TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

RETHINKING THE BODY STRUCTURE OF FORMULA CAR ON THE EXAMPLE OF FORMULA STUDENT TEAM TALLINN

VORMELI KERE STRUKTUURI ÜMBERMÕTESTAMINE TUDENGIVORMELI TALLINNA TIIMI NÄITEL

MASTER THESIS

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Tallinn 2021

(*On the reverse side of title page*)

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THESIS TASK

Student: Karolin Madsen, 192505MADM
Study programme: MADM10/18, Design and Technology Futures
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Thesis topic:
(in English) Rethinking the body structure of formula car on the example of Formula Student team Tallinn
(in Estonian) Vormeli kere struktuuri ümbermõtestamine Tudengivormeli Tallinna tiimi näitel

Thesis main objectives:

1. Understand the current issues and opportunities regarding 3D printing
2. Explore lattice structures
3. Design lattice structure concept solution for Formula Student car body and validate design

Thesis task and time schedule:

Nr	Task description	Deadline
1.	Problem finding and literature review	26.02.21
2.	Analysis and problem framing	12.03.21
3.	Concept development	15.04.21
4.	Concept finalization and validation	03.05.21
5.	Thesis writing finalization	22.05.21

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PREFACE

This master thesis examines 3D printed lattice structures in different fields: automotive, aviation and aerospace, medicine, architecture, and fashion, to find solutions in rethinking the body structure of Formula Student car.

The aim of the research is to offer 3D printed alternative solution to Formula Student team Tallinn formula car body manufacturing. Alternative parts need to take the shape of the car body mould while optimizing the mass and meeting the set requirements. Given thesis is purely studying the form formation of internal structures, not the outside form design, because it is assumed that the shape of the body of formula car is sufficiently optimised to meet the parameters required in competitions.

The main research objectives include understanding the current situation in the 3D printing field and issues as well as opportunities regarding it, exploring the lattice structures as part of the 3D printing innovations, and finally, designing a lattice structure concept solution for Formula Student car body (monocoque) parts that are problematic to manufacture with current techniques used by the FS team.

Five different lattice structure concept solutions were designed in Autodesk Inventor and 3D printed with SLS printer. Feedback on the concepts was received from the chief engineer in the FS team.

The main goal of the solution is to offer more convenient and faster manufacturing method for Formula Student team Tallinn.

Kaarel Haavajõe, Formula Student team Tallinn chief engineer, provided information on the questions related to the formula car. The manufacturing process was explained by him.

Meelis Pohlak, senior research scientist, consulted on the topics regarding 3D printing at TalTech.

Keywords: 3D printing, automotive industry, formula student, lattice structure, master thesis

EESSÕNA

Antud magistritöö uurib 3D prinditud võrestruktuure erinevates valdkondades: autotööstus, lennundus ja kosmosetööstus, meditsiin, arhitektuur ja moetööstus, et leida lahendusi Tudengivormeli kere struktuuri ümbermõtestamisel.

Töö peamine eesmärk on pakkuda 3D prinditud alternatiivset lahendust Tudengivormeli Tallinna meeskonna vormelauto kere valmistamiseks. Alternatiivsed osad peavad võimaldama võtta auto kere vormi kuju, optimeerides samal ajal massi ja vastama seatud nõuetele. Antud töös tegeletakse puhtalt vormi moodustamise uurimisega sisestruktuurides, mitte vormi väliskuju disainiga, sest on eeldatud, et vormeli kere kuju on piisavalt optimeeritud võistlustel nõutud parameetrite täitmiseks.

Magistritöö peamisteks eesmärkideks on mõista 3D printimise valdkonna hetkeolukorda ja sellega seotud probleeme ning ka võimalusi, uurida võrestruktuure kui 3D printimise innovatsiooni osa, ning lõpuks, disainida võrestruktuuri kontseptsioonlahendus Tudengivormeli autokere (monokokk) osadele, mille valmistamine FS meeskonna praeguste viiside juures on problemaatiline.

Viis erinevat võrestruktuuri kontseptsioonlahendust disainiti Autodesk Inventoris ja 3D prinditi SLS printeriga. Kontseptsioonide osas saadi tagasisidet FS tiimi peainsenerilt.

Lahenduse peamine eesmärk on pakkuda mugavamat ja kiiremat tootmismeetodit Tallinna Tudengivormeli meeskonnale.

Kaarel Haavajõe, Tudengivormeli Tallinna tiimi peainsener, andis teavet vormelautoga seotud küsimuste osas. Ta selgitas ka tootmisprotsessi.

Vanemteadur Meelis Pohlak konsulteeris TalTechis 3D printimisega seotud teemadel.

Võtmesõnad: 3D printimine, autotööstus, tudengivormel, võrestruktuur, magistritöö

LIST OF ABBREVIATIONS

AM – Additive Manufacturing

CAD – Computer Aided Design

CM – Conventional Manufacturing

DFAM – Design for Additive Manufacturing

FDM – Fused Deposition Modelling

FEM – Finite Element Method

FS – Formula Student

SLA - Stereolithography

SLM – Selective Laser Melting

SLS – Selective Laser Sintering

STL – Standard Triangle Language

INTRODUCTION

This thesis topic exploration started from 3D printing, to firstly discover what printing options are used, what materials are used, what structures are used and where is this technology applied. The possibilities and problems were briefly studied and were drawn together in a mind map (Appendix 1). From there more specific topic was discovered – lattice structures. Lattice structures are practically only possible to manufacture with 3D printers. In a way, Formula Student team Tallinn is using 3D printing quite vastly, however, the car body manufacturing has stayed the same over the years. This is the place for development and simplifying the process in use today.

3D printing is important and topical because it is spreading to masses. 3D printers are used at homes, offices, industries, schools, and they are used for prototyping as well as for making the final products. It is a way for fast prototyping and still a growing industry field. It is changing the possibilities of production and allowing for more choices. The main advantages of 3D printing are the different structures and designs, which would be very difficult or expensive to produce with regular manufacturing methods. Complicated designs can be manufactured with ease in 3D printing, allowing the designer to use their imagination and focus on complex ideas or unique design, instead of thinking about how to manufacture this design.

3D printing is also shortening the prototyping and testing cycle since multiple vendors exist and they are distributed all over the world. While reducing the manufacturing process time, we are reducing the time needed for assembling and therefore making manufacturing process faster, easier, and cheaper. A good example of this are the assemblies not in need of assembling – they are printed in one piece and have the possibility to move (e.g. gear bearings, hinges, ball joints).

Working as mechanical engineer has given the author opportunity to use 3D printer in work projects' prototyping process. Author's interest in the 3D printing topic is coming from working with FDM 3D printer for years. FDM (Fused Deposition Modelling) works by extruding a reel of plastic through a heated nozzle which melts the plastic, building layers, which then cool down and solidify. Besides work projects, it has been used to print author's own designs as well as others. There is something very enthralling seeing your CAD model taking shape in real life in front of your eyes.

Author's personal interest is especially in 3D printed objects (assemblies) which do not need assembling (e.g., bearings) and structures which are impossible to produce otherwise. The motivation to research 3D printed structures lies also in the fact that studying these structures will give better understanding of them and may offer solutions which could be used in the future in other projects as well. If we were to give up on the mass production and move more towards unique objects, which can also be easily multiplied thanks to computers and algorithms, the idea behind production would be different. Products are not produced to mass but to people who truly find new ways of production promising.

The first frames which started to give shape to the final research topic originated from questions like, how might we take advantage of 3D printing possibilities in manufacturing and where does 3D printing suit in future manufacturing processes - single objects, batch production, mass production? Considering the fact that with 3D printers people are able to create objects (assemblies) which do not need assembling (e.g. bearings) and structures which are impossible to produce otherwise (e.g. lattice structures), where will those improvements lead us? Using 3D printing for producing more effectively, cost-efficiently, and to produce less waste compared to typical manufacturing (e.g. milling) were also important frames when seeking opportunities.

Author's research inclined towards the structures that are impossible to produce with conventional fabrication methods. This results in producing more effectively and cost-efficiently, since optimizing the material will usually require removing the material on the traditional manufacturing methods but 3D printing allows us to place the material only where it is needed. This means that less waste is produced compared to conventional manufacturing.

When using CAD for optimising the structure, the result will be lightweight (using less material) but at the same time the structure maintains the same strength as the regular detail would have. This method is known as topology optimization. It is usually used prior to lattice structure design phase.

Lattice structures are the perfect example and reason of using 3D printers. They can be defined as space-filling unit cells that can be repeated along any axis with no gaps between the cells. Other traditional manufacturing methods are not as optimal or are impossible to use to produce those so-called impossible designs. Lattice structure is a good solution to achieve parts which are lightweight but have good mechanical properties. High strength low mass property is a key advantage of lattice structure. This concept comes from the aspiration to put material only where it is needed.

Even though, recently, lattices have been of greater use due to 3D printers, the benefits of lattices have been well-known throughout time. When looking closely, lattices can be seen in nature (such as bone, metal crystallography, etc.) and in modern architecture as well. For example, the Eiffel Tower metal structure efficiently supports its weight. Like a simple lattice, this self-supporting structure is mostly air. The high strength-to-weight ratio possible with lattices enabled this enormous architectural achievement.

Aside from all the examples brought in given master thesis from various 3D printing fields, this thesis research will be concentrating more in automotive industry and more specifically, lattice structures in Formula Student car. Since reducing the mass is one important factor for formula cars (to ultimately be faster and use less fuel), the possibility to create strong, yet lightweight structures, is a great opportunity to test the lattice structures.

Formula Student team Tallinn was reached as a way to show tangible solutions. There is a possibility to 3D print the structures and test them if the solutions are suitable for formula team. The main problem for formula team are the curves and rounded shapes of the formula car mould. On the mould they place the carbon fibre fabrics to which they attach aluminium honeycomb structure and finally lay carbon fibre on top again. The problem with aluminium honeycomb is that it needs to be cut precisely and it is stiff structure, so forming the rounded shape is very difficult. The shape of the car and rounded corners are necessary for streamlined body shape and lower air resistance, giving the desired speed and better results in competitions. In knowledge available to author, the FS team Tallinn has not used lattice structures in a way that is described later in the design concepts chapter.

Author's goal with the thesis is to analyse and test different 3D printed lattice structures that could be used to make shaping of the formula car easier and time efficient. The characteristics to analyse include flexibility (minimum possible radius), compressing/ elongating the material and surface quality.

One thing to consider when printing, would be the optimal stiff structures designed for the exact location or the structures that are flexible and need fixation in some other way (e.g. with the help of other material). Either way, it seems that connections between different printed parts are required. Simply printing the whole car body would need a huge printer which will make manufacturing more costly. When one part breaks or needs replacing, the whole car needs to be printed again, which is very time-consuming. Also printing the body in one piece might mean rethinking the whole electronical and mechanical system for the car.

Changing the internal structure to flexible structure instead of a rigid one would mean rethinking the whole body structure logic. It is also innovative and eye-opening topic, since from the many examples brought from five different industry fields, the flexible structures are used only in one of them. It is very promising solution in the light of Formula Student team manufacturing methods and additionally provides important knowledge regarding designing flexible lattice structures.

The reframed research question through which the work will be looked through is following:

How to enhance the body structure manufacturing process using flexible lattice structure in internal structure design and make the process more convenient for the team involved?

The 3D models were designed with Autodesk Inventor 2021 and 3D printed parts were fabricated with SLS printer located at TalTech.

This thesis is divided into seven separate chapters. In the first chapter, the methodology of thesis is given. The second introduces additive manufacturing technologies, bringing out the main properties of 3D printing. The third chapter will look more deeply into the field of 3D printing and its usage in different industry fields. The introduction to lattice structures is given. Formula Student and the formula car manufacturing is described in the fourth chapter. The fifth will provide different possible lattice structure solutions for the formula car body parts. The sixth chapter will be dedicated to validation of proposed designs. The last part concludes the results in the light of objectives set.

1. METHODOLOGY

As described in "The Role of Hypothesis in Constructive Design Research" by Bang, Krogh, Ludvigsen, and Markussen [1] the experiments are the core of constructive design research. Their described model allows for constant evaluation of experiments while reflecting back to hypothesis and research questions.

The design research process continuously expanded author's knowledge about the topic and gave insights for creating the experimental concepts, which were the core of this thesis. Reflecting back to research question and constant experiments fit for chosen method.

In another article Krogh, Markussen, and Bang [2] describe comparative experimentation, where each design experiment should reveal as-yet undocumented additional qualities of a concept and confirm some previously found qualities. Every step towards final 3D printed concepts revealed something along the way and the real-life models showed how valuable it is to see the concepts in real life, making the endless speculative ideas valuable and questions easier to answer.

The research included studying books, research papers, articles and websites related to the topic. At first, 3D printing was researched more thoroughly, followed by lattice structures and the usage of 3D printed structures in different fields, including automotive industry. The Formula Student car body (monocoque) manufacturing process was explained by Formula Student team chief engineer Kaarel Haavajõe. Questions about 3D printing were answered and the 3D printed prototypes were manufactured thanks to the support from Meelis Pohlak.

1.1 Design process and methods

After multiple discussions with FS team, the current manufacturing method was understood by the author, and the problem space regarding this was described. This was followed by digital concepts and afterwards, 3D printed concepts. To evaluate the experimental concepts, the research question and hypothesis were set beforehand.

As currently the fabrication method used by Formula Student team Tallinn in building the formula car body structure is time-consuming and complicated in rounded shaped areas, the following research question was formulated:

How to enhance the body structure manufacturing process using flexible lattice structure in internal structure design and make the process more convenient for the team involved?

With the help of research question, following hypothesis was created:

Allowing the internal structure to take the shape of the mould helps to simplify the process of manufacturing the formula car and relieve the stress of team members to finish the project in a short period.

1.1.1 Understanding new technologies in current day context

The goals were to understand where 3D printing originates from and which events enabled the 3D printers to be invented as we know them now. It was important to realise for what and why exactly 3D printers are used and why conventional methods differ from this relatively new field.

The analysis includes different printing methods used in 3D printing with more thorough research on the machines currently used in TalTech. The opportunities for both are brought out. The impacts of AM were looked through and advantages as well as challenges are described. Design implications and unique opportunities of AM are listed, one of those being lattice structures, which were thoroughly researched through.

1.1.2 Discovering the opportunities used in different fields

Various industry fields were researched through to gain knowledge what are the possibilities with 3D printing and what exceptional solutions it offers. In automotive industry, aviation and medicine, AM proved to be well-considered and used for certain purposes. Human-centred solutions are the main value of 3D printing in medicine field. In architecture and fashion architects and designers use this technology more freely. The concepts and design solutions created, concentrate more on the opportunities 3D printing has to offer. The interlocked mechanisms being one of them.

After the insights gained from different fields and based on the examples, a new way to form the formula monocoque started to take shape.

1.1.3 Understanding the fabrication method of formula car

At first, an interview, and later, several discussions with the chief engineer of FS team Tallinn were conducted. It took several attempts to fully understand the complicated process of monocoque body manufacturing. The carbon layering and aluminium honeycomb inner structure method has been used since 2015. Before that, a tube frame was used instead. This method was exchanged due to heavy body mass.

Right now, the FS team needs to cut aluminium honeycomb precisely and use adhesives to merge them together. The honeycomb is usually ordered as fully expanded, meaning that the transportation costs more and due to the properties, they mainly transport air. With current situation in the world regarding all the delays and difficulties in factories, it is highly likely that the monocoque manufacturing time window will shorten due to this. This could be avoided by fabricating parts locally. Furthermore, they have a great opportunity to use the 3D printers located in TalTech.

1.1.4 Experimenting and validating

The information gathered from different sources was used to compile a solution space map for formula car lattice structure concepts.

The main pain points were addressed and concept solutions in the form of CAD models were represented. For better understanding and demonstrating the solutions, all the prototypes were 3D printed with SLS machine.

These prototypes were used to validate the concepts with FS team Tallinn. Improvements on the prototypes were suggested by Kaarel Haavajõe and Meelis Pohlak.

2. NEW TECHNOLOGIES AND NEW OPPORTUNITIES

This paragraph gives an introduction to the technological inventions, 3D printers, and explains the history behind the term 3D printing.

How are new technologies developed? How the opportunity to 3D print something reveal itself? How could one come to the idea of creating a 3D printer? These were the questions the author started to find answers to.

In the book *What Technology Wants*, Kevin Kelly writes: "Our technological creations are great extrapolations of the bodies that our genes build. In this way, we can think of technology as our extended body." [3] He further discusses that technology is not an extension of our genes but of our minds. So, therefore technology is the extended body for ideas. Through technology we can express ideas. 3D printing is a unique technology for expressing or rather materialising the ideas created in CAD software.

