer Meilenstein, da mit dem Roboterarm komplexe Formen und Geometrien hergestellt werden können. Das natürliche Bauprodukt Holz ist ein Material, das für die rechnergestützte Konstruktion nicht einfach zu handhaben ist, aber Forscher auf der ganzen Welt haben verschiedene neue Methoden zur Herstellung von Robotern erfunden, die die rechnergestützte Konstruktion von Holzprodukten ermöglichen. In dieser Forschungsarbeit werden das rechnergestützte Design von Holzstrukturen und die neuen Methoden der Roboterherstellung analysiert. Mit den gewonnenen Erkenntnissen wird es in Shanghai ein mittelgroßes Designprojekt im M50 Creativity Park mit Bauholz geben. Der Herstellungsprozess wird simuliert und parametrisch ausgelegt.

Keywords: ***digitale Fabrikation; Roboter-Holzkonstruktionen; Simulation; Computergestütztes Design; Holzbauwerke; Roboterfertigung; Herstellungsverfahren***

Abstract

This thesis researches the importance of digital fabrication and robotic timber constructions through analysing the historical background of digital fabrication. Different methods of digital fabrication will be researched and analysed and evaluated due to their advantages and disadvantages. Since a long-term CNC milling or cutting was already in use by industries and found its way to architecture. As well robotic arms were used in the automotive industry, but they were programmed to do one job for a lifetime. The computational design made it possible to use this flexible and precise tools to fabricate freeforms. Robotic arms have a high amount of advantages such as the flexibility in their movement, since they are not working in a cubic working space. As well the fact that they are not just attached to one tool, the end effector can be any kind of working tool. The robotic arm can execute every digital fabrication method started from additive method till to subtractive method, it depends on the end effector which is attached to the robot. The computational design is a huge milestone because of this, complex shapes and geometries can be fabricated with the robotic arm. The natural building product timber is a material which is not easy to manipulate for computational design but researchers around the globe invented different new methods for robotic fabrication which makes the computational design for timber products possible. In this research computational design of timber structures and the new methodologies of robotic fabrication will be analysed and with gained knowledge there will be a mid-scale design project in Shanghai at the M50 Creativity Park with construction timber. The fabrication process will be simulated and designed parametrically.

Keywords: ***Digital fabrication; Robotic Timber Constructions; Simulation; Computational Design; Timber Structures; Robotic Fabrication; Fabrication Methods***

Contents

1. Introduction

1.1 Research Background

Robotic arms are gaining in popularity in architecture in the current decade because of raising use of computational design. Even though industrial robots are actually made for mass-production and they are multifunctional machines. They have a wide range of use like load, unload, deburr, laser, bond, assemble and mill (Braumann, 2010) Robotic arms are not developed to perform only one task, instead they can be equipped with almost every tool, which is comparable to human´s hand. In contrary CNC router with 3-axis are limited in their use, because they can only perform their optimized particular task from above (Yuan et al, 2017).

Industrial robots have the potential to change architecture as we have known it so far and it will reshape the view of architecture within the society. Gramazio and Kohler, researchers form Zurich, say that the robotic arms were the bridge between immaterial design and the physical reality of architecture, and the robots succeeded with this feature what digital fabrication alone was unable to reach (Gramazio, Kohler and Willmann, 2014).

New researchers around the globe are working on experimental projects to develop new strategies and innovative methods to fabricate computational designed wooden products. The use of timber as a building material has deep cultural roots and as well a long history. Modern technology makes it possible to work with wood as computational material, to simulate the behaviour of the product and finally to digitally fabricate it. Another important factor of the product is, that it is the most ecological building resource (Menges et al., 2017)

Digital Fabrication and parametric design are benefits which are helping wood to become more and more a future construction material. Timber might have a long history of use in architecture, but it is still a modern material, because researcher and architects are still trying to rethink the potential of the building material, and of course it is own natural advantages will never make it infamous. Digital fabrication can still learn from traditional human made wood crafting (Bianconi & Filippucci, 2019).

Wood products in digital fabrication are great materials to selects, to work with in parametric design. Due to their standardized and manageable conditions, timber products can be manipulated and crafted with less effort and also, they are easy to repair and keep on working. According to their standardized dimensions, a variety of connectors are available, which are adaptable to the geometric style (Beorkrem, 2017).

1.2 Research Question

The research question for this thesis is defined through the new implementation of computational design with timber as building material. Wooden products have important properties like tension forces and compression forces and this kind of abilities make it as building resource very important. Since this decade the wood working was mostly done in traditional or industrial ways but with the raise of computational design and digital fabrication researchers and institutions have focused on working with this historical product.

To research on the field of digital fabrication, computational design and robotic timber constructions, the following research questions have been developed:

1. *How does computational design effect robotic timber constructions?*
2. *What are the challenges of robotic/digital fabrication in the design phase of computational designed timber constructions?*
3. *What are the difficulties between the simulation of the fabrication procedure and the physical world?*

This defined research question will be a starting point for thesis to understand digital fabrication and robotic timber construction.

1.3 Research Methodology

Robotic timber construction is still in its infants and for that reason it is important to understand the development and the methodology of digital fabrication. Due to this the thesis has two main parts: the theoretical and the practical part.

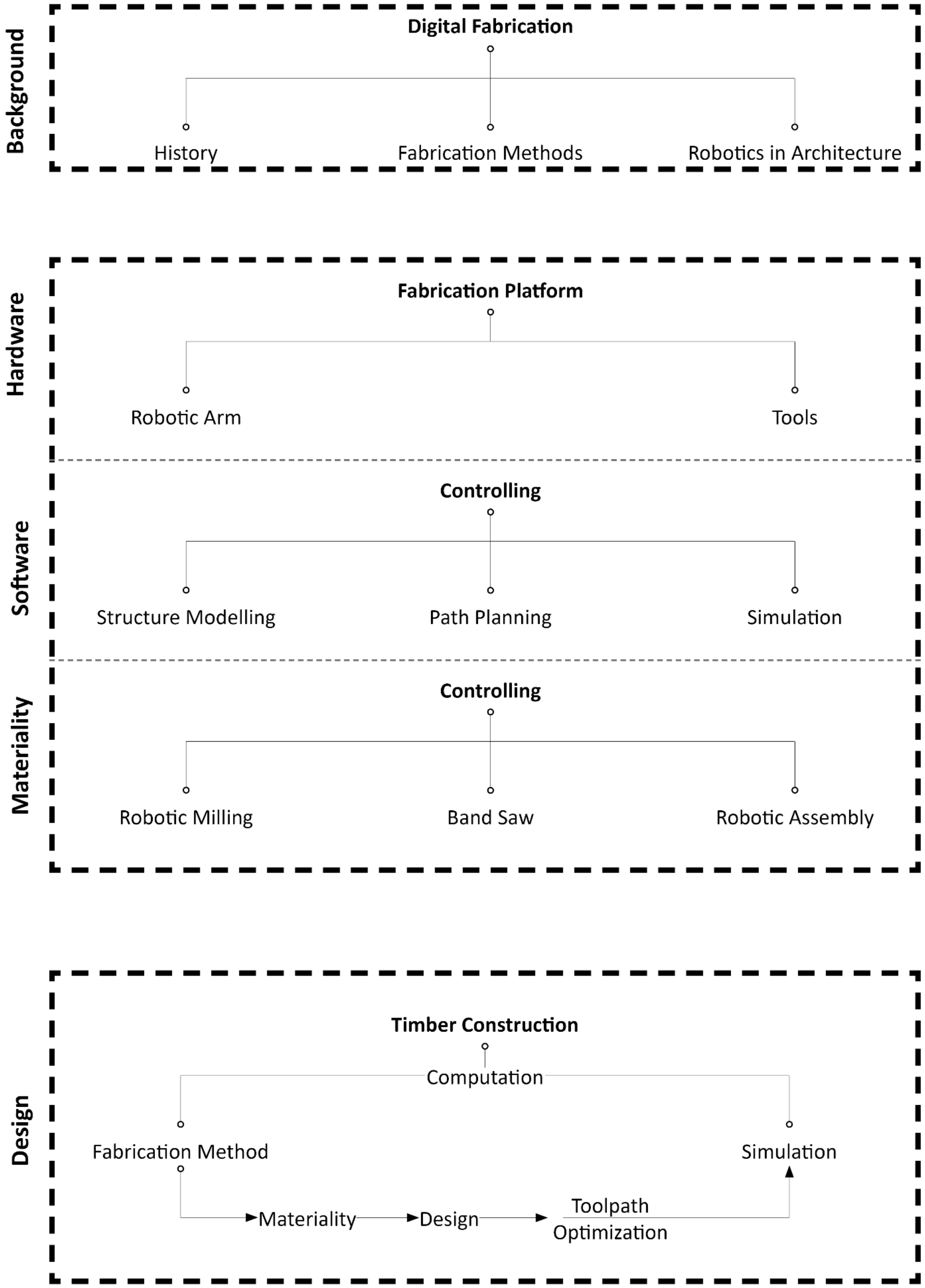
The theoretical part of the thesis is separated in four main chapters. In the first chapter the importance of digital fabrication and its history will be analysed and researched. This is done for an understanding how digital fabrication evolved during the centuries. The first impacts of digital fabrication started when the French engineer Joseph Marie Jacquard invented a programmable weaving loom till to the use of robotic arms as a digital fabrication tool.

In the second chapter of the thesis the research will be on the digital fabrication tools and their different methods like the additional, subtractive, formative and joining methods. This types material manipulation will be researched on their advantages and disadvantages to get a knowledge how digital fabrication works. After this short analyse the focus will be on the main subject of thesis: the robotic arm. The robotic arm is a new tool in architectural digital fabrication, which makes possible that architects can totally involve and make all the decisions through the whole process of a project. Robotic arms can change the view of architecture within the society (Gramazio, Kohler and Willman, 2014)

In the following part the computational design of timber products will be researched and the different methods of wood working with the robotic arm. This research will be done with analyses of built experimental research projects of different researchers which have invented new ways of wood machining with the robotic arm

After the theoretical part, the design approach follows with the gained knowledge about digital fabrication, robotic constructions and computational design. The design is mid-scaled project situated in Shanghai M50 creative park. This project focuses on the computational design of standardized timber products till to the simulation of the digital fabrication with the robotic arm and the parametric definition of the wood machining.

1.3.1 Methodology



2. Digital Fabrication

2.1 Meaning of Digital Fabrication

The production or production of a thing, including a sequence of steps or processes, is called fabrication (Gorse et al., 2012). Digital fabrication tools have been defined as machines that automatically convert a digital object in the design world into a material reality (William J. Mitchell 2003). Numerical fabrication includes all the tools and methods used to produce digital design physically.

Digital fabrication aims to produce the science of the computer science as the atom of physics. For this reason, it can be said that for digital fabrication is the bridge between the digital world and the physical, it is opening a gate to a different dimension.

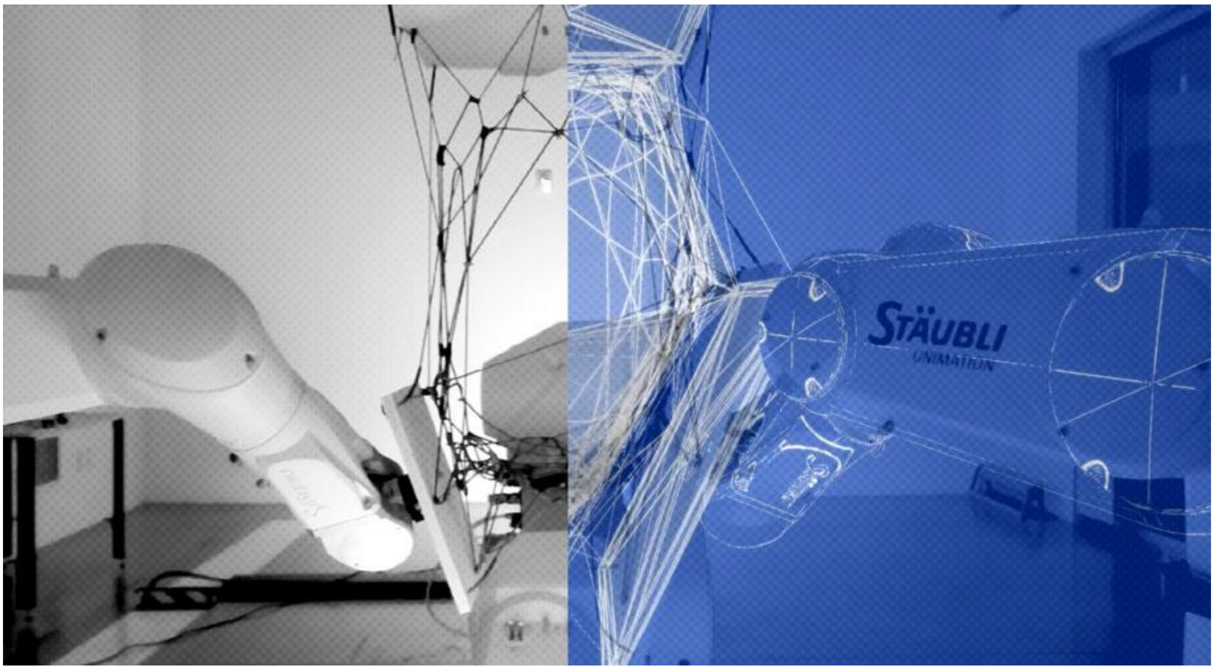


Figure 2.1 Approximation study in which Peter Vikar examined the relationship between numerical and physical in 2012. (URL1)

The traditional production action is based on the operation of hand power and usually uses a number of specialized tools. There is a need for technically specialized, experienced manpower in production using these tools (Gramazio, Kohler, & Oesterle, 2010). On the other hand, digital fabrication tools do not need any expert human operator and experience gained by working for many years in the meaning of traditional systems.

In Branko Kolarevic's (2004) view, the “digital age” has reshaped the relationship between thought and production and has established a direct link between what is thought and what is being produced. According to him, the question that should be asked now is not whether it is a special form to be constructed, but what new application tools are needed to evaluate the opportunities that are generated by digital design in architecture (Branko Kolarevic, 2004).

Gonçalo Castro Henriques (2009) asks, in “Creating New Artifacts”, if Technology can increase the limits of creativity. We think that the way we think and build and the tools we use to realize both are shaped by the cultural environment and education we are in; Depending on the level of knowledge we acquire; we suggest that vehicles will expand our boundaries. In this sense, digital fabrication tools can also extend the limits of thinking and designing architects (Gonçalo Castro Henriques, 2009). The survey conducted by The Architectural Review in 2016 with 200 designers stated that participants had improved the creativity of digital technologies (URL 2). Editor Jon Astbury, in his report on this survey, stated that this development could have the meaning of helping to complete the work in the narrowest sense, allowing a way of thinking in a manner that had never existed before.

The concept of personal fabrication, which began to be discussed in the early 2000s, goes beyond being an area used by experts in advanced private laboratories to explain the use of digital fabrication into the daily life of individuals. In personal (digital) fabrication, the aim is to provide people with the opportunity to produce the products they need instead of purchasing them (URL 3). Of course, digital data is not required for individuals to make physical production according to their own needs. It is a period marked by *Do it yourself!* which is the dictum of personal (digital) fabrication. Neil Gershenfeld (2008) defines the personal (digital) fabrication as an innovation that enables individuals to design and produce concrete objects wherever and whenever they need them (Gershenfeld, 2008).

Digital fabrication is not only the production of three-dimensional mass structures; it also aims to produce a product in one stage with its mechanical and electronic mechanisms. Gershenfeld (2008) exemplifies this situation as producing electronic and mechanical parts with the electronic and mechanical parts to be able to fly as soon as it is out of the printer, and personal (digital) fabrication tools are just like printers in our homes; it does not only “paint” on paper, it prints “things” (Gershenfeld, 2008).

According to Rivka Oxman and Robert Oxman (2015; 2010), the increase in the association between design and technology has developed processes where interdisciplinary new associations are possible. As a result, this new kind of unity in the fields of architecture, engineering and production has supported a new dimension of physical production in design (Oxman et al, 2015; 2010).

One of the most important effects of digital fabrication is the complex geometrical forms that can be designed with digital design possibilities, which can be constructed in the physical world. In this respect, it gives both architects the courage to design and provides great facilities during the production phase. According to Branko Kolarevic (2001), non-linear geometries for many architects trained with Euclidean Geometry are a matter of trust in terms of constructability. However, non-linear geometries can be defined mathematically with NURBS (Non-Uniform Rational B-Splines). Thus, the mathematically definable definition of the non-linear form means that it can be constructed one-to-one and error-free using digital fabrication (Branko Kolarevic, 2001).

According to Yanagawa (2016), although people have developed tools to solve certain problems, each new technological development has created various unforeseen possibilities and the introduction of these tools has encountered unpredictable reactions and results beyond their intended use (Yanagawa, 2016).

Similarly, Tuba Kocatürk (2013) stated that the technology which is taken to use on the architectural process, has an effect on the whole process, thinking and methodology of architecture. Newly acquired technology and subsequent transformation in architecture nourish each other in a cyclical manner. For this reason, Kocatürk considers that any technology should look at a long process in order to understand the effect it has on architecture. In other words, it is not enough to look at where the new technology is now in the architectural process and practice; he emphasized how it started, how it continued, how it transformed, and how it could be transformed (Kocatürk, 2013).

Due to this, every new technology has three directions:

1. The inventor of the technology must predict how the it is going to be used

2. The technologys's puporse of use
3. How it actually applies

Kocatürk (2013) states, that the purpose of inventing new technology can be quite different in its use in architectural discipline (Kocatürk, 2013).

Lawrence Sass, director of the Digital Design Fabrication Group (MIT's Digital Design Fabrication Group) of the MIT Department of Architecture, talks about three important features of digital fabrication in architecture (URL 4):

1. Digital fabrication design connects computational modeling and physical production.
2. Design requires that many representations of an idea be produced in the process. At this point, digital fabrication allows architects to quickly test many options physically.
3. With the use of numerical design and fabrication, it acts as a bridge between materials, form production and complex computational processes.

Although the history of digital fabrication tools and techniques in the modern sense dates back to the 1960s, the use of digital fabrication for architecture dates back much closer. Especially in the field of architecture, digital fabrication comes to the fore in the physical world.

As a result, William J. Mitchell (2001) "Architects draw the buildings they can build and build the buildings that they can draw". Digital fabrication in the exploration of possibilities can be a new tool.

2.2 Important Steps in the Development of Digital Fabrication

Pease (1952) stated in 1952 that MIT's Servomechanism Laboratory was designed specifically for the purpose of developing numerical fabrication tools specifically for aerospace and space engineering discipline, for producing faster, more precise and high quality of complex geometry machine parts (Pease, 1952).

The use of digital fabrication tools in the discipline of architecture is based on a much more recent history. The first examples are the production of models in architectural offices

(Streich, 1991) and the restoration of complex geometrical building elements in the restoration of historic buildings (Kolarevic, 2001).

According to O´Neill (2014), the basis of numerical fabrication is based on three basic technologies developed. The first one is the CNC, which makes it possible for computers to control the fabrication machines in the 1950s, the second is the computer-aided design software (CAD), which is developed to enable the drawings to be made in a digital environment, and the third is the 3D printer technology, which enables the generation of digital designs that emerged in the 1980s as concrete models (O .Neill, 2014). The combined use of these technologies has enabled digital designs to be physically generated and tested by precision rapid prototyping. Rapid prototyping has enabled the physical production of the scale in a digital environment, even if the design is done properly, even if it has a very complex geometry.

Neil Gershenfeld (2008) thinks that the intellectual developments starting from the 15th and 16th centuries, as well as the important developments in the Industrial Revolution and computer technology, are important for the digital fabrication to reach today's level. According to Gershenfeld, the birth of digital fabrication was directly influenced by the humanistic thinking in the Renaissance period and the results of the use of steam power by the use of iron and steel in the machinery industry. The development of computers, such as the Industrial Revolution, played a crucial role in the development of digital fabrication (Gershenfeld, 2008).

Part of the Digital fabrication tools are the computer controlled hand-held machines, such as the CNC milling machine (Pease, 1952); Like 3D printers, some of them have been developed on the basis of digital fabrication from the very beginning (Lipson & Kurman, 2013).

In this part of the thesis, important steps taken in the process from the birth of digital fabrication to the present are examined.

2.2.1 Renaissance and Industrial Age

According to Neil Gershenfeld (2008), it is necessary to look at the 15th and 16th century Europe in order to understand the intellectual development of the digital fabrication as well as the technical development. At that time, there were two important developments in the field of painting. The first is the development of oil painting technique; the second one is the emergence of perspective rules. Gershenfeld believes that it is important that brave trials of the painters of the era are important in the realization of these innovations. The guilds determined the resources and working standards of the painter who was seen as a craftsman at that time. For this reason, the painters had to strictly follow the strict rules laid by the guild. Instead of reflecting their own intellectual and artistic insights, these painters produced their work in a certain, stereotyped way, like a carpenter. Apart from the limitations of the guild, the difficulty was that orders were ordered by the Church. The works, most of which are religious-themed, are described in detail beforehand and the required qualifications are specified in the contract (Gershenfeld, 2008).

The way out of the guild system's for talented painters was to work for private customers. Families such as Medici, who engaged in trade and the bourgeois class, began to give orders to people on human-centred subjects, not for religious reasons, but with personal interests. According to Gershenfeld (2008), the craftsmen became an artist thanks to the families and classes who had an intellectual interest in art. Although the general masses were still very much attached to the church, the bourgeois families supported the universities and started to teach basic sciences (liberal arts) in university. Within the scope of basic sciences, *Quadrivium*, consisting of geometry, arithmetic, astronomy and music, and *Trivium* lessons consisting of grammar, logic and speech were introduced. The basic sciences were not exactly the opposite of church conservatism, and the word u “art” was more about expressing specialization in the seven branches of the Basic sciences. However, it was an important step in the development of humanistic understanding. According to the intellectual understanding of the basic sciences, the act of construction was not as valuable as the idea development, and the construction was seen as lower in the class, at the level of artes illiberales, but rather in the pursuit of economic gain rather than artistic value. With the separation of art from the craft, the existing construction skill was considered only as mechanical production. This artificial distinction led to the emergence of a mass unskilled labour force in the Industrial Revolution, with the deterioration of individual capabilities.

Renaissance architecture was also influenced by this change. As Richard Garber (2009) pointed out, Leon Battista Alberti tried to establish the theoretical background of the concepts of art and construction in the scientific framework (Richard Garber, 2009). In his book *De re Aedificatoria* (On the Art of Building/Ten Books on Architecture), which Alberti wrote between 1443-1452, stating that architecture is one of the branches of all humanist art, he defined architects as intellectual and the profession of architecture as the highest of the professions. In a nutshell, Leon Battista Alberti distinguished the design from the act of constructing an intellectual action in *De Re Aedificatoria* (Strehlke, 2009).

The use of iron and steel in the transition to the Industrial Revolution led to the efficient use of steam power. With the mass production of machines in large quantities, the unemployed craftsmen migrated to the cities and started to work as operators to use machines. Gershenfeld (2008) said, that automated machine can do a lot of work, but at the same time, the craftsman who was able to do a lot of work in the past, turned into only one operator. It has become the job of specialized engineers to think about how to do something with the introduction of automation systems into the production area (Gershenfeld, 2008). Similarly, Agkathidis (2011) stated that the physical changes created by the Industrial Revolution in the urban fabric, in the fabrication systems and in the work organization are deeply embedded in society and culture. Although the mass-scale production lines at the mills increased the yield, the work of the craftsmen was reduced due to the need for repetitive tasks in the production process. In other words, with the use of machines in the workforce, the effect of human beings is reduced and the craftsmen are replaced by the working class working inexpensively (Agkathidis, 2011).

According to Goncalo Castro Henrique´s (2009), traditional craftsmen have developed their own knowledge and skills in the field of production up to the Industrial Revolution. With the realization of the Industrial Revolution, mass production dominated the understanding of production, and this knowledge and skill of craftsmen lost their old value.

In the 18th century, the French engineer Joseph Marie Jacquard invented a programmable weaving loom and first appeared in Paris in 1801 (Figure 2.2) (Gershenfeld, 2008; Llach, 2015). Jacquard's weaving loom is seen as an important step in the production process.

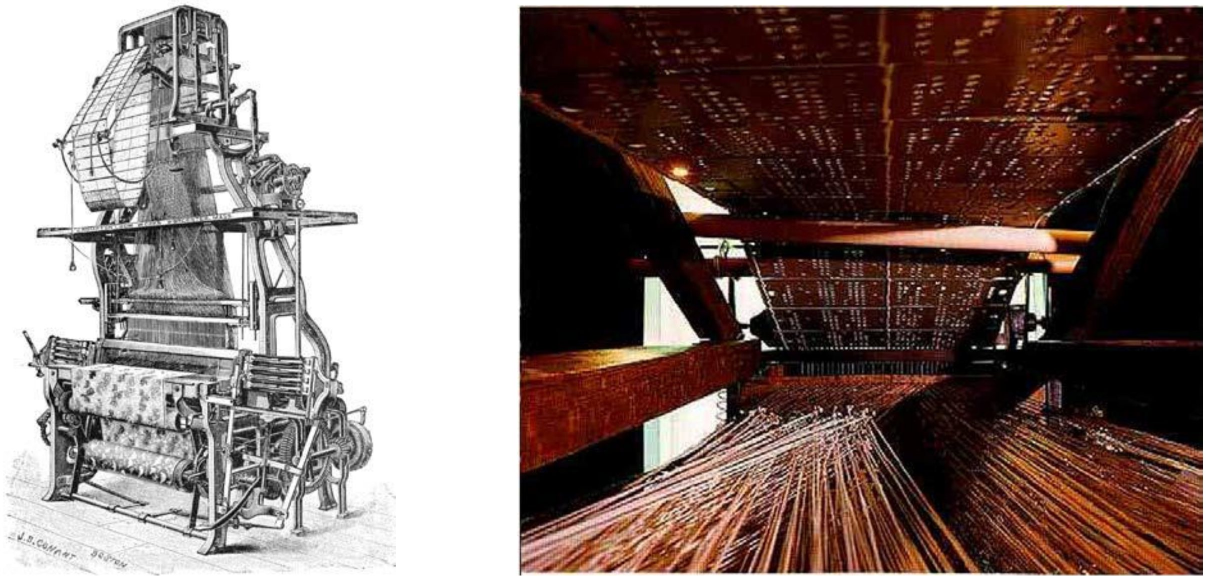


Figure 2.2 Jacquard's Weaving Loom drawing (left) and the perforated card that runs the loom (right) (Kopplin, 2002).

The working principle of Jacquard´s machine is based on the movement of each needle in the weaving loom according to a pre-made card that defines the design pattern. If the the card has a hole in the woven needle the needle moves into the hole, but if the card has not a hole, the woven needle does not move. According to the order of the holes on the card in the process, the fabric is woven according to the pattern defined in the card (Llach, 2015).

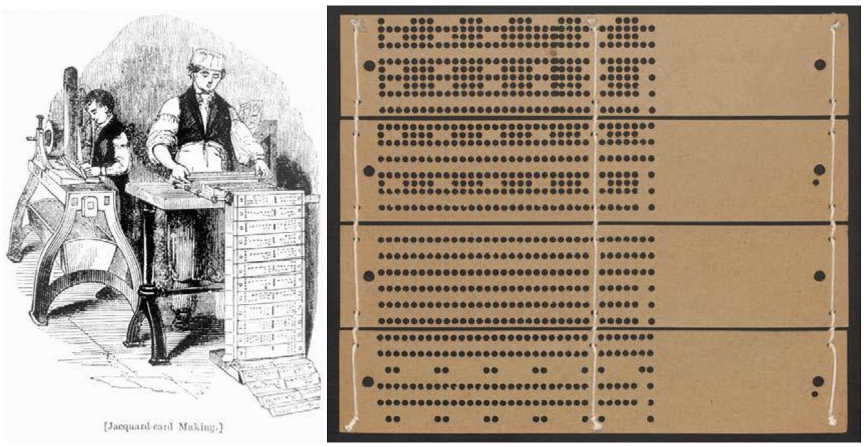


Figure 2.3 Preparation of cards for Jacquard's Loom (left) and an example of a punch card (right) (Kopplin, 2002) (URL 5).

The preparation of these perforated wooden cards with a rope and forming a long row is an important issue in itself (Figure 2.3). Eventhough the production process requires a different time, effort and cost for the preparation of the punch cards, Jacquard's invention has given great comfort to the business owners. Since the weaving machine works according to the given cards, there is no need for operators using the machine (Kopplin, 2002).

2.2.2 Invention of Numerical Milling Machine at MIT

In Alan Turing's (1937) "On Computable Numbers with an Application to the Entscheidungsproblem" essay, in 1928 he investigated the question "Could it be possible to develop a certain procedure to know whether a mathematical theorem is at least theoretically, provable?" by the mathematician David Hilbert. Alan Turing has developed the tool known as the Turing Machine to clarify the concept of the procedure in its work. This machine has a tape that stores instructions and data. A headline moving on the band has interpreted them according to a set of fixed rules by reading the instructions. Then he entered new data on paper tape (Gershenfeld, 2008). This can be regarded as the first example that a computer produces directly in the physical world, even if it is at the level of processing information.

In the 1940s, the mathematician Von Neumann questioned the question *What would happen if the computers could transform the external physical world in the same agility as the digital world within them?* and proposed a theoretical model called cellular automata. According to this model, a universal constructor and a computer (universal computer) will have self-reproduction feature (Gershenfeld, 2008). In this sense, Von Neumann imagined the possibilities of computers in the physical world.

Figure 2.4 The user on the far right of the photo works on The Whirlwind Computer's 16 inch console (URL 6).

The first multi-purpose programmable computer, the Whirlwind Computer, was built in the Servomechanism Laboratory at MIT between the years 1945-1951 during the same period as Von Neumann's theoretical work. Developed for the operation of flight simulations, The Whirlwind is designed to respond to real-time inputs. A built-in display is also included in Whirlwind to see the data coming from the computer instantly (Figure 2.4). Experts working with Whirlwind thought that a computer could control other tools than display on the screen. In 1952, Whirlwind was connected to an industrial milling machine and used for the production of complex aircraft parts. Thus, for the first time in history, machines using digital data produced machine parts (Gershenfeld, 2008).

The operators played an important role in the production of parts before the fabrication tools were under computer control. Operators first took out a template in a 2-dimensional plane, then passed over and through the machine over and over again to shape the part. This process was quite labour-intensive and time-consuming (Llach, 2015). According to Gershenfeld (2008), when the computer controls the milling machine, the complexity of the parts to be produced depends on the capacity of the programs instead of the manual skills of the people (Gershenfeld, 2008).

Both Jacquard's weaving loom and the first developed CNC milling lathe have obtained the information that provides numerical control to produce physically from the perforated paper tapes (Llach, 2015). Pease (1952) stated that for a typical operation on a digital milling machine, a 3-meter perforated paper tape can run the machine for about one hour.The first CNC milling machine was developed in 1952 in the MIT laboratory and consists of two main units. The first one is the milling machine and the second is the manager who translates the

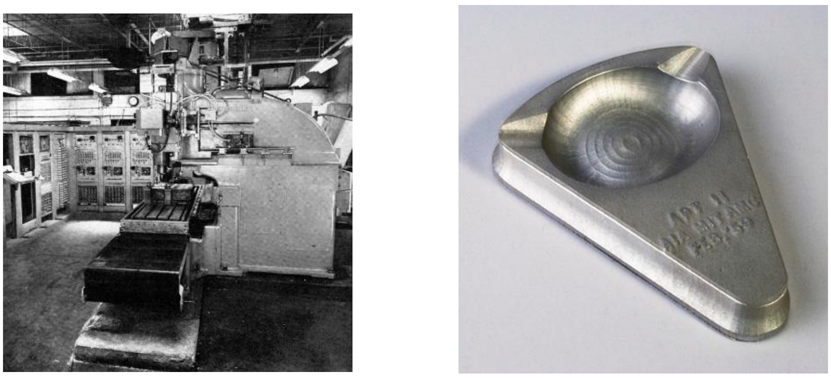


Figure 2.5 *A CNC milling souvenir object (right) in the MIT Museum (URL 7) produced on this machine.*

data on the punched paper tape into the language the processing devices understand and transfer them to the machine as the operation commands (Figure 2.5). The manager has three basic units: data-input system (data-interpreting system) and decoder servo-mechanism (Pease, 1952).In the 1950s, engineers at the MIT Servomechanism Laboratory sought to replace the production pattern and the operator's task with numerical data that the machine could read. Gordon S. Brown, chief executive of the Servomechanics Laboratory, stated in his notes the following:

The aim of this research is to design the milling machine that can produce machine parts surfaces with special curvature or irregular lines automatically without a special model, template or other reference parts. Instead of producing reference surfaces, they would like to use the numerical data representing the desired surface as machine coordinates. (Aranda & Lasch, 2006)

In the 1950s, James O. McDonough and William M. Pease, who worked on the numerical milling machine at MIT, developed a new route system (incremental-coordinate continuous-path system). The route to be followed by the milling machine is defined by straight lines in 3-D space. With this approach, a straight cut of any length could be controlled by the coordinate, direction and rotation speed of the head. In practice, this means that the amount of data is not related to the size of the product, but is related to the geometric complexity of the product. The system made possible by commands and algorithms has assumed the human operator's physical and intellectual task with mathematical certainty and symbols that the machine can read (Llach, 2015).