From John von Neumann he quotes: "Technology will in the near and in the farther future increasingly turn from problems of intensity, substance, and energy, to problems of structure, organization, information and control." [3]

John von Neumann said it in 1949 [3] and with the development of technology, especially computers and internet, we can definitely say that problems of information and control have increased since then. Problems and also opportunities with physical structures are the topics which will be analysed more deeply in this thesis.

New technologies make it easier to invent even better technologies [3]. All the improvements in technology lay the ground for better inventions. It is certain that without the computer, 3D printer in the form we know it now, would not have been invented. When was 3D printer invented and what was the comprehension behind the term 3D printing?

"The group of technologies today (2020) termed additive manufacturing (AM) began commercialization in 1988. The original term was rapid prototyping /…/" In the early 2000s several new terms came into use, such as, additive techniques, layer manufacturing, rapid tooling, additive layer manufacturing, freeform fabrication and three-dimensional (3-D) printing. [4]

As often brought out by Kevin Kelly [3], the evolution of technology repeats itself, multiple people come to the same ideas and inevitable inventions around the same time. As it is in many different fields, starting from inventing (or discovering) calculus (credited to Newton and Gottfried Leibniz) [3] to writing books (J. K. Rowling Harry Potter series) [3], the term 3D printing was also separately brought out by different people and was 'inevitable' as Kelly says.

"The term 3D printing was clearly applied to modern AM processes in the 1980s, according to multiple independent sources." The earliest known use of the term 3-D printing as applied to AM was in an article by Wohlers in 1988 that reviewed the stereolithography machine. The concept of printing an object was introduced in 1984, when stereolithography (SLA) patent was filed, which said, "'Stereolithography' is a method and apparatus for making solid objects by successively 'printing' thin layers of a curable material…" Another patent, this time on binder jetting process, was filed in 1989 and used the term 3D printing. Emanuel Sachs from Massachusetts Institute of Technology (MIT) was the co-inventor of this process and helped to popularize the term 3D printing. By the end of the 2000s, the term 3D printing was used in reference to the MIT binder jetting process, to AM in general and to low-cost AM machines. This remains the same today. [4]

Now that the term 3D printing is explained and the background behind it, the 3D printer inventing history follows.

"Technologies are like organisms that require a sequence of developments to reach a particular stage. Inventions follow this uniform developmental sequence in every civilization and society, independent of human genius. You can't effectively jump ahead when you want to. But when the web of supporting technological species are in place, an invention will erupt with such urgency that it will occur to many people at once." [3]

Historical cases reveal that the number of duplicated innovations has been increasing with time – simultaneous discovery is happening more often. In the conceptual stage there are many similar brilliant ideas, but with each progressing stage, the coparents will reduce. When trying to bring the idea to market, you may be alone, but in reality, you are a pinnacle of pyramid of others, who all had the same idea. [3]

The first modern AM company, Helisys, was founded by Feygin in 1985. His process was a stack-and-cut sheet lamination process. The first machine was shipped in 1991. The Denken was established in Japan in 1985, but their first stereolithography machine was introduced in 1993. Hull and Freed established 3D Systems in 1986. Their modern AM fabricator, SLA-1, was introduced in 1987. [4]

All of these technologies and machines were introduced to the wider audience around the same time and about two decades later, since 2010, 3D printing has increasingly become a household name. Several factors contributed to this transition. The vast growth of AM resulted from several interrelated events [4]:

- The development of low-cost units. The first one available to public was Fab@Home, an open-source 3D printer developed at Cornell University.
- The expiration of patents, which encouraged competition in the marketplace.
- The development of free or low-priced open-source hardware and software.
- The availability of purchasable 3D parts or downloadable 3D models.

Albeit Kelly says that technologies get better, cheaper, faster, lighter, easier, more common, and more powerful as we move into the future, he also mentions that things are getting better for humans but because of that we are destroying or consuming natural resources at an unsustainable rate. "Progress is real, but so are its consequences. There is real, serious environmental damage caused by technologies. But this damage is not inherent in technologies. Modern technologies don't have to cause such damage. When existing ones do cause damage, we can make better technologies." [3] The impacts of AM are further discussed in next chapter.

2.1 Additive manufacturing a.k.a. 3D printing

This chapter is giving a brief overview how to define 3D printing and why it is advantageous. Concerns regarding AM are brought out as well. The process of 3D printing is looked more thoroughly in chapter 3.1.

2.1.1 The definition

The definition of the term tries to distinguish additive manufacturing from 3D printing, but as mentioned before, 3D printing is more widely spread and popular use of the term.

Additive manufacturing (AM) is broader and more all-inclusive term. It is associated with industrial applications, functional prototypes, and end-use objects in mass production. Whereas 3D printing may be associated with different areas in AM. For some, it may be the FDM machine, to others vat photopolymerization - they both are AM processes. 3D printing is usually connected with consumer applications, singular objects and one-of-a-kind ornate objects. [5]

The terms '3D printing' and 'additive manufacturing' are used interchangeably throughout this thesis.

Additive manufacturing (AM), popularly known as 3D printing, is a collection of automated manufacturing processes, each of which builds a part (3D artefact) additively based on a digital solid model (from computer aided designs) without the need of any tool, jig or fixture [6]. Parts are usually built layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [4].

2.1.2 Impacts of AM

The traditional application space for AM has been low-production parts with complex shapes and geometric features. The fields include aerospace, automotive, biomedical, and other industrial sectors. AM can be used for prototypes, tooling, jigs/fixtures, moulds, mass customization, jewellery, and artwork. For low-cost AM systems, part cost can be much lower than that of conventional manufacturing for small to medium quantities. [4]

There are numerous advantages of AM processes [6]:

- There is no need for tools and fixtures thanks to layered fabrication method. Also, punches or moulds are not required.
- The complexity of the component has no significant impact on the time and cost of the final AM product compared to conventional processes.
- Highly customized parts can be made easily. Additionally, complex and intricate geometries can be achieved.
- Reduction in lead times results in time and cost savings.
- It takes less time for the product to reach the market since the prototyping takes less time and the design cycle is compact.
- It is noise free and can be operated from home or office.
- Reduced material wastage and improved qualities.

Better results can be achieved with 3D printing. More prototypes can be produced and tested since the manufacturing is local and faster, leaving out the transportation time and cost. More physical tests can be done thanks to numerous prototypes and through the analyse, finer ergonomics and appearance can be reached. 3D printing is less costly and faster than the traditional manufacturing method. In serial manufacturing, depending on the detail, every 10th or 15th variation will be manufactured, but with 3D printing every variation can be printed and tested, since it is cheaper.

Milewski [7] brings out the fact that, AM allows designs to be combined from different materials and parts, which historically needed joints, fasteners and assembly. Now, high-performance materials, composites, and even ceramics offer the promise of hybrid components made from materials previously unavailable.

AM enables influencing materials' microstructure - it is possible to control the texture. AM is used in part repair and it enables to manufacture much earlier in the product development process. "Having a prototype part early in the process facilitates final design." [4] Because of that, the product can reach the market earlier.

Creating functional prototypes impacts the process and supply chain – since we can manufacture prototypes earlier, there are less delays and the manufacturing is distributed. Also, customers are given more vendors and sources for subassemblies and products. [4]

Another impact on the supply chain is the cost to transport parts. With a distributed manufacturing, it is possible to print the part at or near its final location, resulting in savings in transportation costs. AM also reduces the risk of availability of parts only from single supplier by having access to multiple manufacturing facilities. From societal impact: final user becomes equipped to manufacture with a reduction in assistance from other companies. [4]

As brought out previously, one of the main positive aspects are the intricate geometries and complex features. Some parts have such complex shapes where no other manufacturing routes are available. A common example is internal flow fields in parts, including cooling channels in moulds and dies, as well as gas or aerosol flow channels for mixing and distributing fuel and oxidants [4].

Complex geometries are being mainly used in single parts or low-production parts, but besides from single pieces, assemblies are re-thought as well, and multiple-part assemblies are reduced to single parts through additive manufacturing, which is economically advantageous.

Reducing the amount of parts enables manufacturers to reduce errors on assembling, eliminate the time spent on assembling this part, reduce the overall dimensions and reduce the overall costs, which is economically advantageous. At the same time, this could mean that the investment into new technology will increase, more complex shapes need more vision and need to be completely thought through, the time spent on printing could be higher than that of the conventional method.

Other challenges that AM is facing, include [6]: low or non-optimal build speeds, limited choice of raw materials, poor surface finish, high system cost, selecting optimal layer thickness, and need of support structures for some type of printers.

Typically, the build rate is slow compared with conventional casting, moulding, or forming. Surface finish varies and might be poor. It depends on the machine, printing speed and layer height. Most of the AM processes require support structures when building the parts, except the simpler shapes. Removal of the support material and giving finishing touches to the part, may constitute a significant portion of the time, effort, and cost of manufacture. In addition to everything, the system cost is high – all the necessary equipment and material needs to be bought.

So, it can be said that technologies do get better, cheaper, easier and more common, as mentioned before, but it could also mean that the technology needs different inputs and knowledge, which the company, producer or designer may be lacking. The challenges are dependent on the skills of the machine operator, the machine itself and on the printable model.

In conclusion, the reasons to use AM lie in the complexity of design, no need for extra tools, prototyping speed, reduction in lead times and lower cost in transportation, and maybe the most important: creating less material waste. AM technology also impacts the process and supply chain in a good way. Centralized manufacturing is in transition to distributed manufacturing, resulting in savings in transportation. On the other hand, the reasons to avoid 3D printing lie in the slowness of creating the part and the extra time and effort needed to remove the support material and have a good surface finish.

2.2 Design and manufacturing implications of AM

AM processes fabricate parts in a layer-by-layer manner in which material is added and processed repeatedly. This process has important implications on part characteristics as well as on design opportunities, manufacturing practices, supply chains and business models. [4]

Due to layer-by-layer fabrication, AM processes have some unique characteristics [4]:

- Shape complexity: As already introduced before, parts can practically have any shape. AM has the capability to fabricate complex geometrical shapes, unique and customised shapes.
- Material complexity: Material can be processed differently in different regions of the part, leading to different properties in these regions. Multiple materials can be deposited and processed, leading to potentially complex material compositions and property distributions.
- Functional complexity: Working devices can be manufactured on the spot, inside the AM machine, without the need for assembling. It includes working mechanisms (e.g., kinematic joints) and parts with embedded devices. One method to create such parts, is to insert external components (like sensors or actuators such as electric motors) into parts as they are being fabricated, since the interior of them are accessible during fabrication.

The most promising characteristic in regard to this thesis aim is the shape complexity. The functional complexity needs to be achieved through shape and the main focus point is the flexibility and possibility to take the shape of the mould of formula car. It could include material complexity as well.

2.2.1 Design for AM: Opportunities versus constraints

The main objective of design for additive manufacturing (DFAM) is to maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions. Redesigning a component or a system is necessary to take advantage of its benefits and opportunities when adopting AM. [4]

There are steps (commitment levels) in the redesigning process, which are divided into reversible substitutions (e.g., improved functions) and irreversible substitutions (e.g., multifunctional design). When the part is completely redesigned, then there is no going back, and it means that the design threshold from conventional manufacturing (CM) process is crossed to AM process. "At the highest commitment level is system-level design for AM, in which a complete change in design philosophies would result in the realization of all of the benefits from AM." [4]

The system-level design means that all the details to be manufactured with AM technology need to be already designed for AM. The philosophies behind require thinking outside of the box for manufacturers as well as for designers, which in the end realize the benefits of AM.

AM can fabricate parts with complex geometry without tooling (moulds, cutting tools), so that customized and complex geometries can be achieved readily. The complex design can be structured by using topology optimization, shape optimization, internal features (cooling channels), and cellular structures (foam, lattice, honeycomb). [4]

"Depending on design applications, these complex geometries can lead to performance improvements: weight reduction, custom material properties and functionality, uniform temperature distribution, active cooling, energy absorption, and vibration control." [4]

Part consolidation is a redesign practice in AM that allows replacement of multiple parts that were manufactured by CM with a single part or smaller number of parts. It results in part count reduction, assembly interface integration and working mechanism fabrication without assembly. These advantages reduce assembly time, repair time, replacement part inventory, cost, and the number of required tools. [4]

These practices will be useful in designing solutions for FS team Tallinn. Reducing parts will reduce the assembly time and overall mass.

Although there is high degree of design freedom in AM, the freedom is limited by AM manufacturing constraints. Those often lead to problems like overhangs, abrupt thickness transitions, trapped volumes, layering, and cleanliness issues. The design-for-constraints methodology has been studied and those design constraints result in direct constraints in relation to part design, process, and material properties. Most design rules focus on constraints during the manufacturing process rather than on constraints for postprocessing. [4]

2.2.2 Additive versus conventional manufacturing processes

Conventional manufacturing is restricted by the need for tooling, while AM fabricates parts without tooling. Current AM processes have drawbacks such as slow manufacturing speed, limited available materials, limited size of final parts, and lower surface quality. [4]

Following table (Table 2.1) collects the manufacturing processes in comparative summary form from all the previous chapters.

Table 2.1 Conventional vs additive manufacturing

Conventional manufacturing	**Additive manufacturing**
Tools are needed.	No need for tools when fabricating.
Fabrication usually requires setups for different details, and also needs different machines. Nesting is not possible.	Fabrication does not require multiple setups, parts can be parallelly processed/ nested.
The amount of waste is process-dependent, usually more waste.	Very low material wastage.
Very complex design is costly, time-consuming, and maybe not manufacturable at all.	Allows complex design (geometry), multifunctional design, and material complexity.
May be very noisy and operators are usually needed.	Noise free and operator work is mostly supervisory.
Lead times vary and depend on transportation, costly and takes a lot of time.	Reduction in lead times, saves money and time.
Fast manufacturing speed.	Slow manufacturing speed.
Final parts do not have size limits.	Limited size of final parts (build chamber size sets the limit).
Usually no need for post-processing.	Parts need post-processing (removing supports, curing, surface treatment etc.).

3. 3D PRINTING

The term 3D printing and its' origin are already explained in chapters 2 and 2.1. Given chapters' section is focusing on explaining the printing processes itself based on different principles. The most suitable printers for this thesis goals are introduced in chapters 3.1.1 and 3.1.2. Following are the cellular structure and lattice structure chapters. Then, Usage of 3D printing in different fields, is introduced. Finally, every field chapter will discuss which structures and examples from different fields are most promising in the case of this thesis.

The impacts of AM including the environmental factors, for example reduction in wastage and minor noise pollution, were mentioned in previous chapters, but why 3D printing is important, was not covered that well.

The importance of 3D printing is the introduction to wider public audience, the spreading to masses. 3D printers are used at homes, offices, industries, schools and they are used for prototyping as well as for making the final products. It is a way for fast prototyping and still a growing industry field. New materials to print with emerge from time to time. New materials are being invented, used, and tested to print with (e.g., composite of coffee and PLA [8]). Even new printers are manufactured for them, for example clay printers in EKA. Overall, it is developing field. It is changing the possibilities of production and allowing for more choices.

What vividly shows that AM is a developing field is the recent breakthrough in 3D printers. Chengkai Dai developed a new method of 3D printing: 3D printing with a robotic arm. The object is built up on a robotic arm, which moves in all directions. As a result, the layers can be formed in all directions, not horizontal layers as usual. This allows printing without support structures meaning even less material goes to waste and the final product surface is smooth, without traces of cuts from removing supports. [9]

It is worth mentioning here, that author's personal interest are the unique and complex shapes, which are sometimes referred to as impossible design. The possible creations of 'impossible design', such as built-in interlocked objects that require no assembly and cannot be disassembled, internal channels that could not be created without 3D printing, etc. [10] are depicted in Figure 3.1.

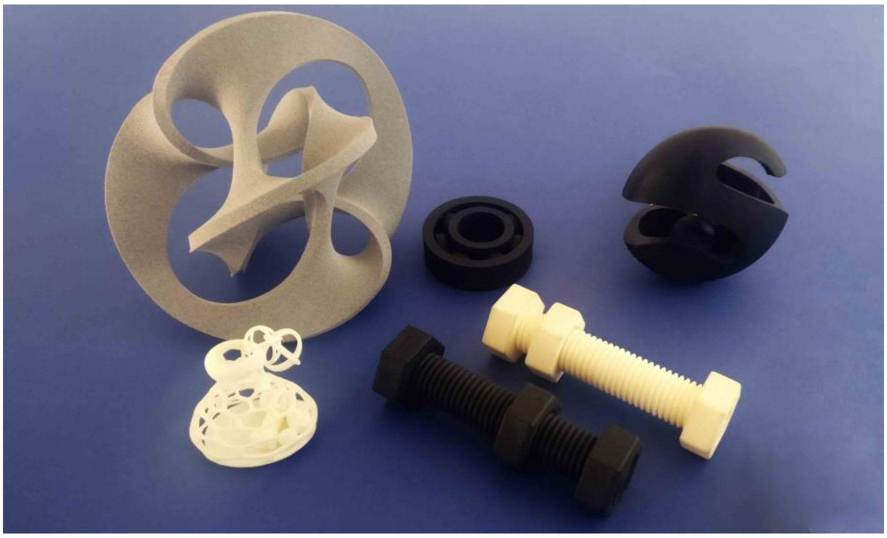


Figure 3.1 'Impossible designs' examples [10]

3.1 AM processes

AM techniques can be classified on various bases. The most common one being the physical state of raw materials, i.e. liquid, powder and solid sheets. The second one is the mechanism employed for transferring STL data into physical structures. Then, third one is the combination of the two aforementioned bases. The fourth is the working methodology. The next classification is based on the energy source used to join materials (e.g., laser, electron beams, etc.). Another classification comes from the raw materials being used, such as ceramics, powders, plastics, etc. The seventh basis is material delivery system, like powder bed or powder feed. The last classification is based upon American Society for Testing Materials (ASTM) F42 Committee guidelines. [6]

The most common way of classification is shown in Figure 3.2.

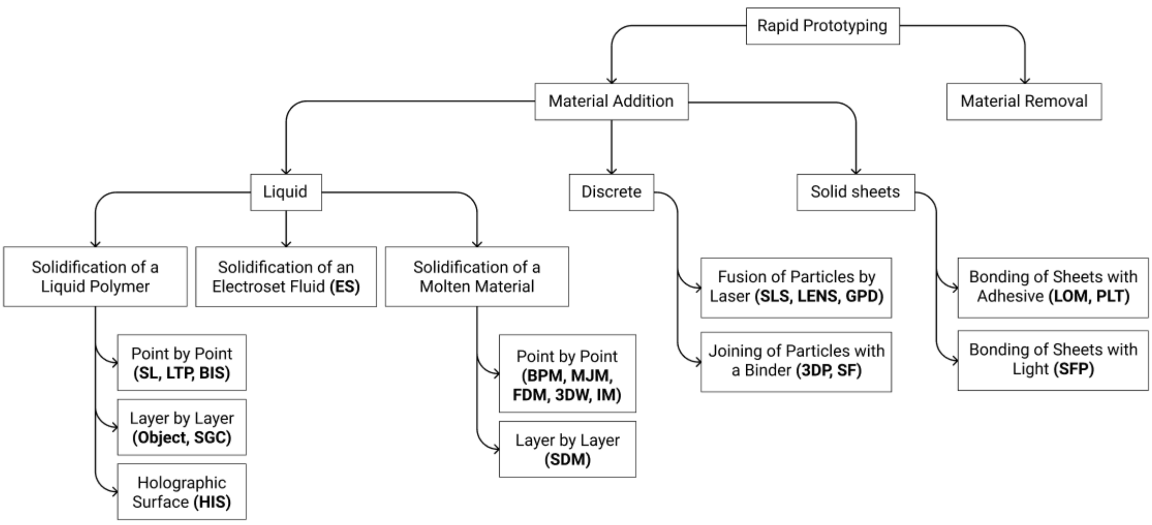


Figure 3.2 AM classification based on raw material state. (Source: [6]. Reproduced from *Additive manufacturing: fundamentals and advancements*)

ASTM F42 divides AM into seven categories [6]:

1. VAT photopolymerization (SLA)
2. Material jetting
3. Binder jetting
4. Material extrusion (FDM)
5. Powder bed fusion (SLM, SLS, EBM)
6. Sheet lamination
7. Directed energy deposition

From the listed categories, powder bed fusion method will be explained more thoroughly. Both SLM and SLS methods, introduced in the next chapters, are by physical raw material, powder systems. By working method, they are classified into powder bed binding/ fusion class. While, SLM technology is used in metallic machines, SLS is used in non-metallic machines. Energy source is the same – laser, but raw material is different: SLM – metals, SLS – plastics. [6]

Based on the information from [6], [11] and [12] some of the beforementioned methods are not as widely known and were left out of consideration due to the lack of access to these 3D printers. Other known methods, like FDM, SLA, EBM were left out of consideration due to their characteristics. Namely, FDM and SLA need supports when building complicated parts. FDM is also rather slow method compared to others. With FDM and SLA mainly plastic parts can be printed. EBM uses electron beam and operates with hot powder bed. Overnight cooling times are required to cool down the powder bed. The process is slower compered to laser options and it is more expensive than SLM. Additionally, EBM method requires vacuum and restrictions exist in terms of the minimum size of a cell in a lattice structure/honeycomb.

3.1.1 SLM – Selective Laser Melting

SLM uses a laser beam to form 3D parts. Based on the information from [7] and [13] the process description is following: a laser melting machine distributes a layer of metal powder onto a build platform, which is selectively joined or welded (melted) by a laser (or multiple lasers). The build platform will then be dropped, and the roller or blade (recoater) will spread the next layer of metal powder on top. By repeating the process of coating powder and melting where needed and incrementally lowering the build platform, the parts are built up layer by layer in the powder bed. When the process is completed, a human will remove the unused powder from the object.

The general principle is shown in schematic of Figure 3.3.

SLM printing is commonly used with 3D parts that have complex structures, geometries, and thin walls. It is quite widespread among the aerospace and medical industries. For example, aerospace industry uses it in projects that focus on precise, durable and lightweight parts, medicine again for orthopedics. [14]

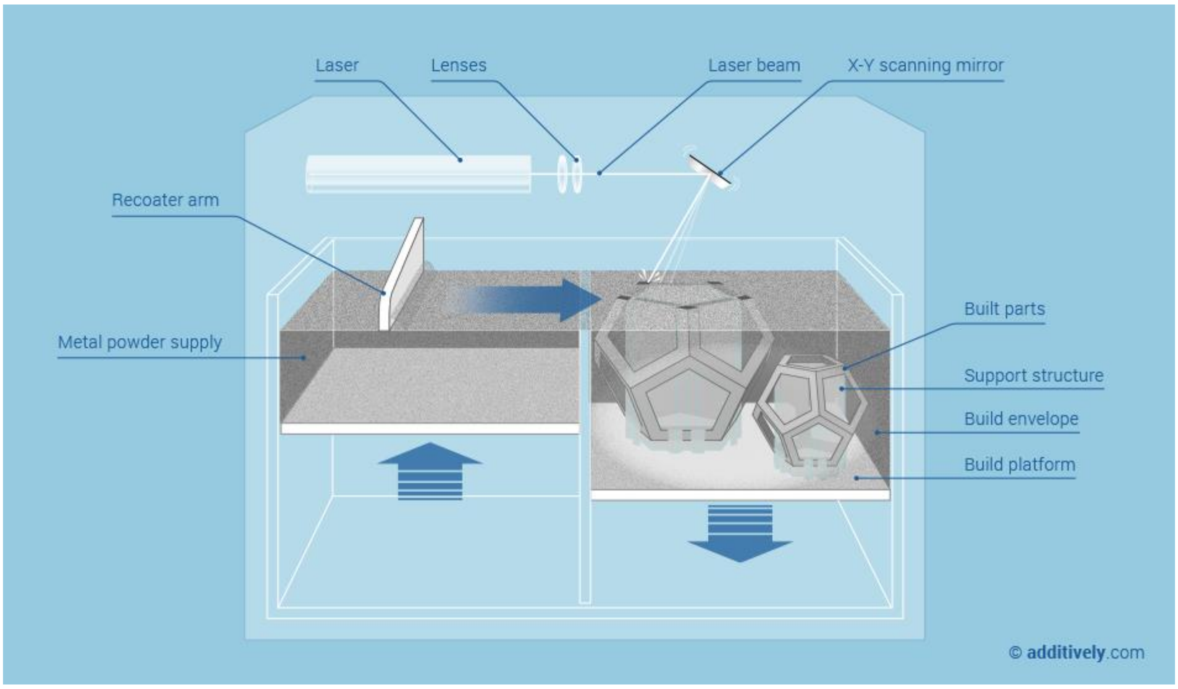


Figure 3.3 SLM principle [13]

In Tallinn University of Technology there are two Selective Laser Melting printers, which use metal powder for printing.

Materials used for printing with Realizer SLM-50 device and SLM Solutions 280 2.0 [15]:

- Stainless steel
- Aluminium (Al)
- Silver (Ag)
- Fe, Al, Co based alloys

Advantages:

Parts can be manufactured in standard metals with high density (above 99%), which can be further processed as any welding part. The technology manufactures parts with good mechanical properties (comparable to traditional production technologies). A constantly widening set of standard metals is available. SLM has very good accuracy: +/- 0.05-0.2 mm (+/- 0.1-0.2%). [13]

Complex structures like shells, internal lattice structures or internal cooling channels can be fabricated by this method. These unique shapes will further minimize the use of metal, optimize strength, or extend functionality. Powder bed will act as a support material. [6][7]

Multiple objects can be printed in one build cycle, using the build volume efficiently. This applies to both same parts and different parts. The productivity is high. [7]

Disadvantages, based on the information from [7] and [13]:

The technology is rather slow, expensive and complex. Tolerances and surface finishes are limited, however they can be improved through post-processing. Surface finishing operations could be peening, polishing, or coating. Also, heat treatments may be utilized to reduce thermal stresses or modify mechanical properties. Those are however costly and time-consuming.

Support structure design may be required since the unsupported material can warp or distort. Support structures anchor parts and overhanging structures to the build platform, enabling the heat transfer away where the laser is melting the powder. Therefore, it reduces thermal stresses and prevents wrapping.

Powder may be left unfused in some regions causing decrease in properties and performance. They could be pores, voids, or defects. The cost of the metal powder might be an issue and additionally the environment, safety, and health issues associated with powder handling and processing need to be controlled.

3.1.2 SLS – Selective Laser Sintering

Same as SLM, SLS uses a laser beam to form 3D parts.

Process description is following: a laser sintering machine distributes a layer of plastic powder onto a build platform, which is selectively melted by a laser (or multiple lasers). The build platform will then be lowered by an amount equal to layer thickness and the next layer of plastic powder will be laid out on top. By repeating the process of laying out powder, melting where needed and incrementally lowering the build platform, the parts are built up layer by layer in the powder bed. When components are fabricated, some cool-off period is normally required to avoid warping and to allow parts to arrive at a manageable handling temperature. Finally, the process is completed, and loose remains of powder are removed. [6][16]

The general principle is shown in Figure 3.4.

With wide range of materials available, SLS produces durable and high precision parts. It is a perfect technology for fully functional, end-use parts and prototypes. [14]

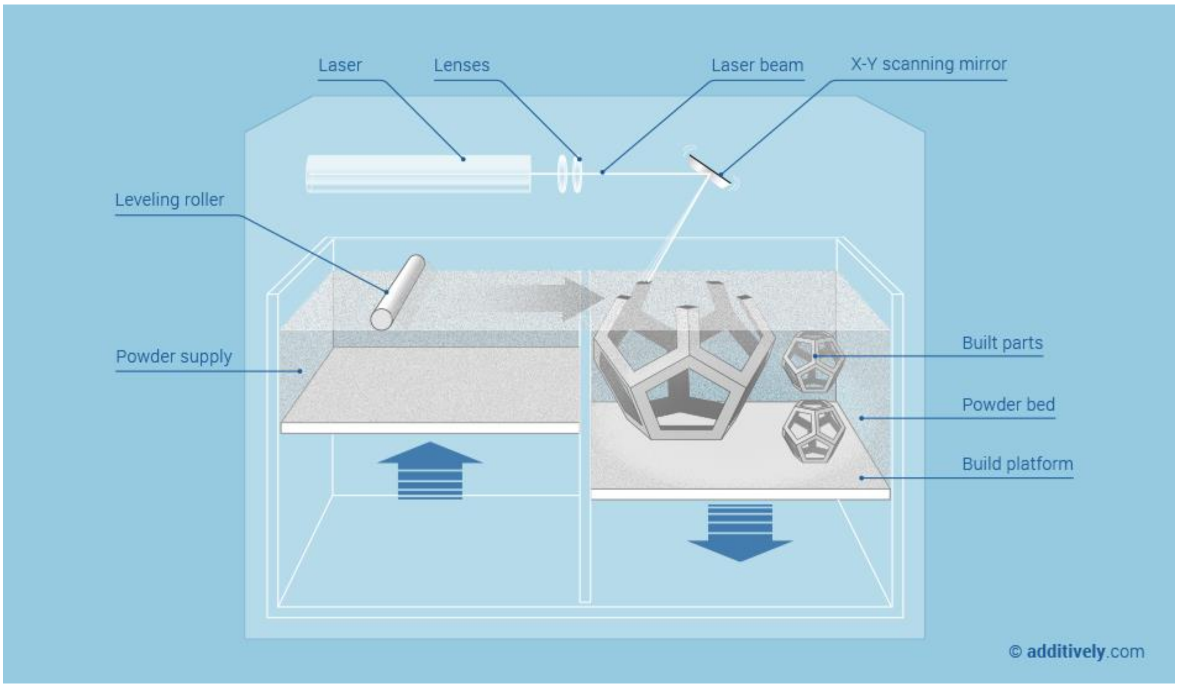


Figure 3.4 SLS printer [16]

In Tallinn University of Technology there is Selective Laser Sintering printer (EOS Formiga P100) [15], which uses polyamide plastic powder for printing. It is very similar to SLM, but the variation is in material.

Advantages:

The technology can manufacture parts in standard plastics with good mechanical properties. A constantly growing set of materials is available. For small batches, laser sintering is price competitive and often the cheapest solution. [16]

Laser Sintering does not require any support structures: the built parts are supported by the loose plastic powder. "The entire build volume can therefore be filled with several parts including stacking and pyramiding of parts, which are then all produced together. The process chamber is preheated and under a protective gas environment." [16]

There are no restrictions on the geometry of the part (no casting slopes, no need to think whether the tool can be accessed, etc.). Very complex models can be created. Flexible assemblies can be fabricated without assembly operations. Also, thin-walled products can be made (minimum wall thickness 0,5 mm). [15]

No tools or fixation tools are required and SLS is relatively fast process. [15]

SLS printed parts have almost isotropic mechanical properties because the bond strength between layers is excellent. [17]

Disadvantages:

Laser sintering parts do not have the same properties as their injection moulded counterparts. Especially regarding surface finish – the SLS parts are typically post-processed. Surface finish is improved by traditional techniques meant for polymers. [4][16]

The part size has limitations and porosity could be an issue with parts, therefore needing post-processing. [6]

Large flat surfaces and small holes cannot be printed accurately, since they are susceptible to warping. [17]

Based on the info from [6], [12] and [17] only industrial SLS systems are available, so lead times may be longer. They have high power usage and the machine itself is expensive.

3.1.3 Differences between SLM and SLS

Although the main working principle is the same, the major difference between SLM and SLS machine is the powder material.

Even though SLS system can process metals/ ceramics indirectly, they cannot process pure metals/ ceramics [5].

"The main difference between SLM and SLS is that SLM completely melts the powder, whereas SLS only partly melts it (sinters). In general, SLM end products tend to be stronger as they have fewer or no voids." [14]

3.2 Cellular structures

Before the lattice structure appeared, the name of cellular structure was more widely spread. The term "cellular structure" was originally proposed by Gibson, Ashby, Evans and Hutchinson. They considered foams and honeycombs as cellular structures. However, lattice structure is different from previously mentioned cellular structures because of its' unit cell topology and scale, and properties. [18]

"In order to classify more clearly the types of cellular structures, Dhruv Bhate, Tao and Leu classified cellular structures into three categories, i.e., foams (open-cell and closed-cell foams), honeycombs, and lattice structures." [18]

In the foam structures the shape of unit cells are randomly generated and the cell walls have random orientation in space as shown in Figure 3.5 on the left side. Foams can be used as energy absorbers, filters, silencers, flame arresters, heaters and heat exchangers, electro-chemical devices, etc [18].