These developments in the Servomechanism Laboratory raised the following question in the 1950s: How can designers describe the ways in which computers produce parts? CAM (Computer Aided Manufacturing) and NC (Numerical Control) with CAD (Computer Aided Design) developed. APT (Automatically Programmed Tool), the first of this software, was run in 1955 on the Whirlwind computer. Whirlwind and a machine for the first time in the physical world moving in three dimensions to reach a level that can produce something physically. The APT software is a representation that focuses on the principle of machine operation, in other words, it defines the steps that the milling machine will follow while working. (Gershenfeld, 2008).

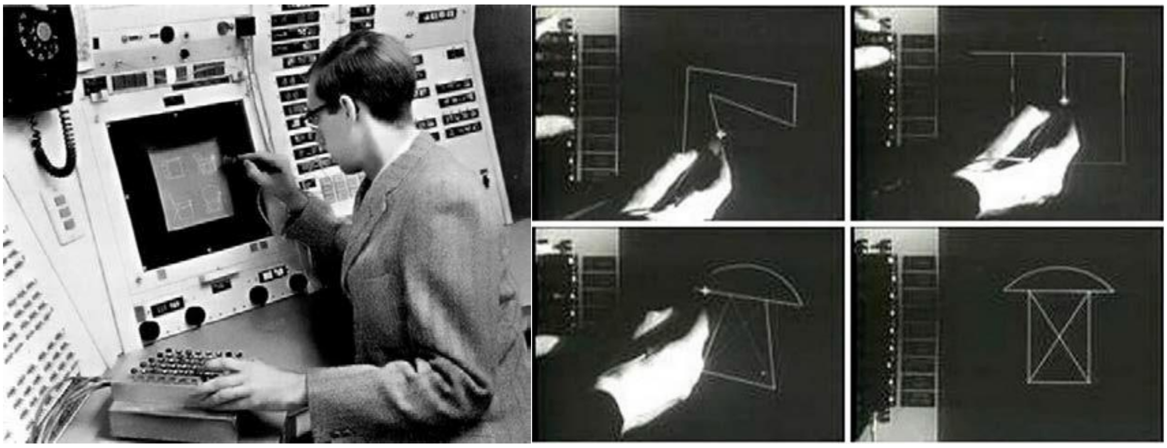


Figure 2.6 Ivan Sutherland SketchPad drawing (left) and using Light Pen to perform drawings in digital form (right) (URL 44)

The use of computers for design purposes was made possible by the TX-0 developed between 1953 and 1957 at the MIT and by the TX-2 which was put into service in 1958 as the next model. In 1960, Ivan Sutherland (1964) designed the Sketchpad land program using the possibilities of the Lincoln TX-2 computer and the light pen drawing tool. Sketchpap is the first computer aided design (CAD) program designed for design purposes in digital media (Figure 2.6) (Gershenfeld, 2008; I. Sutherland, 2012; I. E. Sutherland, 1964).

2.2.3 Emergence of 3D-Printers and Rapid Prototyping

Traditional fabrication tools usually process raw material in the principle of drilling, cutting, engraving. The first digital milling machine developed in MIT in the 1950s is working in the core principle. A big breakthrough in numerical fabrication was realized in the 1980s with the invention of 3D printers working on an additive principle. Between the years 1980-1988 a lot of research has been done on 3D printers and 3D printers have been developed that work with different methods (URL 8). The invention of the 3D printer is controversial because five people or groups from different places claim the rights for inventing it.

Hideo Kodama, who has a doctorate in applied physics, developed single-beam laser curing technology during his studies at “Nagoya Municipal Indutrial” in Japan and applied for a patent for rapid prototyping system in Japan in May 1980. Kodama could not obtain full patents due to economic disability (URL 8, URL 9). Hideo has produced a house model for the first time in a 3-hour printer in 1 hour 40 minutes (Figure 2.7)

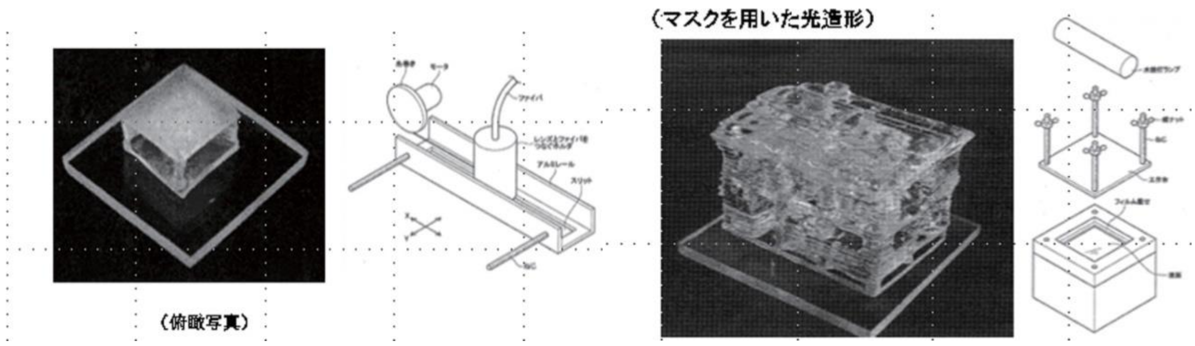


Figure 2.7 Hideo Kodama´s 3D printed house (URL 9).

Another development of 3D printers took place in France between the years 1984-1986. In 1984, the French mathematician Alain Le Méhauté sought to produce a concrete object with fractal geometry to prove his theories on fractal geometry. In 1984, due to the complex geometry of the fractal object, it was unable to perform this production with any tool. The French team, which consists of Alain Le Méhauté, Olivier de Witt and Jean Claude André, has started a machine development project that produces fractal objects. The first object they produced with the 3D printers they developed was a spiral staircase. The steorlithography machine they developed was patented by the French Patent Institute in January 1986, but due to economic insufficiency, development work did not continue (Figure 2.8) (URL 10).

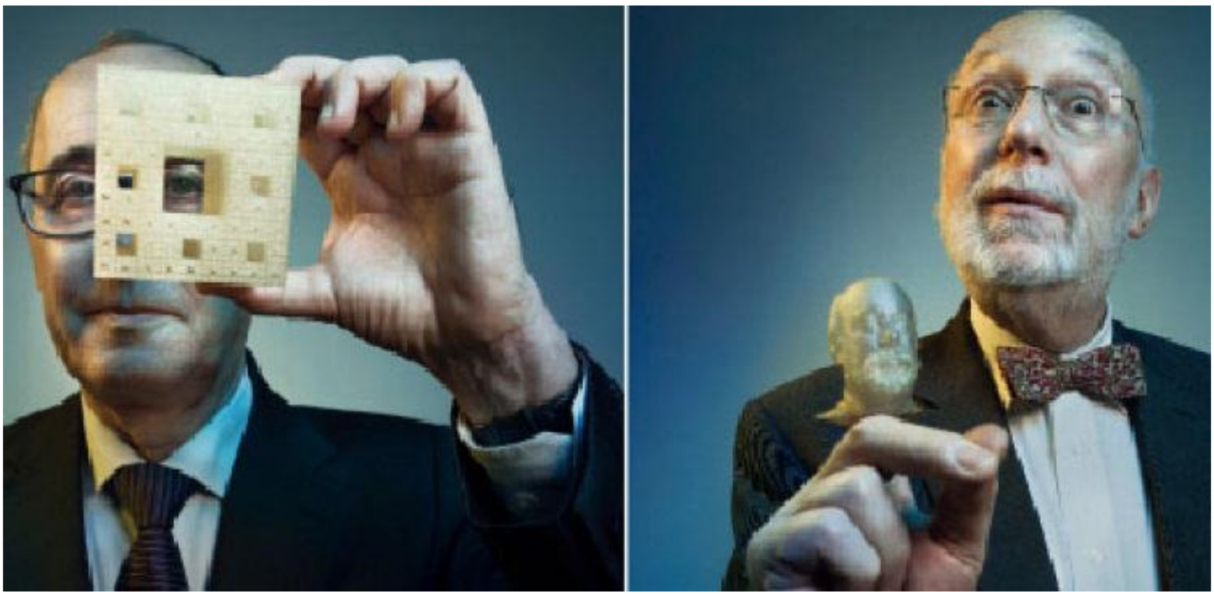


Figure 2.8 Alain Le Mehaute and Jean Claude-Andre (URL 10).

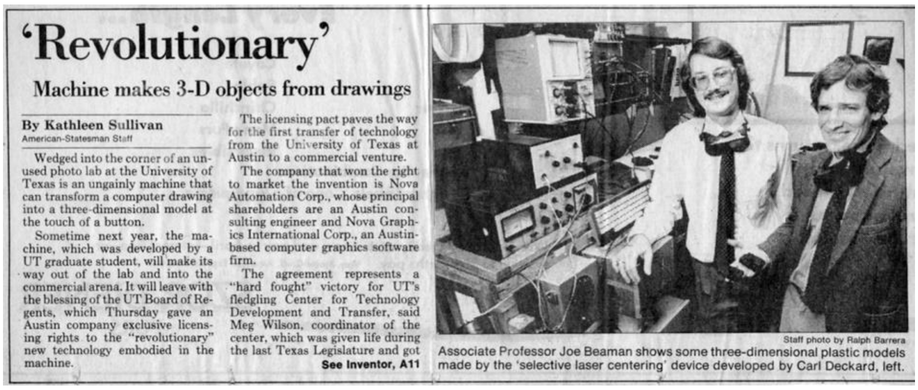
The third person in the development process of 3D printers is Chuck Hull. Hull, who did his master's degree in Physics Engineering, succeeded in printing a concrete 3D object from digital data in 1983. In 1986, Chull Hull set up the world's first 3D printer company 3D Systems. In

1987, he launched the first commercial 3D printer *the SLA-1 Stereolithography* (SLA) (Figure 2.9) (URL 11).

Figure 2.9 3D System manufactured by 3D System in 1983 and the first commercial 3D printer called The SLA-1 Stereolithography (SLA) Printer (URL 11).

Another important contribution of Chuck Hull to digital fabrication is the *.STL* (Stereolithography) file format based on the principle of slicing the numeric model in addition to the hardware it has developed. This file format is supported by many 3D design softwares (Chua, Leong, & Lim, 2003).

Another kind of 3D printer, the Selective Laser Sintering Printer (SLS), was invented by Prof. Dr. Josef Beaman and his assistant Carl Deckard in 1986 during his doctorate at the University of Texas in Austin (Figure 2.10) (URL 12, URL 13).



'Revolutionary'

Machine makes 3-D objects from drawings

By Kathleen Sullivan
American-Statesman Staff

Wedged into the corner of an unused photo lab at the University of Texas is an ungainly machine that can transform a computer drawing into a three-dimensional model at the touch of a button.

Sometime next year, the machine, which was developed by a UT graduate student, will make its way out of the lab and into the commercial arena. It will leave with the blessing of the UT Board of Regents, which Thursday gave an Austin company exclusive licensing rights to the "revolutionary" new technology embodied in the machine.

The licensing pact paves the way for the first transfer of technology from the University of Texas at Austin to a commercial venture.

The company that won the right to market the invention is Nova Automation Corp., whose principal shareholders are an Austin consulting engineer and Nova Graphics International Corp., an Austin-based computer graphics software firm.

The agreement represents a "hard fought" victory for UT's fledgling Center for Technology Development and Transfer, said Meg Wilson, coordinator of the center, which was given life during the last Texas Legislature and got

See Inventor, A11

Staff photo by Ralph Barrera

Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

Figure 2.10 Newspaper article published in 1987 to promote the SLS machine (URL 13).

The fifth person who can be counted in 3D printers is Scott Crump. Crump developed the Fused Deposition Modeling (FDM) technology in 1988, based on the principle of melting and pushing a rigid thermoplastic material (filament) in the print nozzle, and the movement of the nozzle in this way. In 1992 he produced the first functional FDM 3D printer and soon after he founded the company Stratasys. By 2017, nearly half of the 3D printer industry is based on

FDM technology (URL 14, URL 15). The company, which provides service for industrial type production, started to serve MakerBot and also started to serve small business and low consumer group (Figure 2.11) (URL 16).

Figure 2.11 Stratasys founder Scott Crump (URL 16, URL 17).

3. Digital Fabrication Tools

As explained in the chapter *Important Steps in the Development of Digital Fabrication*, almost all of the digital fabrication tools were developed outside the discipline of architecture. In other disciplines, they have been transferred to the discipline of architecture much more recently. This section briefly explains the numerical fabrication tools used in architectural research groups. It should be kept in mind that all of these tools work using digital data in computer control.

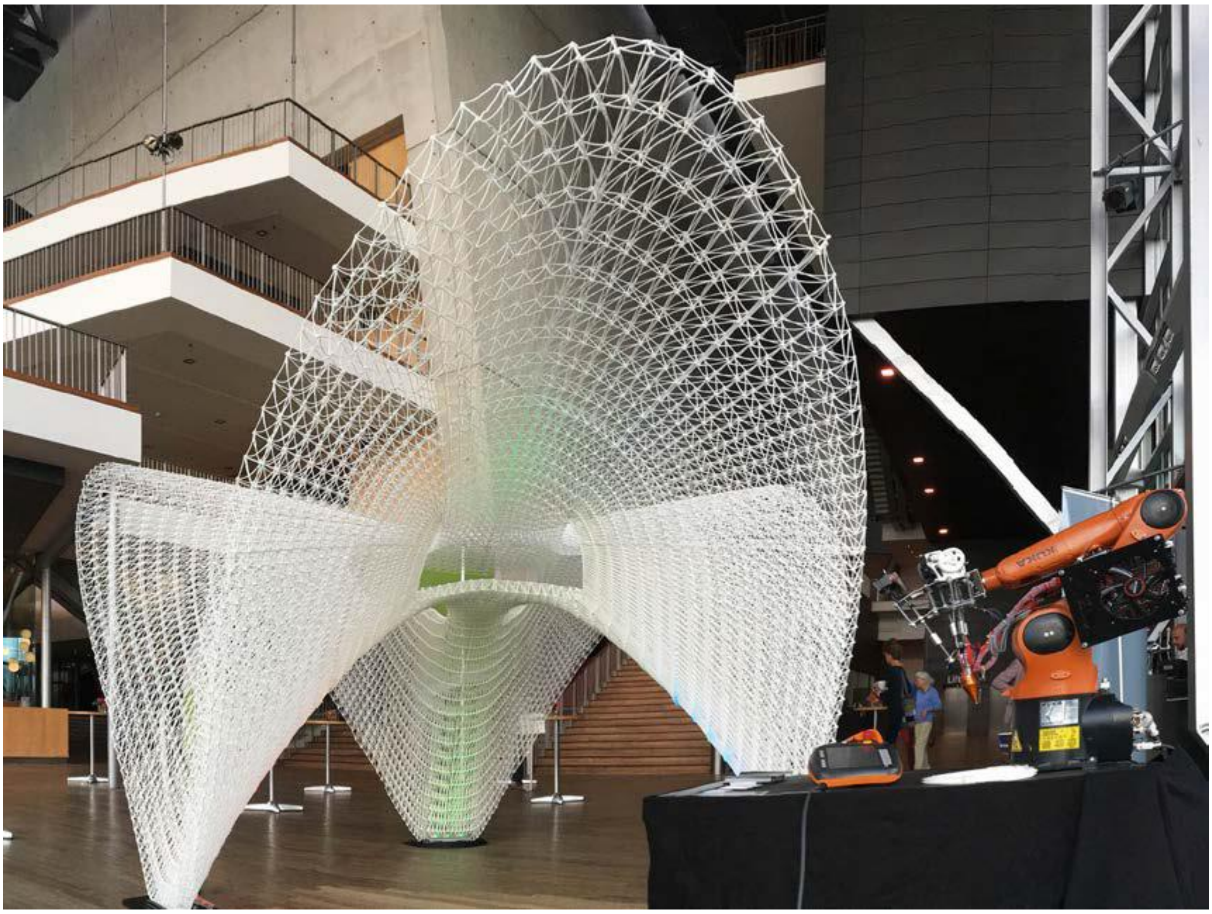


Figure 3.1 Designed by Ai Build, the Daedalus Pavilion was built using robots with 3D printing capabilities (URL 17).

Digital fabrication tools such as 2D laser cutter have been used by architects in architecture offices for a longer period and have been widely used by architects; robot arm, unmanned aerial vehicle (UAV), as well as some of the more recent and experimental level is used. According to the data obtained from the literature and interviews with architects, it is seen that the numerical fabrication tools commonly used in the architectural design process are 2D laser cutter, numerical milling machine and 3D printer. In addition, there are also studies using robot arm and unmanned aerial vehicle (UAV) at experimental level.

Digital fabrication tools are developing and diversifying at an increasing rate though many scientific and technical researches. On the other hand, it can be seen that some numerical fabrication tools lost their importance as of 2017 and left their place to other tools within this technological speed. There are various classifications made in order to understand the working methods of these vehicles more easily and to understand their relations with each other in the large family of digital fabrication tools. It should be kept in mind that these classifications can change, expand and expand with new tools developed in the future.

According to Moritz Hauschild and Rüdiger Karzel (2011), numerical fabrication tools can be divided into four basic groups according to their working methods. These methods are: generative procedures, subtractive procedures, formative procedures and joining procedures. Hauschild and Karzel say that the use of joining procedures in architecture is almost no use (Hausschild & Karzel, 2011).

Within the scope of the thesis study, the current technological developments have been evaluated and a classification has been proposed for numerical fabrication tools (Figure 3.1). Based on the classification of Moritz Hauschild and Rüdiger Karzel (2011), a recent recommendation was made for this classification to be made in the recent history and to be more comprehensive. In the proposed classification, it is thought that the robots can enter a separate classification under a title. Although industrial robots are almost always meant to be called robots, it is considered appropriate to include drone underneath (Picon, 2014; Willmann et al., 2012). Works for the construction of one-to-one scale buildings using special robots such as ArchiUnion can also be evaluated under robots, although they are still in the concept phase (Yuan, Leach & Menges, 2017).

While all of the digital fabrication tools provide the physical production of the numerical data, otherwise, the scanners that translate the existing physical object into numerical data are included in this classification as a sixth group. Especially in the architectural design process of the browsers, it is seen that it supports the architects to improve the design by increasing the flow from physical to physical to digital to physical.

3.1 Additive Manufacturing

Numerical fabrication tools working with additive or generative procedures enable the production of components in the desired form by combining the amorphous small raw materials with physical and chemical means. Today there are about 50 types of productive vehicles working according to different methods (Hauschild & Karzel, 2011).

3.1.1 3D Printer

The 3D printers enable the design of the digital media to be produced as a 3-dimensional physical object quickly, without the need for traditional methods, using CAD data. The production of 3D printers is generally called rapid prototyping, rapid procedures, layered manufacturing, and solid freeform fabrication.

All rapid prototyping methods start with the production of horizontal cross-sections of the design in digital media. Then each numerical layer is completed with the amorphous, raw material, the head of the fabrication tool, printing or processing the 3D physical product (incrementally) in layers using laser light, heat or chemical processes (Dunn & ebrary, 2012; Hauschild & Karzel, 2011; Kolarevic, 2004). 3D printers are among the most widely used by architecture offices among digital fabrication tools (Figure 3.2) .

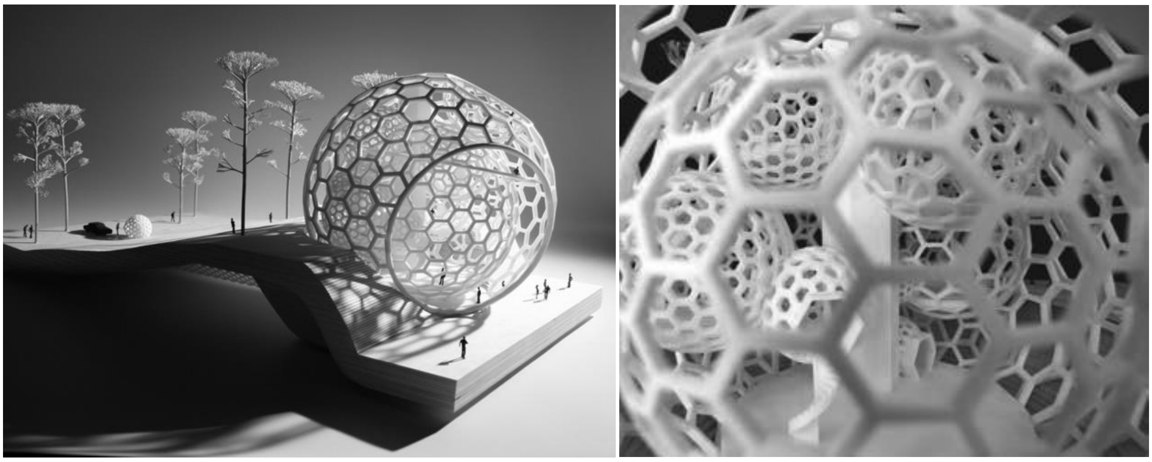


Figure 3.2 Villa Rotterdam Project designed by ZUS Architecture (URL 18)

A fine semantic distinction is found between rapid prototyping and rapid manufacturing. While rapid prototyping refers to the production of more scale architectural models, rapid production is used to express the production of 1: 1 scale results products directly (Hauschild & Karzel, 2011).

As with the majority of digital fabrication tools, digital data for 3D printers should be ready without going into production (Ryder et al., 2002). Once the digital design data is transferred to the 3D printer, the user cannot take any action on the process.

3D printers range from table-top compact models to large industrial sizes (Figure 3.3).

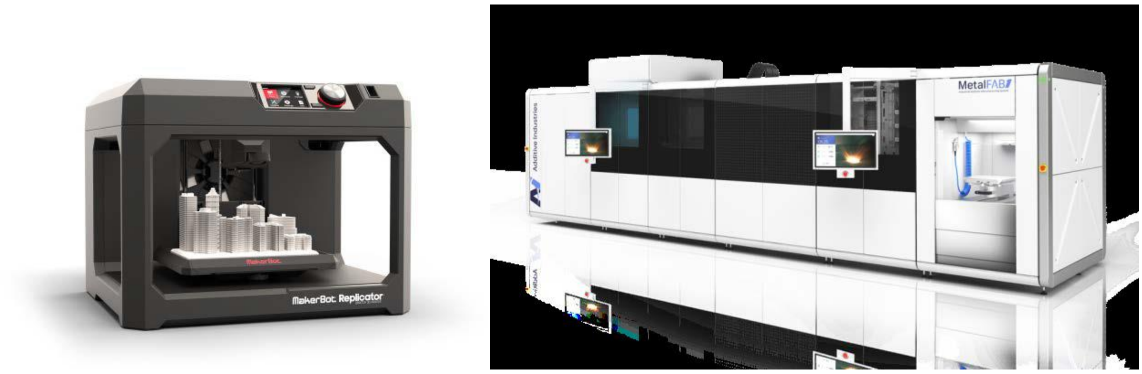


Figure 3.3 Examples of desktop-scale and industrial-type 3D printers (URL 20, URL 21).

The most common file format for these technologies is *.stl* (Hauschild & Karzel, 2011). A wide variety of materials can be used with 3D printers. (Dunn & ebrary, 2012; Kestelier, 2011; Kolarevic, 2004). Mainly these materials are various plastic derivatives and metals. Stainless steel, aluminium, Inconel, titanium, fiberglass, HSHT (high temperature) fiberglass, onyx (micro carbon reinforced nylon), carbon fibre, nylon, Kevlar materials such as 2017 can be printed in 3D printers (URL 22).

In 2017, it has become possible to print on clay material from 3D printers. Designer Oliver Van Herpt has designed and manufactured his own 3D printer and developed 6 clay vases in 2014. Herpt: “For me, design is about creating new shapes and exploring new possibilities through the development of tools. By studying the limitations of what can be made and improving processes step by step, I'm essentially designing the manufacturing technology itself.” (Figure 3.4) (URL 23).

Figure 3.4 Vases made of clay with a three-dimensional printer (URL 23).

Bernd Streich (1991) states that two problems should be discussed if architectural models are to be produced using stereolithography method in *"Creating Architecture Models by Computer-Aided Prototyping"* which is one of the first articles in which rapid prototyping is examined. Although these questions have been asked for *stereolithography*, they are actually valuable for thinking about all 3D printers. First, he asked, *What new possibilities does Stereolithography offer to architects, and what preconditions do existing CAAD systems have to meet for the use of this technology?* This question points to the more technical side of 3D printers. As of 2017, almost all digital design software can produce file extensions that support these tools as a file format. When evaluated in terms of printed products, evaluation criteria such as resolution-sensitivity, size, speed-time, material, cost and user interface come to the fore (Ryder et al., 2002). Nowadays, it can be said that these criteria develop quite rapidly. Streich (1991) asked the second question *What important architectural design criteria should be considered and critically evaluated for stereolithography?* This question points to the contribution of 3D printers to the design process. One of the most important opportunities that 3D printers offer to architects is that they support the development of designs other than Euclidean Geometry not only in digital environment but also in the physical world (Peters & De Kestelier, 2008; Strehlke, 2009; Whitehead & Peters, 2008).

Streich (1991) states according to the design stages that there are three levels of architectural models. These are models of feasibility, planning and delivery (final project). The scale, size, cost, time, material, level of complexity and sensitivity are the criteria that determine the characters of these models. In view of the studies by Peters et al. (2008) and Strehlke (2009), the use of 3D printers appears to be efficient for the production of all three model types. Especially if the project has a complex geometry form, the use of 3D printers is almost the only choice for architects (Peters & De Kestelier, 2008). Kolarevic and Dunn (Dunn & ebrary, 2012; Kolarevic, 2004) likewise stressed that rapid prototyping allows designers to develop models of complex, curvilinear geometry, allowing design to be developed without being bound to the digital environment alone. In addition to the production of architectural models in architectural offices, 3D printers also contribute to architectural detail development, installation, pavilion and industrial product scales.

Lipson and Kurman (2013) listed the possibilities of 3D printers in the field of production in the book *Fabricated the New World of 3D Printing*:

1- It does not require additional cost for the production of complex geometries. As the geometric complexity of the product increases in the traditional production methods, the cost of production increases, but the cost in 3D printer technology is not related to the geometric complexity. The production of a complex ornament or double curvature geometry does not require more time, labor and cost than printing a rectangular prism.
2- It is possible to produce a wide variety of geometries with a single machine. While traditional fabrication tools produce a series of products, a 3D printer can produce very different products.
3- It does not require post-production assembly. Parts produced in pieces in the mass production concept are assembled in a production line in an additional process or workmanship. On the other hand, the 3D printer takes place in a single operation during the production process.
4- Provides instant production and delivery in local area. Whenever a product is needed with a 3D printer, it can be produced at that location.
5- Offers unlimited design space. The capacity of a craftsman to produce form is proportional to the instrument options available to him. For example, a conventional woodworking lathe can produce only cylindrical objects; a mold machine can only produce objects in the form of a mold. In a 3D printer, the production capacity of many types of vehicles is combined.
6- It does not require special talent. A traditional craftsman needs to work for years to get the skills he needs. This special capability is reduced to a minimum of 3D printers.

7- It offers compact, portable fabrication. Nick Dunn (2012) states that the biggest problem of rapid prototyping is related to the small size of the products produced. Industrial high-end 3D printers can produce up to 1 meter size (URL 24). If the print head is outside the production bed with a free-to-move arrangement, the physical production volume does not have a dimensional limitation.

8- Less consumption per product. The loss of material is very low, especially when faced with traditional metal production methods. Besides, it produces very little waste material.

9- It can be produced with a wide variety of materials. Many kinds of plastic and metal material can be produced.

10- Offers high precision production. The resolution of 3D printers has decreased to micron sensitivity.

In addition to these, Hauschild and Karzel (2011) emphasize the ability of the material to support itself without the need for any structure, the subsequent dyeing and cutting of the produced product (Hauschild & Karzel, 2011) . Gershenfeld (2012) emphasizes that it is possible to produce internal structure parts with 3D printer technology. For example, the production of a wheel and shaft before the 3D printers would only be possible by combining each of them with separate assembly and produced in separate parts. The 3D printers enable the moving parts to be produced at one time. In this way, the wheel and shaft can now be produced on one machine at a single time (Gershenfeld, 2012).

Although it is based on the principle of producing 3-dimensional physical object on the basis of 3D printer technology, there are various types of materials and methods due to some differences in the method. The most common and important ones are Stereolithography - SLA (STL), Selective Laser Melting - SLM, 3DP, Fused Deposition Modeling - FDM, Selective Laser Sintering - SLS (Dunn & ebrary, 2012; Hauschild & Karzel, 2011).

According to the survey conducted by The Architectural Review, a quarter of architects in the United Kingdom and the United States stated that they had 3-D printers in their offices (URL 10). Gershenfeld (2012) stated that in a fabrication laboratory, 3D printers were used on average in 1/4 of jobs (Gershenfeld, 2012).

According to Lipson and Kurman (2013), 3D printers offer a fascinating opportunity for people to design and produce. According to them, in the future, 3D printers and people will have the opportunity to design and manufacture in modest budgets as well as designers with great opportunities and big production companies. In such a future people will be able to produce what they need at the time and place they want (Lipson & Kurman, 2013).

3.1.2 Large Scale 3D Printer

In the last 20 years, materials such as ABS, carbon-reinforced polymamide, polycarbonate and stainless steel and titanium can be used in rapid prototyping technology. Thanks to advances in the use of materials in rapid prototyping technology in the field of engineering and industrial design, there has been a transition from prototype-intended production to the production of real products. However, this transition is difficult and limited in architecture. The main reason for this is that the result of architecture is that the products are quite large compared to engineering and other design areas. While there is often no difference in scale between the prototype and the reality of an industrial product, in architecture it is in the range of 1/10 to 1/1000, (Kestelier, 2011).

The founder of Enrico Dini, D-Shape (UK) is the center that develops a 3D printer capable of producing at the first building scale. Enrico Dini describes its goals as building or printing the environment we live in by moving 3D printer technology to the next stage (URL 25). In this method, a space of 6x6x6 m can be produced in 24 hours. With this 3-D printer, the strength of the material determines the boundary of the construction height. Sandstone (sandstone) is used as material in these studies. In the structures produced in this technique, an additional carrier system is not required as long as the strength of the material allows.

Although this printer is 6x7.5x7.5 m in size, it is light and modular and easy to carry. The installation of the printer after moving to the site takes about 2 hours. The printer can print data produced in, .stl 3.6 format with a precision of 0.1 mm (Figure 3.5) (Hauschild & Karzel, 2011).

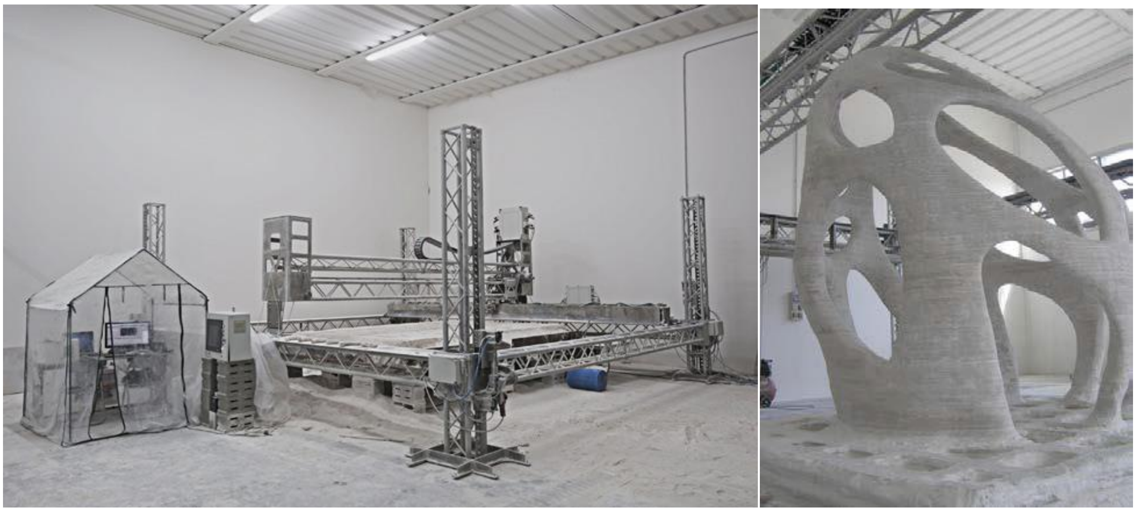


Figure 3.5 D-Shape printing tool and Radiolaria Pavilion (URL 26).

Another important technology in large-scale printing is *contour crafting* developed by Behrokh Khoshnevis in *The University of Southern California*. In the use of the *Contour crafting tool*, the production of the bearing walls takes place in stages. First, the wall is printed as a hollow shell, then the empty interior of the wall is filled by the machine. It uses extrusion to form the wall shell, and pouring or filling to fill the inside of the wall (Figure 3.6) (Kolarevic, 2004).

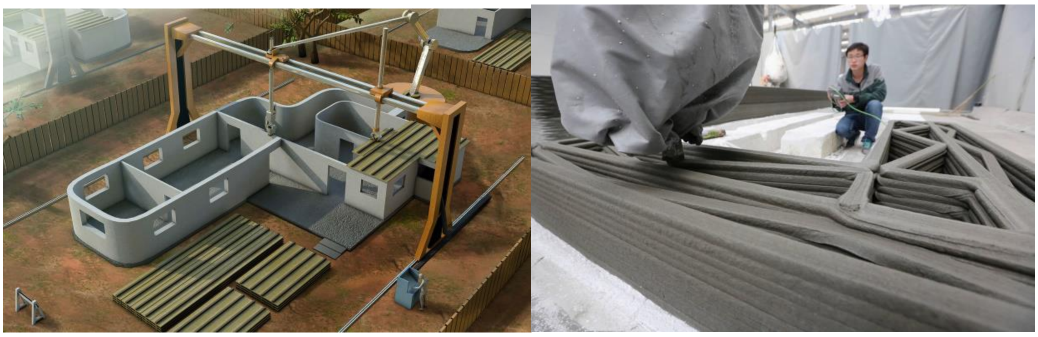


Figure 3.6 Contour Crafting tool and printing moment in the work (URL 27).

3.2 Subtractive Manufacturing

Numerical fabrication tools working with subtractive procedures enable the desired form to be obtained by cutting or milling excess material from a certain volume of solid material. Mechanical, chemical or electrical processes can be used in this extraction process (Hauschild & Karzel, 2011; Kolarevic, 2004). In this method, when the product is obtained, there is a mass reduction since the material is removed. Economic criteria become very important when selecting subtractive methods because of material loss (Hauschild & Karzel, 2011).

3.2.1 CNC Cutting Tools

Various CNC cutting tools such as laser beam and water spraying include two-axis cutting on a plane material. These tools have types such as the cutting head is moving, the product bed is moving or both are moving together (Kolarevic, 2004). CNC cutting tools have three sub-types: CNC laser cutting, CNC jet cutting and CNC hot wire cutting.

CNC laser cutting is now widely used in architecture offices, especially in the production of models (Figure 3.7). Large-scale CNC laser cutting tools are also used for the production of mesh and panel elements on building facades. CNC jet cutting is often used to cut very hard materials in heavy industry.

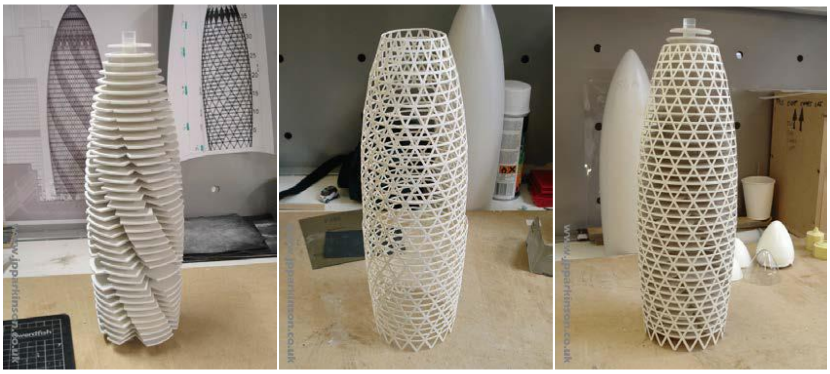


Figure 3.7 Foster + Partners'ın 30 St Marry Axe binası maketinin üretiminde lazer kesici (solda) ve 3 boyutlu yazıcının (ortada) bir arada kullanıma örnek (URL 28).

The CNC hot wire cutting tool cuts styrofoam or similar volumetric materials with a heated hot wire moving under computer control. This method is often used to produce large-scale forms. High precision production is achieved by CNC. With these tools, it is also possible to produce large models of 1: 1 scale. After the production of the form is completed, or GRP Coating or can be used to cover the styrofoam surface and make the product suitable for outdoor use. The waste (styrofoam) material removed from the block can be recycled and recycled. Therefore, it is a very environmentally friendly technique (Hauschild & Karzel, 2011).

3.2.2 CNC Milling

The CNC milling machine works according to the principle of obtaining the desired form by removing the material from the block with a hard and sharp tip rotating rapidly. CNC milling machines have two types of milling and routing. The difference is that milling is more suitable for metal materials and routing for wood and plastic materials. As with 3D printers, CNC milling machines also have a wide variety from desktop small versions that allow models and prototypes to be produced from materials such as wood, foam, to very large models where very hard components such as 1: 1 scale metal are produced (Figure 3.8) (Dunn & ebrary, 2012).

Figure 3.8 Examples of desktop-scale (left) and industrial-type (right) CNC milling tools (URL 55, URL 56).

According to Nick Dunn (2012), the CNC milling machine has two important types of use. The first is to obtain the desired components by engraving from a volumetric material. Architects use this method to produce complex geometries and fluid forms precisely and efficiently (Figure 3.9). The second is that it allows the production of the mold to be used in the casting process, not the component itself.

Figure 3.9 NIO Architecten's The Amazing Whale Jaw bus stop project (left) (URL 29) and foam milling (right) (URL 30).

Milling heads of various types are selected according to desired surface finish, cost, production accuracy and speed (Hauschild & Karzel, 2011). The CNC program controls the vehicle's motion control, tool change, tip rotation speed, etc. The order of the control settings is generally called “tool path” and provides a wide range of instructions to the machine. In this way, the vehicle offers designers a wide range of ways to shape the material. Minor changes in the instruction may result in significant differences in the product. For this reason, especially in 4-axis and 5-axis vehicles, an experienced operator is of great importance (Dunn & ebrary, 2012).

CNC milling tools can be used in architectural offices to produce land and complex geometry building models (Figure 3.10).

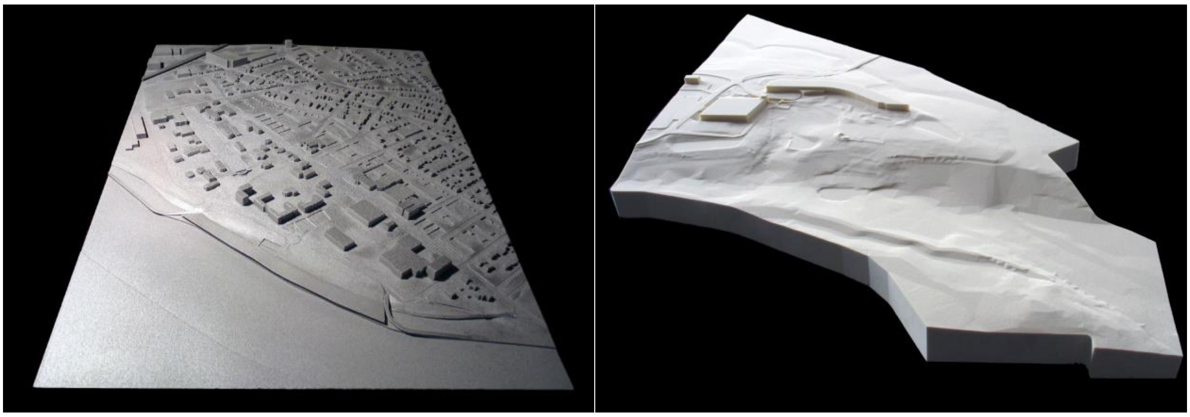


Figure 3.10 Eisenman Architecture (left) and FxFowle Architecture (Right) offices are produced from high density foam in CNC milling and then painted models (URL 31).

The negative aspect of this tool is that production takes too long, causes too much material loss, and the possibility of limited processing in the inner corners of the object (Hauschild & Karzel, 2011).

3.3 Formative Methods

With the mechanical forces applied on the material in transformative procedures (formative fabrication), it is ensured that the desired form is obtained without a mass change. In this method, heat or steam material is generally used to gain flexibility and form more easily. After completing the forming process, the cooled material becomes rigid again (Dunn & ebrary, 2012).

CNC-shaped formatting tools are used to produce complex surfaces in a fully designed manner. These tools usually form materials such as metal, plastic, glass (Kolarevic, 2004). Wood and mineral based materials can also be used (Hauschild & Karzel, 2011).

There are basically two types of formatting process. These (Hauschild & Karzel, 2011):

1- Cold Forming: Process is performed below the temperature at which the crystal structure of the material changes.
2- Warm Forming: Process at the temperature at which the crystal structure of the material changes. The molecular structure of the material changes.

The CNC bending edges, folding tool gives a numerically pre-defined form of unprocessed or semi-finished materials (plates, wires, pipes, etc.). It is used in the production of special carrier elements in architecture and thus prevents costly connections such as welding. The type of material which is decisive for production with these tools is the bending angles which vary according to the type and thickness and hardness of the material. It is important to use the reference marking points (graining) since the components obtained after bending are usually passed or assembled later. In particular, it is important to mark the connection points for installation to be healthy (Hauschild & Karzel, 2011).

CNC punching and nibbling tools with numerical control of the vertical axis of high pressure on the material by moving the drilling head allows the form to change (Hauschild & Karzel, 2011).

These tools can be used in architecture to obtain special textures and forms in facade elements of buildings (Figure 3.11).

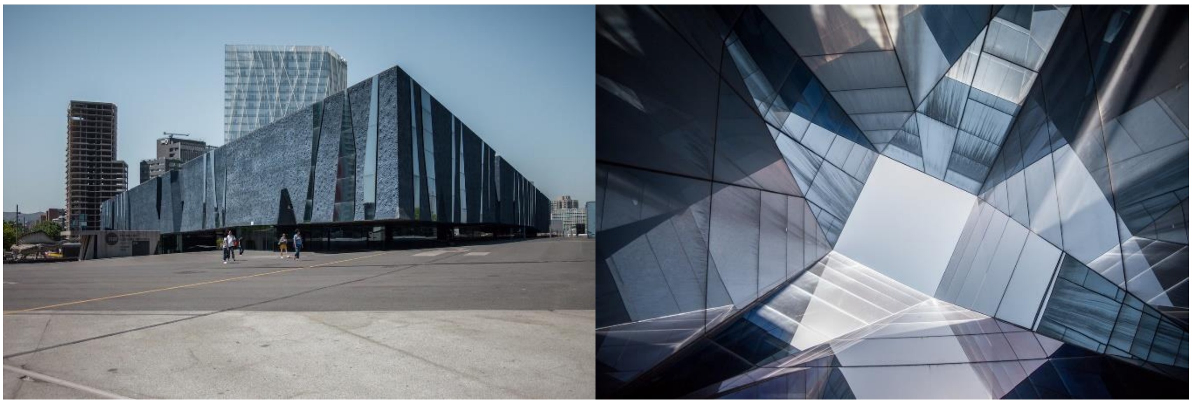


Figure 3.11 Surfaces produced in the Herzog & de Meuron's Forum Barcelona Project using punching tools to achieve the reflection effect of water on the facade elements (URL 32).

3.3.1 Joining Methods

According to Hauschild and Karzel (2011), joining procedures provide a solid and permanent combination of various component parts. Manufactures where the parts are combined with automatic welding can enter this class. This method can be compared to the production of automobiles in the automobile industry on the production line with fully automatic CNC tools (Figure 3.12). There is almost no use in architecture.

Figure 3.12 Fabrication of Tesla Cars with robotic arms (URL 33)

It is debatable whether or not the combining methods are appropriate for architecture because they seek to be unique in every product due to the architectural context. As with cars, most of the industrial products can be diversified by small interventions such as color changes on the production line. The difficulty of the architecture to achieve this is that it works on larger scales and has very large differences with its functional, structural and aesthetic aspects.

3.4 Robotic Manipulation

3.4.1 Robotic arm

The use of robots in architecture refers to robots and industrial robots, although there are often robotic arms. In order to avoid this confusion, in 2012 the definition of International Standards Organization (ISO) can be taken into account. According to ISO 8373 *"The industrial robot is a multi-purpose manipulator that can be automatically or controlled, programmed in three or more axes, automatically controlled, reprogrammed to be used in industrial automation applications"* (Morel, 2014) .

Industrial robots are actually made for mass- production and they are multifunctional machines. They have a wide range of use like load, unload, deburr, laser, bond, assemble and mill (Braumann, 2010) Robotic arms are not developed to perform only one task, instead they can be equipped with almost every tool, which is comparable to human´s hand. In contrary

CNC router with 3-axis are limited in their use, because the can only perform their optimized particular task from above (Yuan et al, 2017).

The robot arm can be considered as a variable function tool of digital fabrication. The end portion of the robotic arm is termed as *end effector*, which can have various functions and can be programmed to perform complex operations. Thanks to these inserts, the robot can perform a wide range of tasks such as moving, placing, milling, welding and scanning. The robot arm is highly articulated, and it is highly advantageous in the production of complex geometry forms thanks to its ability to position itself by accepting the materials to be processed (Dunn & ebrary, 2012). Generally, a 6-axis robot arm is placed on the horizontal movement mechanism and increases the working area considerably. The robot arms operate at high precision and are very suitable for repeated operations, even if they are changing the tool.

Articulated robots are primarily relevant to the construction industry, as they can function as a universal, programmable processing machine. A 7-axis articulated robot is usually a 6-axis robot with a linear drive unit, which increases the working space. Alternatively, the workpiece is moved in the working space of the robot. As the highest possible degree of prefabrication is becoming more and more important in the construction industry, there is great potential for industrial robots to take on complex subtasks. As in mechanical engineering, they can be used in the production of repetitive but varied work processes. These include façade construction, the preparation of wooden components and the reconstruction of natural stone facades in the preservation of monuments. At the construction site, however, the use of robots only makes limited sense, since their mechanics and electronics are too vulnerable and the precision suffers (Hauschild & Karzel, 2010)

Antoine Picon (2014) thinks that working with robots forces architects to think differently; Picon stated that robotic arms in architecture schools are used in surface, texture and structure research. Sigred Brell-Çokcan and Johannes Braumann (2013) are also beyond the CNC fabrication approach of robot arms in architectural education; they think that architecture students can be used in problem solving, geometry and programming education.

According to Picon (2014), we need to look at the modern industrialization period in order to better understand the impact of modern robots. The developments in the modern era influenced the discipline of architecture and questioned what the design was and the architectural product was reshaped with these effects. By referring to Walter Gropius, one of the pioneering architects of modernism, Picon thinks that *Industrialization is not only perceived as how the buildings are produced differently, but it is a liberating actor who frees architecture from stereotyped aesthetic understanding and outdated technologies.* According to Picon, the use of robots in architecture has three main effects:

- Robot arms direct designers to think directly in three-dimensional space, without any dominant directions. Articulated structures remind the designers of the basic character of rotation (circular motion). The human body is composed of various rotational movements of the limbs. Modern industrialization emphasizes linear repetitive movements instead of rotation. In this sense, Picon thinks that the robots will create a new space for designers and will allow them to design in an approach where rotation and linear movements are combined.
- Working with robots teaches designers a very subtle distinction between objects and processes. It allows entry of motion and time concepts in design.
- The notion of robotic fabrication in architecture may change our understanding of beauty. Picon states that simplicity and unity are fundamental qualities of beauty according to scholastic philosophy, and that digital technology and robots critically criticize this perception. For him, complexity and diversity are the natural conditions designers must begin to design.

Robust programming of robotic arms is another important feature. There are three basic types of programming: the procedure programming, in which the designer has already calculated the working procedure, is the self-teaching programming, where the designer manually controls the work teaching programming and automatically decides which steps to take with the receivers placed on the robot arm (Hauschild & Karzel, 2011).

It is possible to use the end of the robot arms with a 3-dimensional print head. In addition, the ability to place the components of the structure beyond the sensitivity of the human hand also paves the way for new possibilities in design (Figure 3.13).

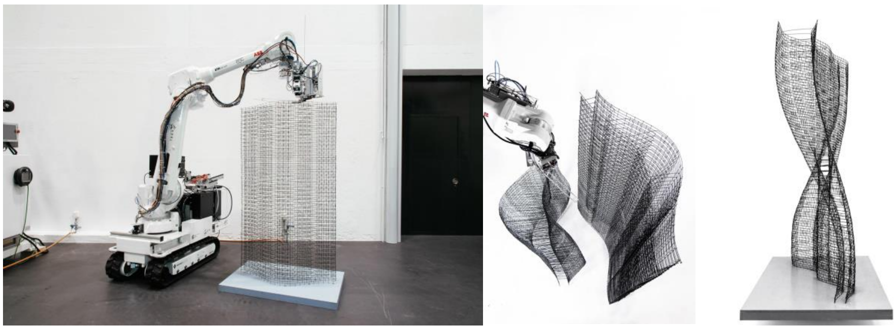


Figure 3.13 Gramazio & Kohler Research's Mesh Mold Metal Project uses the robotic arm for additive methods (URL 34).

The robotic arms have hot-wired cutting, which is placed in an auxiliary device and milling by inserting the piercing head into the end parts, in particular for removal methods.

Figure 3.14 Woodchip Barn Project (URL 35) realized using a robotic arm under AA School's Design & Make Program.

The RoboFold research center that Gregory Epps founded in the UK, there the use of robotic arms with formative methods is being studied (URL 6).

Many innovative architectural projects have been made standard end-effectors like e.g. milling spindles, welding equipment and gripper but those end-effectors are no innovation, due to the fact that all these tools are already in use by the several industries *(Braumann & Brell-Cokcan, 2012)*

According to Nick Dunn (2012), the negative aspect of robotic arms is that due to their kinematic structure, their use is highly complex and has the potential to cause harm to the people around it when used incorrectly. Picon (2014) also stated that the robot arms are still quite unstable for standard site applications, and that the problem with security and maintenance cannot be solved

3.5 Robotics in Architecture

In mass production robots and robotic arms are dominating a lot of branches in the industry. There was almost no use of robots in architecture until the 1980s. The first attempts of using robotics in the architectural field started in Japan when construction companies tested them as mass construction tool, but the progress was extremely slow. These Japanese companies are the pioneers of using robot in architecture. Almost two decades later a new attempt happened in around the millennium in the 2000s (Bock et al., 2014)

Robots in architecture are already being used in some areas today. Often robots are borrowed from the industry, which e.g. have been used in the automotive industry for decades. These robots have high precision and can be equipped with various tools. The field of autonomous robotics in architecture in which this work also falls is a new field of research. The robots are no longer regarded as tools, but form a new "companion species" (Donna Haraway, 2003) that exists alongside humans and independently tackles problems and finds solutions.

3.5.1 1980s – 1990s – Robots used in Japan

In Japan during the 1980s and 1990s construction companies used robot for several workflows on site e.g. for finishing concrete slabs or painting the facades. Automated construction was important in Japan these days, to reduce construction workers and on developing the productivity, and to have more safe construction sites (Bechthold and King 2013). These robots were very specialized for one task and specified, expensive and were not flexible enough. Due to these lacks in their use, it turned out the specific robots were inefficient (Gramazio, Kohler, and Willmann 2014). Japanese companies which have used the robots stopped the actively operating with them in mid-2000s. (Bechthold and King 2013).

Figure 3.15 Shimizu Corporation, Concrete finishing robot (left) and Kajima Corporation, Facade inspection robot (Bock et al., 2014)

In Germany, researchers operated with a 5-axis robotic on the construction site to assemble brickwork in the 1990s. He explored with this research project the automation on the construction site but with his approach it helped construction companies to establish specified robots.

Nevertheless, two primary effects had influenced the use of robot and architectural robots in the 2000s. Robotic tools became cheaper and a change in the architectural discipline.

3.5.2 After the Millennium

After the year 2000, there was a mind change in using robot in architecture, when the attitude to architecture developed. In addition to the rapid integration of computer-controlled machines into architectural research projects, the computer movement has decisively determined the direction of research into robotics in architecture.

Robotic pushed the borders of thinking differently in this new research field. The combination of computational design and robotics detached from known typologies (Budig, Lim, and Petrovic 2014).

Digital design as a constructed relationship between information and complex shapes has fundamentally changed the way designers design objects (Sass and Oxman 2006). Digital design gave designers the freedom to shift their job from designing artifacts to creating the production process that generates instances of the design process (Gramazio and Kohler 2008). This approach allowed them to integrate more complex and diverse information into the design process (Menges 2012). Thirty-four designers have come to grips with this paradigm in the late 1990s and early 2000s, as the required technologies were advanced enough, CAD software packages were available, and computing power was plentiful and cheap. These factors convinced architectural firms to take the risk and extend the spectrum of digital design from academic to professional practice.

Nevertheless, conventional fabrication methods were not enough in in this stage of design complexity. The solution was in using digital fabrication (Sass and Oxman 2006). In the early stages of the 2000s CNC routers were easier to reach and the problem of building what digital design offered vanished. Therefore it opened the doors for designers and architects to design more digitally (Hack and Lauer 2014).

CNC routers had restriction in their function because these machines are task specialized, so robotic arms had huge advantages with the various ways of use but it took them more than 10 years to operate actively. For that reason the development of CNC routers expanded significantly.

The architects Gramazio and Kohler from Switzerland leaded the research institution of ETH Zurich. This institution focused on architecture and numerical fabrication and in their laboratory they used robotic arms in 2005. Secondly at Harvard the use of robotics started in 2007 (Castle, 2014).

Gramazio and Kohler are known for their computational designs which are also built mostly by robotics and these two researchers shaped the beginnings of the architectural robotic (Bechthold and King 2013). They were mainly focused on computational brick assemble and the worked fabrication oriented and they closed the gap between the digital design and the construction site (Sass and Oxman, 2006; Helm et al., 2014).

After the ETH researchers started this movement with robotic arms the computational design increased and other Institution in Universities all over the world researched in this field. For that reason the conferences of Rob|Arch started in Vienna in 2012.

3.5.3 Importance of Robotics

Various researchers around the globe as Gramazio and Kohler at ETH Zurich, Philip F. Feng at Tongji University at College of Architecture and Urbanism Tongji University, Achim Menges at ICD Stuttgart showed the importance of robotic arms in Architecture with their several researches with these robot and academic publication. Architects should use and master these robotic arms to create new computational forms (Gramazio and Kohler 2008). According to Gramazio and Kohler industrial robots will change the roots of architecture and also reshape the view of architecture within the society. For those researcher forms Zurich architecture developed with robotic fabrication reached that where digital fabrication was unable to succeed because it was a bridge between the immaterial design on the computer and the physical reality of architecture (Gramazio, Kohler, and Willmann 2014).

They argue also the importance of industrial robots due to its flexibility, adjustability and its cheap price. With these attributes, robotic fills the gap between the fabrication and the design procedure (Gramazio, Kohler, and Willmann 2014).

The link between design and production will be continuously due to the use of robotic arms (Cardoso Llach 2015) because it is working directly linked to the materialization. With the variety of the changeable end-effector and wide range of use, robotics can give rise to more diverse and computational architecture. According to Budig et al., robots create digital and physical designs (Budig et al., 2014) and this will lead architects to design corresponding to materials. The benefits of architectural robots not only differ from traditional manufacturing methods, but also from popular digital manufacturing systems in a variety of areas, including:

Adjustability:

Due to the flexibility of the *End Effector* of the industrial robotics, a robotic arm can perform various tasks by just changing the End Effector in an acceptable time. This adjustability of the robot makes the use: Universal and Simple to programme.

Universal Use: Robotic arms are represented in a variety of industries and in almost every industry they have another work duty and due to this property, they are not specialized on just on job. Various tools have been developed for standards and there are also generic connectors, and also these different tools are used in a wide range of fields like the steel industry and the gaming industry. Other digital fabrication instruments as the 3D printer is only invented to print and the CNC cutting just to cut a plane material. In contrast a robotic arm can do a milling job and switch in the next to a camera to film it. A variety of industries are using these advantages in their own special field.

Programming: Producers of these robotic arms developed mostly their own programming language and they also provide the scripts or they teach through their libraries and thiss made the learning procedure more effective. For the company KUKA there has been developed a new way to control the robotic arms and even to simulate them easily with Rhinoceros. KUKA|prc (KUKA parametric robot control) is a plug-in of Grasshopper and due this, robots can be reached by wide field of researchers and robot enthusiasts (URL 37).

Accuracy:

When the robotic arms are calibrated advisedly, they operate in very high precision.

Work span:

Most digital fabrication instruments have small work areas; in contrast the robotic arms can operate in huge range of different distances, e.g. there are versions which fit on an average desk but other models like the KUKA Titan can reach a working diameter of 7m. A benefit is that the working area is non-cubicle working space (Brell-Cokcan et al., 2009).

Setting up robots in architecture does not just mean relying on a few script lines to calculate the G code directly from the digital model. The architecture of robotics offers first and foremost methodological adaptations in the entire file-to-factory process (Quartara & Stanojevic, 2019).

In fact, the robot is no longer just a mechanical sub-contractor, but offers the architects the necessary discernment to design working prototypes that advantageously compete with industrial mass production. Apart from that, a minimum amount of knowledge of logic and mechanics is needed, which is behind the production methods for robots. (Anderson, 2012)

The automated production processes of industrial robotics enable innovative features and allow the fusion of computer-aided design and constructive materialization as a characteristic of the architecture in the post-digital age (Quartara & Stanojevic, 2019).

The efforts of the early pioneers in this field, coupled with the adoption of open standards for robot programming, have reduced the barriers to exploring the ingenious application of industrial robotics in architecture. However, the highly experimental nature of applied academic research and the prevalence of traditional mass-production techniques on construction sites leave open the question of instant practicability (SuperLab (2016).

4. Digital Wood – Robotic Timber Construction

4.1 Sustainable and Computational Wood

In Architecture is Timber an interesting material which has a long history and cultural roots. Also it offers wide perspective for expected building surrounding. It is effected by two main factors: first of all the expanding possibilities of construction and design, and computation gives the opportunity for simulation and digital fabrication; secondly wood is one of the few ecologically compatible building resources (Menges et al., 2017). Also the unsurpassed environmental virtues, wood has important benefits in contrast to the various commercial semi-finished products and these advantages increase the interest of its use as building material. Wood is an essential production material for the construction of accommodation, utensils and transport since the human history (Quartara & Stanojevic, 2019). Wood as a building material is different than the other materials in architecture because of it being natural instead of being produced in the industry for special requirements. Wood grows natural for its own benefits and requirements (Menges et al., 2017). The wood elements intended for the construction and the various supporting applications bear the specific name Timber. In these days, wood products, which are widely used historically and in the field of construction, highlight the influential role that wood plays in material constrained construction, particularly in the combination of structural and decorative expressions within a numerical path (Beorkrem, 2013). In view of the rapid technological progress and the major environmental challenges that the architecture is facing, wood can no longer be seen as out-dated material with poorer properties and unconventional properties when compared to man-made building materials. Rather, it is increasingly considered a future-oriented building material with unrivalled environmental benefits (Menges et al., 2017).

Wood appears as a single material, but its numerous varieties offer diverse products and experimental alternatives. Wood is the porous and fibrous structure of trees, so it is a heterogeneous and hygroscopic material. Its chemical composition varies from species to species but has four main components: water, cellulose, hemicellulose and lignin (Quartara & Stanojevic, 2019). The cellulosic structure of wood attempts to keep the moisture content in balance with the relative humidity of the environment by added in the dry state moisture from the atmosphere and moisture is discharged to the atmosphere in the wet state (Menges & Reichert, 2015). The cellulose fibres have high resistance compression forces. How timber behaves is determined of the cells´ structure (Quartara & Stanojevic, 2019). Wood can shrink and swell up to 10 per cent perpendicular to the grain in a tangential cut, due to its cellular structure and its micropillar orientation. In contrast there is almost no shrinking or swelling in the grain direction (Menges & Reichert, 2015).

Nowadays Architectural debate has been shaped by materials like concrete, steel and glass but timber provides an alternative to these materials with its lightness and environmental compatibility of its features. Those features make wood a valuable material. It offers the opportunity to build with energy and structural point of using sustainable, completely renewable and high-performance materials (Bianconi & Filippucci, 2019). In connection to design, architects choose wood intuitively because of its cheap price; easy wood machining and a variety of connections tools are possible (Beorkrem, 2017).

Digital Fabrication and parametric design are benefits which are helping wood to become more and more a future construction material. Timber might have a long history of use in architecture but it is still a modern material, because researcher and architects are still trying to rethink the potential of the building material, and of course it is own natural advantages will never make it infamous. Digital fabrication can still learn from traditional human made wood crafting (Bianconi & Filippucci, 2019). On the earth 30 per cent of the surface is still overgrown with forests, which are of an area approximately 3.900.000.000 hectares .Wood is a resource which can grow back to its full size, due to this it is a renewable material and this can be a factor to fight climate challenges and because of these properties it is becoming an important aim in Europe. The building industry has the important problem of climate change and reducing the energy consumption, $CO2$ emission and waste management/production must be seen (Menges et al., 2017). Also, it is tried to reduce the distances between the construction site and the wood production area, so it also tried to reduce the $CO2$ emissions (Bianconi & Filippucci, 2019). Compared to other building material for example steel, to produce and fabricate wood is 500 times less energy required and with this property is wood certainly more ecological (Gordon, 2003).

Wood also offers high performance of structural performance as building resource. Due to its cellular structure which consists of cavities, wood can be defined as natural composite and due to this characteristic, it is a natural insulating material (Menges & Reichert, 2015).

Under these facts, wood as a building material with unparalleled ecological benefits is receiving renewed interest. It has a very low proportion of built-in power and even if today's high industrial wood processing is considered a positive CO2 footprint (Kolb, 2008; Scheer et al., 2006).

Wood´s unique character, in contrast to the most used building materials, provides a way of using it in more tactile and intimate ways. Due to the various types of wood there is also a variety of colours and textures, even with industrially manufactured timber products or with natural wood and these textures and colours are used in a lot of different cultures (Beorkrem, 2017).

Further advancement of technology is one the critical reasons why the interest in wood crafting and designing with timber increase. While the first wave of industrialization resulted in a departure from wood architecture, recent technological progress has made it possible to reconcile the inherent capacities of the material with the characteristics of contemporary design and construction procedures. Computation is an important factor in this development as decisive enabling technology. It provides architects, designers and the manufacturer to work in an interactive procedure, in which they can rethink and redesign the wood´s structure according to its complex properties (Menges et al., 2017)

Innovative architectural designs are increasing in number in specializing with wood. The reason for that nowadasy is that the feasibility and customization of wood and its performance with engineering and fabrication for needed structural requirements (Bianconi & Filippucci, 2019).

Due to computational design architects, designer and engineers are able to reevaluate wood´s properties and characteristics with having the benefits of digital fabrication processes (Menges et al., 2017).

4.2 Robotic Timber Manipulation

Wood products in digital fabrication are great materials to selects, to work with in parametric design. Due to their standardized and manageable conditions, timber products can be manipulated and crafted with less effort and also they are easy to repair and keep on working. According to their standardized dimensions, a variety of connectors are available, which are adaptable to the geometric style (Beorkrem, 2017). The properties according to mechanical wood working, like stiffness and strength and of course the visual and haptic characteristic are remarkable in combination with workability. Since human history, wood working was relevant, because of its extraordinary properties. In contrast to other materials which can also be found in the nature, wood appeared in a wide range of cultures. The mentioned properties can also be found in traditional timber porducts and detailed structures, this shows the evolution of wood manipulation techniques (Menges et al., 2017).

CNC machines in digital fabrication are used in wood working since the last decades and like mentioned its automation is the main reason why it is so successful in wood working. Due to this automation standardized products are faster and easier to produce and it is not just ease of the manufacturing, the improvement of the products quality is also established (Bianconi & Filippucci, 2019).

Complex timber construction is hard to deal with and CNC milling was to only way to handle with this complexity. But there is rise in the number of researches who are working on robotic fabrication. Those researchers are trying to develop and invent new ways of wood working processes by operating with robotic arms. Robotics proved that they have huge impact on changing the ways of designing (Menges, Sheil, Glynn & Skavara, 2017). One of the reasons why robotic manipulation is becoming more important and famous is that CNC milling takes long time but also is produces too much waste which cannot be used again (Willmann et al., 2019).