Honeycomb structures have regular shape, and unit cells have the same shape and size (Figure 3.5 on the right side). The typical cell shapes include: tetrahedron, triangular prism, square prism, hexagonal prism, etc. Some shapes, like re-entrant honeycomb auxetic structures (Figure 3.6) and chiral honeycomb structures (Figure 3.7) improve the performance and extend the application of honeycombs. Honeycombs can be used as energy absorbers, biomedical implants, filters, sensors, actuators and vibration absorbers or dampers, etc. [18]

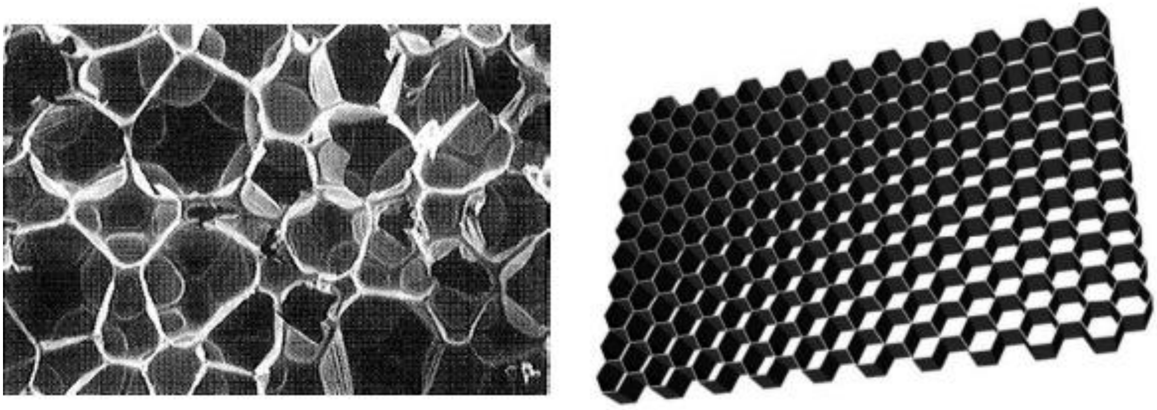


Figure 3.5 Different types of structures. On the left: foam, on the right: honeycomb [18]

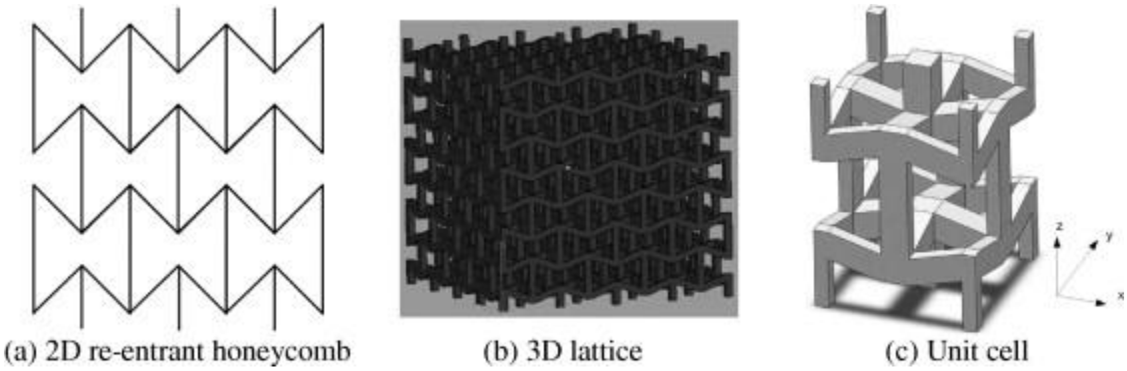


Figure 3.6 Re-entrant honeycomb auxetic structure [19]

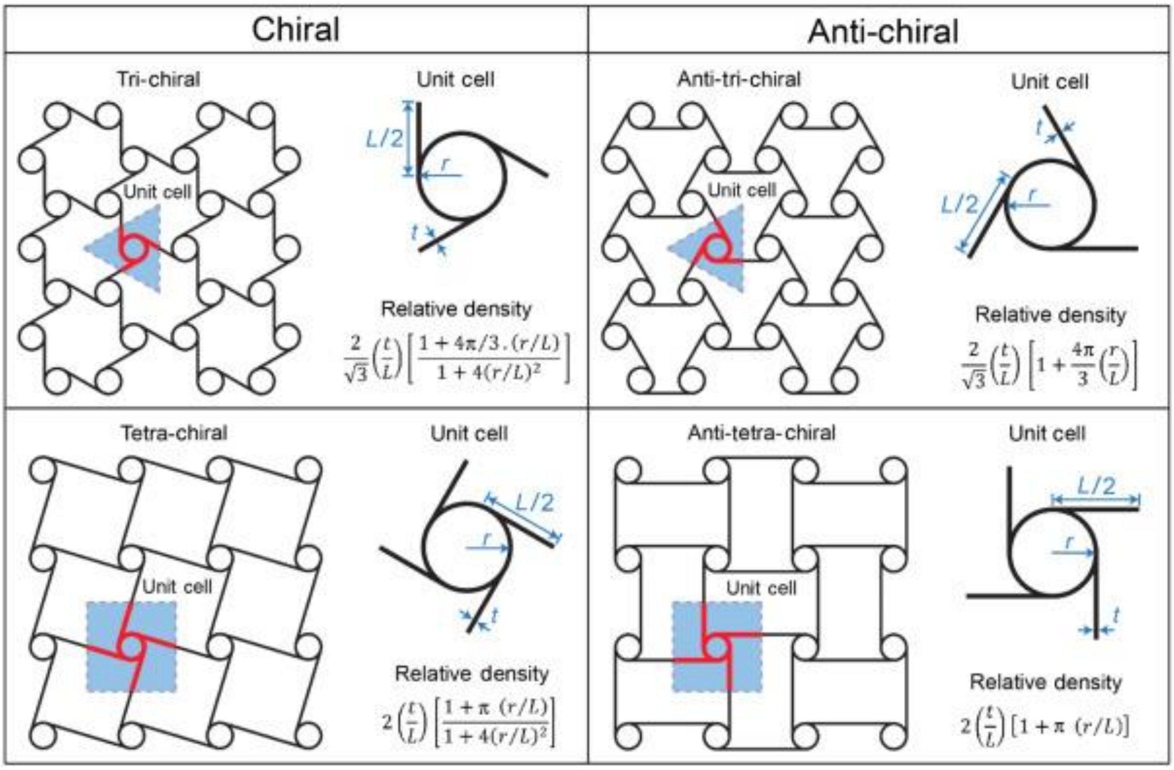


Figure 3.7 Schematic of the structure and unit cell for chiral and anti-chiral honeycombs [20]

"Lattice structure is a type of architectured material, which is a combination of a monolithic material and space to generate a new structure which has the equivalent mechanical properties of a new monolithic material." Architectured materials are also known as cellular structures. [21]

Lattice structures are formed by the array of spatial unit cells with edges and faces (Figure 3.8). Cellular shape and size can be uniform or non-uniform. Compared with foams and honeycombs, lattice structures have better mechanical properties and performance. They have improved compressive and shear strength when designed to suppress buckling. Each unit cell, and even each strut in the lattice structure can be set as the design variable and be optimized to satisfy specific customized requirements functionally, which means mechanical properties of lattices are more flexible than that of foams and honeycombs. Lattices can be used as energy absorbers, heaters and heat exchangers, engine hoods, biomedical implants, wings, gas turbine engine fan blades, vibration absorbers, robotic systems, spacecraft and aircraft structures, etc. [18]

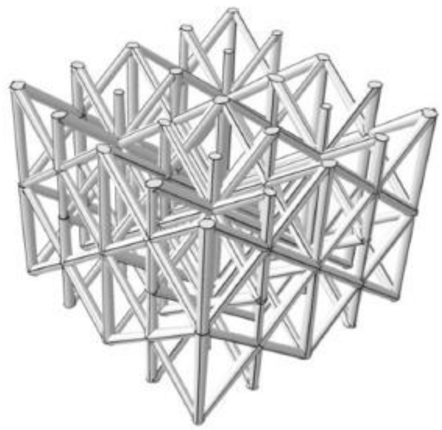


Figure 3.8 Different types of structures. Lattice structure [18]

3.2.1 Introduction on lattice structures

As the world becomes more competitive, industries are trying to be ahead of the competition by looking into viable prospects. Economical, as well as environmental needs are pressuring companies to reduce costs, reduce waste and increase performance. Due to increasing energy conservation, the lightweight parts become more important as well. In aviation and aerospace industry, where every gram counts and the need to reduce weight is important, companies are trying different solutions and structures to manufacture lighter aircrafts. These help to use less fuel and contribute to vast amount of savings in fuel expenses. It is the same situation in automotive industry, where reducing vehicles weight contributes to fuel economy and lower CO_2 emissions. Studies indicate that reducing weight 10% can save around 6-8% in fuel consumption. [21]

As important as it is to produce lightweight parts, it is important to produce parts that have good mechanical properties too. Lattice structures (described by Figure 3.9) are good in achieving this target. Lattice structure key advantage is high strength low mass ratio, where material is added only where it is needed. They can be used to achieve excellent performance and multifunctionality while reducing weight. Besides aerospace and automotive industry, lattice structures are also important in biomedical engineering, where it is suitable for cell attachment and growth on implants. [21]

All in all, lattice structures have many superior properties, which make it a promising solution for various applications, such as a lightweight structure due to its high specific stiffness and strength, a heat exchanger due to its large surface area, an energy absorber due to its ability to undergo great deformation at a relatively low stress level, and an acoustic insulator due to its large number of internal pores. [22]

A lattice structure can be defined as space-filling unit cell that can be repeated along any axis with no gaps between the cells. [23]

Figure 3.9 Lattice structures [24]

A parallel from architecture history and nature can be brought with nowadays lattice structures: in nature - bone, wood, metal crystallography, etc., and from history - Eiffel Tower. For example, the Eiffel Tower metal structure efficiently supports its weight as it reaches into the sky. Like a simple lattice, this self-supporting structure is mostly air. The high strength-to-weight ratio possible with lattices enabled this enormous architectural achievement. [24]

The design factors to consider when designing lattice structures (DFAM considerations) include cell structure, cell size and density, material selection and finally, cell orientation.

Cells are the repeated unit in a lattice and there is an enormous array of them. The most common cell structures are cubic, star, octet, hexagonal, diamond and tetrahedron. Some structures work more efficiently (higher stiffness-to-weight ratios), others dampen energy better, and some show better aesthetic quality. [24]

Cell size refers to the size of an individual unit cell and density refers to how many cells are repeated within a space. "The cell size itself depends on the thickness and length of its members and connecting nodes." Larger cells can be easier to print but can be stiffer. Smaller cells allow for more homogeneous system responses. [24]

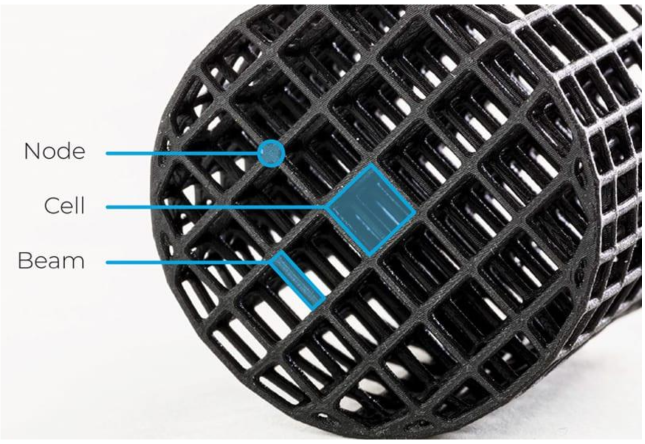


Figure 3.10 Lattice structure node, cell, beam [24]

Material can define possible lattice properties. Generally, elastomeric, or soft materials require a smaller and denser cell population. On the other hand, lattices printed with a more rigid material generally allow thinner members and larger cell sizes. [24]

Material choice will be limited to the specifics of a 3D printer. Based on printer choice (SLM or SLS), it could be stainless steel, aluminium, silver or polyamide.

Cell orientation means the angle a cell is printed at. It can affect the success of a print because it influences the amount and placement of supports required. In general, a well oriented lattice is self-supporting, requiring no additional supports. [24]

As mentioned before, SLM and SLS methods are great for printing, because they usually do not require supports to print complicated structures. Therefore, cell orientation should not be a problem support-wise.

3.3 Topology optimization

In recent decades, with the increasing performances of computers and computing algorithms, structural optimization methods have developed tremendously. Solutions of complicated optimization problems are satisfying severe multidisciplinary design performances. One of the most promising techniques is topology optimization. [25]

Structure optimization methods are classified into three categories [25]:

- sizing optimization,
- shape optimization,
- topology optimization.

Sizing optimization is a classical method and easy to control by choosing cross-sectional dimensions of trusses and beams or the thicknesses of membranes, plates, and shells as design variables. It is a detailed design procedure of the structural model involving many design variables. [25]

Shape optimization purpose is designing structural boundaries or holes in a structure. This method can be used to improve local performances such as stress distribution. Usually there are small number of geometric design variables. [25]

Sizing and shape optimization methods are both detailed design practices without changing the specific topology of a structure. [25]

Topology optimization target is finding an optimal solid-void pattern of the material layout over a specific design domain with given boundary conditions. It is often used at the conceptual design stage to optimize global performances such as the rigidity and natural frequencies of a structure. [25] To put it more simply, it is a way of optimizing material layout and structure within given 3D design space by the set of rules, like loads, to maximize performance.

In general, it can be said that inefficient materials are gradually removed from the design to approach optimal topology. However, the optimized design accomplished in the standard topology optimization is only a rough material distribution. Subsequent detailed designs are necessary for the purpose of engineering applications. The optimized design will be post-processed by adding more engineering features considering manufacturing, assembling and functional purposes. This can be done in CAD platforms by designers, but the detailed configuration and performance of the model will depend upon the subjectivity and experience of the designer. [25]

Once the optimized design has been post-processed into a detailed engineering model, additional shape and sizing optimizations are needed to improve the structural performances that are not completely considered in topology optimization, for example, local stress, buckling, dynamic response, etc. [25]

In topology optimization, only the forces applied to the structure are considered and the structure is optimised according to them, which means if an outside force comes from another direction the designer did not consider, the structure might fail. This is one of the reasons further shape and sizing optimization are required.

A Figure 3.11 from a case study [26] is brought below. Additionally, to human factors, the Generico chair acts as a new way of design thinking where the topology optimization principles were used.

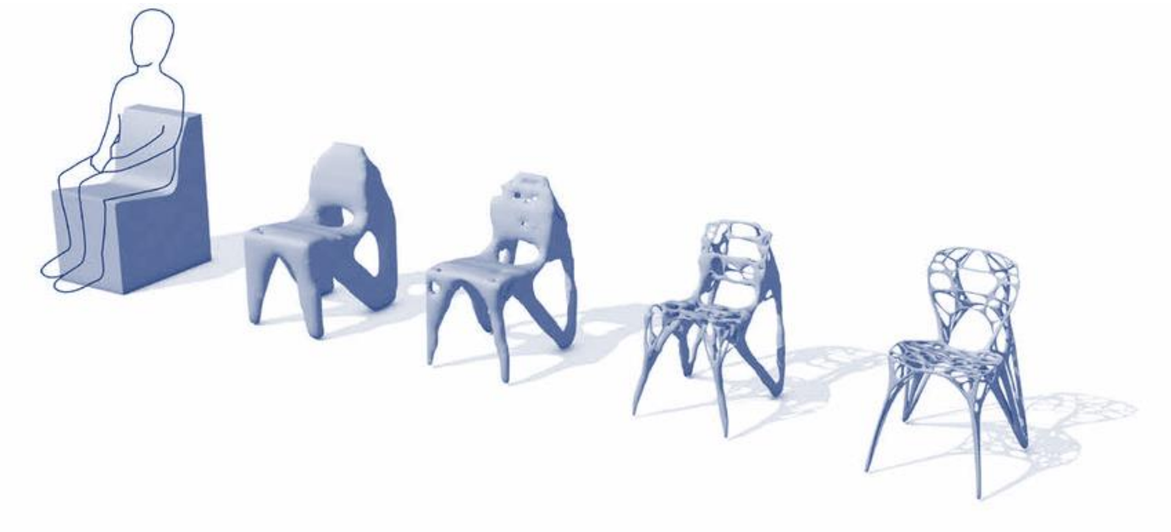


Figure 3.11 Generico chair [26]

In most structural designs, typical conceptual designs were reached through best load carrying path generated by a global strain energy-based topology optimization design. Then, further shape and sizing optimizations were carried out. [25]

The manufacturability of those optimized designs has been a question for topology optimization researchers for years. Nowadays, with 3D printing advancements, it has become more beneficial to fabricate those structures. [25]

Based on Zhang *et al* [25], many new aircraft and aerospace projects bring great challenges in developing innovative design methodology and dealing with new scientific and technical problems issued from the complicated engineering practices. Main scope in aircraft and aerospace projects is topology optimization.