Since robotic fabrication with industrial robotic arms was introduced to architecture, it has changed the approach between computational design and the physical materialization. This technique is new in the architectural field and for that reason it is necessary for architects, designers and engineers to research the materialization process in the early stages of the design (Quartara & Stanojevic, 2019).

Industrial robotic arms are different to CNC which are specialized, with their feasibility and also in the practicality. Robotic arms are flexible in their use because of the variety of the end effectors which operates with wide range different tools. These tools can be attached with the Numeric Control (Bianconi & Filippucci, 2019). Robotics work in real time and the design information is transferred in a simple way into the fabrication process´ tool path (Menges, Sheil, Glynn & Skavara, 2017). Due to parametric and computational design the request for complex timber is increasing and the possibilities in wood working with robotic fabrication is also increasing and that this trend and research has potentials shows the high number of projects which are made with robotic timber fabrication (Willmann et al., 2019).

Industrial robotic arms have high potential in timber construction because of the wide range of kinematic movement and feasibility of new developed digital manufacturing processes. This is possible due to the customized end effectors which are developed by a variety of researchers and institutes around the world, and also because of this the production of complex and different building components is possible. These end effectors are mostly not developed by the producers of the industrial robotics. Institutions develop these end effectors according to their need (Bianconi & Filippucci, 2019).

Since the robotics are machines without any specified use. They are programmable machines with high accuracy in operating, and they can be equipped with new special end effectors, which can perform in high feasibility in the architectural field (Quartara & Stanojevic, 2019).

As mentioned before a wide range of institutions and researchers are developing new ways how to deal with robotic timber construction and fabrication. ETH Zurich has researches in industrial fabrication of non-standardized systems (Menges et al., 2017). End effectors like the Bandsaw Bands are being researched in different institutions as an alternative to the most traditional robotic fabrication of the milling method due to that milling produces a lot of useless waste (McGee, 2014). Hybrids are also being researched: industrial robotic arms are equipped with a gripper with combinational use of a circular saw which is the case in the project *Fusta Robotica* (Quartara & Stanojevic, 2019).

In the following part there will be the focus on different methods of robotic timber manipulation.

4.2.1 CNC Milling

In contrast to robots, computer-controlled (CNC) laser cutters, 3D printers and CNC milling machines in architecture workshops, architecture schools and architectural offices are already state of the art (Brell-Cokcan & Braumann, 2010).

A typical milling usally operates in two steps: the first step is the rough cut, where the material is removed step by step, and after that the second step is the fine cut, where the tip of the spindle is removing the rough cut matrial. To achieve a smoother cut, the costs of the production raises, and for that reason there must be compromise between the the needed time and the final costs. This method can also cause high amount of material loss and due to this it has to be used carefully (Brell-Cokcan et al., 2009).

The difficult controlling of the robotic arms and the complex geometries is one of main reasons why this kinematic robotics are not used in architectural offices and also in educational institutions (Brell-Cokcan & Braumann, 2010).

Usally robots are not used for milling, normally they are part of the automotive industry for single jobs where they repeat the same movements during their whole lifetime. They are following curves and points to execute the same job (Aigner & Brell-Cokcan, 2009).

Other reasons why robots are not used for milling that often to date is because of the difficult working process and that there is the need to control the robotics through on- or offline programmed workflow, which can be unsuitable for a computational architecture and design. (Brell-Cokcan & Braumann, 2010).

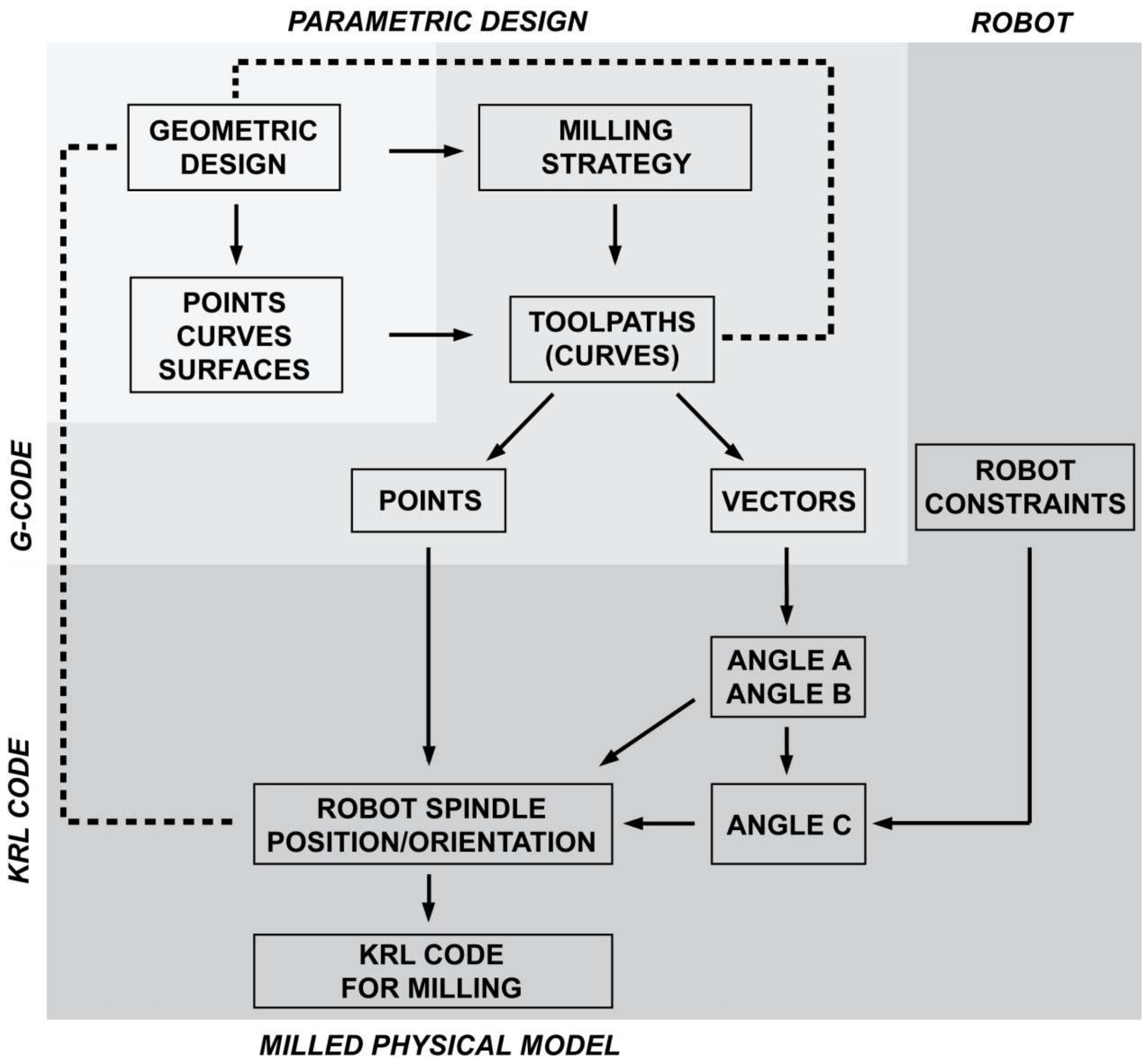


Figure 4.1 Robot milling data flow in Grasshopper(Brell-Cokcan & Braumann, 2011).

Due to the fact that milling is new field of application for robotic arms, there must be prototype tasks for various applications (Aigner & Brell-Cokcan, 2009).

Milling with a robot shows various advantages, in comparison to milling machines (Aigner & Brell-Cokcan, 2009):

- Due to the flexibility in the work area, the robot can work from every postion and for that reason undercuts are also possible. The positioning of the material must be according the robot, so the system can work properly without mistakes.
- That the working area of the robotic arms are non-cubic and that is an important advantage. Normal portal milling machines are fixed in a frame but in contrast to milling machines, robots have no frame and also due to this their flexibility is increased

when it is working with the object. Extra tilting tables can increase the flexibility of the robotic arm and give them the 7th axis.

The robotics have the important feature that can calibrate itself and reposition it according to the model. Due to the autonomous operation of robotic arms, the order of the cutting sequences does not have to be in the used order, which is from rough cut to fine cut. There are also several disadvantages of structural CNC milling and the removal of material through the subtractive methods, and this can be very inefficient because large scale projects can cause a huge amount of waste which can also be very time consuming. (Brell-Cokcan et al., 2009).

The workflow of 3D milling has more complexity than normal 2-dimensional milling. 2D cutting working procedure is working with predefined toolpaths which are created with automatically with commercial CAM softwares. The 3D process works with parametric designed working procedure which removes material from the created geometric form (basically a freeform) (Brell-Cokcan & Braumann, 2011).

With flank milling, the material can be ground tangentially to the surface to be machined over the entire depth of cut of the tool. This offers several advantages that the final form is reached just one single cut. For this reason, the raw material need not be roughly removed beforehand, thereby eliminating the rough cut. If it is not thrown away, the second can also be used. This process creates surfaces that are cut torsional which are unfoldable or non-torsional which means that the cut be only done in straight lines. (Brell-Cokcan et al., 2009).

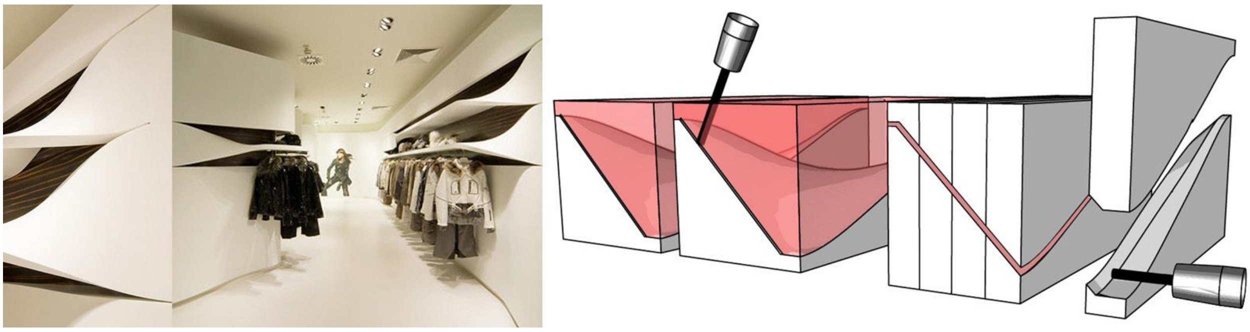


Figure 4.2 CNC Milling and Flank milling comparison (Brell-Cokcan et al., 2009).

4.2.2 Band Saw Bands

In the field of wood machining with digital fabrication of complex structures and geometry the only way of manipulating the material was CNC milling (Willmann et al., 2019 The conventional method of CNC milling produces a large amount of unwanted waste, the duration can take a lot of time and as well the information and data transformation during the design phase to the manufacturing procedure is known disadvantage of this subtractive method (Menges, Sheil, Glynn & Skavara, 2017).

All these constraints are factors for researchers to develop new parametric and mass customization methods for robotic fabrication, which is gaining in popularity in the field architecture. In a lot of cases of research, the methodology is to work with standardized building materials (McGee, 2014). To create the possibility to work without standardized timber blocks, researchers like Philip F. Yuan and his research team are working on new possibilities. They do research on other wood working machines than the CNC milling. In the wood industry, bandsaws are involved since a long time. This tool can be used from small scale objects to large scale projects. The most important advantage, compared to other tools is that bandsaws produces less kerfwaste (Yuan & Chai, 2019). Hot-wire cutting is a similar methodology to the bandsaw technique in the field of robotic fabrication, which is already in use. The bandsaw takes over the function of the hot-wire (Menges, Sheil, Glynn & Skavara, 2017).

Figure 4.3 Robotic cutting simulation in Kuka Prc (Yuan & Chai, 2019)

For the first time researchers from Greyshed and Princeton University used this type of wood working in their experimental project and due this research they proofed the material efficiency of bandsaws as an end effector. They cut curved forms from an irregular natural wood plate (Willmann et al., 2019).

Computational designed objects, which are complex geometries and double curved, can be manipulated by the robotic arm with the bandsaw as end effector. Special customized construction timbers are easier to create the designed shape with this technology (McGee, 2014).

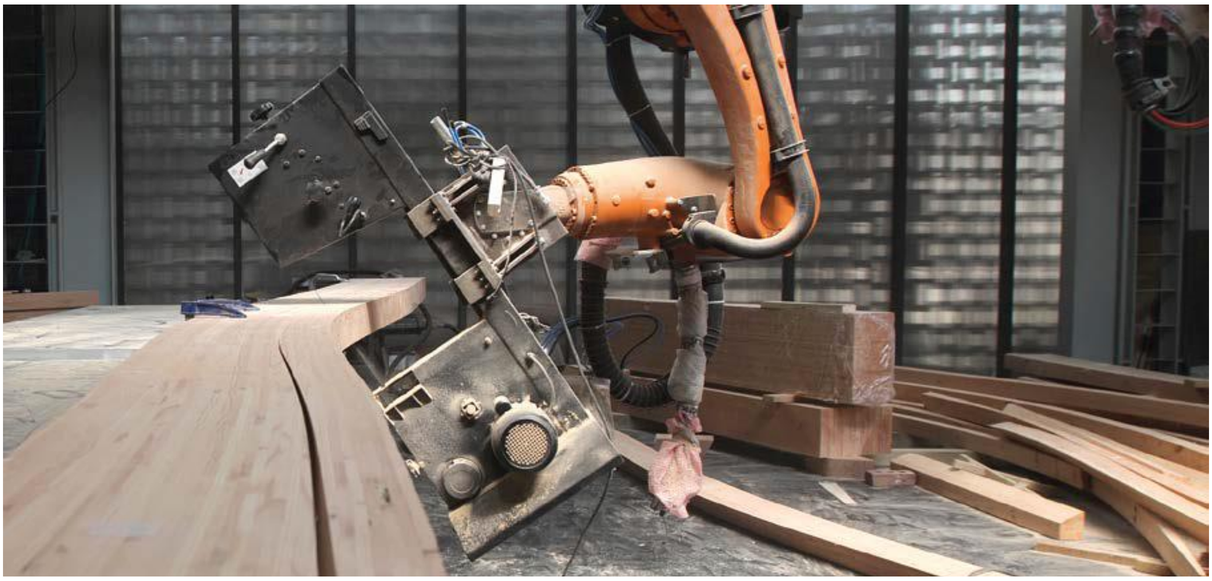


Figure 4.4 Robotic Bandsaw fabrication procedure (Menges, Sheil, Glynn & Skavara, 2017)

The flexibility of robotic arms makes it possible to cut the desired shape through rotating the bandsaw continuously during the cutting process. As well due to the stability of robots, the material can also be moved during this procedure. This possible because of the small cutting blade of the bandsaw. If this is done by human-hand the workers must use complex tools and hold the stability during the cutting process which can be inflexible and as well the precision would suffer with this method. But the robotic bandsaw methodology has also its difficulties, because it cannot be reduced to just a simple line, like the hotwire cutting methodology, because of the thickness of the blade. Due to this factor the cutting blade must be always parallel to the tangential direction of the created object (Willmann et al., 2019).

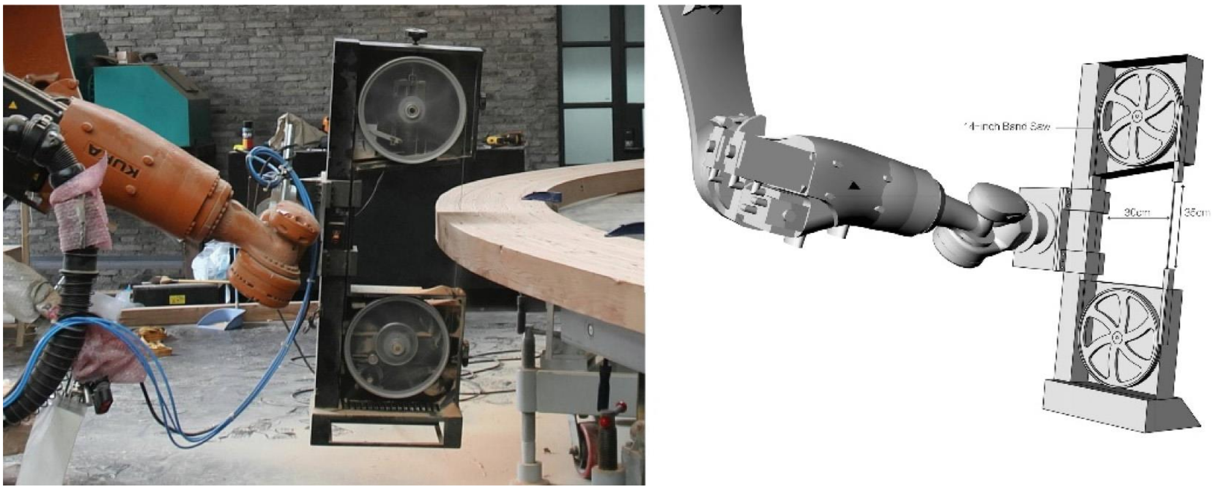


Figure 4.5 Bandsaw end effector in working process (left) and simulation of the end effector (McGee, 2014)

For this methodology the bandsaw is not constructed specifically as an end effector, actually it is a conventional bandsaw, which is also used in the industry. The machine is removed from its base and attached to the robot, the only difference is that the tool have to be reinforced with an extra steel frame. The biggest advantage of the bandsaw technique is that there is minimal amount of kerfwaste and additionally the waste can be minimized with computational designed and customized timber products (McGee, 2014).

But to minimize the waste the production of the specific timber products must be in without a lot of tolerances during the production compared to the digitally designed material. Techniques like CNC cut templates can guide the workers and producers to achieve the desired geometry (Menges, Sheil, Glynn & Skavara, 2017)

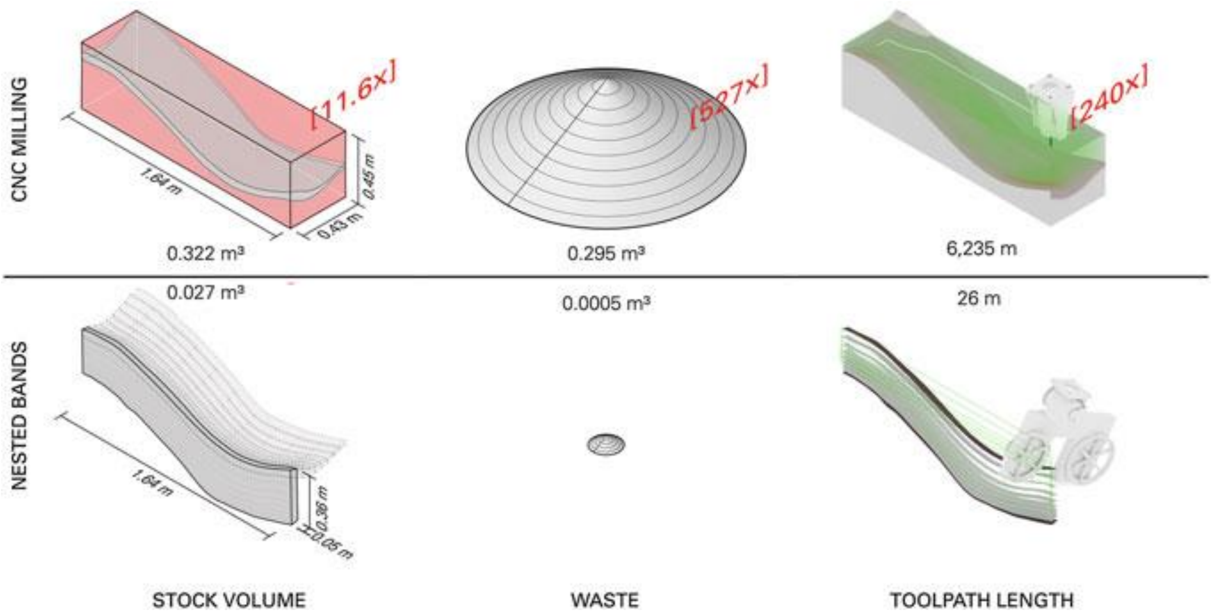


Figure 4.6 Waste amount of CNC milling and robotic band saw (McGee, 2014)

This methodology with less waste during the production can be a trigger to use more expensive and rarer timber products because if it must be CNC milled the designed shape has to be removed from a block of the material and this causes a lot of unwanted and unusable waste (Figure 4.6). In CNC milling methodology mostly wood products like Ash or Birch are used due to their low costs (McGee, 2014)

4.2.3 Non-Standardized Assembly

In the timber production the prefabrication and the digital fabrication are very advanced compared to the assembly tasks which are mostly done by human-hand. Due to that the computational design is suffering because of the inflexibility of the CNC machine and this causes that computational design is losing popularity with wooden products and this is an obstacle for the automated production process (Willmann et al., 2016).

Figure 4.7 Robotically fabricated construction system as additive method (Helm et al., 2017)

Robotic timber construction of computational design and complex geometries is still in its infants and for that reason the timber sector is limited to fabricate each piece individually and after the production process the assembly is still by human-hand. This way of handling wooden products causes high consumption of resources because of unoptimized CNC milling methods. In the construction sector the costs of projects must be considered and wasteful productions and manual assembly can raise the costs (Helm et al., 2017).

Nevertheless, by using robotic the problems of waste and time and because of this, costs can be reduced but it is not only that robotics solve this kind of problems, it also brings other advantages along. Robotics can transfer the computational designed object and data directly to the real world. This property of transferring data to physical world, makes the assembly for non-standard timber structures possible (Menges, Schwinn & Krieg, 2017).

Figure 4.8 1:1 construction of the "Sequential wall (left) and "The Sequential Structure", (Willmann et al., 2016)

Researches of non-standard timber assembly showed three different methodologies of assembling the material:

1- Design process according the assembly

2- Systems according to material and construction

3- The integration of robotic fabrication

Robotic timber construction is to integrate all these three methodologies and consider specific design, materiality and as well the robotic procedure. (Willmann et al., 2016).

First attempts of fully robotically assembled structures were to layer the unique wooden products to create a non-standard wall and other constructional structures. The experiments lead to totally robotic assembly methods of elements which can stand freely in space. Due to the computational process of robotic fabrication, every element will be placed on the exact location because robotic transfer the data to the physical world and there will be no need for repetitive manual work (Menges, Gramazio & Kohler, 2017).

To sum up, non-standardized timber assembly is the combination of computational design and autonomous fabrication during the design phase and the construction process. Robotic timber fabrication is the extension of the traditional manual assembly method which is in the production industry already in use. Non-standard assembly are the future for complex timber construction and complex geometries created by digital design and can reduce repetitive work simply by transferring data to the real world (Willmann et al., 2016)

4.3 Case Study

This part of the thesis will focus on three cases in architectural use of robotic timber manipulation. The case studies are chosen after their properties e.g. computational design, wood construction and of course robotic fabrication. The chosen architectural projects are research projects from ETH Zurich, ICD Stuttgart and Tongji University CAUP. All three designs differ in robotic manipulation method. In *Landesgartenschau Exhibition Hall* designed and fabricated by ICD Stuttgart, CNC Milling method is used for the joints of the computational designed building (Menges, 2017). The pavilion designed by Tongji University CAUP, developed in their project the robotic bandsaw method for computational designed non-standard timber products (Menges, Sheil, Glynn & Skavara, 2017). ETH Zurich is researching in assembling methods and in the project *The Sequential Roof* they designed the computational assembly method of non-standardized timber products (Willmann, 2016).

4.3.1 Landesgartenschau Exhibition Hall

The Landesgartenschau Exhibition Hall is a timber building by researchers of the University at the Institute of Computational Design, Institute of Building Structures and Structural Design and Institute of Engineering Geodesy, which is designed in spring 2014 (Schwinn & Menges, 2015).

In contrast to other experimental structures, this project is built for permanent use, which is fully enclosed, insulated and waterproof and the primary beech plywood structure is fabricated by a robotic arm (Menges, Schwinn & Krieg, 2017).

Figure 4.9 Finished Construction of "Landesgartenschau Exhibition Hall" (URL 38)

Site

The project was designed for the Landesgartenschau, which is horticultural and landscaping expo in Schwäbisch-Gmünd in Germany. The function of the project´s brief to create an exhibition space, which can be transformed and used for different events, including associated facilities. This kind of functions are normally not included in experimental and temporary buildings, for that reason this case is a speciality to other projects. The location is in a park in Schwäbisch-Gmünd next to dense forest of local beech trees, of which the building is made from (URL 38; Menges, Schwinn & Krieg, 2017).

Computational Design

Through computational design and simulation methods, the structure of the complex plywood plate is designed from. For that reason, the optimisation of the biomimetic construction principles and the simulations are possible in architecture. The researchers developed digital and computational tools to parameterize characteristics of the material and the fabrication procedure during the design phase. To include this parameter during the design is an important characteristic of robotic timber fabrication because with these properties the designer do not have to create and draw every plywood manually, in contrary due to the computational design the material will be generated digitally (Menges, Schwinn & Krieg, 2017).

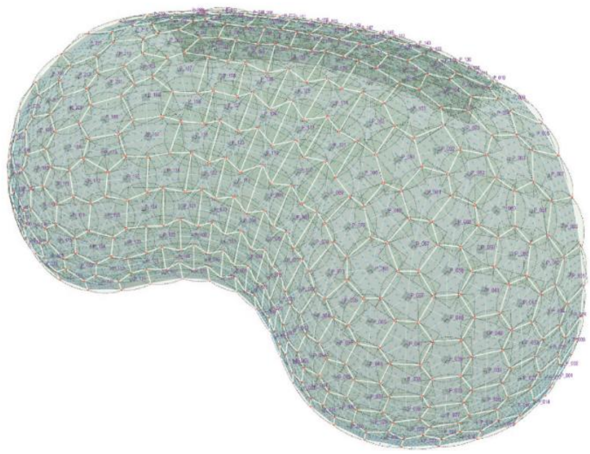


Figure 4.10 Agent System for the plates (Menges et al., 2017)

The shell is created through Gaussian Curvature and the changing is reflected by plates of the surface which is showing the primary zones and functions of the building. The visitors of the Exhibition Hall are entering from the south side of the façade, which is lower than the 6m high exhibition space and the areas also separated through contracting and turning form. The main area, the exhibition space, contains a large glass facade which connects to the surrounding landscape. Through the shell structure, the designers created a surface, spanning 17x11m with two domes. These two domes are connected by saddle shaped geometry. In total the two areas are creating a usable space of 125 m² in this project (Menges, Schwinn & Krieg, 2017).

For the reason that the project is design computationally, each plate of the building is individually unique. For the connections and joinery, the researchers decided for finger joints, and every plate is interlocking with these joints along the edges. They have created the finger joints in collaboration with a professional timber manufacturer. (Schwinn & Menges, 2015). The shell of the exhibition space contains 243 geometrically unique plywood plates and a total number of 7600 unique finger joints, which is important for the structure of the building (Yuan, Leach & Menges, 2017).

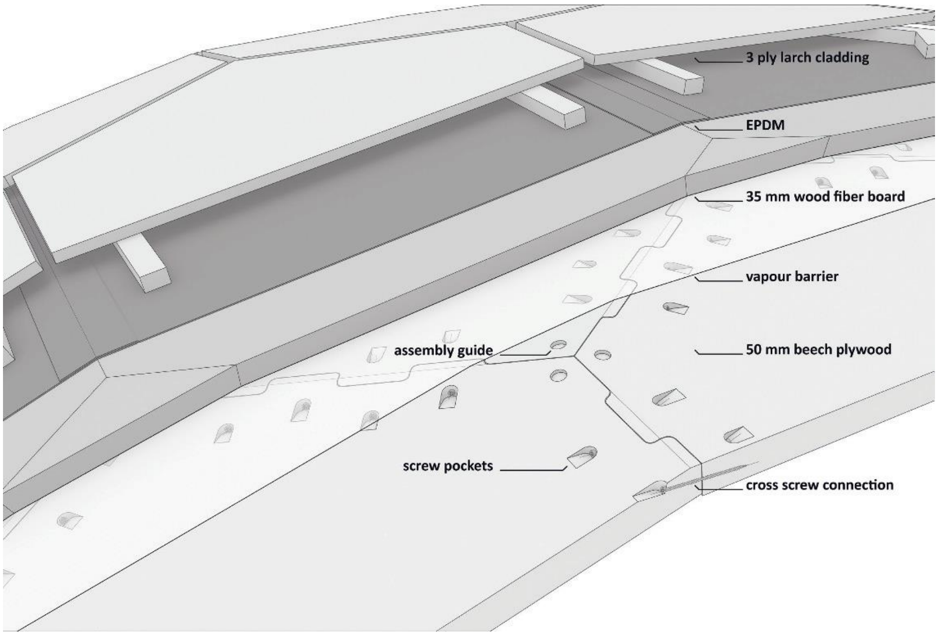


Figure 4.11 Each layer of the construction shell (Menges, Schwinn & Krieg, 2017)

Fabrication Process

The main structure of the project are the 7600 individual finger joints, and the robotic fabrication of this joinery caused challenges because of the interlocking system (Schwinn, Menges & Krieg, 2015)

For the fabrication process the researchers of the University of Stuttgart installed a mobile robotic milling cell in the timber manufacturer´s workshop for being a bridge between research and practice (Figure 4.12). They located this robotic fabrication cell into the existing infrastructure of the timber fabricator´s workshop to implement a new customized fabrication process and test this in the real construction world of professional wood working (Yuan, Leach & Menges, 2017).

The fabrication workflow consists three main steps:

1- first of all the oversized plywood plates will be pre-formatted in CNC panel machine. In this process the plates will be cut out from 2550x1850mm plywood sheet. After the cut-out the sizes are ranging from 960-2090mm. The order of the cut-out procedure is optimized to reduce material loss. The waste material which is created of the plates cut, will be used as a resource for the floors and due to this, during the fabrication will be the waste material minimized (Menges et al., 2017).

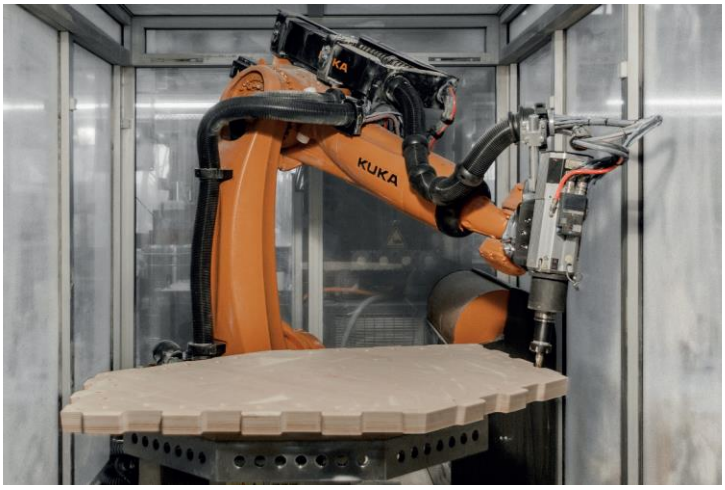


Figure 4.12 Milling procedure of the finger joints (Menges et al., 2017)

2- the next step is the fabrication of the joints by robotic fabrication in the cell, which was constructed in the manufacturer´s workshop. The robotic arm is an industrial robot with 6-axis with a spindle as an end effector. In the cell there is a turning table which works as an extra axis for the fabrication. the plywood plates are placed on this turning table. the last step of the fabrication procedure is to sort the labelled plates in order of the assembly (Menges, Schwinn & Krieg, 2017).

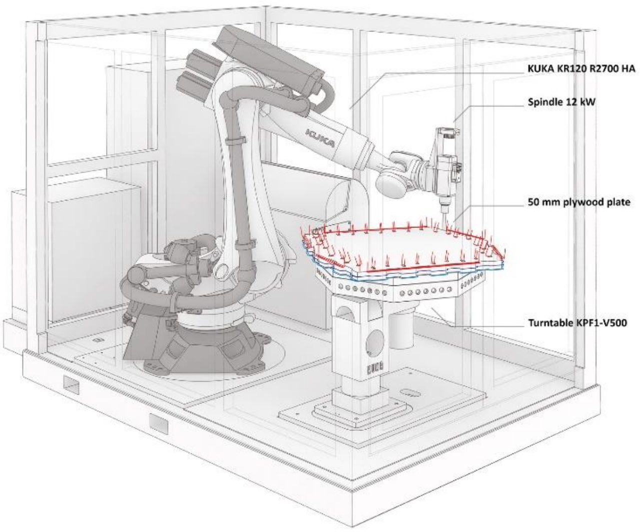


Figure 4.13 Fabrication Simulation (URL 38)

The major challenge was that this project was not just an experimental pavilion, for that reason the building codes and other relevant regulations had to be followed. The thin plates must carry the forces which are occurring in this project, so the researchers developed a system where the forces are transferred from plate-to-plate on the edges with the joints. To carry the axial forces the designers fixed the plates with crossing screws in the edge (Figure

4.14). The plates where minimized in their thickness, but they had to overlap enough, which had to be done according to the building code for screwing the edges (Menges, Schwinn & Krieg, 2017).

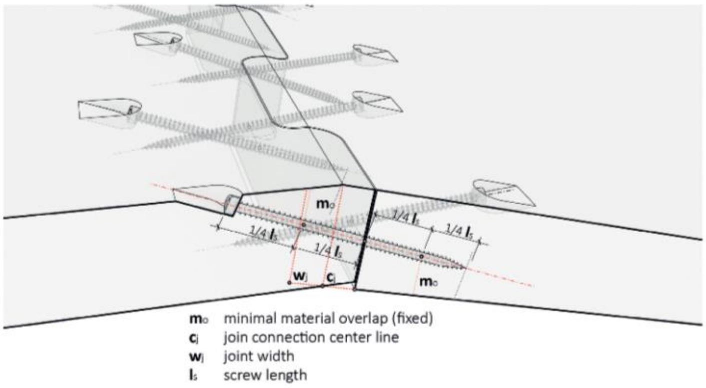


Figure 4.14 Diagram of screws in the joints (Menges, Schwinn & Krieg, 2017)

In total there was just a need of 12m² of plywood for the structural system and there was almost no waste created, because the waste, which occurred in the fabrication process was used for the flooring of the building. All of the layers like waterproofing, insulation and cladding were created by digital fabrication, and the structural system by robotic fabrication and for that reason the assembly and construction of the project was very time saving and done in only four weeks (Yuan, Leach & Menges, 2017). The project Landesgartenschau Exhibition Hall demonstrates that the combination of computational design, simulation and robotic fabrication offers architects, engineers and manufacturers to work interdisciplinary. Of course, the material- and fabrication-oriented design is an important key factor for working this way. By working with this methodology, the whole project can material efficient, due to the fact, that nowadays working sustainable is a design parameter and all of this can lower the costs of the building (Menges, Schwinn & Krieg, 2015).

4.3.2 Robotic Wood Tectonics – Pavilion Tongji University CAUP

The main aim of the researchers of the "Robotic Wood Tectonics Pavilion" was to design a full-scale timber building and its fabrication procedure. The design parameters for this project are to integrate timber properties, structural performance of wood and robotic fabrication process by implementing industrial customized pre-fabrication before the robotic fabrication process (Menges, Sheil, Glynn & Skavara, 2017).

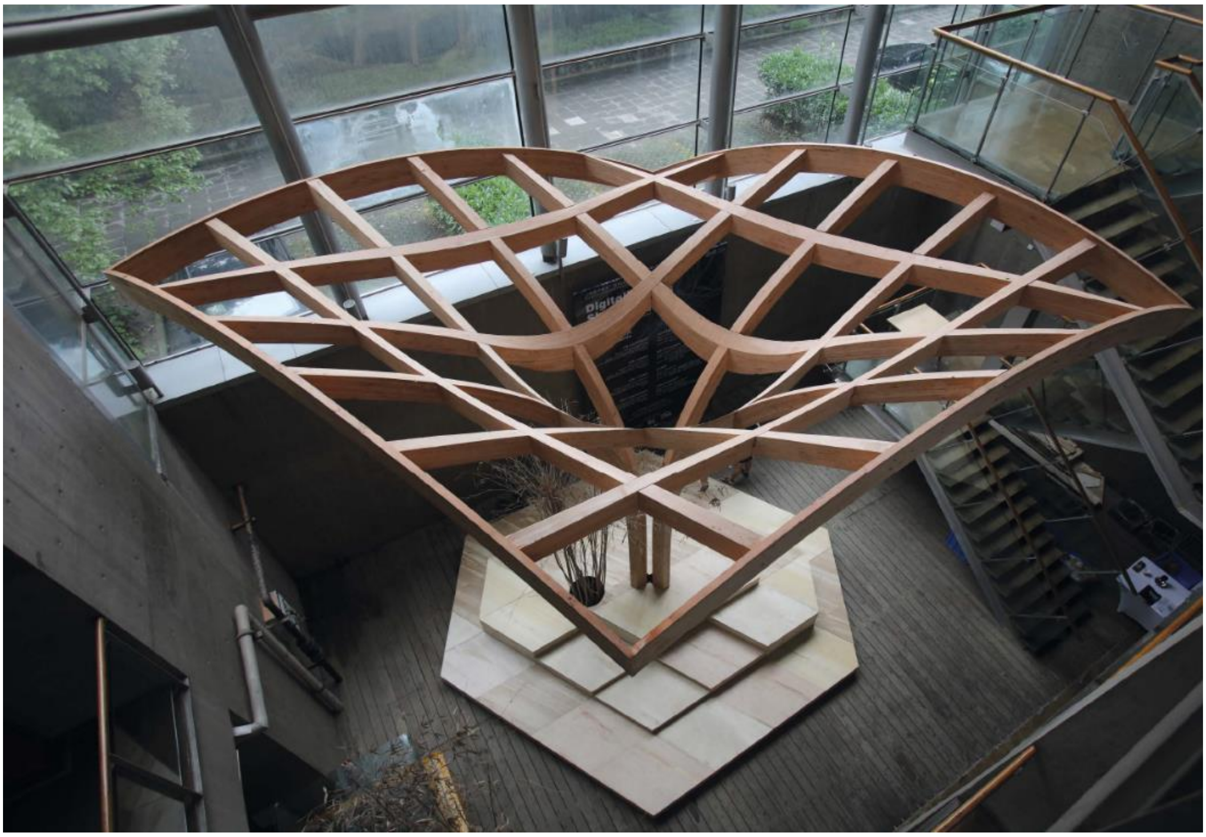


Figure 4.15 Finished construction of the pavilion (Menges, Sheil, Glynn & Skavara, 2017)

Computational Design

The computational design methodology for form-finding is based on structural performance. The form-finding is created through the Rhinoceros plug in Rhino-Vault and the Grasshopper plug-in Milipede. The is to create a form which only contains of compression forces through the whole structure, to use the advantages of timber properties, and to optimize the sizes of every structural component. With the plug-in Rhino-Vault the main geometry was created and then the form is transformed into grid-beam-system. In this system the material size of the beams is changing between 5,8 – 7,5m of length (Chai & Yuan, 2019). As well the the thickness of the material is optimized which is 100mm constantly and the height is changing between

120 – 200mm. Two sides of the beams, top and bottom side of each beam, are generated with ruled surfaces in order to fabricate them with the robotic bandsaw technique. The whole project is separated in four groups and the traditional mortise tenon technique is used for the joinery (Menges, Sheil, Glynn & Skavara, 2017).

Fabrication-Oriented Design

The final shape of the pavilion is column structure in a funnel-shape, which has quadrilateral grid system, when it is viewed from top. The structural elements are 16 beams in total and all beams are plane curves with a minimum length of 5,8m and maximum 7,5m. Due to the fact that the beams are planar, the thickness is maintained the same in the overall cross-section (100mm) but because of the performance optimization the height of the beams have to be between 120mm and 200mm. For structural performance optimization, the researchers used the plug-in Millipede and its property of analysing the structure under gravity. The beams did not change their thickness during this process, only their height, which means that they are still plane. The optimization just changed the top and bottom surface of the beams and these surfaces are changed into ruled surfaces to use this property for the robotic bandsaw method. The thickness of the material is small, compared to the length of the timber beams, the changing surface is hardly recognizable. The pavilion is a design-to-fabrication project and because of the material is separated in four groups for the final assembly. All the beams are connected with mortise-tenon joints and there is no use of metal connectors (Chai & Yuan, 2019).

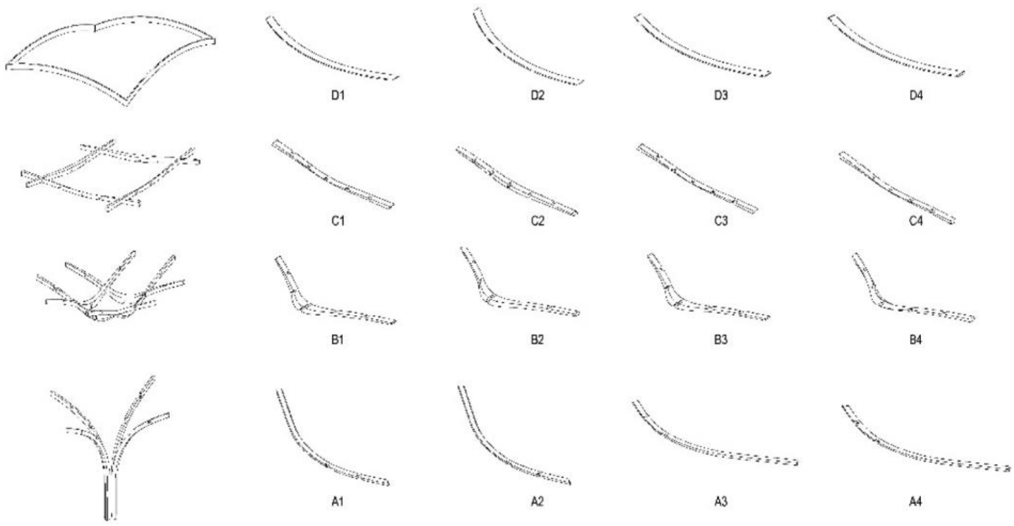


Figure 4.16 plane curved beams (Chai & Yuan, 2019)

Material

The beams are following the horizontal outer limits of the computational designed object and to have tolerances during the production and the fabrication process, the material width is offset 1cm to the outside of the borders. The raw beams are produced in the industry, and for this procedure the Douglas fir Glulam is used, because this type of wooden products is used for construction very often. The reduction of waste was also important for this pavilion, so CNC templates are implemented to guide the producers of the timber products. To produce specified wood products this way, can cause difficulties in the reduce the accuracy of the desired shape and for that reason they added 1cm more tolerance to the width of the timber (Willmann et al., 2019).

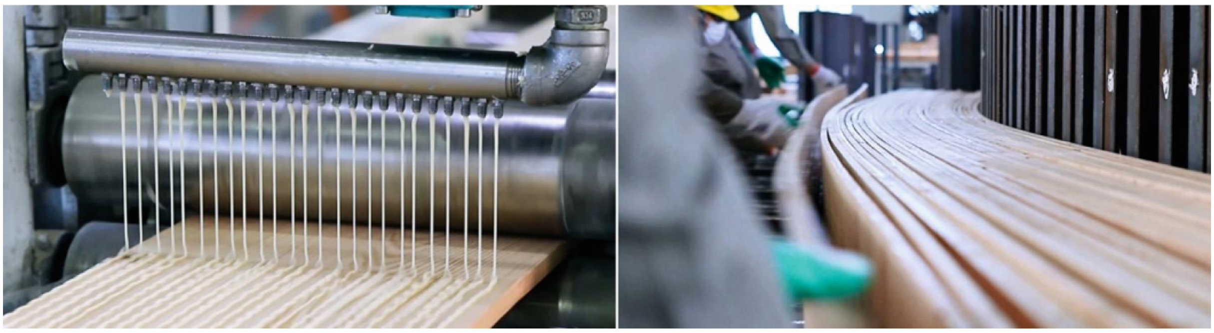


Figure 4.17 Production process of the building material (Chai & Yuan, 2019)

Robotic Fabrication

The pavilion is a very sustainable and material-efficient project and in order to preserve this methodology the beams were produced in planar curve shapes and as well the thickness was set to minimum because of the structural performance optimization. (Yuan & Chai, 2017).

For the robotic fabrication the researchers of “Robotic Wood Tectonics Pavilion” used a hanging KUKA KR120 robotic arm and used a conventual bandsaw as an end effector. The whole robotic arm and its end effector is also attached to a gantry system, which makes the robotic arm more flexible and provides new possibilities for large-scale production. Through this system robot can move 11m-6m-3.6m. For the fabrication of the beams were attached with woodworking clips to two moveable tables, which height can also be adjusted. In order to avoid collisions, the part which will be cut, are outside of the tables. Because of the tolerances and the possible inaccuracy during the production of the beams, digital model for

Rhinoceros and Grasshopper, is generated after measuring the correct location of the beam and after that, the fabrication toolpath is created and simulated in the Grasshopper plug-in KUKA prc (Willmann et al., 2019).

A professional carpenter was guiding the researchers during fabrication process with the bandsaw, because high speed and curvatures on the surface can block or break the blades of the bandsaw. The blades also must be perpendicular during this process, to avoid difficulties and fabrication mistakes. The employment and guidance of the traditional manufacturer was an important key during the process because professionals can show the known mistakes and dangers in the practice. The researchers and the carpenter decided for a 13mm blades for the fabrication, after they tried out different methods. These blades guaranteed the efficiency of the fabrication (Menges, Sheil, Glynn & Skavara, 2017).

Figure 4.18 Bandsaw cutting procedure (Willmann et al., 2019)

For the assembly of the of the timber structure, a steel base was installed. Because of the design-to-fabrication methodology, every element was labelled and had an assembly order, and due to this method, the assembly of the project, setting up the steel base and removing the scaffolding could be done in two days by five workers. The combination of the accurate robotic fabrication and using a traditional joinery technique, made the installation with less difficulties. In the end the project had height of 7m and a span of 4.5m (Figure 4.19).

Every process was implemented in this project. The complex grid-shell structure was performance optimized, the beams were customized building resources, the robotic bandsaw fabrication till the assembly on site. By making sure all of this process during the design phase can reduce the needed amount of time and difficulties in the production, fabrication and construction of a project. The project demonstrated that robotic bandsaw can be used as a valid woodworking tool for cutting curved geometries (Willmann et al., 2019).

Figure 4.19 Assembly of the project (Chai & Yuan, 2019)

The whole process demonstrated the corporation of design and the fabrication methodology and it also provide an innovation for timber construction in computational designed timber constructions, by choosing the fabrication methodology beforehand and implement it as design parameter in the design phase. (Menges, Sheil, Glynn & Skavara, 2017).

4.3.3 Sequential Roof

The project “Sequential Roof” is designed for the Arch-Tech-Lab Building at the Institute of Technology in Architecture of ETH Zürich. The building contains of various functions as the new laboratory and office building. The laboratory will research the state-of-art of robotic fabrication, create space for offices and studios. The most important part of the building is timber roof design which is created with robotically (Menges, Schwinn & Krieg, 2017).

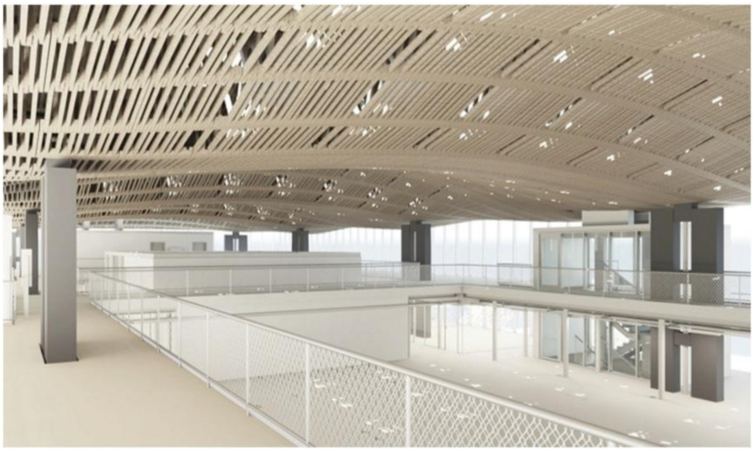


Figure 4.20 Rendering of the "Sequential Roof" (Willmann et al., 2016)

The project demonstrates the full-scale fabrication process of the “Sequential Roof”, which is a 2300m² timber roof (Figure 4.21). The timber construction totally assembled automatically with layer construction timbers. The project demonstrates the full-scale fabrication process of the “Sequential Roof”, which is a 2300m² timber roof. The timber construction totally assembled automatically with layer construction timbers. For this project, the researchers must come up with new innovations for the computational design, develop a framework for the construction including structural analysis of the timber roof and the autonomous fabrication procedure. The development of this structure can influence conventual assembly methodology in architecture, which is mostly done manually (Willmann, Gramazio & Kohler, 2017).

Computational design

The timber roof´s design is a free form structure, which contains an area of 2300m² and a totol number of unique timber constructions elements of nearly 50.000 pieces. So, it is generated through a bespoke algorithm and fabricate with a large-scale robot. The dimensions of the structure are 28m width and 80m length and spans a double height open office plan. It is resting on 12 steel columns (Menges, Schwinn & Krieg, 2017).

The whole structure contains 168 trusses with a span of 14,7m and a width of 1,15m and the structure is continuing seamless through the whole construction. The trusses are all designed computationally so the stacking design of every truss with 23 layers of 50mm construction timbers is unique. A traditional layering methodology of top and bottom chords with diagonal structure in-between was used for the truss system. The chords are designed continuously which chain-like three-layer system and trusses are always only one layer (Figure 4.23) (Willmann, Gramazio & Kohler, 2017).

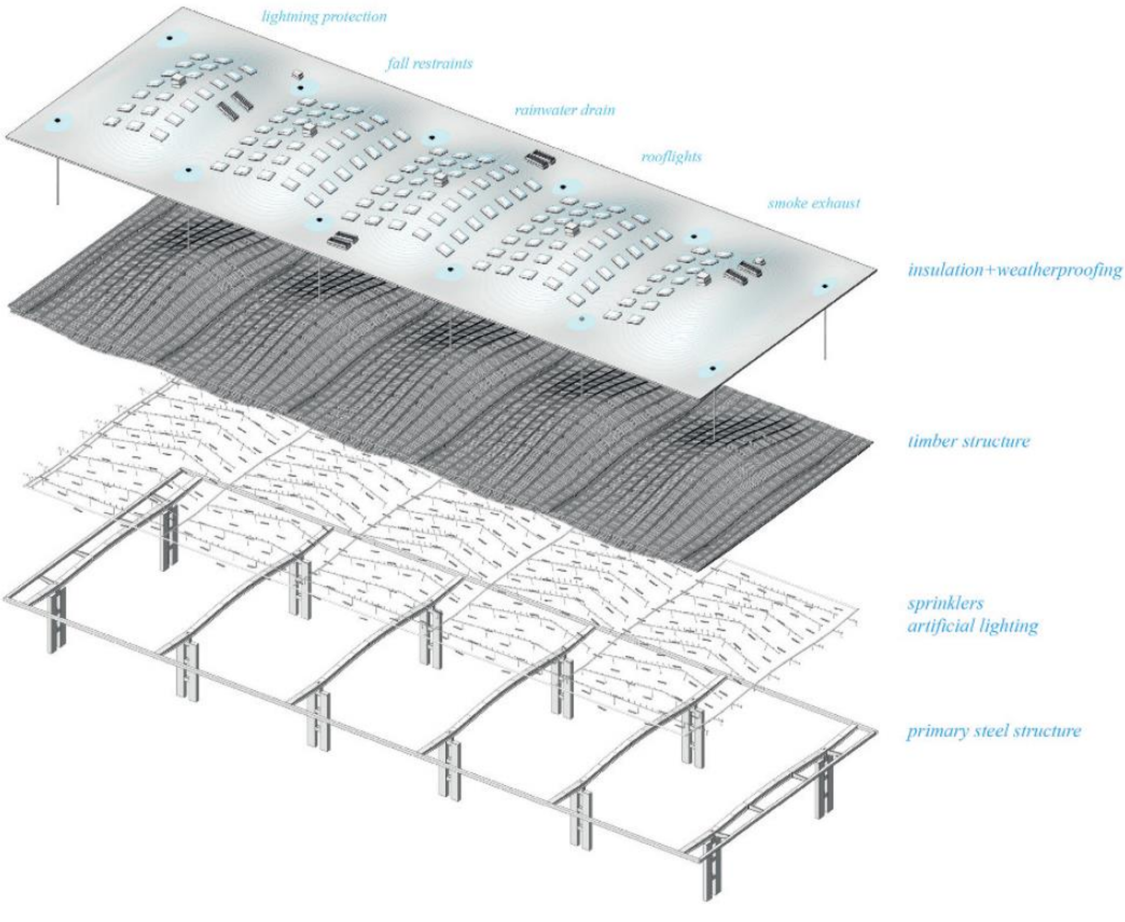


Figure 4.21 Overview of the roof structure and. Roofing layers, skylights, smoke exhaust, sprinklers, lighting (Willmann, Gramazio & Kohler, 2017)

Due to the fact that the seamless and dense structure of the roof, there is the possibility to attach the waterproofing layer on the top of this system and there is no need to construct an additional system for it. Compared to a double curved panel system, this type of methodology causes less problems (Willmann, Gramazio & Kohler, 2017).

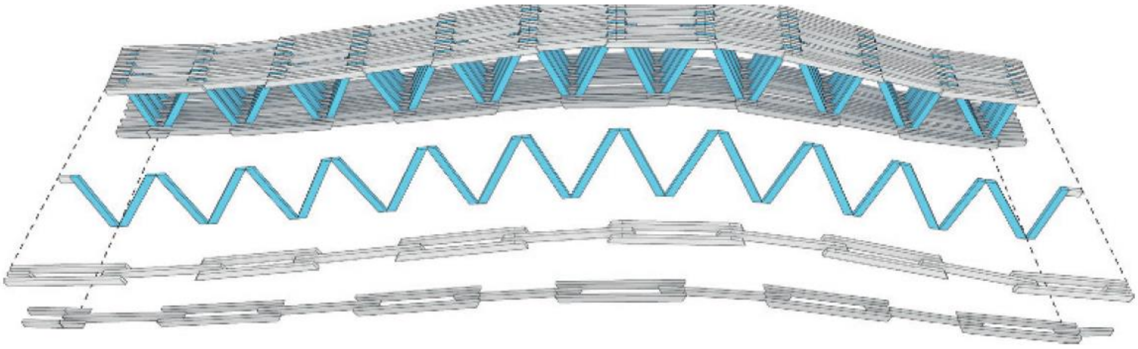


Figure 4.22 Layering logic of the trusses (Menges, Schwinn & Krieg, 2017)

The design of the roof structure has also influence in the acoustics of the interior open space and supports the artificial lighting, sprinklers and various subsystems (Willmann, Gramazio & Kohler, 2017).

The spaces between the timber slats are designed after serial tests for optimal natural lighting and the dense geometry is as optimized to carry all the loads which are occurring on the roof (Bianconi, Filippuci, 2019).

Totally automated connection systems are chosen to achieve an autonomous production procedure. Under loads the wooden product can bend and deform before it breaks and to hold this movement the researchers decided to use nails as mechanical connectors which can hold the movements of the whole structure. With the nails the construction will not collapse in a fast manner, it will transfer the stresses in the structure smoothly. The positioning of the nails depends on the direction of the grains so the timber will not crack during the production process and each nail will carry two pieces of wood. So, the number of nails needs to be raised because of two different grain directions (Figure 4.24) (Menges, Schwinn & Krieg, 2017).

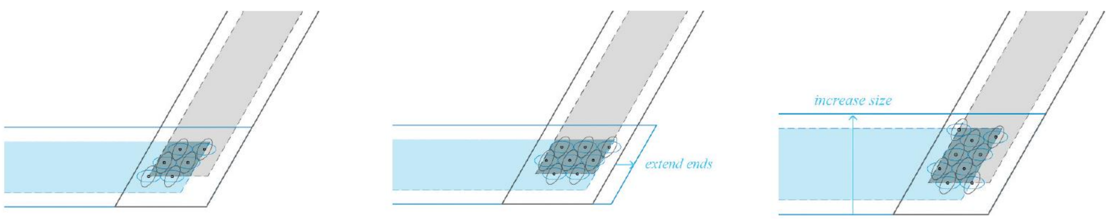


Figure 4.23 Joinery of two timbers (Willmann, Gramazio & Kohler, 2017)

Robotic Fabrication

For the fabrication process, a large-scale gantry robot is applied which is developed by the contractor of the projects. The gantry system contains of a 6-axis robot with a mechanical wrist to reach difficult angles and also various end effectors like a sawing machine, a rack to change the tools and of course a repository for the material (Bianconi, Filippuci, 2019).

The robotic fabrication process for the trusses are built in four steps: 1- as first step the robot is grabbing and cutting the timber in the correct length and angle. 2- After the cutting sequence, the material will be placed into the correct location and be fixed with only one nail in each end. After being sure that it is placed correctly the timber will be fixed with more nails. 3- this step is an extra procedure and is only used when some parts have to be cut after the layering is done and for this process the end effector will be changed with a circular saw. 4- the last step is to make sure the layer-positioning is correct before building up the next layer. The machine has camera attached which controls every joint of the fabricated layer to avoid mistake and irritations (Willmann, Gramazio & Kohler, 2017).

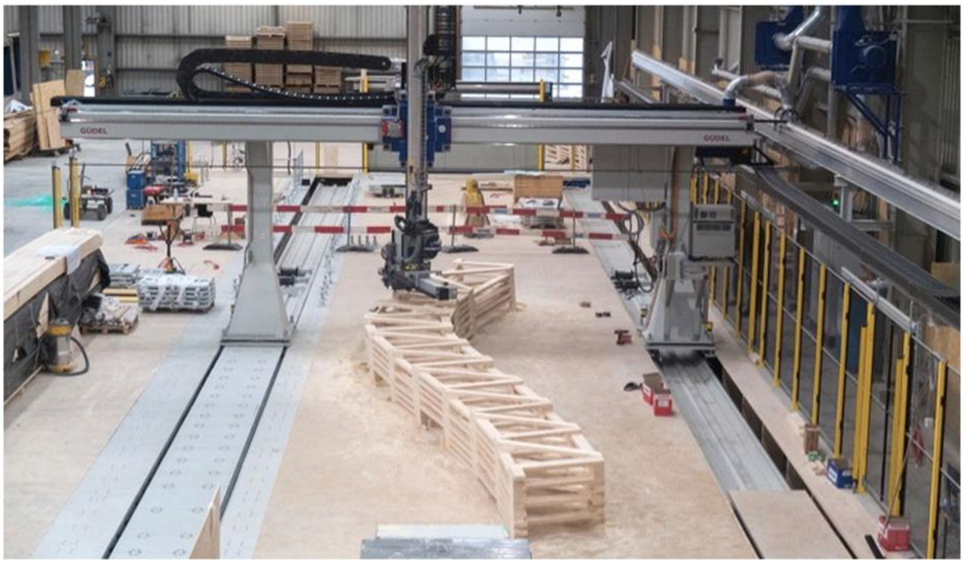


Figure 4.24 Robotic assembly (Willmann er al., 2016)

After finishing the fabrication of the timber trusses, they were brought to construction site and assembled on site. This project demonstrated the achievement of computational design and modern robotic fabrication and that design-oriented-fabrication can save time in the construction process and optimised structural performance can lower the costs of a building, by working sustainable with the resources. (Menges, Schwinn & Krieg, 2017).

5. Design Approach

The aim of this thesis is to make a research of robotic timber construction, computational design of wooden products and the digital fabrication of timber. It will function as an additional exhibition space for the contemporary art space M50 Creative Park. This location is chosen due to its atmosphere and as well there are almost no use of space in the exterior. Every function is situated in the galleries and artists' studios.

During the computational design, the materiality is also an important factor for the project. Most of timber products are prefabricated and for that reason they are fabricated in specific dimensions. This important property of timber products is used in this research as an advantage.

5.1 Overview and Site

Overview of M50 Creative Park

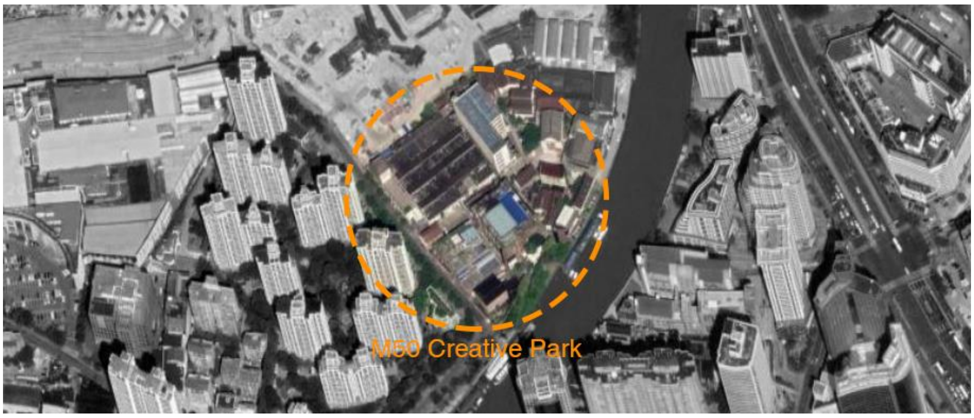


Figure 5.1 Surrounding overview (URL 39)

M50 Creative Park or 50 Moganshan Road is located in Shanghai and it is an exhibition space with over a hundred artists who exhibit their artwork to to the public and it is the contemporary art district of Shanghai. M50 is the same for Shanghai like SOHO in New York and 798 Art Zone in Beijing.

Figure 5.2 Building site (URL 40)

The art district is located in an industrial area close to the Suzhou Creek and also the residential Putuo District. Nevertheless, it is very close to the downtown and the Jing'an District.

Figure 5.3 Building site opposite view (URL 41)

The start for this extraordinary art exhibition space started in the 2000s when the artist Xue Song went there because of the cheap rent of the abandoned industrial area. After him other artists followed him. Nowadays all of the factory buildings are converted in galleries and studios of different artists (URL 41).

5.1.1 Building Site

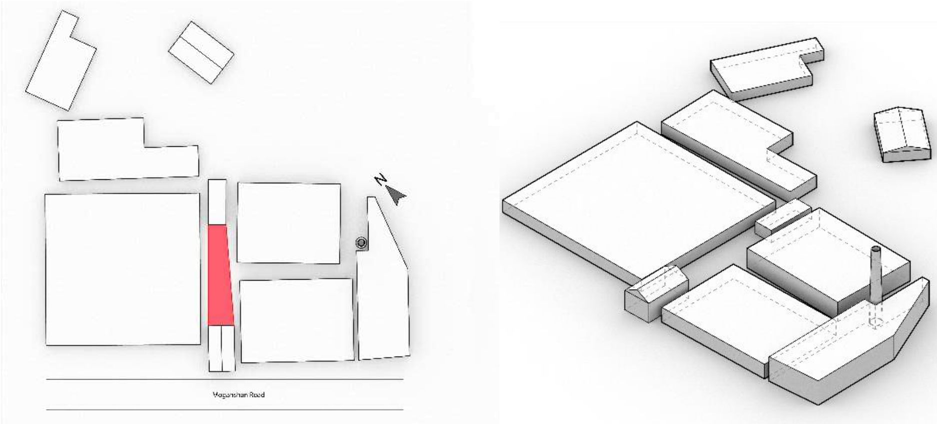


Figure 5.4 Building Site Top View (left) and Axonometry (Right) (author)

The chosen site for this project is located at the courtyard of M50 Creative Park. It connects two galleries of the art exhibition space and it is close to the Moganshan Road entrances.

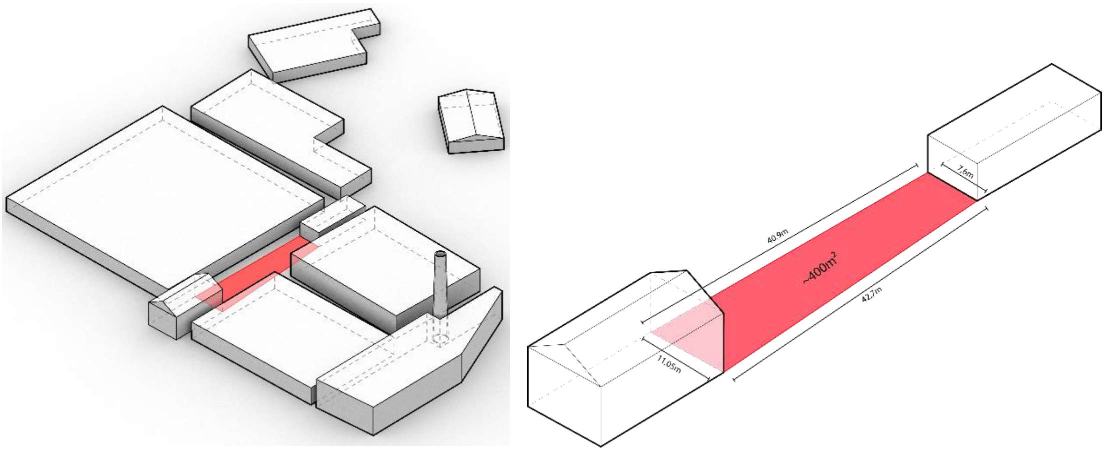


Figure 5.5 Building site (red area) (author)

It has total area of 400m² and a length of 40,9m at the shorter side and 42,7m at the longer side. Width is at one side 7,6m and 11,05m at the other side.