It is believed that in the upcoming future the aircraft and aerospace structures will be designed and fabricated as unconventional integral structures to save weight and simplify the assembling procedure, where AM will play an important role.

3.4 Usage of 3D printing in different fields

Different fields of industries were researched through and several of them are discussed more in depth in following chapters. They were looked as a source of inspiration in developing new internal structures for Formula Student car body.

Mass customization required in automotive industry, new legislation targets for fuel efficiency in automotive industry, weight optimized shapes and integrated components in aerospace industry are just few examples of possible ways of using new technology such as additive manufacturing.

3.4.1 Automotive industry

Increasing performance and efficiency are the priorities in automotive industry. AM offers a great balance of unique part construction, part count reduction, weight optimization, mass reduction, energy-absorbing designs, unique ergonomics, enhanced cooling, and smart components, which help car manufacturers to meet new legislation targets for fuel efficiency. AM allows design freedom to combine several parts into one to reduce weight and simplify the supply chain, therefore being cost effective. The areas manufacturable with AM technology in a car are brought in Figure 3.12. [27]

Besides from all the new areas of development, old cars that are out of production and discontinued are still in use by public, and the growing population of old cars' enthusiasts creates the need for replacement parts. 3D printing is a valuable for them by allowing to create parts which production may have ended decades ago.

The challenges today are the complex geometries and functional integration, low quantities and highly differentiated manufacturing, and lean production.

Components must perform increasingly complex functions requiring integration of new materials, mechanical and electronic capabilities. Designing these combined components requires manufacturing technologies aside from conventional possibilities. [27]

Mass manufacturing methods are incapable in delivering variable short-term production with the high customization required by the automotive industry and the customers.

Weight optimized designs with balanced stress distributions increase energy efficiency and performance. However, combining the best performance with minimal material is limited by design tool capabilities and manufacturing process constraints. [27]

AM allows cost effective complex component manufacturing in a flexible and lean supply chain. AM addresses challenges of weight reduction and functional integration in a cost competitive way. [27]

High customization is supported in AM, and production (lead) times are shorter than that of the conventional methods. Material usage is minimised, and functional capabilities optimised to have better performance. AM method is allowing custom designs achieved with topology optimization to be manufactured in a cost-effective way.

Automotive AM materials include stainless steels, nickel-based alloys, titanium alloys. [27]

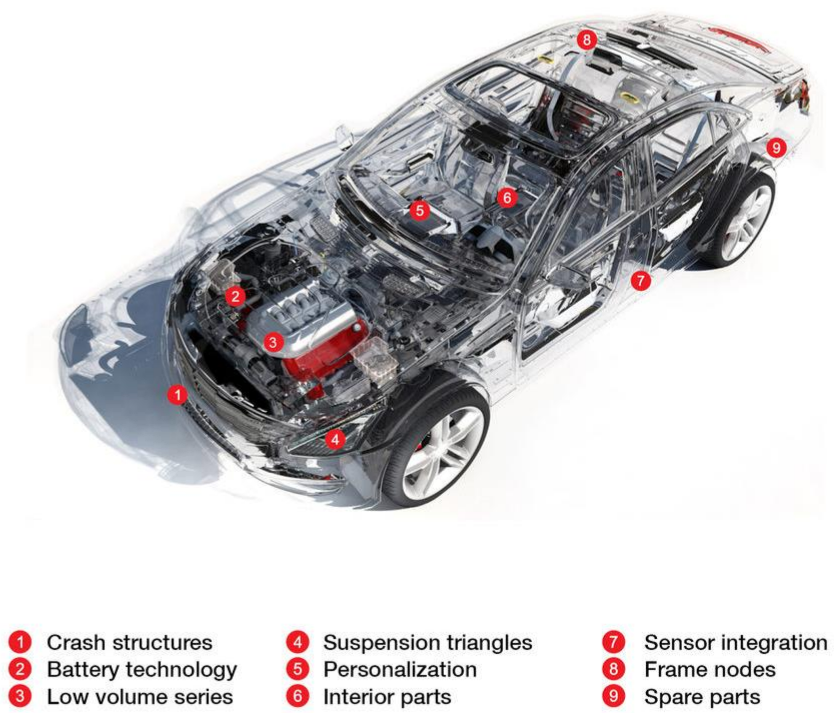


Figure 3.12 Automotive AM applications [27]

One design example in automotive industry can be brought from collaboration between HRE Wheels and GE Additive [28] who revolutionized the wheel fabrication with the “HRE3D+” wheel. The wheel itself is depicted in Figure 3.13.

Thanks to AM they were able to reduce the weight from 50 kg to 10 kg and therefore producing 80% less waste. Post processing was reduced from 5 hours to 15 minutes. [29]

Figure 3.13 The world's first 3D printed titanium wheel "HRE3D+" [28]

3D printing is actively used in automotive field, especially in racing cars. However, in automotive industry, cars are looked through energy resource prism – the need to use less fuel, spend less money on fuel, make vehicles lighter etc. The focus seems to be only in one end goal – to maximize performance. With the increasing needs from customers, automotive industries are struggling to manufacture various solutions that could be cost-efficient and time-efficient with conventional manufacturing. Therefore, the AM is offering a great alternative for manufacturing. However, the solutions for AM in general automotive industry are in the very beginning of the journey. The most promising fact from automotive industry, is the mass optimization regards to FS.

3.4.2 Aviation and aerospace

Making aircraft safer, lighter, and more efficient are the priorities in aerospace. Additionally, this industry requires quality, traceability, affordability, reliability, weight optimization and good performance. AM allows all that in a cost competitive framework. In aviation and aerospace AM finds usage in complex engine parts, antennas, rocket engine nozzles, satellite brackets, structural components, and replacement parts. These parts' masses will be lower and life-cycle costs are reduced compared to conventional methods. AM can be leveraged for weight and flow optimization, sound reduction, part substitution, and part count reduction for aircraft applications like brackets, ducting, and seat belt buckles. [30][31] Typical aerospace AM applications are brought in Figure 3.14.

The challenges today are the weight reduction and the increasing efficiency [30]. Additionally, the complex stage in manufacturing 3D printed details for aircrafts includes material testing and certification [31].

As mentioned before, weight optimized shapes are expensive or impossible to create with conventional techniques. New engine concepts, for example, increase fuel efficiency but require components with complex geometry such as cooling channels. Some materials, like high temperature Ni-based alloys or titanium, are difficult to machine. [30]

Machinability is not a problem with AM, because it is by its' origin additive method, meaning no tools are required. Also, complicated structures, such as internal profiles and cooling channels can be manufactured.

"With AM, form follows function, because it enables weight optimized designs with balanced stress distributions to increase fuel efficiency and enhance performance." [30]

Weight optimization is more than the weight of the part itself. By designing a component exactly in the shape and size required to fit into the tightest space it is possible to reduce the entire weight of the system around a 3D printed part. AM is not only for optimizing small parts, but it makes it possible to also optimize and reduce the weight of enormous systems. [31]

AM can have a significant impact on various applications (e.g., diffusers, heat exchangers) by integrating components to reduce part count and mass. AM is the solution in a variety of rotorcraft and defence applications, like unmanned aerial vehicles. [30]

Aerospace AM materials include titanium, aluminium, nickel-based alloy, cobalt chrome and steels. [30]

Figure 3.14 Aerospace AM applications [30]

Two examples are brought below. One of them showing propeller options displayed in Paris Air Show 2019 (Figure 3.15) and the other one being a case study for a satellite antenna bracket (Figure 3.16).

Figure 3.15 3D printed propellers at the Paris Air Show 2019 [31]

Sentinel Satellite Antenna Bracket 40% weight reduction was achieved with topology optimization. Costs were also optimized and the failures reduced. Antenna was tested according to static and vibration test requirements. [30]

"AM can make a difference on the smallest of parts, and those small parts typically add up to a much greater whole. This is definitely true in the case of Sentinel Satellites. If a single component like an antenna bracket fails, the satellite's mission could be doomed from the start." The ideal mix of project partners and the flexibility of AM technology allowed Oerlikon to produce an aerospace structure that exceeded expectations. [30]

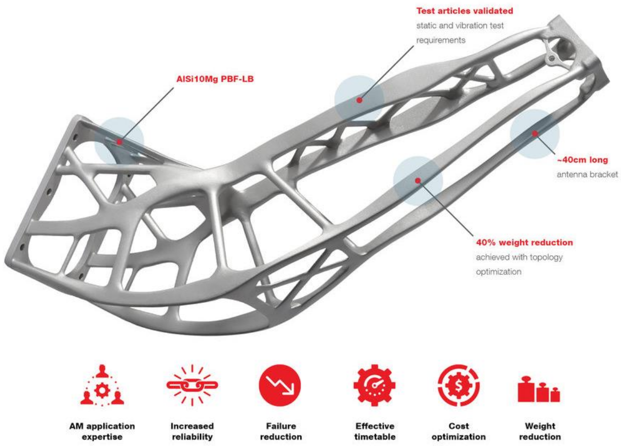


Figure 3.16 Sentinel Satellite Antenna Bracket, Oerlikon case study [30]

As for the case with automotive industry, aviation seemed to be a promising start for the project as well since 3D printing is already actively in use in this field, but in reality planes are looked the same way as cars - through energy resource prism. When aircraft uses less fuel, it is naturally better for the environment, but in the case of this thesis, the human factor is not considered that much. Weight optimization principles from aviation are one of the factors to be used in the case of FS monocoque.

3.4.3 Medical industry

Medical field is moving towards personalised healthcare. Being able to provide better and more human-centred healthcare is one of the main points why to use solutions provided by AM.

3D printing enables patient-specific anatomical level productions with high adjustability and resolution in microstructures. 3D printing has become a leading healthcare and pharmaceutical manufacturing technology, which is suitable for variety of applications including tissue engineering models, anatomical models, pharmacological design and validation model, medical apparatus and instruments. Today, 3D printing is offering clinical medical products and platforms suitable for emerging research fields, including tissue and organ printing. [32]

Medical 3D printing is a perfect technique for making custom objects, for example, casts, which are used to immobilize a limb during a sprain or a fracture. In 2013, Jake Evill, an English designer, made the first 3D printed cast, called the Cortex exoskeletal, depicted in Figure 3.17. The Cortex is computer generated from a 3D scan of the patient limb. The cast is therefore personalized to the patient's morphology. It offers a hygienic solution to replace the traditional plaster, which is heavy and inconvenient. [33]

"The Cortex exoskeletal cast provides a highly technical and trauma zone localized support system that is fully ventilated, super light, shower friendly, hygienic, recyclable and stylish." [34]

Parametric design of prosthesis/ orthosis allows the designer to create more attractive prosthesis. An orthosis is a support that helps a patient to heal from injuries or helps them to move. The product will be affordable and very light and perfectly adapted to each patient. [35] The prosthesis/ orthosis design is unique and custom-made. It does not need to be massive or robust anymore.

Figure 3.17 3D printed orthosis [34]

3D printing gives medical industry the opportunity to be more human-centred and less costly. Individuals are taken into account and personalized healthcare is closer than ever. With new morphological prosthesis, there will be no more skin irritations or uncomfortable casts, which need special care before contact with water. Cost savings come from the effective material usage and manufacturing method – 3D printing enables the creation of complex shapes and structures. Medicine field examples seem to be promising for the concept designs in this thesis.

3.4.4 Architecture

The development of lightweight structural systems has made it possible for structures to carry a lot greater load than their self-weight. Shells and spatial structures (including lattice structures) are on the very front of this breakthrough in efficient use of materials. The continuing development of design, analysis, and construction techniques of shell and spatial structures has resulted in an increasing fund of information of practical interest to architects, engineers, and builders. [36]

3D printing in architecture mainly has two applications: to create low-cost architectural models as study models or to build realistic and detailed architectural models showing final result in 3D, e.g. pavilions, floor surfaces, and wall panels.

The benefits of AM technology include cost effective models, saving time, precision, increased productivity, and lower production costs. Models are easily updatable compared to regular architectural (study) model building method and they also help to visualize and give better understanding via tangible model to clients, designers etc. [37]

Following are two examples from architecture field. The first one being pavilion and the second one space divider.

In the fifth year of Beijing Design Week (BJDW) (2013), visitors were able to see a gigantic sci-fi object in the atrium at Beijing's Parkview Green which was actually 'Vulcan', world's largest 3D printed pavilion (Figure 3.18). "This tripodal pavilion is structured onto three inward arched tunnels, which lead to the central polyhedron core. With a sinuous membrane running all across its form, the aesthetics of the pavilion are majorly inspired from silkworm." It is 8.08m in length and 2.88m tall. This unprecedented structure is an assembly of 1086 3D printed modules (close up in Figure 3.19). [38]

Figure 3.18 3D printed pavilion 'Vulcan' in BJDW [38]

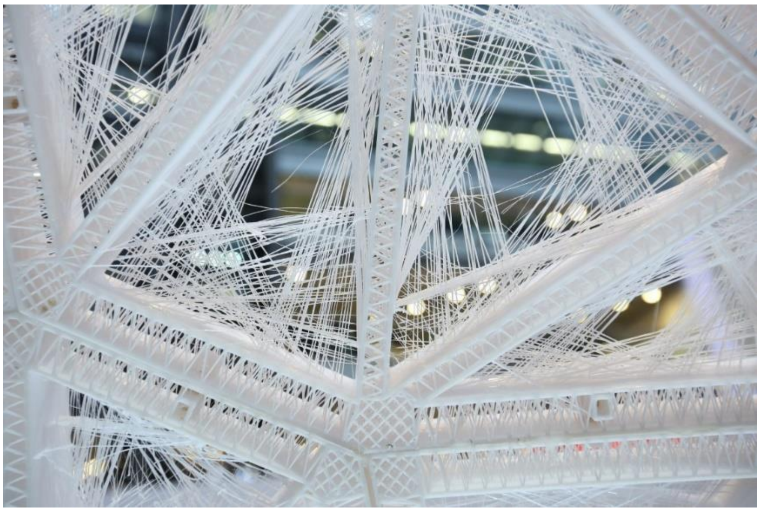


Figure 3.19 Close up of 'Vulcan' structure [38]

Space divider by Aectual can be seen in Figure 3.20. Aectual is offering high-resolution digitally printed architectural products from floor surfaces to wall panels, which can be customized. Their mission is to bring tailor-made and sustainable architecture to everyone. Since with 3D printing you only use the material you need, it is a zero-waste production method. It opens the possibility to re-design products, re-think the use of materials, and design in a way you can recycle all materials into new products: creating a circular future. [39]

Figure 3.20 Aectual space divider [39]

3.4.5 Fashion

Traditional apparel design and production involves customer, retailer and/or designer, textile factory and clothing factory. The traditional method contains different problems like long lead time and extensive wastage. Instead, 3D printing involves personalized clothing design, shorter lead time and less wastage compared to conventional fabrication. Moreover, AM offers freedom to designers and fabrication of complex and flexible structures. 3D printed add-ons/ sensors have potential to be used in athletic footwear, sports gear, e-textile etc. to monitor real-time health conditions like heart rate, steps, sleep, etc. Advancements in machines has made it possible to even create fabric from high volume of fibers. [40]

Many of the leading innovative designers and companies are trying out new concepts created with 3D printers. In this chapter, a company called ‘Nervous System’ is looked more closely. Especially their design, which they have named ‘Kinematics Dress’ (depicted in Figure 3.21). Additionally, NASA 3D printed fabric is introduced.

Figure 3.21 Flow of Kinematics Dress [41]

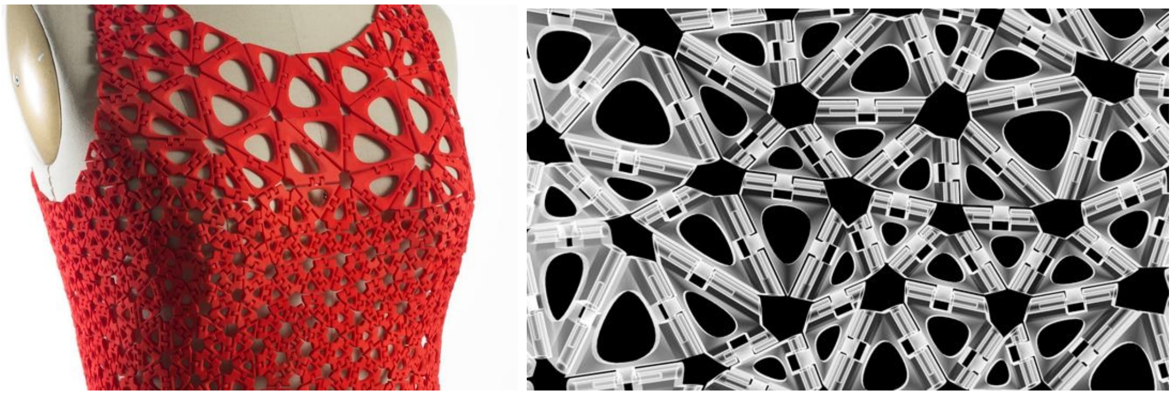


Figure 3.22 Details of Kinematics Dress and the hinge system [41][42]

This dress depicted above (Figure 3.21) is made from interlocking panels (Figure 3.22). The creation authors' call it a 'Kinematics Dress 6'.