5.2 Concept

The main function of the project is to create an exhibition space at the courtyard of M50 Creative Park which is situated in-between the galleries close to the entrance. Due to the close situation to the main gates on the Moganshan Roade, the movement of the visitors will be used as the main concept of the form development.

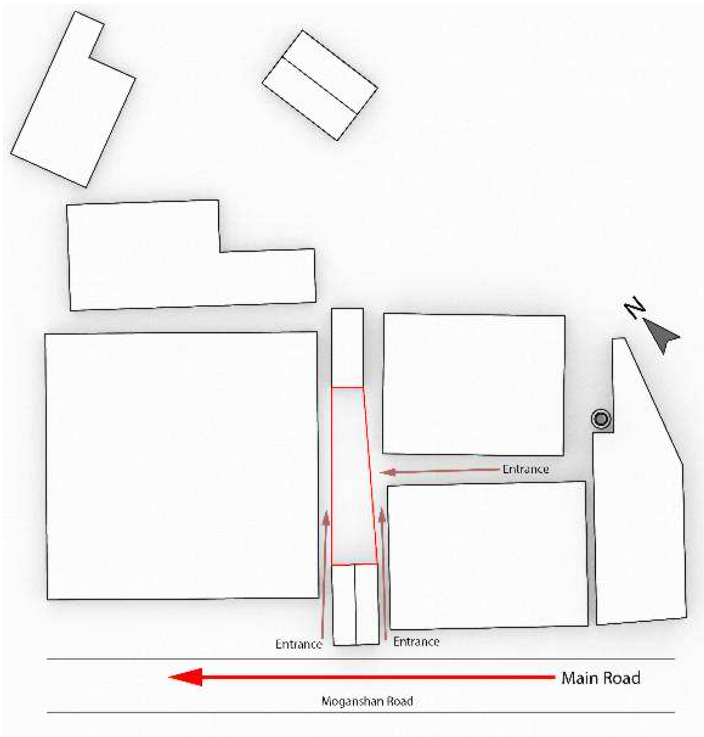


Figure 5.6 Main Road and entrances to Site (author)

The following aim is to create a path between the galleries which provides the borders of the construction site. By making this path the both building can interact through the project.

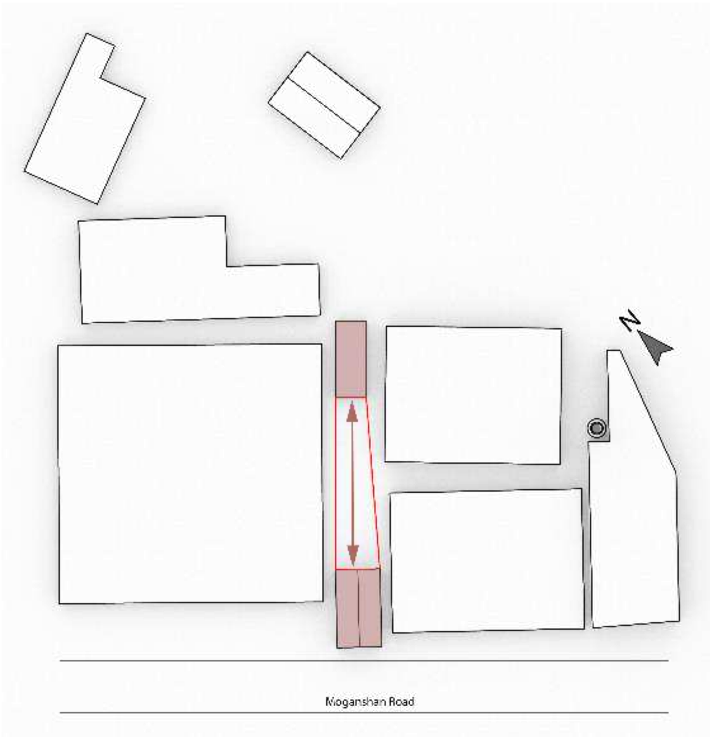


Figure 5.7 Interaction on Site between the galleries (author)

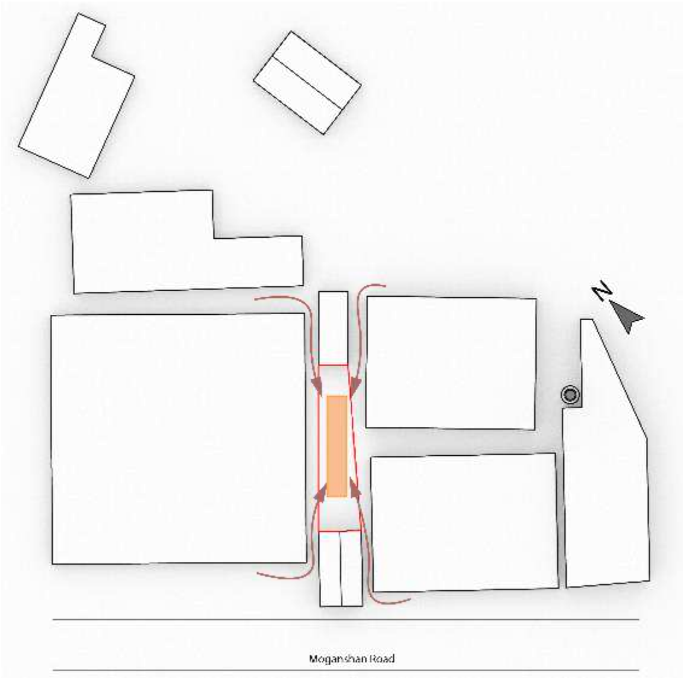


Figure 5.8 Entrance to the designed pavilion (author)

As a result of combining the art galleries the visitors will be attracted to the project and they can pass through the interior and enjoy its atmosphere.

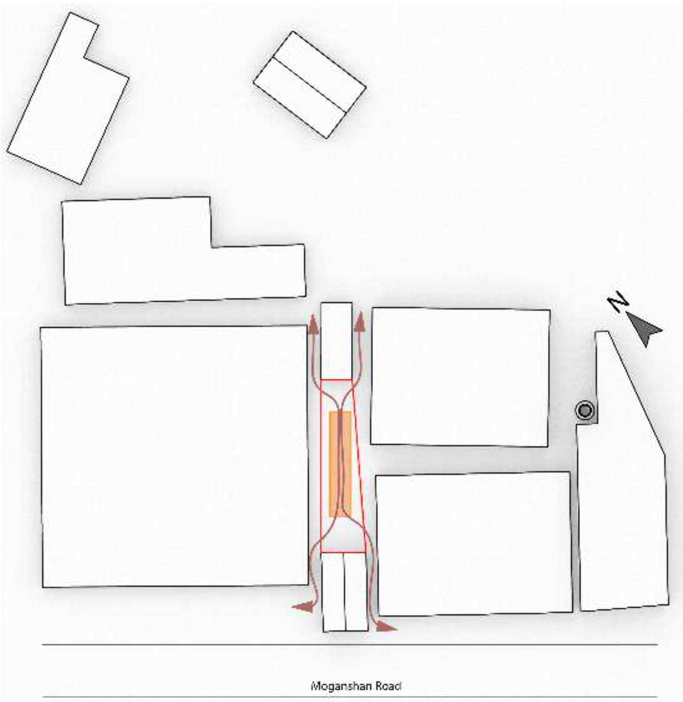


Figure 5.9 Crossing the interior (author)

The designed project will create interactions between the project itself and as well the single art studios and galleries in the surrounding.

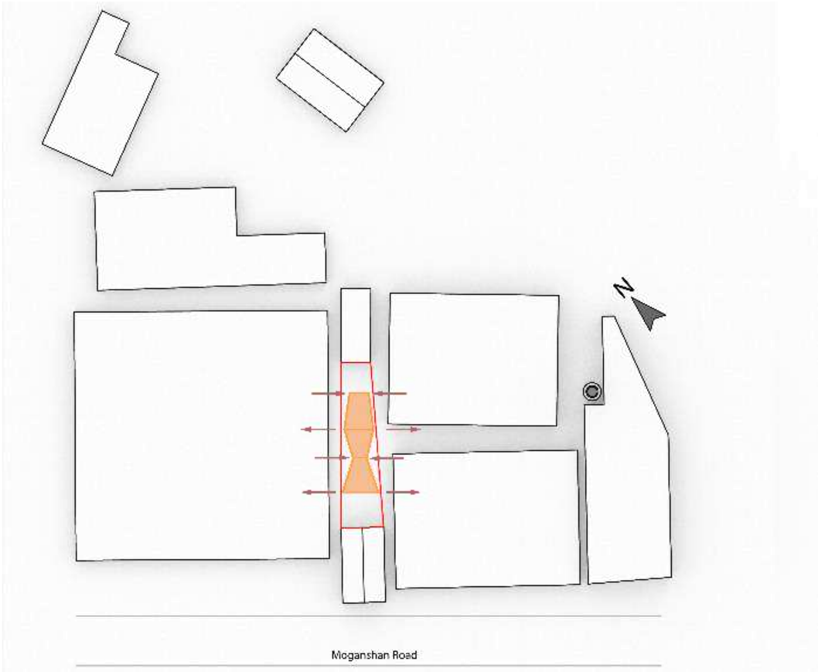


Figure 5.10 Sizing the section of the pavilion to create interaction to surrounding (author)

The object will be divided in four section and the first section and the third one will be wider and in contrary the second and the last section gets narrower and as a result of these simple operations, new areas are created in relation to the close surrounding buildings and the square.

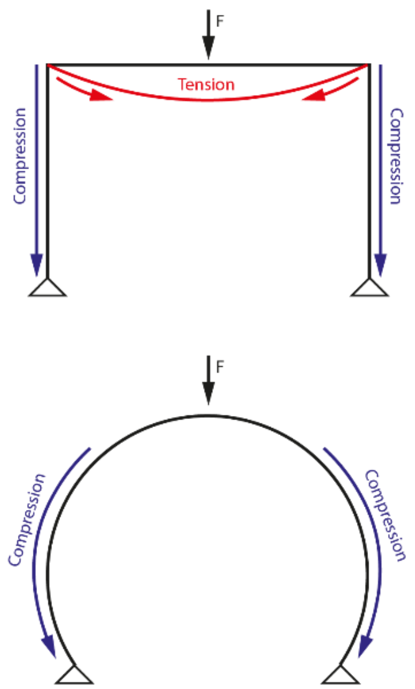


Figure 5.11 Forces in frame (Top) and arc (Bottom) (author)

As well in the interior of the building the different sizes provide a totally different atmosphere for thse visitor. The sections will not be as frame construction because in this kind of frames tensions and compression occur and those forces can cause problems for a wooden construction. Due to this condition the section profile will be an arc because in arc constructions there are only compression forces.

5.3 3D Workflow

The design was developed on the CAD and 3D programme Rhinoceros and Grasshopper plug-in.

5.3.1 Form Development

Step 1: The first step was to create the form according to the concept which is explained in the previous part. Four arcs with different diameters were placed on the sites.

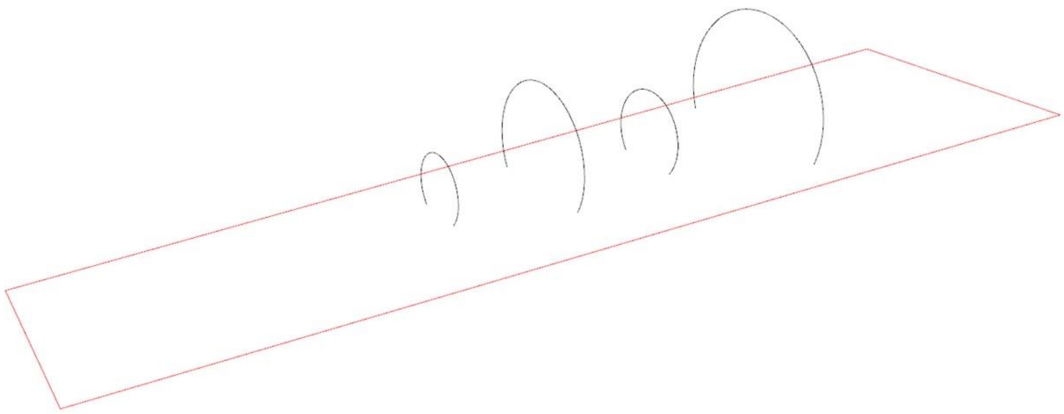


Figure 5.12 Section curves for to loft surface (author)

Step 2: In the next step the arcs got lofted and created a freeform. The shape gives the impression of opening one site and closing the gate on the other site.

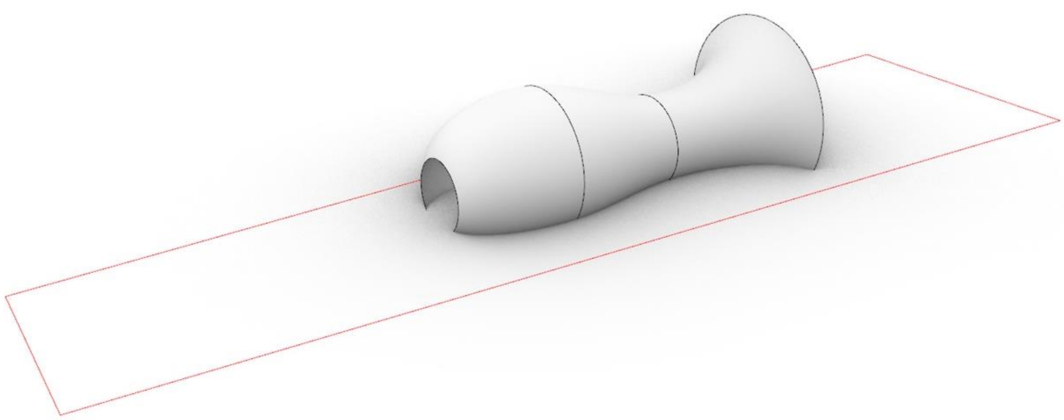


Figure 5.13 Lofted surface (author)

Step 3: After that operation the form must contoured in direction of X-Coordinates with distance of 100mm for placing the construction timber.

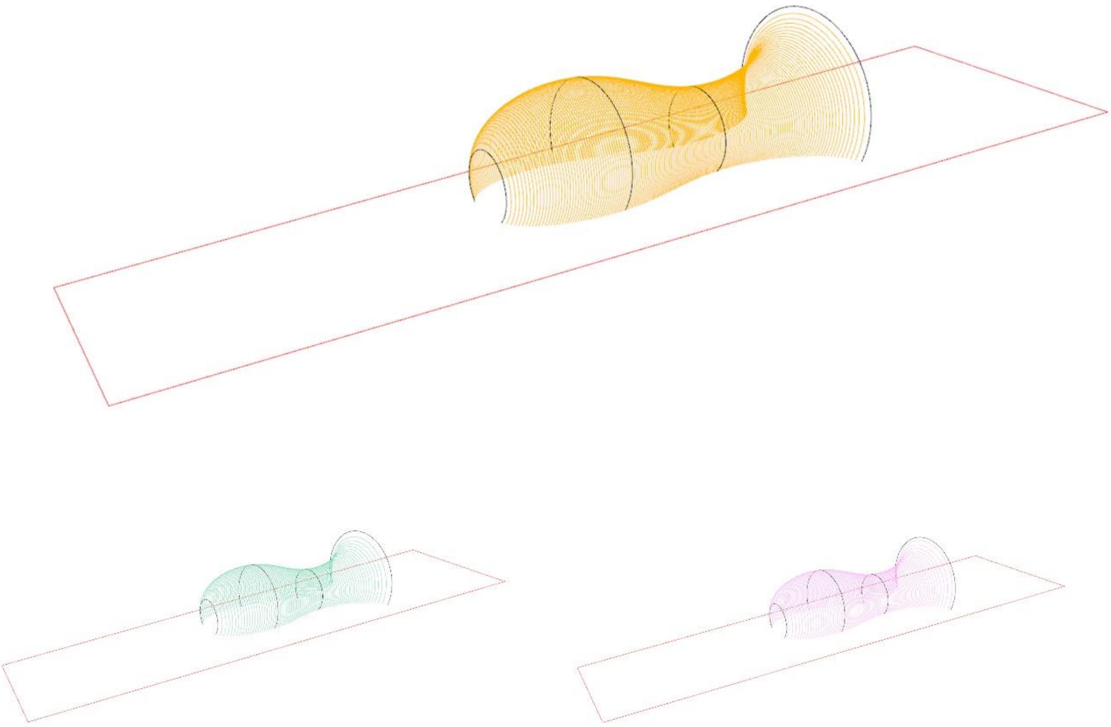


Figure 5.14 Contoured surface in total (top) and separated in two groups by choosing every second contour line (Bottom) (author)

Step 4: The contour lines will be separated on Grasshopper in two different groups because in the following steps the operation of both will be made separately. After separating the lines, the distances between the lines are 200mm each.

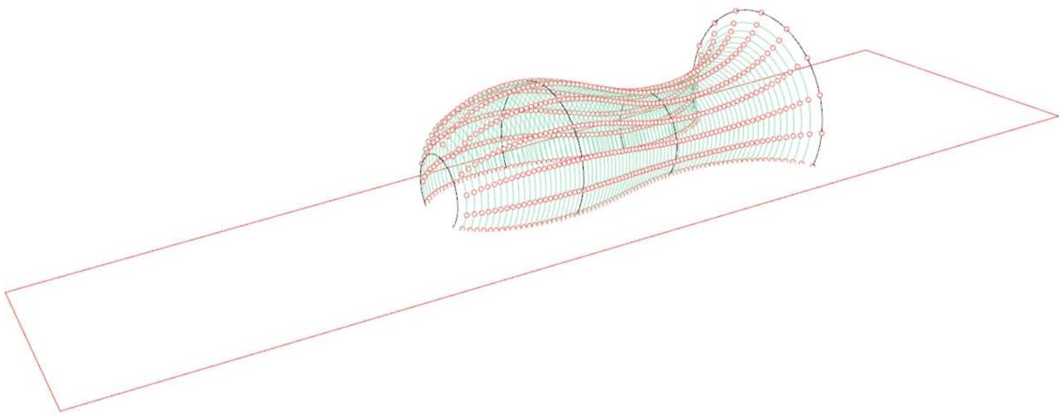


Figure 5.15 Division points of contour lines (author)

Step 5: The first group of the contour lines will be divided in with a total of 10 points for each line. These points are the centre points of the construction timber.

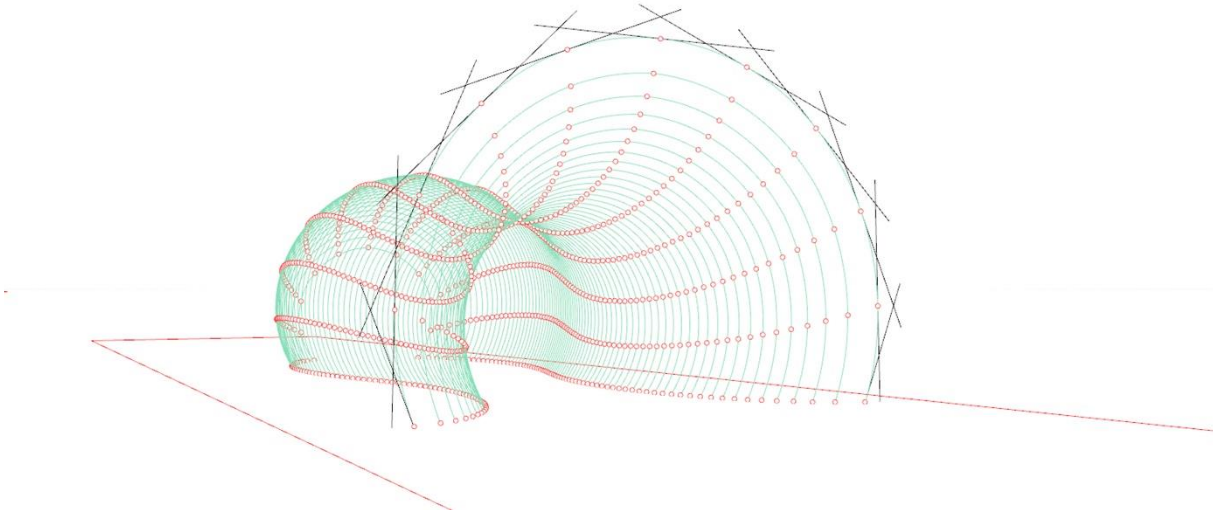


Figure 5.16 Tangential lines through the division points (author)

Step 6: In the steps these points and their properties are used for creating the tangential lines on the arc. The points will be extended in both directions with a length of 2m – total lengths of 4m.

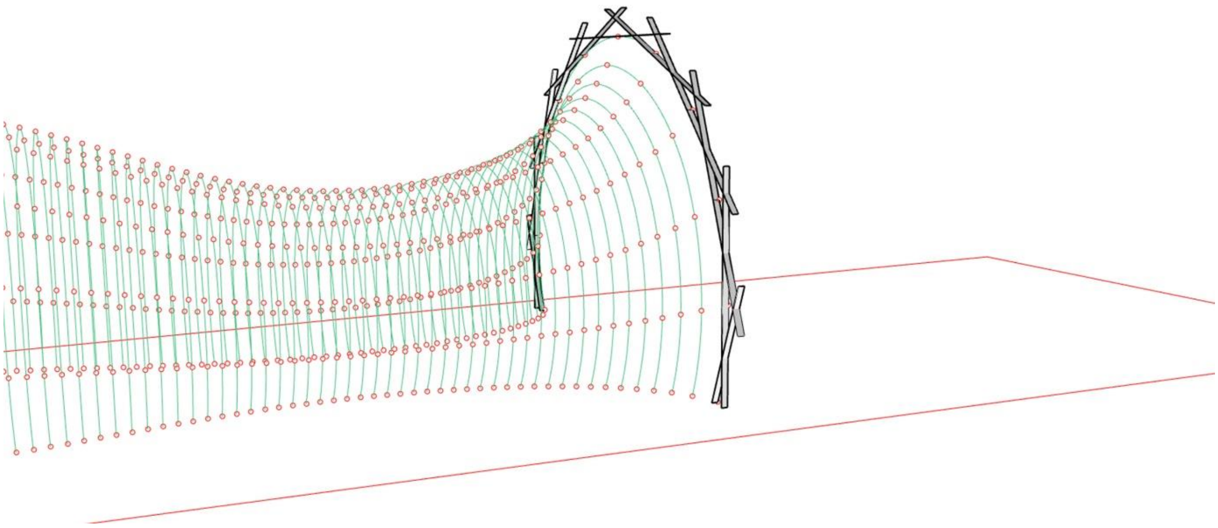


Figure 5.17 Extruded lines (author)

Step 7: The tangential lines are extruded 100mm in X-Direction to create the main section of the construction timber. After this operation it is visible that the surfaces are intersecting. The last step will be the extrusion of the created surfaces in Normal-Direction to the surfaces.

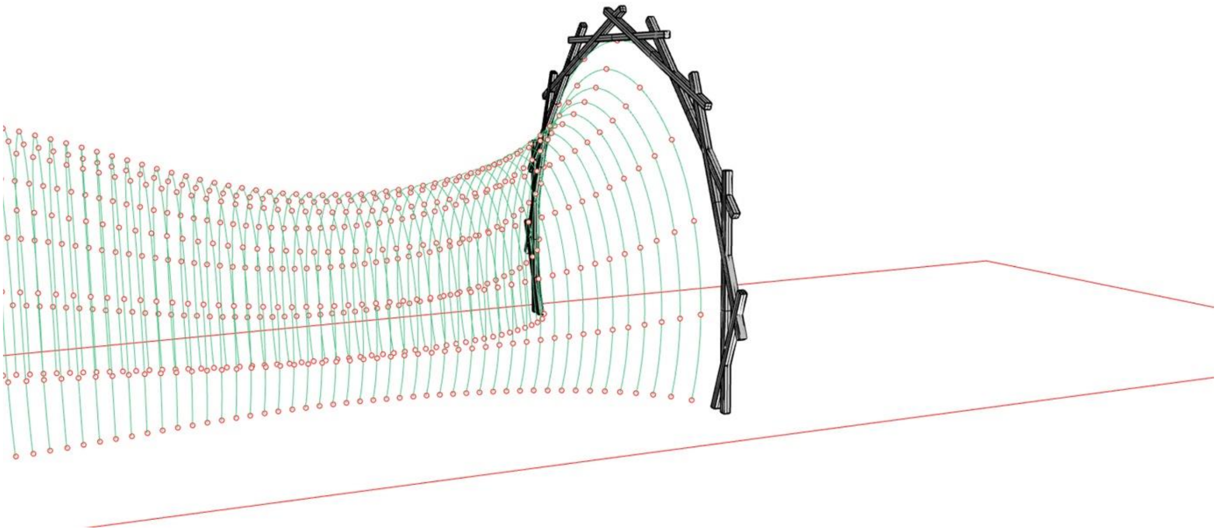


Figure 5.18 Solid objects extruded from plane curves (author)

All these operations will be applied on the second group the contoured lines, so the construction timber will be aligned in two lines.

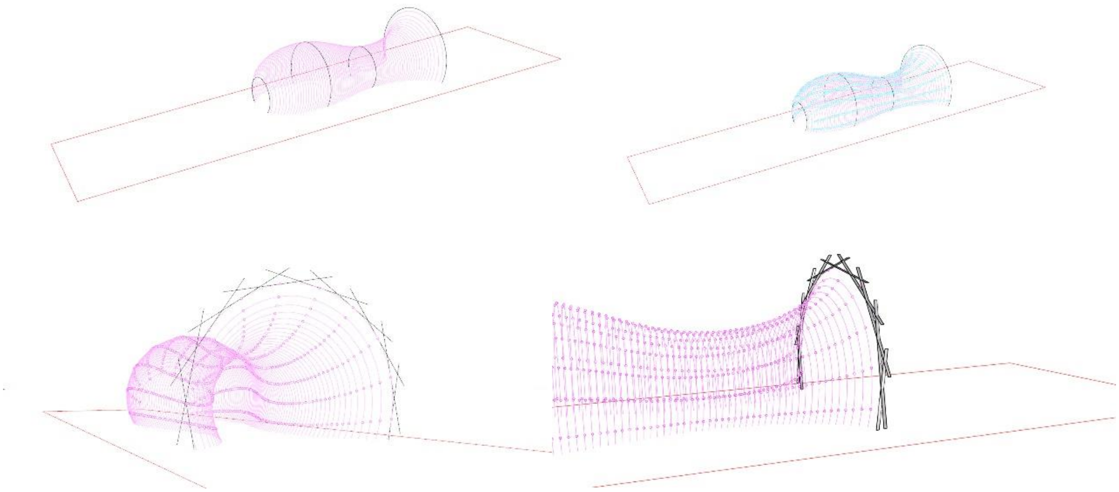


Figure 5.19 Contour lines of second group (top left) and division points on curves (top right); tangential lines on points (bottom left) and extruded curves (bottom right) (author)

All these steps will be generated on Grasshopper so the design phase will be almost totally parametric so the length and the distances can be adjusted according to the shape and needs of the project.

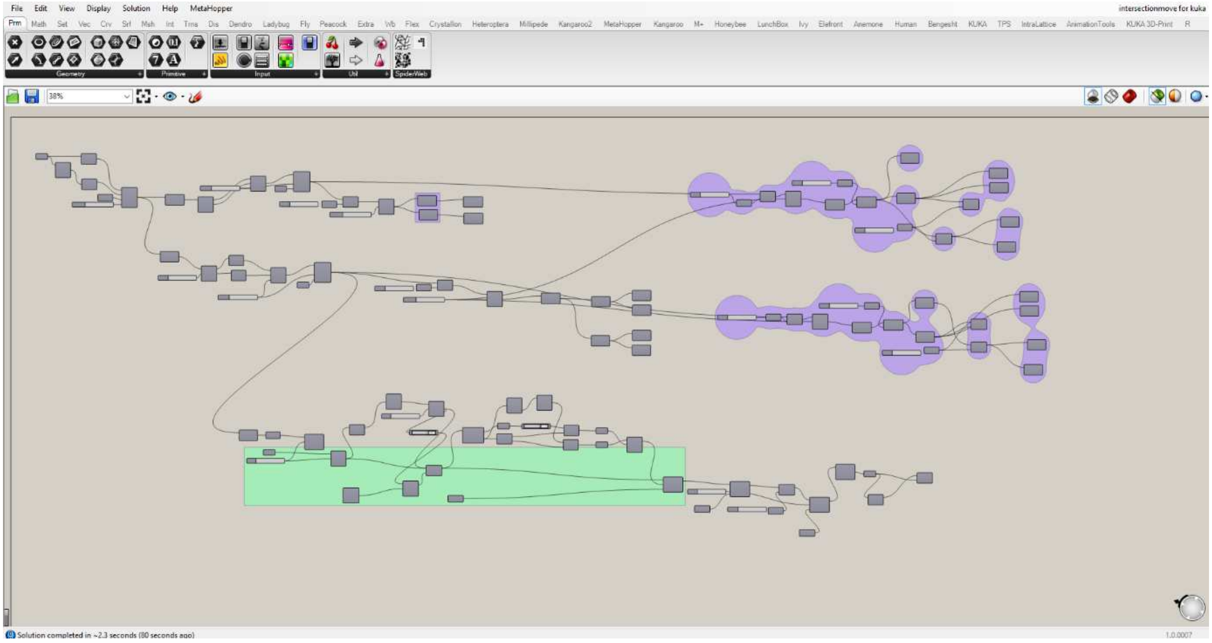


Figure 5.20 Grasshopper definition of 3D Workflow (author)

5.4 Architectural Drawings

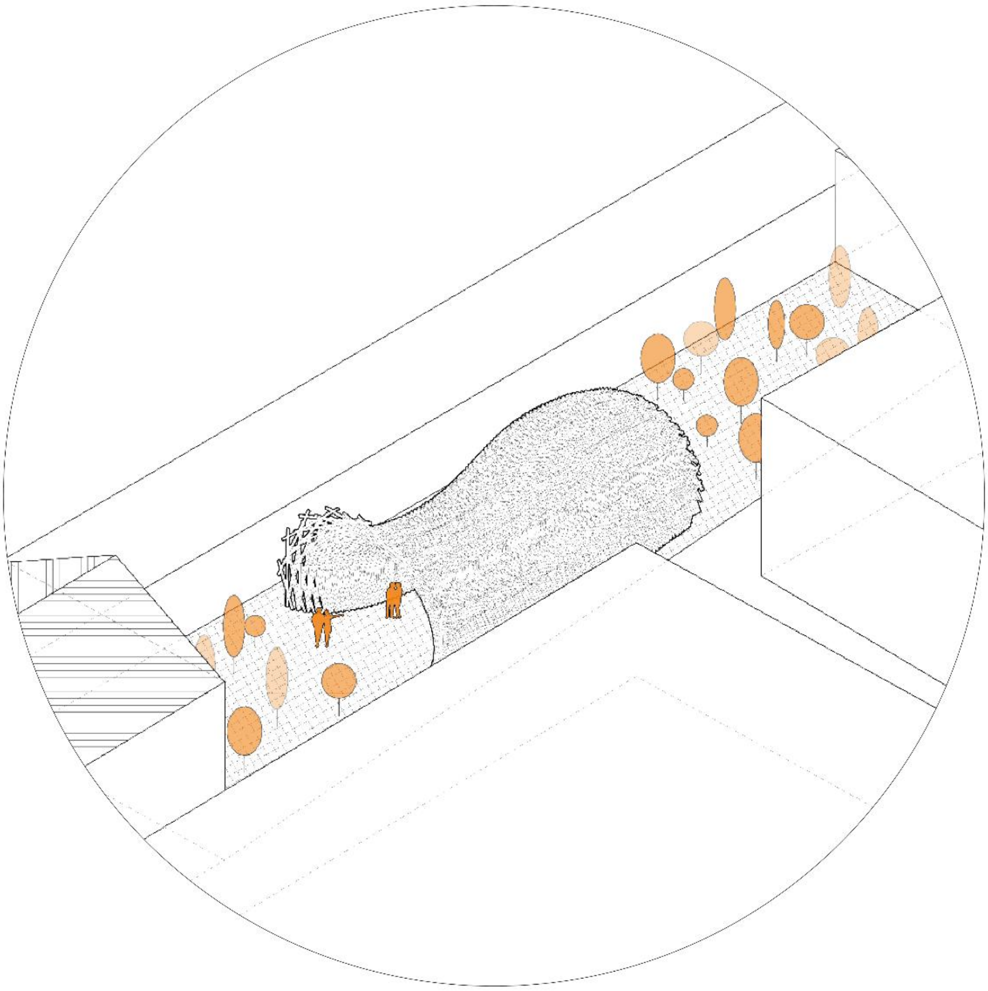


Figure 5.21 Axonometry Zoom-in (author)