Kinematics for them, is a system for 4D printing that creates complex, foldable forms consisting of articulated modules providing a way to turn any 3D shape into a flexible structure using 3D printing. Computational geometry techniques are combined with rigid body physics and customization. It allows to compress large objects down for 3D printing through simulation. [42]

Designs are composed of tens to thousands of unique components to construct dynamic, mechanical structures. Together they act as a fabric but each component is rigid. [42]

The hinges seen in Figure 3.22 on the right are 3D printed in-place and do not need assembly.

Even NASA is trying out 3D printed fabrics. Raul Polit Casillas and his colleagues are designing advanced woven metal fabrics to use in space. The material is foldable, and its shape can change quickly. The potential uses for this material are wide – it could be the spacesuit of astronaut, spacecraft shield for meteorites, or insulation of a spacecraft. [43]

This piece (in Figure 3.23) was created in one piece via 3D printing. Casillas said that they call it 4D printing, since they can print both the geometry and the function of these materials. He also mentioned that it is critical to think about new forms – forms should be multifunctional. "Spacecraft housing could have different functionality on its outsides and insides, becoming more than just structural." This kind of design-based thinking could revolutionize the way spacecraft is engineered. Instead of having to assemble dozens of parts, the future spacecraft could be created "whole cloth" - and with added function, as well. [43]

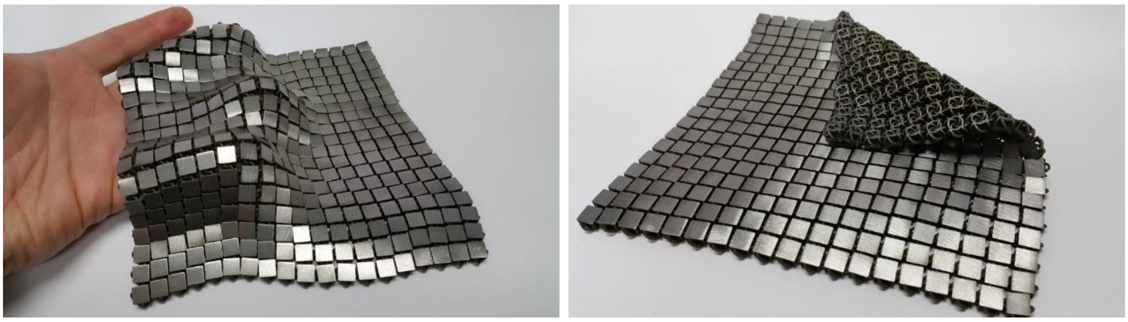


Figure 3.23 NASA 3D printed metal fabric [43]

Compared to all previous research in different fields, fashion seemed the most fun and experimental. Designers are trying to create new fabrics with the opportunities provided by AM. Not only that, but the new fabrics are created on the principle to change the fashion industry fabrication methods and add additional value to the fabric with functions. Even though automotive industry seemed to be the most promising area for this thesis topic, it now seems that the exceptional solutions in fashion industry enable more experimental possibilities which can be used in the context of this work.

4. FORMULA STUDENT

When discovering where 3D printed lattice structures could be applied, Formula Student seemed as a tangible option for thesis author. When giving a brief overview of lattice structures to Formula Student team Tallinn, the chief engineer of FS team, Kaarel Haavajõe, mentioned a huge problem for them regarding building the formula body. The main problem being giving shape to round features. The information regarding FS team Tallinn working methods was gathered through multiple discussions and interviews with chief engineer.

For the team, 3D printing means that they can create parts that are totally unique and designed to the optimum by them. It is a fast way to prototype and test the solutions and see if anything needs modifying. This creates the perfect circle of testing and prototyping. Additionally, the time usually spent on manufacturing and waiting for the items to be produced and shipped, is now significantly shortened. This is also great since the time window to fabricate the formula car is rather short – they have one school year (9 months) to produce a proper formula car.

Due to some restrictions from FS team side, this season's car is mentioned as little as possible. The pictures and examples are from earlier models.

Figure 4.1 Formula car FEST19 [44]

4.1 Formula body manufacturing

Formula Student team Tallinn uses moulds to build the formula car. For every season (1 year) a new car is built. The shape of this mould is carefully designed and tested to give best results in competitions. This resulting in streamlined body shape and lower air resistance, giving the desired speed and better results in competitions. In Figure 4.2 is depicted Formula Student car mould.

Figure 4.2 Formula Student car mould. Author's photo

The body (monocoque) building starts from layering carbon fibre fabrics on top of each other, then aluminium honeycomb is placed and finally layers of carbon fibre are placed on top again (cross-section of a piece of formula car is shown in Figure 4.3). The carbon fibre used by the team is prepreg carbon fibre meaning that it is impregnated with suitable resins. It is activated in autoclave or oven, gaining the final shape of the mould. The oven temperature is maximum 120°C. Adhesive film is used to combine carbon fibre and aluminium honeycomb together. More adhesive is used in corners. The most difficult part in manufacturing is giving shape to convex surfaces (example piece is in Figure 4.4). Even the slightest radius multiplies the workload. Each piece of aluminium honeycomb structure needs to be cut and glued and matched together with other parts.

One other option would be to use over-expanded aluminium, which allows more flexible bending. However, it is much more expensive.

Aluminium honeycomb is usually used in wide variety of applications due to its incredibly high strength-to-weight ratio and is applicable wherever lightness and strength are required (e.g., aerospace, marine, defence and automotive industries) [45].

Figure 4.3 Cross-section of car body. Credit: Kaarel Haavajõe

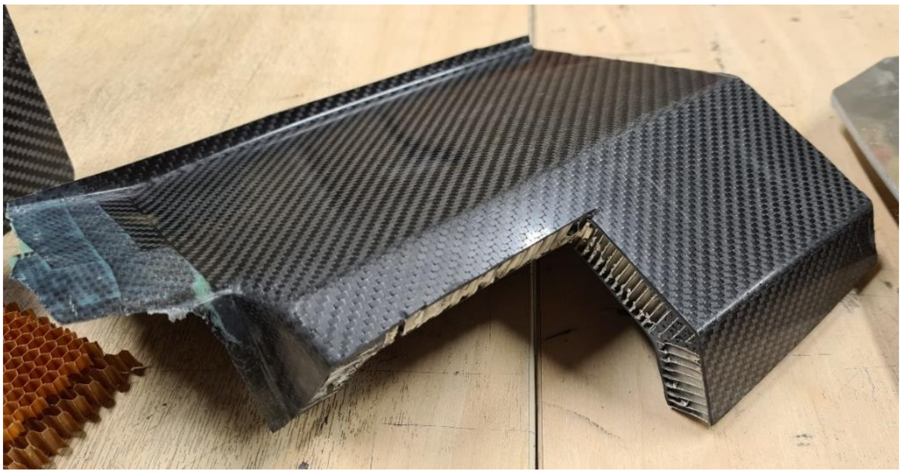


Figure 4.4 Piece of formula car body. Author's photo

The slightest corners and convex surfaces in more close-up are brought in Figure 4.5 and Figure 4.6.

Figure 4.5 FEST19 car details up close. Author’s photos


Figure 4.6 FEST19 details on the left, FEST20 on the right. Author's photos

One option to show 3D printed lattice structure in use is to discover different variants for body forming internal structure which could take the shape of the mould and preserve it afterwards.

The other option would be to look in a new way the construction of the formula car nose (Figure 4.7), where rather heavy structure is used to keep the driver safe by absorbing impact energy. The requirements to withstand the impact of collision are following: withstand the drop of weight of 300 kg from height of 3 meters [46]. At the moment the whole nose is made from aluminium.

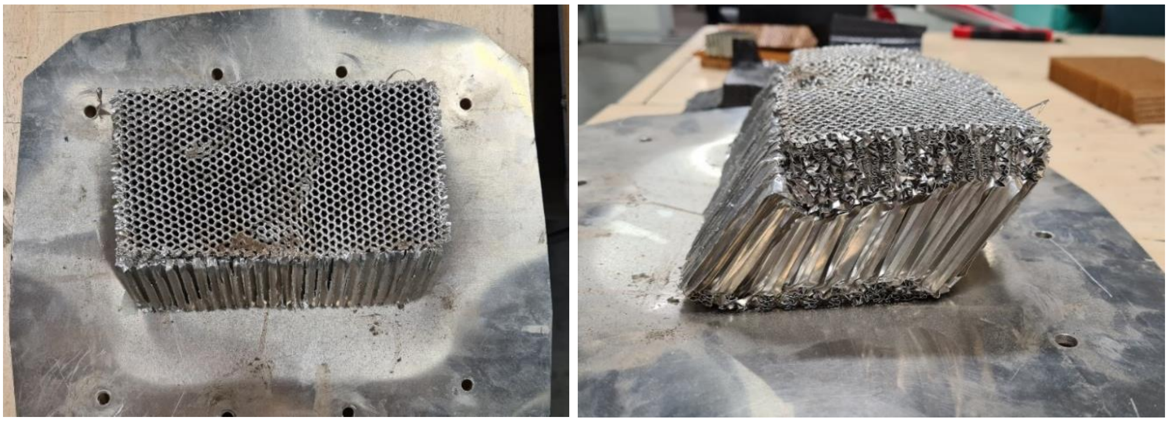


Figure 4.7 Formula car nose. Author's photos

Author decides to continue with discovering different options for the structure of the formula body due to greater experimental opportunities. Hereby, a decision must be declared that author does not redesign the shape of the car but deals with the shape formation itself.

Based on the interviews the following problem space regarding Formula car monocoque manufacturing was established:

- They have limited time to build the body. The earlier they can start testing the car, the better.
- Manufacturing of the monocoque is limited to 3 weeks and several team members build it when they can – meaning that manufacturing takes place 24/7 and Kaarel mentioned that sometimes they stay up for a few days straight to get this part of the process done.

- All the body building takes place in TalTech and they need special equipment for it as well. Carbon needs to be laminated (cut to suitable pieces and pressed down onto the form). Some parts need more than one layer. It is time-consuming process. Then the carbon layered mould is put into vacuum bagging film and it is cured in huge oven.

- Aluminium honeycomb cutting, adjusting, and placing takes a lot of time. All the necessary parts for later attachment of tires etc. need to be combined into honeycomb structure.

4.2 Parts created for FS team Tallinn

To see for what the team has used 3D printing before, an interview with Kaarel, chief engineer of team Tallinn, was conducted.

They mainly use AM to print their own designs. It is a great way for fast prototyping. One of the most important part is to give shape to the wings with plastic structure elements. Polyamide plastic (PA6) is used because the wing needs to be lightweight. Metal 3D printed parts have been used in different areas in the car, one being around engine. Metal is used where plastic cannot be used due to mechanical properties or in difficult conditions (like around engine, since it emits heat).

Following are two examples from formula car.

The first one is guidance block near engine for wire bypass (Figure 4.8). It is made from aluminium. It needs to be light, yet stable enough to guide the wire and dissipate the heat coming from engine. It is used because the engine maintenance is very expensive, and this detail will not allow the wire to break near engine.

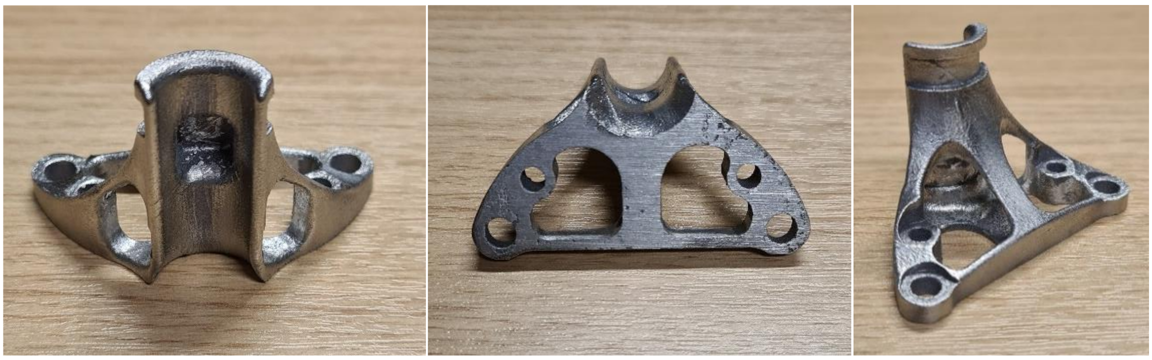


Figure 4.8 Guidance block near engine for wire bypass. Author’s photos

The second one is a profile of wing (Figure 4.9) and its' structure elements (Figure 4.10), which are made from PA6.

Figure 4.9 3D printed structures inside formula car wings. Author's photos

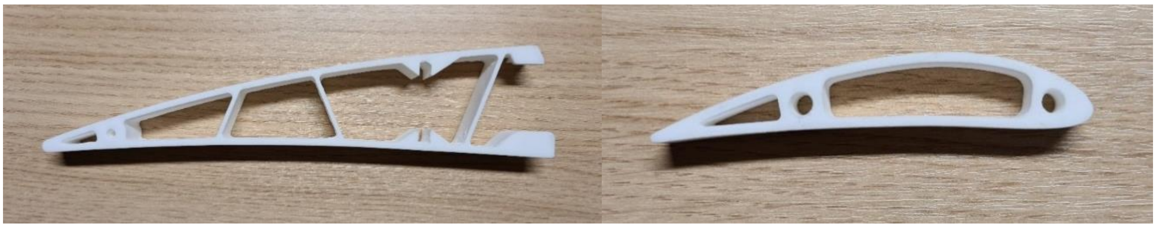


Figure 4.10 An open and closed structure for wings. Author's photos

4.3 Examples on the field of Formula Student

Two examples from other FS teams are brought below.

4.3.1 Oerlikon AM Case Study, UBRacing team

The first example is Oerlikon Case Study for UBRacing team (University of Birmingham racing team) on throttle and brake pedals, which can be seen in Figure 4.11.

Figure 4.11 UBRacing team throttle and brake pedal optimised versions [27]

Their challenge was to reduce component weight and reduce parts. Following requirements had to be fulfilled:

- 500N load for throttle pedal,
- 2400N load for brake pedal.

Their solution uses strong yet lightweight Scalmalloy (AlMgSc) material. Structure is designed for AM. Topology is optimized for the process and load conditions. Bionic and lattice structures are used to reduce weight. Everything is tested under loading conditions and pedals were also tested in brake test and endurance run. To summarize, about 19% weight savings were achieved per pedal. [27]

4.3.2 TU Delft Formula Student team, steering wheel

The first 3D printed part that Delft Formula Student team utilized in the build of their car was the steering wheel (can be seen in Figure 4.12). Not only the steering wheel prototype was 3D printed, but the final competition design was also made in the same way.

Figure 4.12 The steering wheel and inside of the formula student car [47]

The biggest interface between the driver and the car is the steering wheel, making it debatable topic for the designers and drivers on how it should feel, grip, and perform. The best way to solve the constant back and forth between the design team and drivers was to use FDM 3D printing, an affordable and fast way to go through many iterations. 3D printing was chosen because the curvature and geometries of a steering wheel are an issue for CNC (Computer Numerically Controlled) mills which would need long passes around a part and would take a long time as well as being expensive. With 3D printing they can reduce the large costs and avoid the delays. [47]

The design process of the steering wheel began with a laser cut plywood, with clay stacked on top of it. This was then pressed into form, with driving gloves on, to create a rough outline and 3D scanned into modelling software (can be seen in Figure 4.13). During the modelling process, they created a steering wheel without the need of supports so that it would print in a short amount of time. The steering wheel was used during the 2016 season. [47]

Figure 4.13 The design process, clay models and 3D model [47]

5. DESIGN CONCEPTS

This chapter is giving the overview of concepts designed for FS team Tallinn formula car monocoque internal structures. The main purpose is to use the concepts in rounded areas where current method is lacking in delivering fast and comfortable forming method. The CAD software used to model the solutions was Autodesk Inventor 2021 and the 3D printer used to print the solutions was SLS (EOS Formiga P100) located at TalTech.

The main idea behind creating the concepts, considering the human factor, was to reduce the amount of work of FS team to build the monocoque in a faster and more convenient way.

The overall principle of body formation remains the same – carbon fibre fabrics are layered on top of each other, to which internal structures are attached with resins and then, carbon fibre is placed on top again.

The possible solution space for creating concepts is depicted in Appendix 2.

5.1 The goals for concepts

From the problems gathered through the interviews and discussions, a wider understanding of the scope of the project was realised – through simplifying the working methods and writing down the procedure, the instructions to new team members will be clearer than they have been until now. On the other hand, for given thesis topic, the goals set for the internal structure are following:

- Body shaping and manufacturing should be more convenient and faster than it is with current fabrication method.
- Structure needs to be attachable to other body parts.
- Final shape of the structure needs to be rigid.
- It should not interfere with the airflow. Aerodynamic factors need to remain the same.
- Possibly be even lighter than the original part.

Author's goal with the thesis is to design, test and analyse different 3D printed lattice structures that could be used as an internal structure to make manufacturing of the formula car more convenient and time efficient. The characteristics to analyse include flexibility (minimum possible radius), compressing and elongating, and the surface quality.

5.2 Material selection

From the possible materials, mainly the ones printable in TalTech were looked at. Since most of the monocoque building takes place at TalTech, the transportation lead times are shorter when using printers located there, and the costs are lower than that of the ordered honeycomb. Especially, considering the COVID-19 situation, transport is an enormous issue.

Additionally, because the monocoque internal structure is already made from aluminium (honeycomb), the selected material should be with similar properties. That means, the density of the material needs to be considered, since aluminium honeycomb is rather lightweight material - 76.9 kg/m^3 (0,0769 g/cm^3) [48]. The density of Al is 2,7 g/cm^3 [49]. The density of PA6 is 1,14 g/cm^3 [49]. From the listed materials brought in chapters 3.1.1 and 3.1.2, the weight restriction will eliminate stainless steel. Also, Ag (silver), is not a reasonable choice cost-wise. Based on density, PA6 might be a better choice than aluminium.

When choosing between polyamide (PA6) and aluminium, the temperature resistance (melting point of material) needs to be compared, since the body of the car is cured in oven where temperature raises up to 120°C. The PA6 melting point is 223°C [50], meaning that it can be used for 3D printing FS monocoque parts. Aluminium is already used in body manufacturing, meaning that there will not be issues with it.

The final material choice for prototypes was suggested by consultant, who advised to use the SLS machine and white polyamide.

5.3 Creating concepts

Given section focuses on explaining the work process of creating the concepts, the concepts themselves are brought in following section items.

Due to the restrictions from FS team side and possible information leaking, original formula car shape as 3D model cannot be used. Therefore, an open-source model from GrabCAD [51] is used as the basis of car shape. It is modified according to the needs. Rendered version of this car is depicted in Figure 5.1.

Figure 5.1 Rendered formula car [51]

Thesis author is taking a closer look at the biggest rounded shaped part of the body, which is just after the car nose and before the driver cockpit (shown in Figure 5.2 with red).

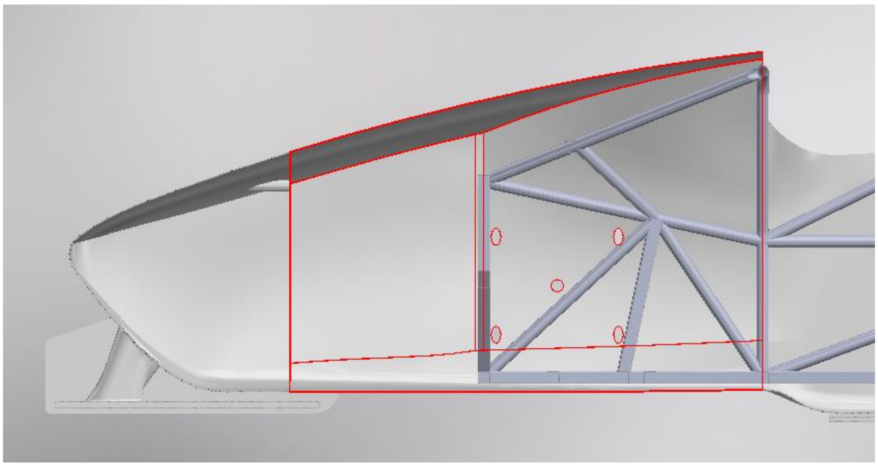


Figure 5.2 Formula car body part

The honeycomb used by the FS team has a 76.9 kg/m^3 (0,0769 g/cm^3) density [48]. The density is inserted into Autodesk Inventor 2021 and when adding the layer thickness of honeycomb structure, the mass of the part brought in Figure 5.3 is approximately 4,3 kg. Carbon fibre fabric is not taken into consideration at the moment, because the lattice structure is supposed to replace only the internal structure. Most probably, carbon fibre is added on top of lattice structure as well to give proper appearance to the body.

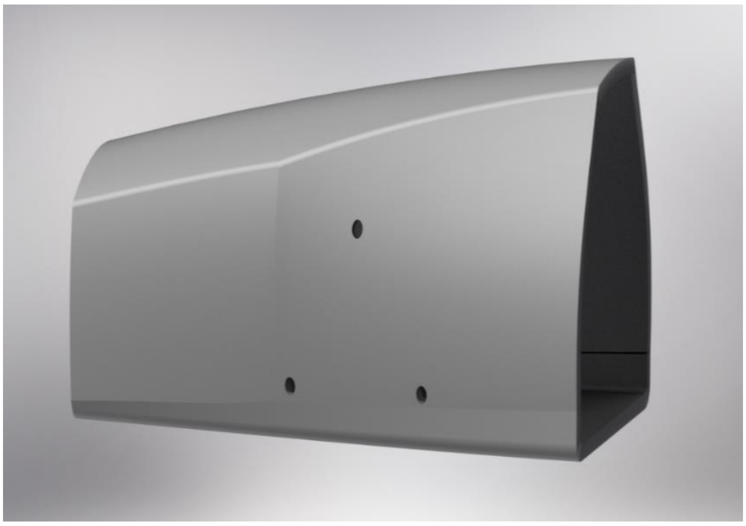


Figure 5.3 Formula car body part with added thickness

To get to the results, multiple programs were experimented with before. The concepts were meant to be from lattice structures provided by some of the computer programs. For that, early experimentations of lattice structures in a flat surface were tried out. Some of the options available in Siemens NX 12 software are brought in Appendix 3.

The options were tried on a radius as well. For that, a 90-degree angle part was 3D modelled in Inventor and lattices were chosen with NX. Some examples are brought in Appendix 4.

Many of the examples seen in Appendix 4 proved to be unsuccessful. The author was unable to modify the structure according to the radius so that the pattern would follow the radius, it only followed the origin base point location and rotation. The beams of the cells were not even connected with themselves sometimes or formed very few connections. It was evident that the beams were difficult to change. When one would want to create a flexible structure, some beams need to be destructed, in other words deleted, which would mean endless of hours of work and even then we cannot be sure that all the necessary points are loose.

Another program and another method was tried out. Appendix 5 shows an experiment of a lattice structure on a 90-degree angle with Autodesk Fusion 360.

Since the experiment with Autodesk Fusion took a lot of time and this software has some limitations, for example, all the beams visible in pictures (Appendix 5) were manually controlled by the author, and the option to choose 'lattice structure' from drop-down list did not exist in there, the author decided to drop the idea to create a structure with this software.

The main reason for dropping the Fusion 360 software is that it will not be a repeatable process with same result every time. The software itself is not offering lattice structures by the definition of it (area of repeated units a.k.a cells) and all the placement controlling of beams was irregular. In some cases, it might be more useful, but in the case of creating a repeatable process (considering the future monocoque manufacturing) and a structure that could be flexible and take the shape of the curves with given software seemed inefficient.

It became clear that the lattice structure by its' origin is meant for simpler objects and mainly two-dimensional transforming. Programs allow to create structures in the size we want and the repetation we want, but rarely follow the curves as needed. One cannot create flexible structures. They are meant to be rigid. Another approach had to be considered.

Before that, one experiment with nTopology proved to be more successful and author recommends to use it when FS team may need to develop lattice structures in further future. The example model is brought in Appendix 6.

To come up with a totally new approach, the author went back to get inspiration from fashion industry and it became clear that in order to create different structures, a unique cell needs to be defined. One, that would be able to connect to the next one beside it and move within the space between them. Examples of those structures are brought in following chapters, but now the working method for getting into the position of starting to 3D model them, follows.

The generation of lattice structures starts from optimizing the topology to see where are the forces that limit the shape by removing the material from where it is not that necessary. For the part of the body under consideration, main forces are coming from wheel attachment (control arms). Those parameters are calculated and analysed by the FS team beforehand.

In following figures (Figure 5.4, Figure 5.5), gravity is depicted with yellow arrow, forces along the axes from wheel attachment are red and blue. Red is 2 kN[1] per control arm and blue – 9 kN per control arm. These are the maximum forces.

The regions to preserve are marked with green boxes. It means that the shape generator in Inventor will need to at least preserve these regions. They are necessary for firstly, attaching the wheel construction, and secondly, to attach this body part to the ones next to it.

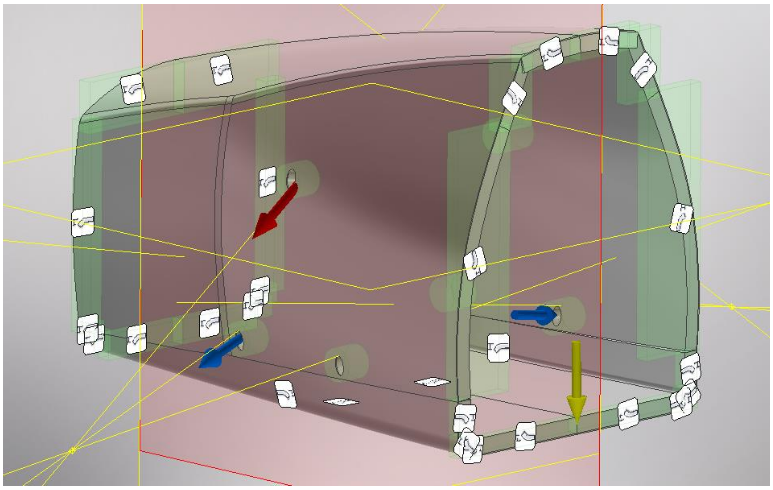


Figure 5.4 Isometric view of formula body part with forces and preserved areas

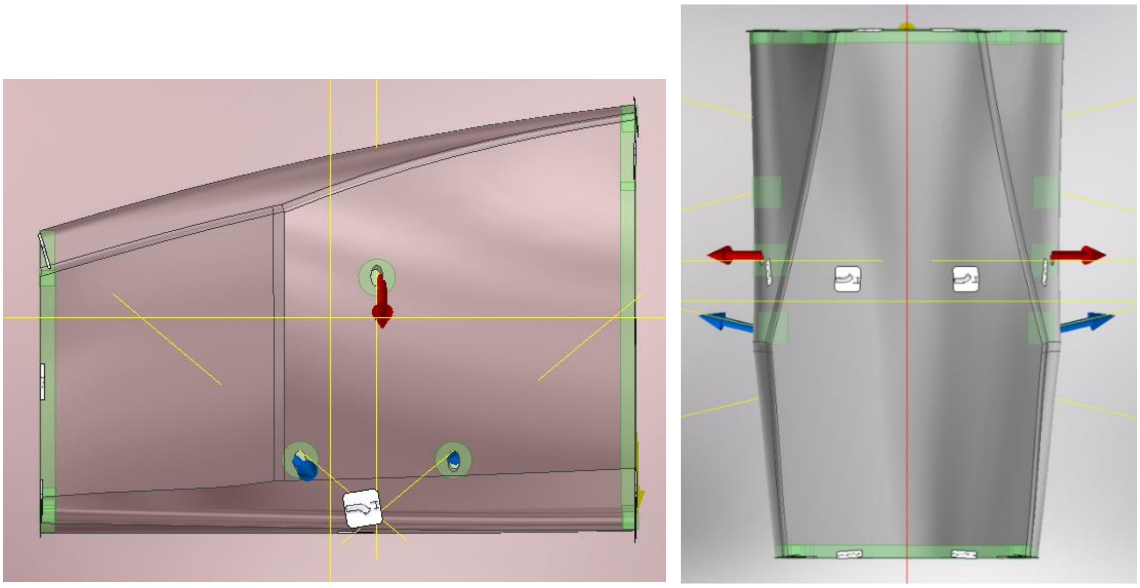


Figure 5.5 Side view and top view of forces and preserved areas

[1] 2 kN = 2000 N, which means about 200 kg. Author’s comment.

After assigning the forces and preserved regions, mass target is set. For this occasion, it was set to reduce the original by 50%. Calculated results can be seen in Figure 5.6 and Figure 5.7.

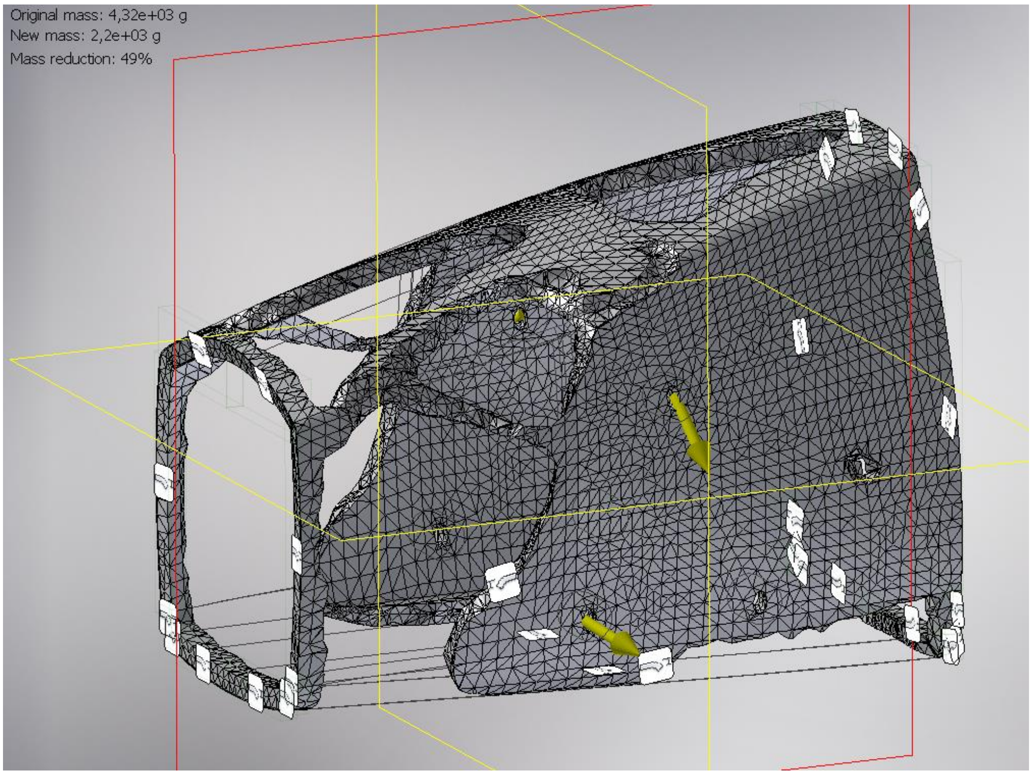


Figure 5.6 Topology optimization results, isometric view

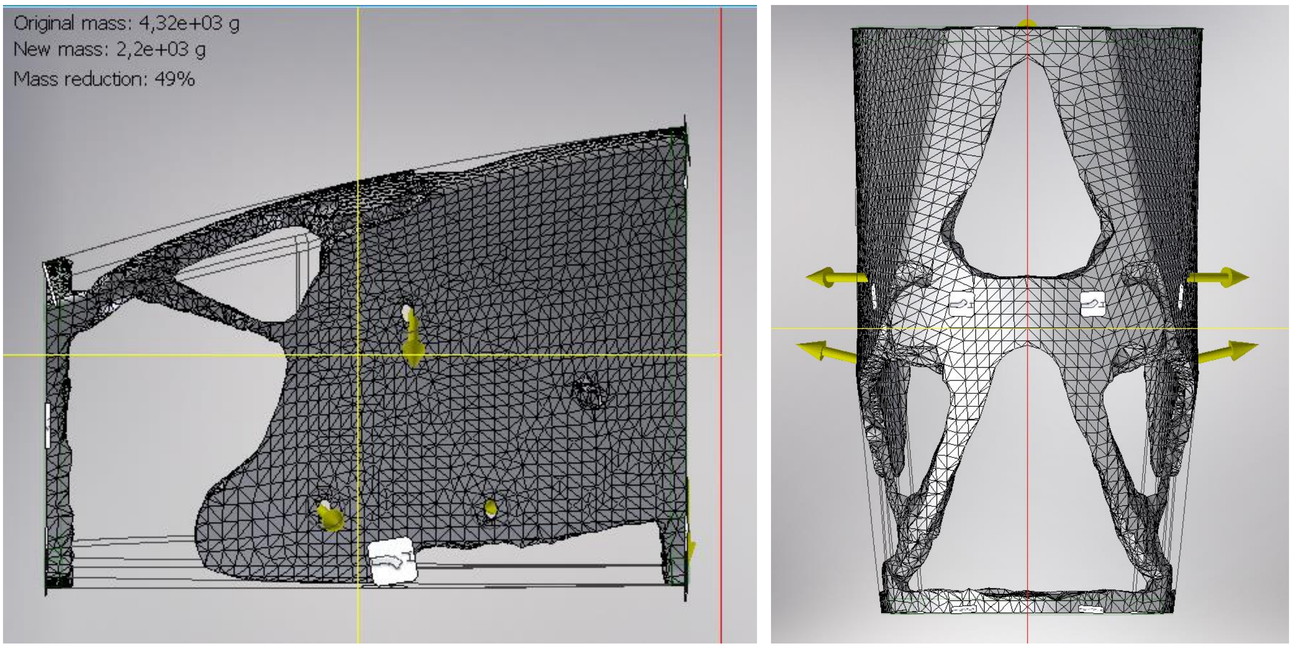


Figure 5.7 Topology optimization results

Topology optimization results were converted to 3D model and suggested areas were removed from the base as seen in following figures (Figure 5.8, Figure 5.9). The mass of the body part was in total reduced from 4,3 kg to 3,25 kg. It was then divided into two (seen in Figure 5.9 with grey and blue colour) for simplification matters.