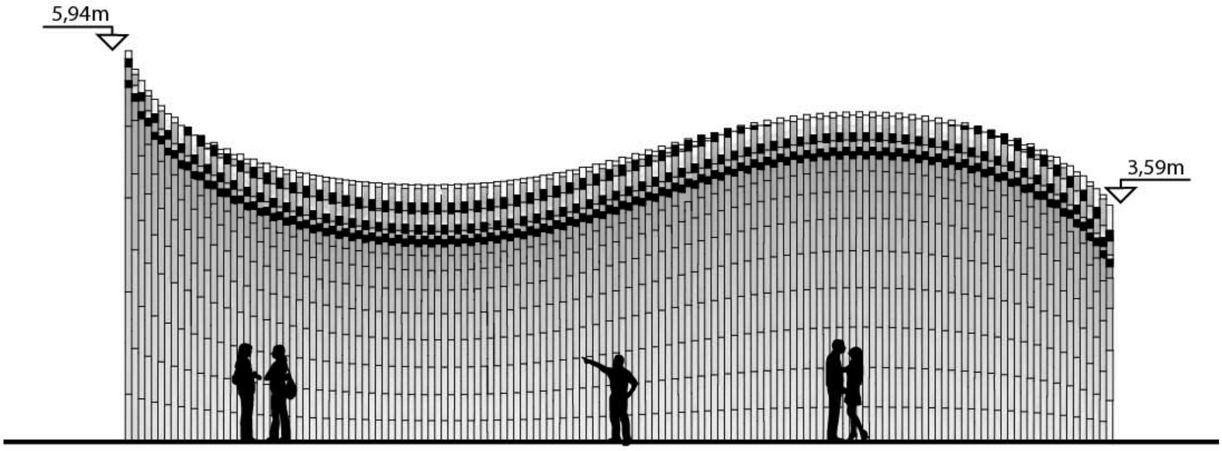


Figure 5.22 Section A-A (author)

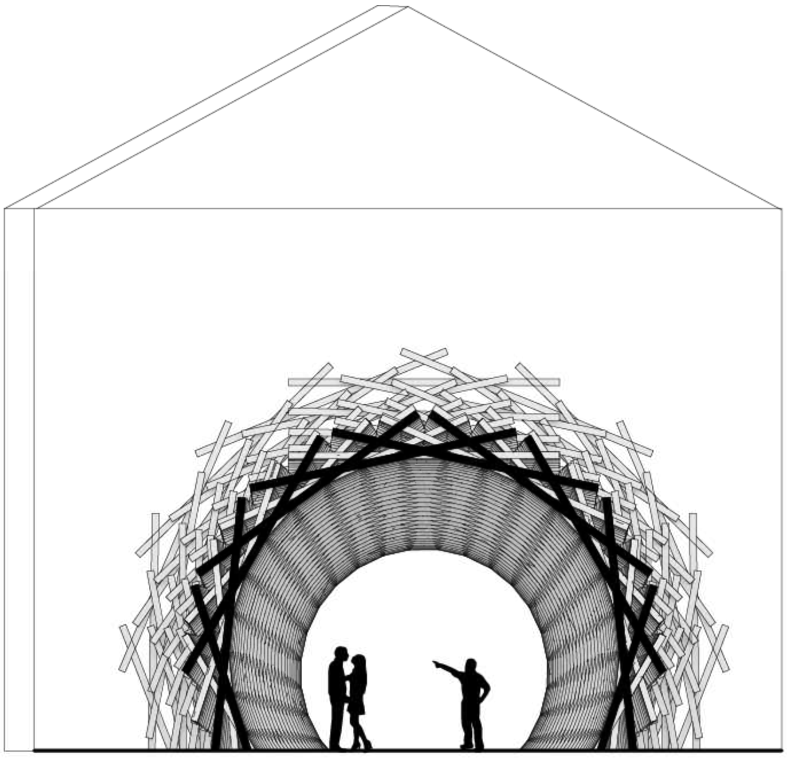


Figure 5.23 Section B-B (author)

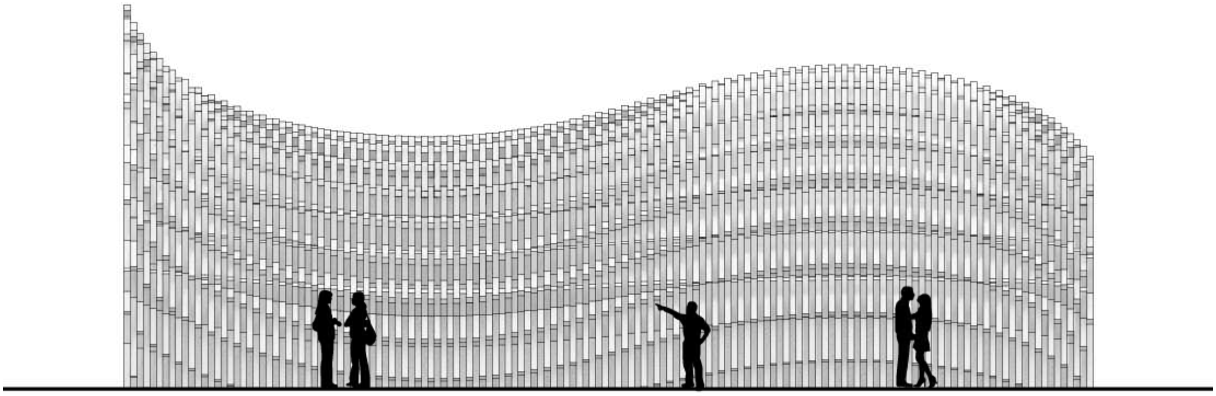


Figure 5.24 East Elevation (author)

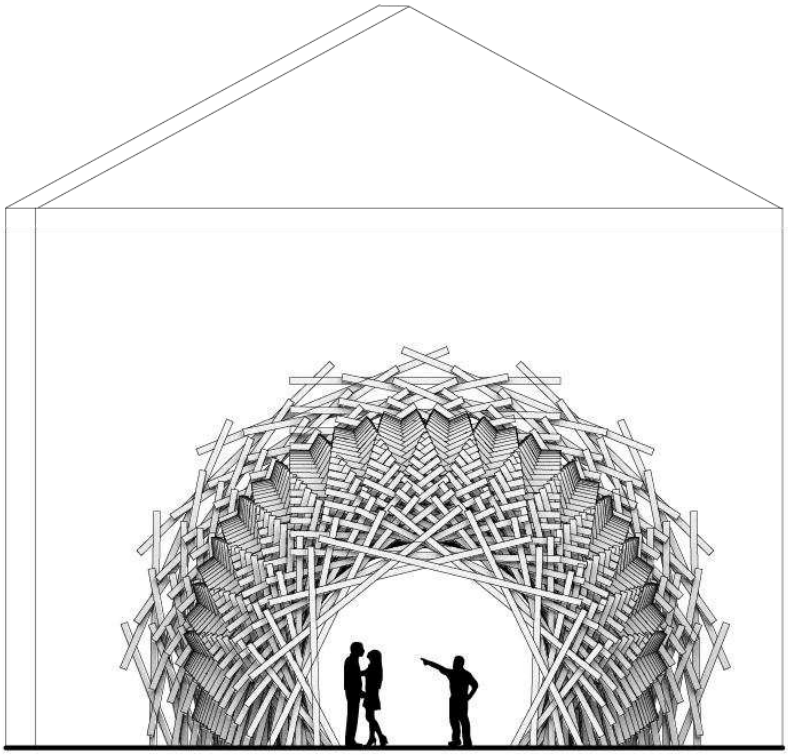


Figure 5.25 North Elevation (author)

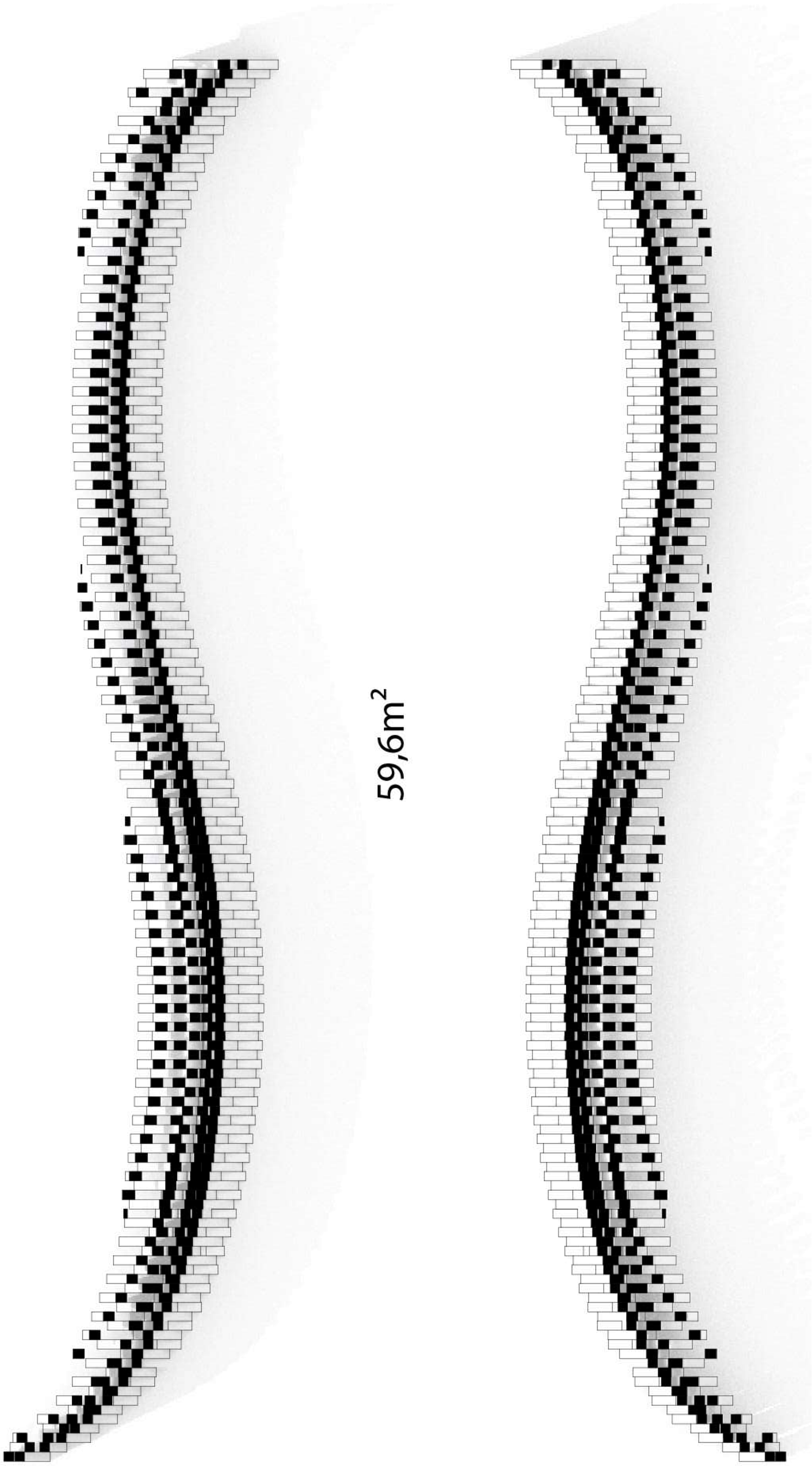


Figure 5.26 Floor plan (author)

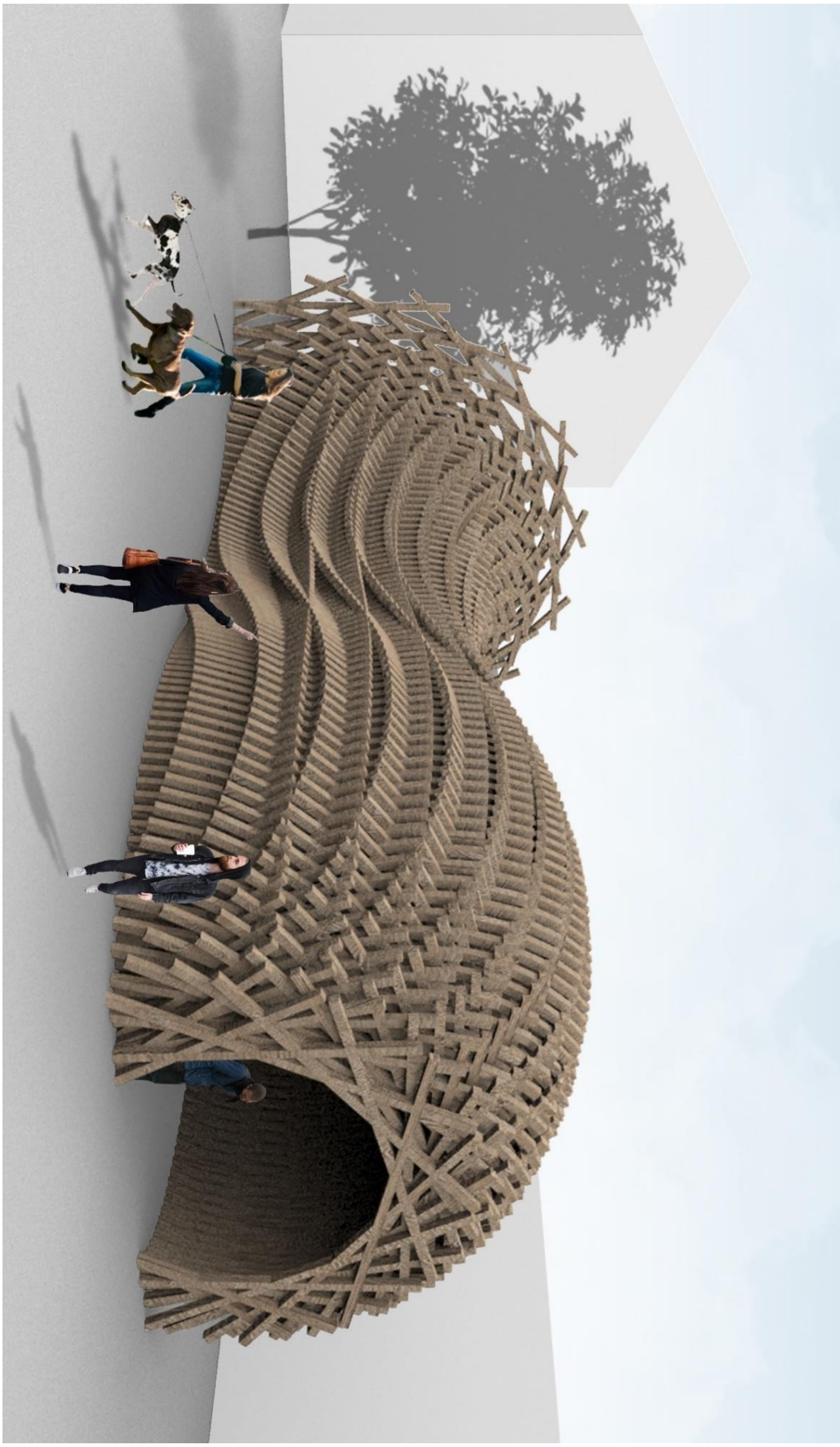


Figure 5.27 Rendering Backside (author)

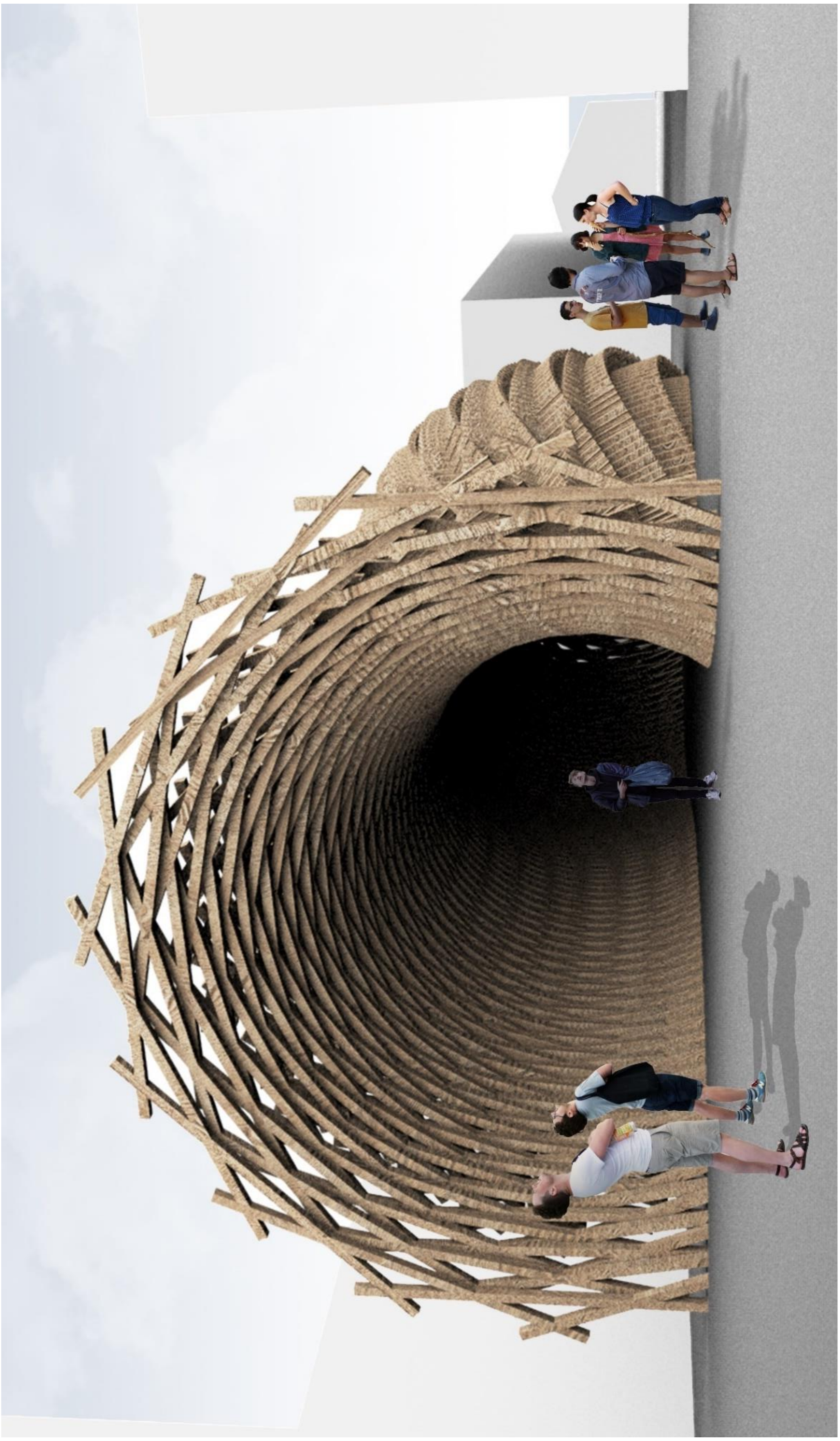


Figure 5.28 Rendering north side (author)

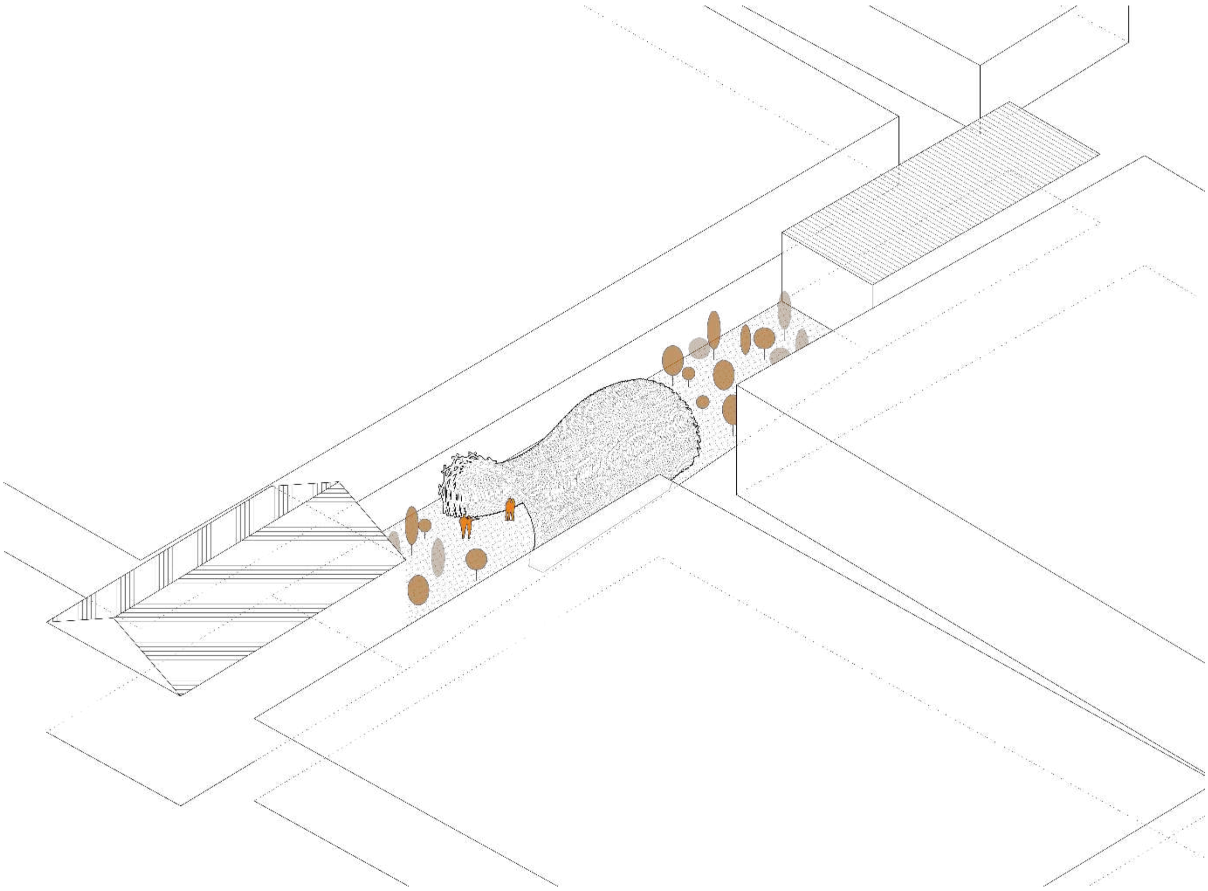


Figure 5.29 Surrounding axonometry of M50

5.5 Materiality

This research is based on computational design and digital fabrication of timber construction and therefore the chosen material for this project is construction timber to use the advantages of the prefabricated timber blocks. There cross sections are 10 x 10 cm section and 400 cm in total length.

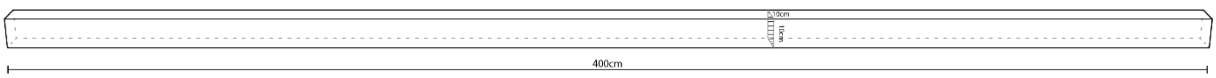


Figure 5.30 Timber construction bar dimensions (author)

This project has a total amount of 1575 pieces and this corresponds to a volume of 63m³. Each timber has the same length and they will be fabricated one by one with the robotic arm. Due the complexity of the projects each joint is unique.

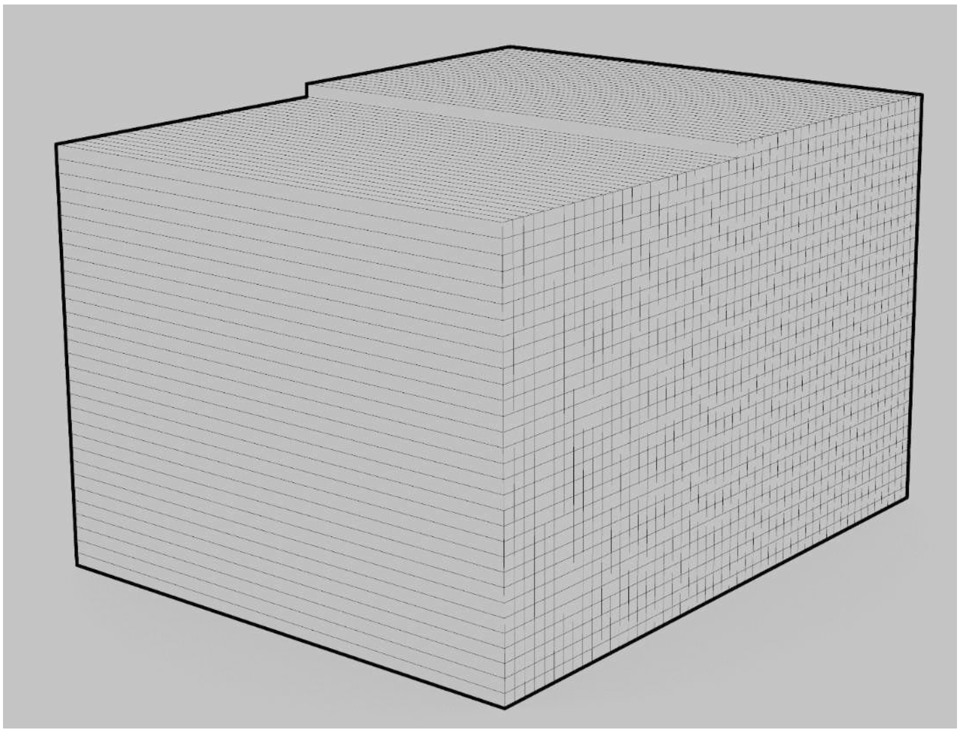


Figure 5.31 Total amount of necessary material (author)

5.6 Joints

The whole project contains of 1575 pieces of construction timber and a total number 3524 connection points. Each joinery has unique dimensions and a unique form, for that reason digital fabrication is an important tool to simulate and generate each connection digitally.

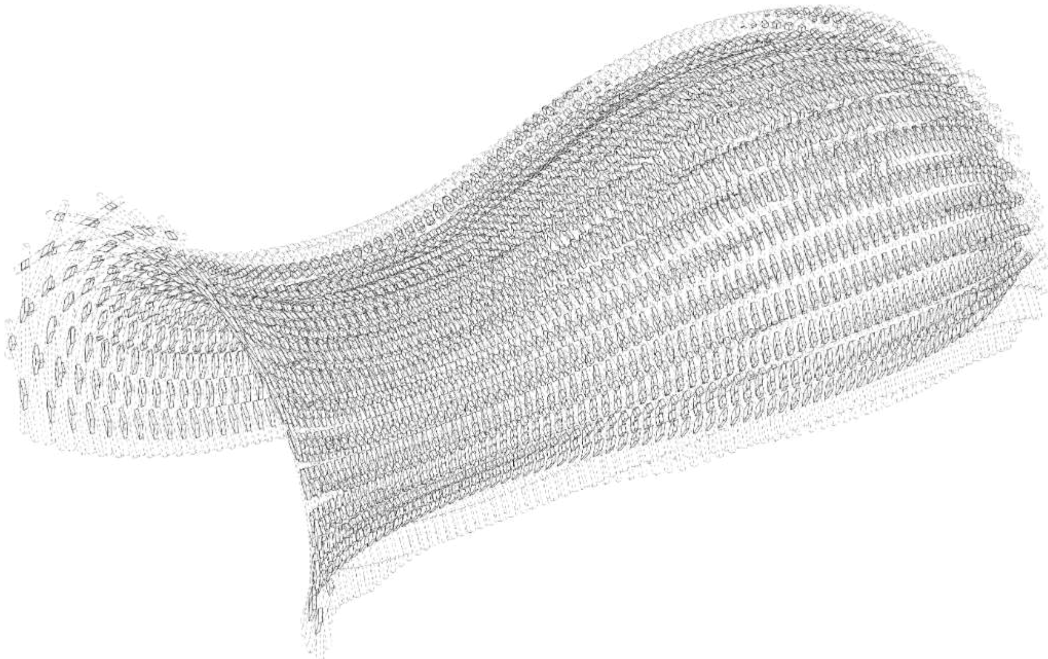


Figure 5.32 Intersection areas diagram of the bars (author)

The joints are created through the intersection of construction timber row and therefore they are intersecting several times. The intersection areas will be used in the following steps for a carpenter technique.

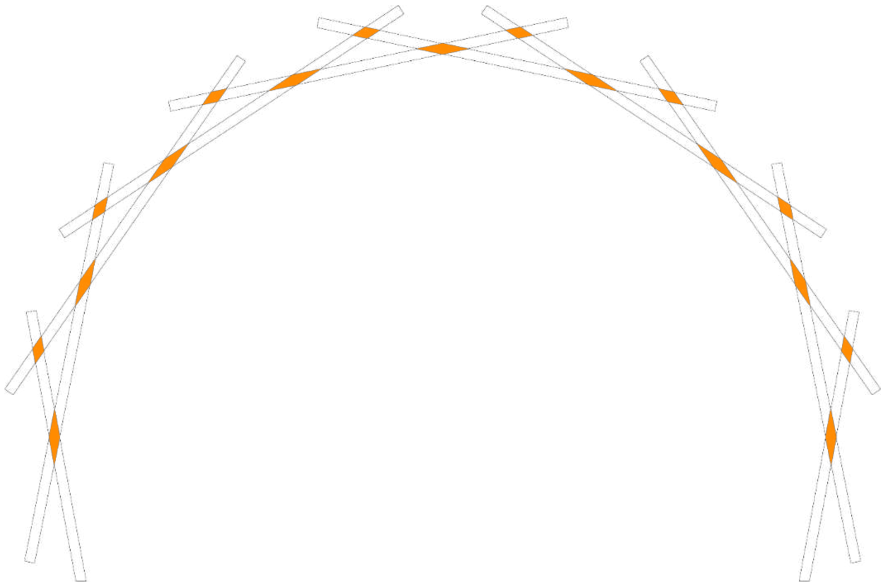


Figure 5.33 Intersection areas for joinery for one row (author)

The construction timber is overlapping 5cm on each side, so every part is interlocking with each other. The bars have at least one interlocking joint up to 4 interlocks.

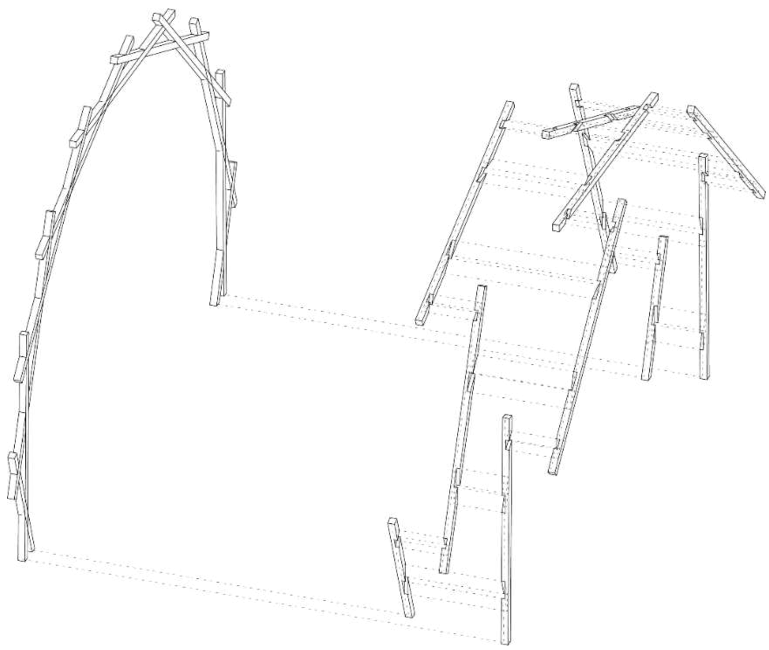


Figure 5.34 Explosion diagram of one row (author)

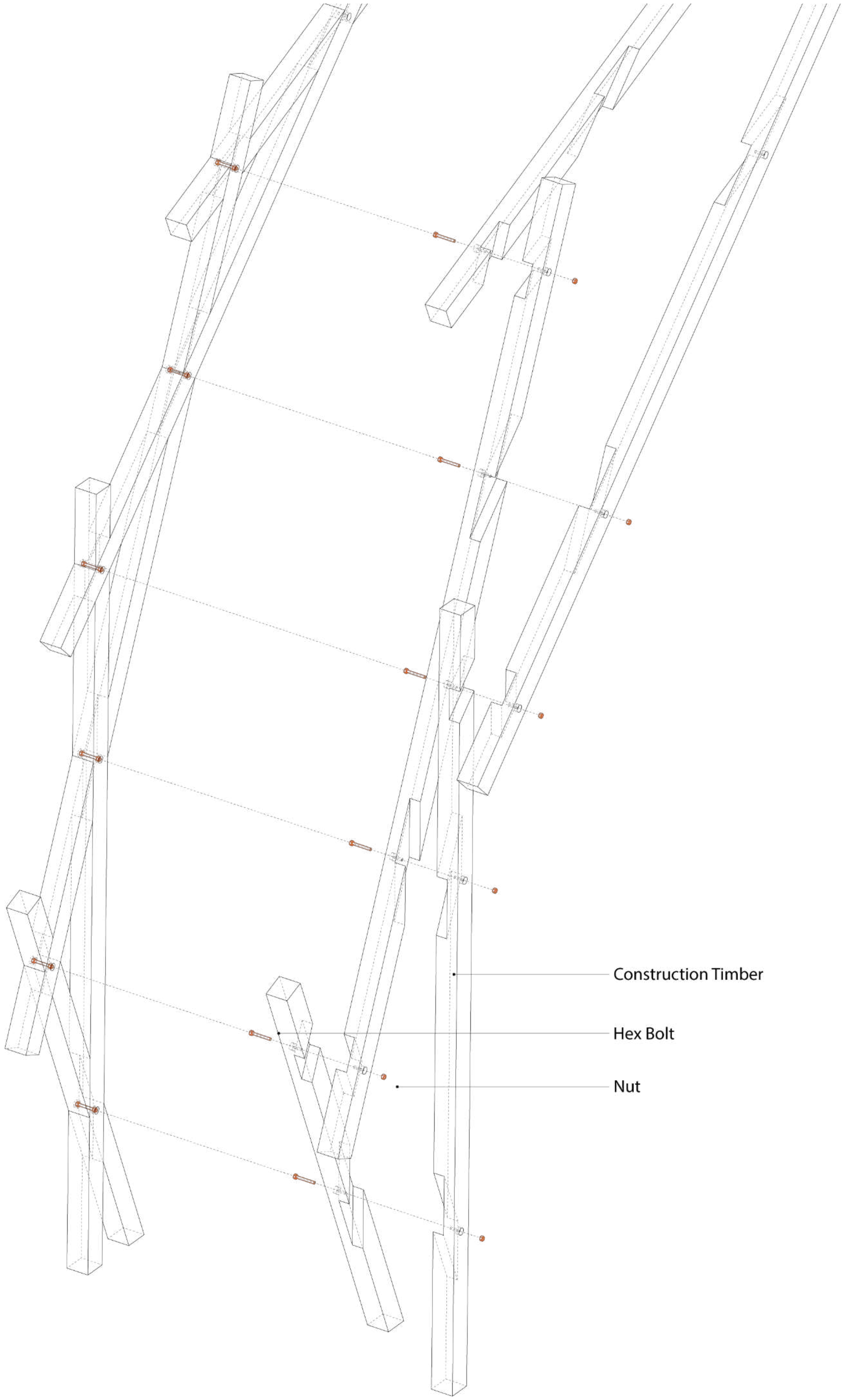


Figure 5.35 Construction diagram for connecting timber to each other (author)

The construction of the timber bars is with hex bolts and nuts to fix them. The openings for the bolts will be done with the robotic arm so the location of the holes is on the exact same place, so the joints fit properly. M10x100mm bolts are chosen to connect the bars and on the other end of the bolts are M10 nuts tighten up the construction.

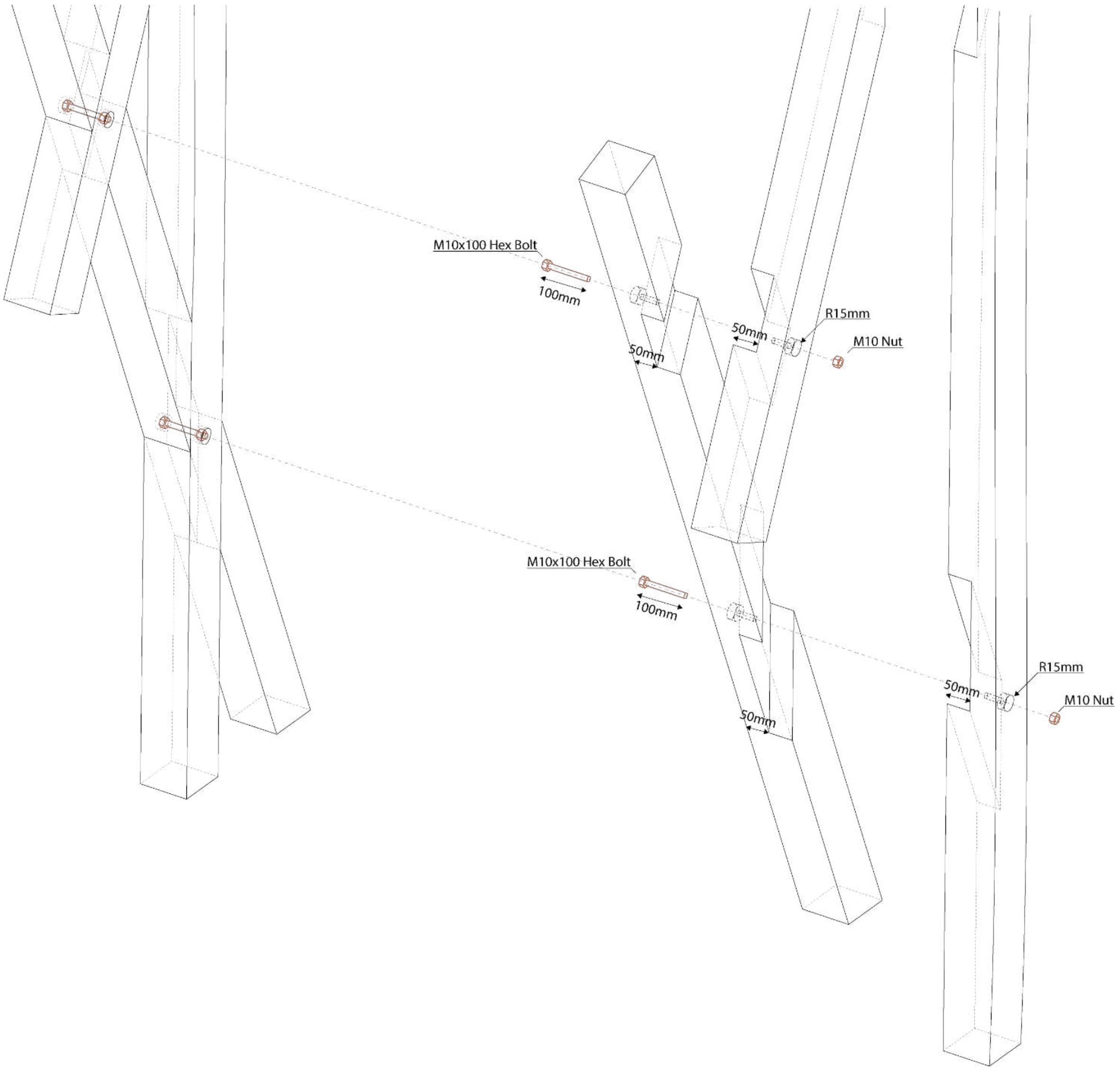


Figure 5.36 Detailed diagram of connection (author)

5.7 Fabrication and Simulation

The fabrication procedure of the design is almost totally automated. Due to the construction timber bars it is way easier to operate with than customized wooden products. In customized products problems like unwanted variations of dimension and form can cause mistakes in the fabrication procedure.

As important as the timber product, the right decision of the robotic arm is also an important key. The robots have limited reach when they are not working in the 7^{th} axis. The 7^{th} is for usual a railway where robotic arm sits on. On this railway system it can move side to side to enlarge the reach of the robotic arm.

5.7.1 Robotic Arm

For this project the robotic arm KR Quantec Prime by KUKA is chosen due to its advantages of distances. This kinematic robot can reach between 2496 to 3701 mm in a spherical area and can lift 90 to 240 kg. As a console robot, they are optimized for the smallest space requirement - which extends the economic reach range.

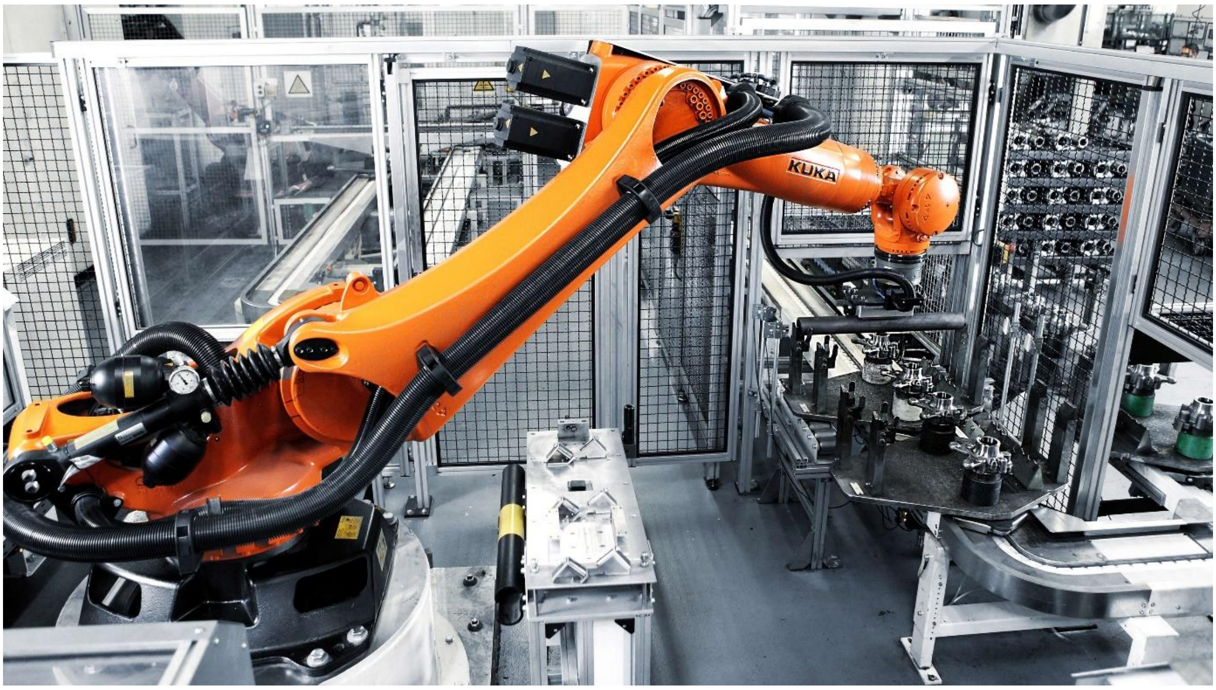


Figure 5.37 KUKA KR Quantec Prime (URL 42)

The KR QUANTEC prime impresses with its robust construction - and is nevertheless extremely light. It is trimmed to high cycle times by high acceleration values. He delivers the best process results. It has a very small ecological footprint.

5.7.2 End Effector

To process the wooden product milling is an optimal solution because of the small areas which are getting milled. Robotic arms can work with all kind of different tools as an end effector and do precise work.

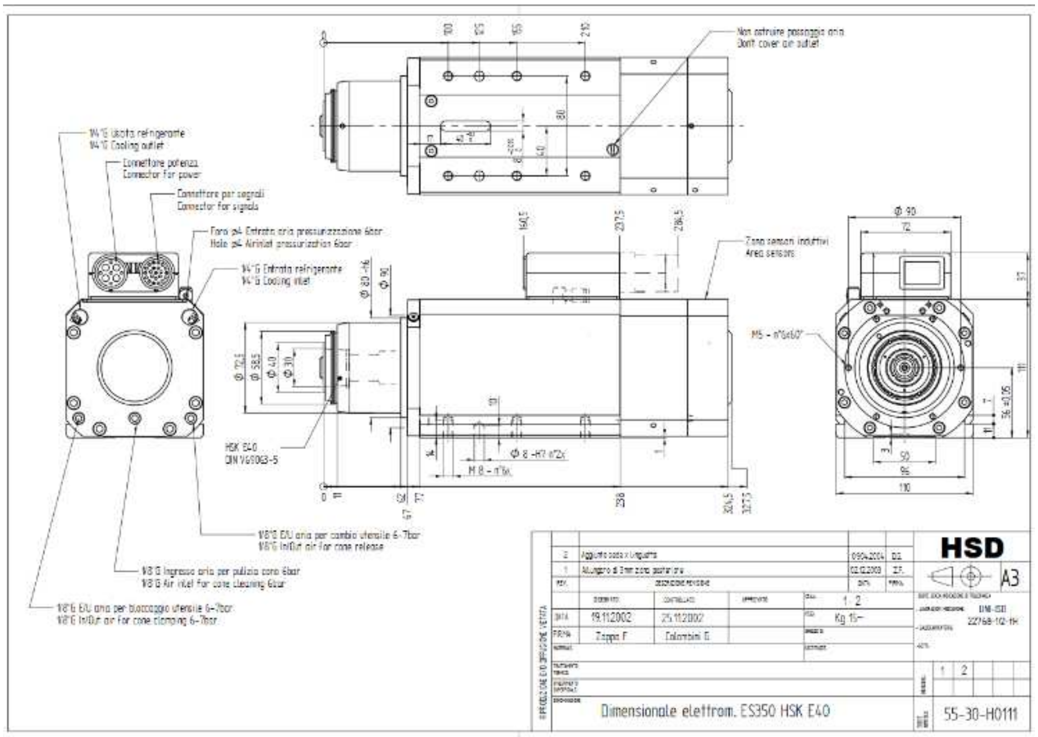


Figure 5.38 plans of HSD Spindle (URL 42)

The standard KUKA Spindle by HSD will be used as the milling tool. It is designed to work with KUKA robotic arms. The length of the spindle will be 200mm to avoid collisions and the diameter of the spindle is 6mm to have precise workflow.

5.7.3 Working Area

For the digital fabrication workflow, the construction timber must be placed on the same location for every piece. Therefore, the platform on which the wooden product has specific dimensions and the distances of the timber as well. The material of the platform is wood because of the milling procedure. This kind of fabrication can cause damage to the working area and wood can handle that damage and the spindle will not be damaged as well.

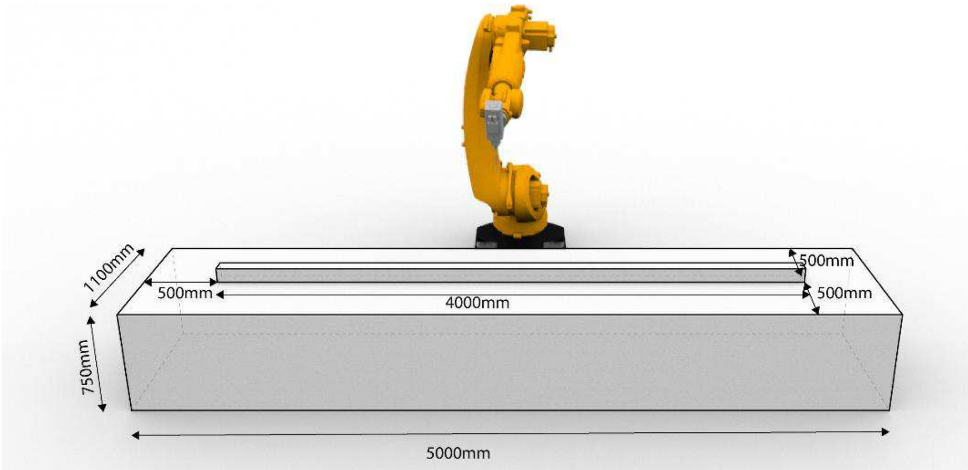


Figure 5.39 Working Space for fabrication process (author)

The height of the platform is 750mm, length 5000mm, so the 4000mm construction timber fits on it, and it has a width of 1100mm. The material is placed in the centre of the table with distances of 500mm to the edges. The distance of the robotic arms platform is 1200mm.

5.7.4 Robotic Arm Positioning

The position of the robotic arm and its end effector must be same in the simulation and as well in the reality. Therefore, the arm has specific values of positioning. The values for the position of the robot can be defined in the KUKA prc plug-in. For this design the start and the end position are the same location because the is no possibility of collision.

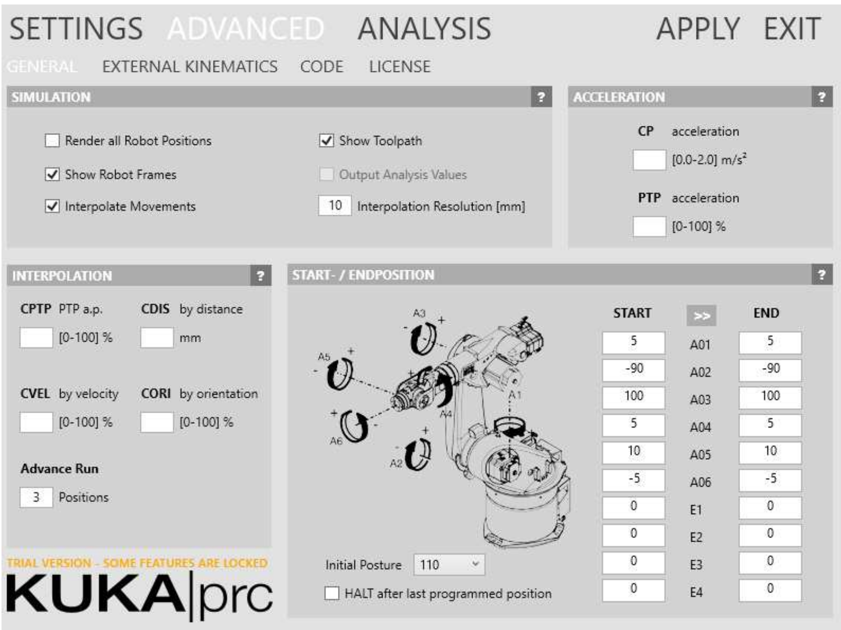


Figure 5.40 Settings for robotic arm (KUKA prc)

In the Start-/ Endposition the values can be changed according to the needs of the user. The robotic arm has six different axes, for that reason it can move smoothly in every direction. All six axis can be rotated in every direction and the values are in degrees. The posture of the fabrication for this design are the values in the figure xx.xx. With this feature the movement can be optimized so there is no unnecessary movement.

5.7.5 Simulation Definition

The simulation for the fabrication procedure is developed in Rhinoceros with Grasshopper plug-in and the for KUKA created KUKA prc plug-in in Grasshopper. This tool is developed for parametric robot control of the robotic arm, and with this feature of the plug-in the fabrication workflow does not have to defined for every single piece of the project. 1575 pieces are defined as objects in the Grasshopper definition and the areas which must be milled are used for the toolpath which the end effector follows.

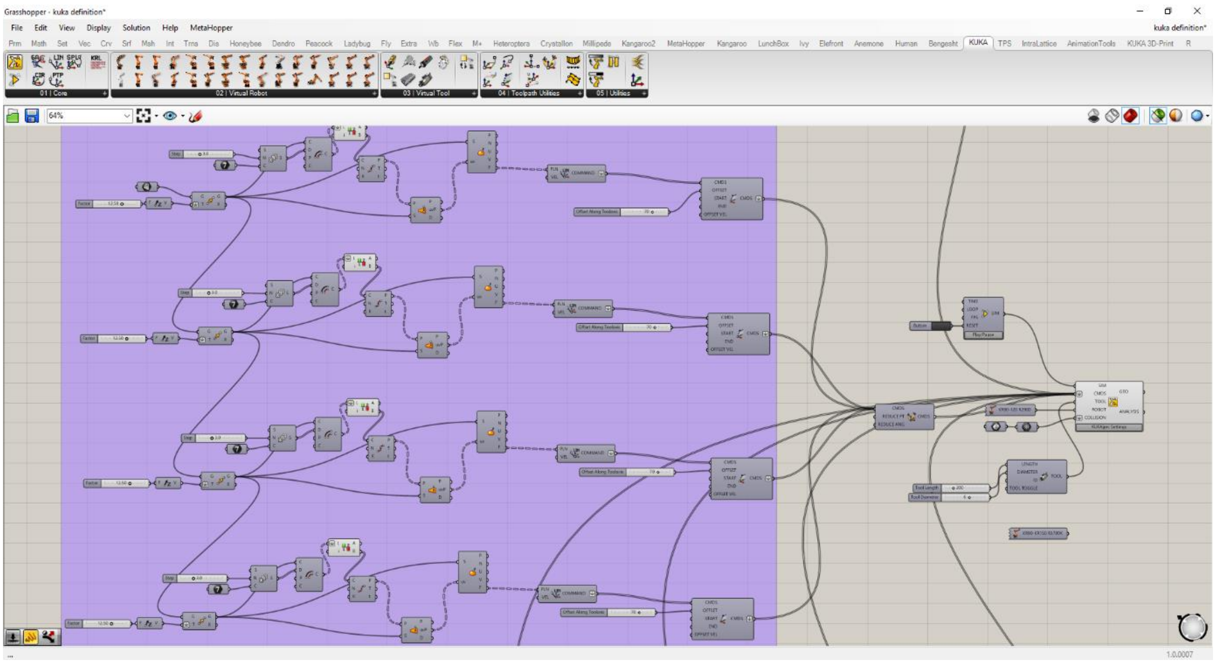


Figure 5.41 Grasshopper for fabrication (author)

5.7.6 Toolpath and Fabrication Process

The robotic arm and the end effector are following the parametrically created toolpath with the KUKA prc plug-in for Grasshopper. The fabrication workflow has several steps to reach the necessary form of the joints and the construction timber.

In the first movement the end effector starts to drill the hole for the M10x100 hex bolts. How many drills the robotic arm has to do, is automated by the number of joints of the timber bar. So that means, that for 4 joints the robotic arm must create four openings for the bolts.

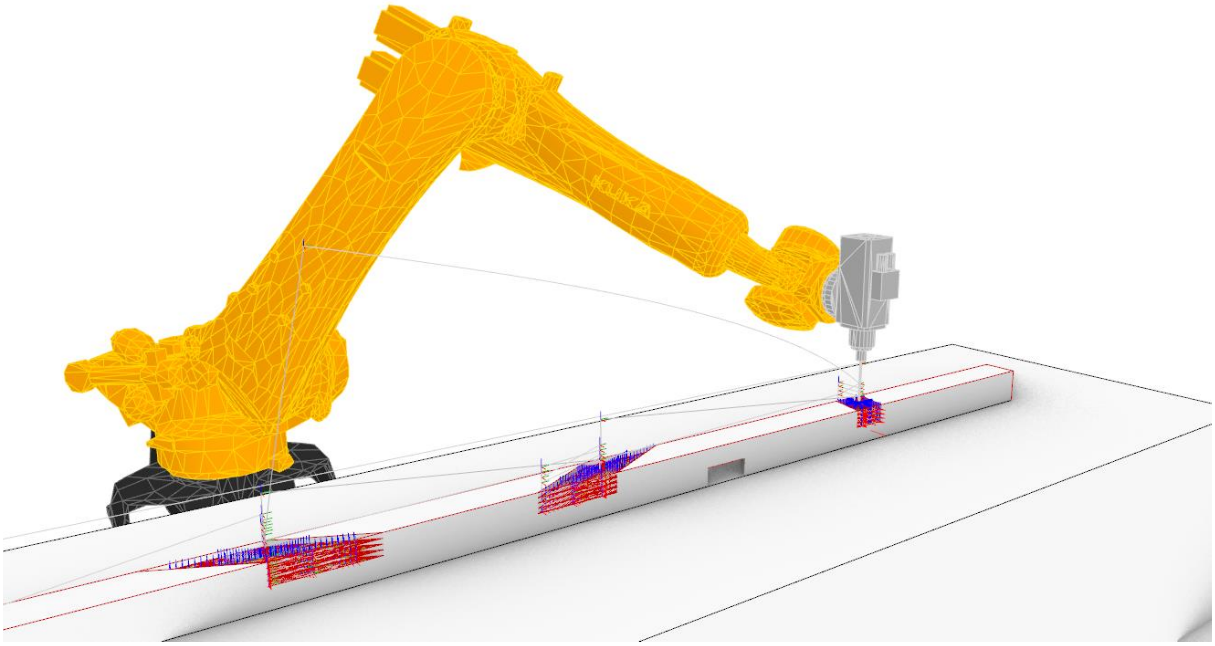


Figure 5.42 Fabrication Simulation with Toolpath (author)

This movement starts at the surface of the wooden product and the spindle drills a hole for 100mm and after finishing this movement it moves back in the opposite direction till it is 70mm over the bar, so it does not collide in the next command with the timber. In the next step the robotic arm drills two more hole in the centre of the polygons.

For the milling of the joints the movement has five movements till it reaches the wanted depth of the opening. To create the toolpath for this movement the polygon is offset for the first curve 3mm and for 17 times to remove this layer of material in a depth of 12,5mm. It repeats the movement for 4 times and every step is +12,5mm deeper till it reaches 50mm.

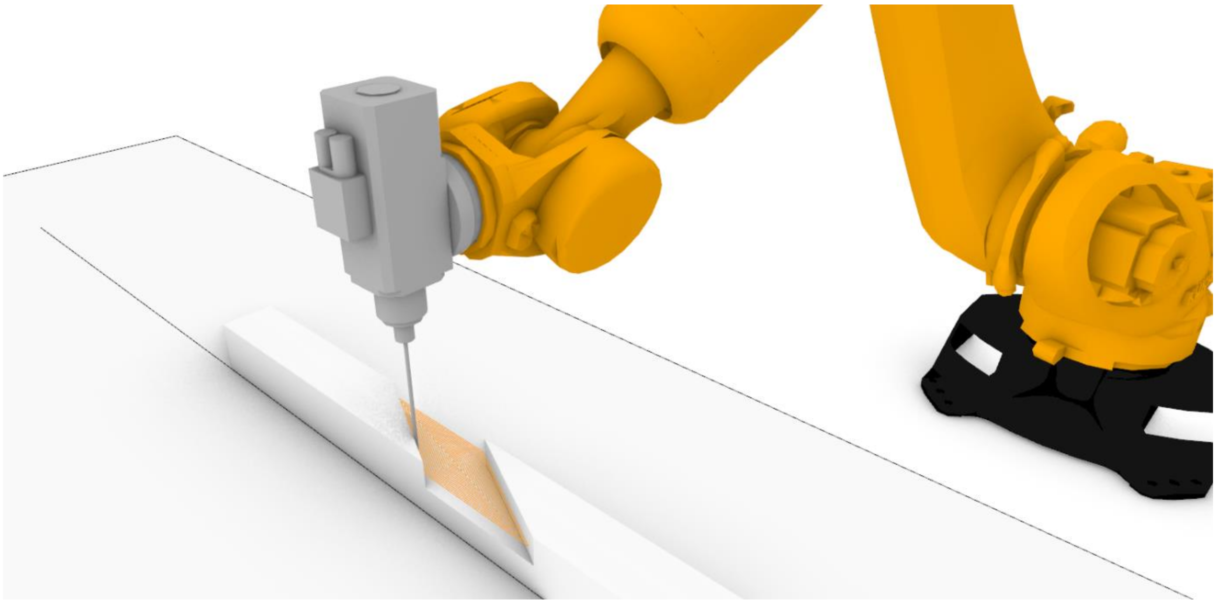


Figure 5.43 Fabrication Simulation of cutting the intersecting areas (author)

After finishing all the joints with the same workflow, timber bars with less than 4000m of length has to be shortened. It works in similar way of milling like for the joints. The end has to be milled till 100mm of depth along curves every 12,5mm. This movement is again 3mm offset of the edges because of the diameter of the spindle, in order to have correct length of the timber product.

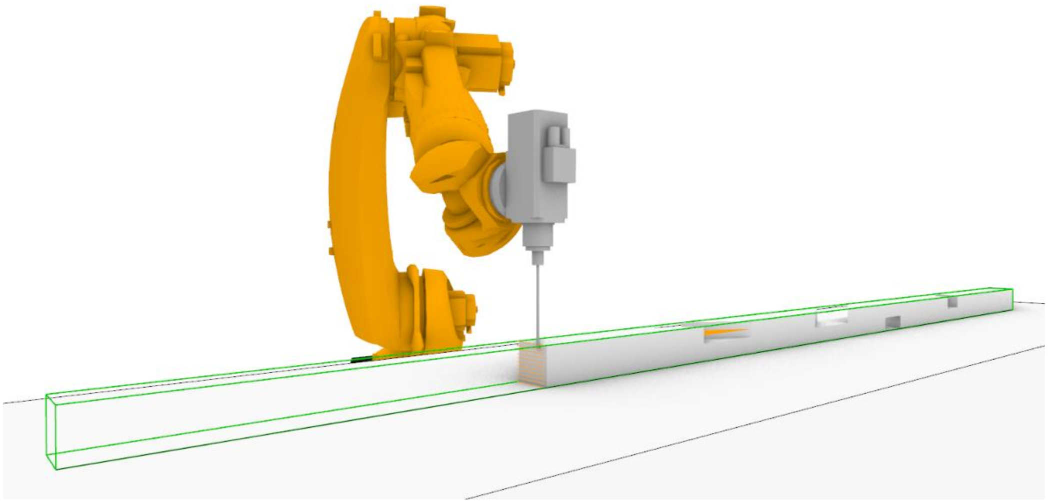


Figure 5.44 Cutting special elements which are shorter than 4000mm (author)

This workflow is defined for every piece of the construction and all of them are created automatically so the workflow and creating the .src-file for the robotic arm is totally parametric and this time saving way of working can help architects to focus on other things during a project.

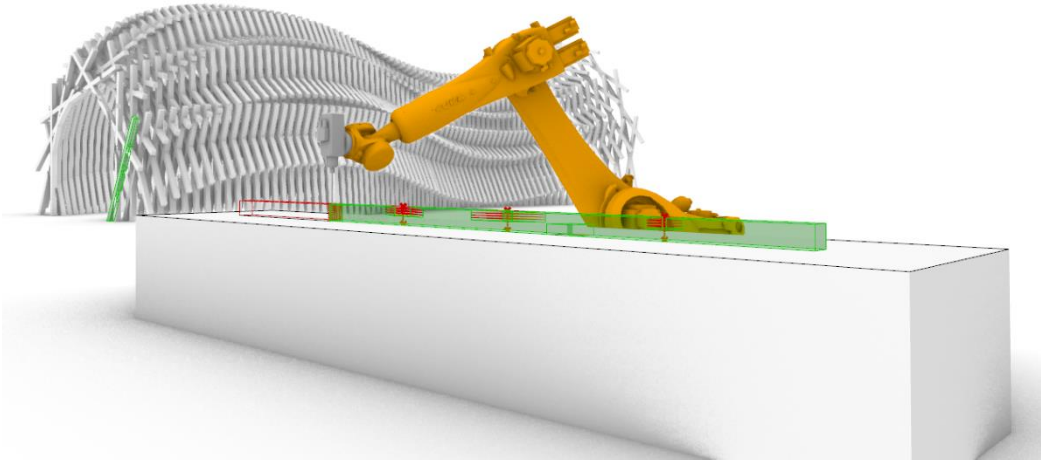


Figure 5.45 Parametric created fabrication process (author)

After defining the work of the robotic arm, the plug-in KUKA prc generates the final toolpath with all the steps and the robotic arm and as well the end effector follows this created toolpath. The simulation of the milling procedure can show errors and collisions during the fabrication and the designer intervene to this and optimize the toolpath.

6. Conclusion

In the field of architecture, digital fabrication and robotic timber constructions are gaining in importance. New researchers around the globe are working on experimental projects to develop new strategies and innovative methods to fabricate computational designed wooden products. Modern technology makes it possible to work with wood as computational material, to simulate the behaviour of the product and finally to digitally fabricate it. Digital Fabrication and parametric design are benefits which are helping wood to become more and more a future construction material. Timber might have a long history of use in architecture, but it is still a modern material, because of that researchers and architects are still trying to rethink the potential of the building material, and of course it is own natural advantages will never make it infamous.

Wood products in digital fabrication are great materials to selects, to work with in parametric design. Due to their standardized and manageable conditions, timber products can be manipulated and crafted with less effort and also, they are easy to repair and keep on working. According to their standardized dimensions, a variety of connectors are available, which are adaptable to the geometric style.

It is important to think about the materiality and the properties of wood during the computational design phase. For that reason, standardized timber products were used, so the fabrication process and its simulation can be created parametrically. The combination of computational design and robotic timber fabrication can be very time saving for architects and designer, due to the fact that everything created can be requested on demand and robotic arms can be connected to any kind of end effector, that’s why it is possible to manipulate timber with almost every wood working tool.

Finally, the research about the history and all methodologies was an important learning process to understand what is possible to do with robotic arms, also the analyses about the cases showed in the thesis that wood can be a parametric and computational design material. The materiality in the design phase was always a key factor of the form development and the fabrication procedure. The material was decided beforehand so the project can be designed according to its dimensions and properties. In every step of the 3D workflow, the dimensions were always a parameter of the design. The high number of intersection areas of the construction timber made the robotic fabrication process necessary because every intersection and joinery were unique and to produce this industrially or by human-hand would take a long time to finish it because every single piece of a total amount or 1575 pieces of construction timber must be designed for the fabrication process one by one and because the parametric designed joints this process is also handled by the architect and costs and time were saved through this process.

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