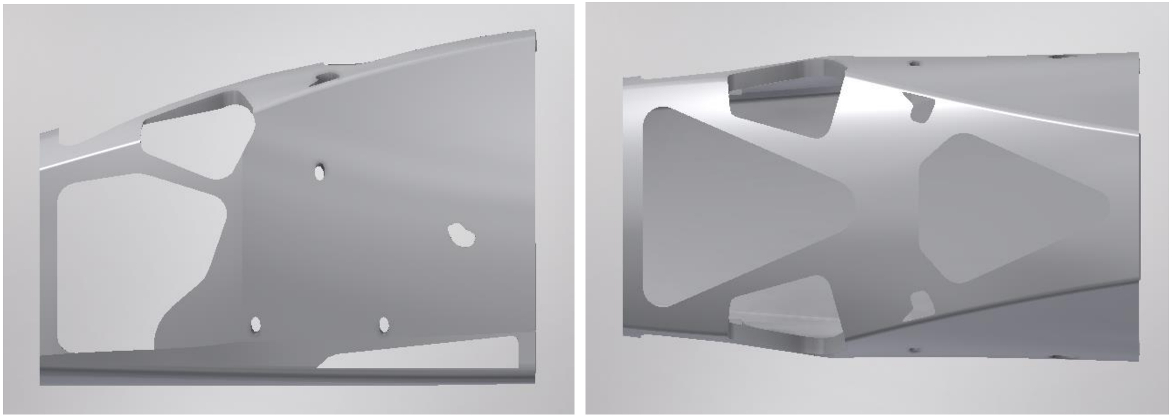


Figure 5.8 New model base generated through topology optimization

Figure 5.9 New model base on the left and divided model on the right

As it follows, the top part of the body was in turn divided into separate regions (Figure 5.10): blue - to mark the areas that need to be solid parts to give stiffness, grey - where dense lattice structure could be applied, purple - where more sparse structure could be placed and pink - where the flexible parts are needed. When the parts cannot be left empty, the flexible structures or sparse ones can be used instead.

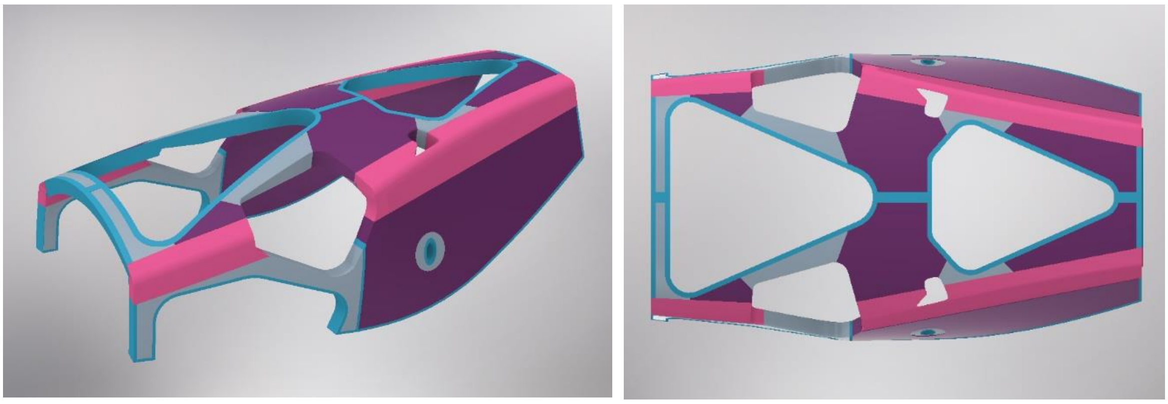
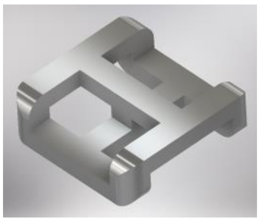
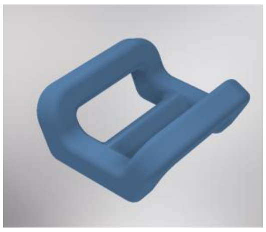
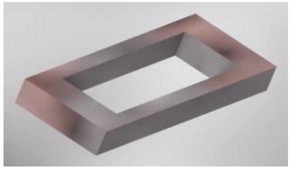
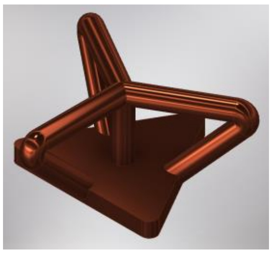
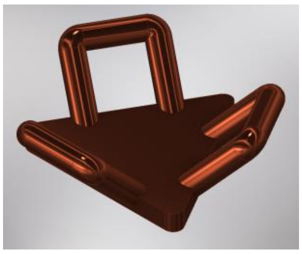


Figure 5.10 Divided areas of upper body part

For the flexible parts, five different structures were designed. They consist of links depicted in Table 5.1. Concept solution descriptions follow in next chapters.

Table 5.1 Structure elements

1. 	2. 	3. 	4. 
5.(1) 	5.(2) 		

5.3.1 First concept solution

The first solution is letter H shaped from the top and bottom, the bottom being turned by 90 degrees (Figure 5.11). They are connected with small beams and sharp corners are rounded.

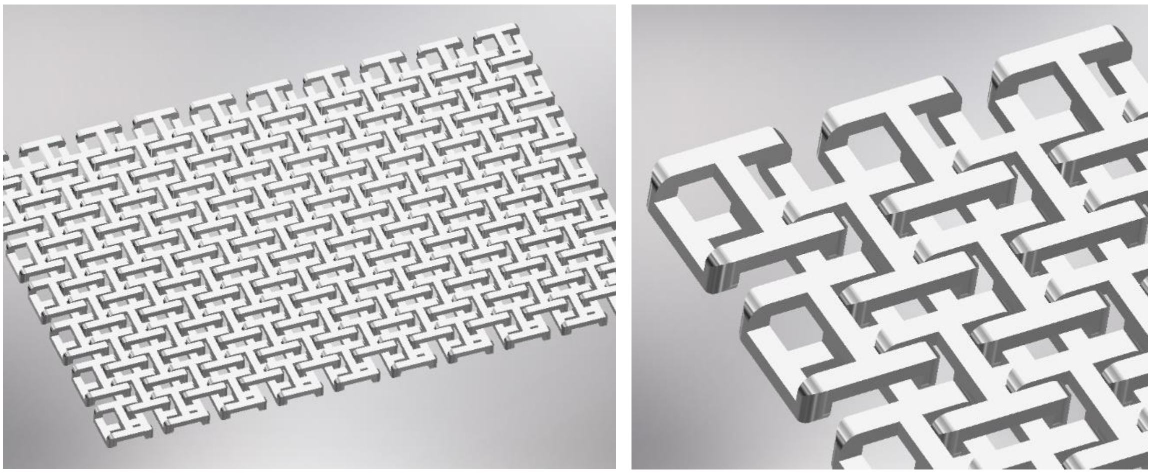


Figure 5.11 Concept solution 1, straight

Links are successfully interlocked and printed as one unit. The small gaps between links allow the structure to be flexible. The curved CAD model is depicted in Figure 5.12.

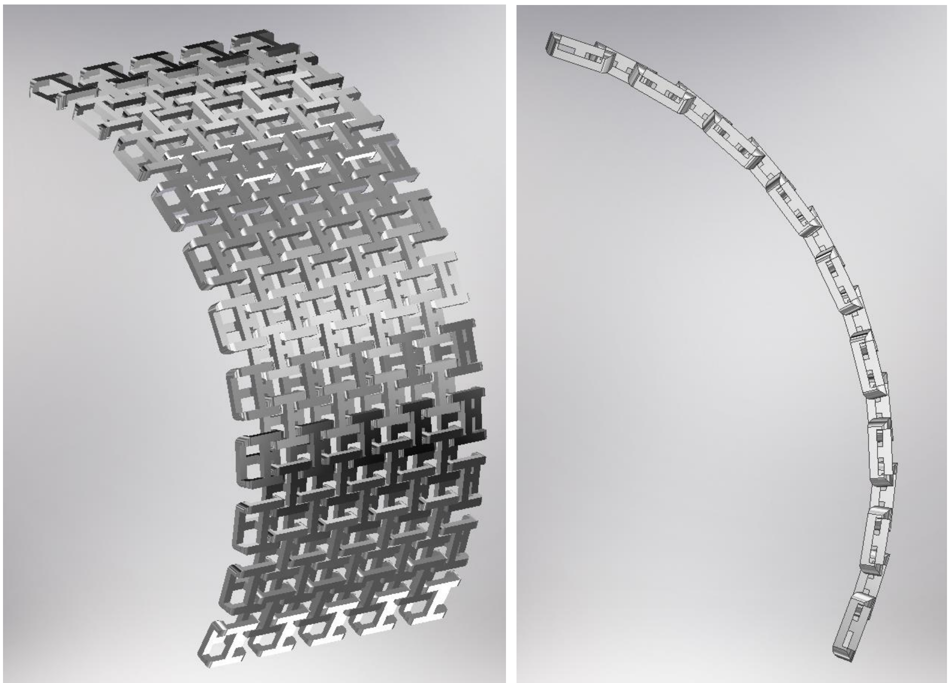


Figure 5.12 Concept solution 1, curved

5.3.2 Second concept solution

The second solution consists of beams where sides are angled upwards to create room for movement. All the sharp corners are rounded. The link is captured from under different angles and depicted in Figure 5.13. For the simplification matters, the concept may be referred onward as Wave.

Figure 5.13 Second concept links from different angles

Side view and top view of links attached togehter are brought in Figure 5.14. With curved model (Figure 5.15), it is clearly visible that one side of the surface is rather straight (Figure 5.16), while the other has peaks.

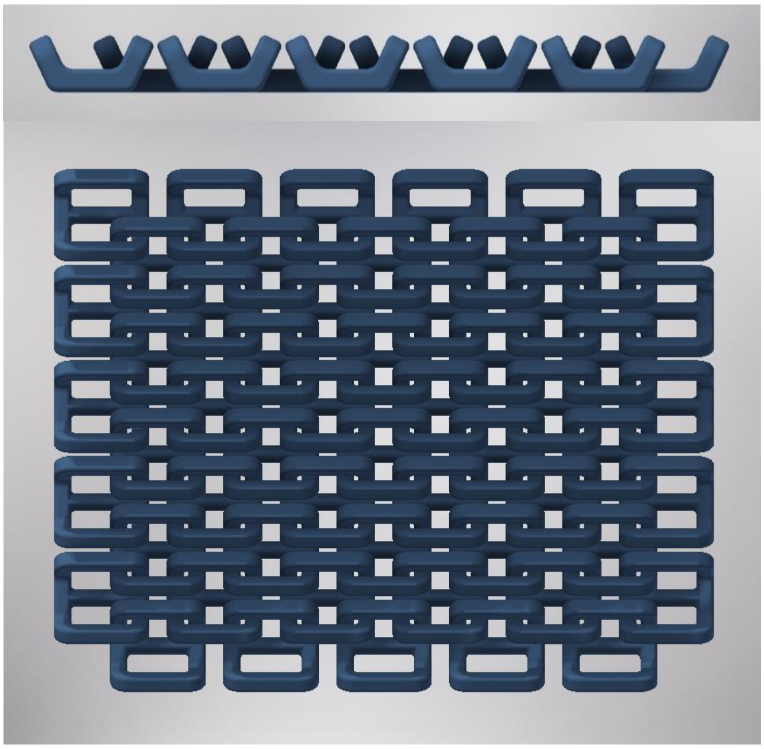


Figure 5.14 Concept solution 2, straight

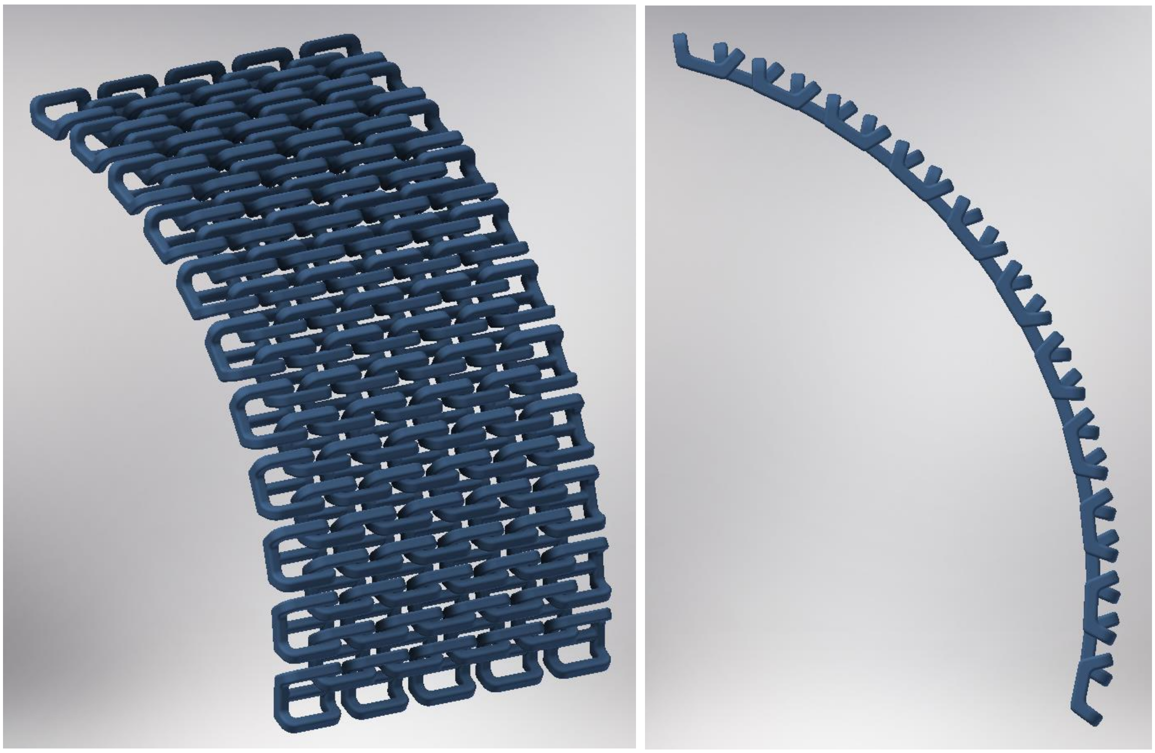


Figure 5.15 Concept solution 2, curved

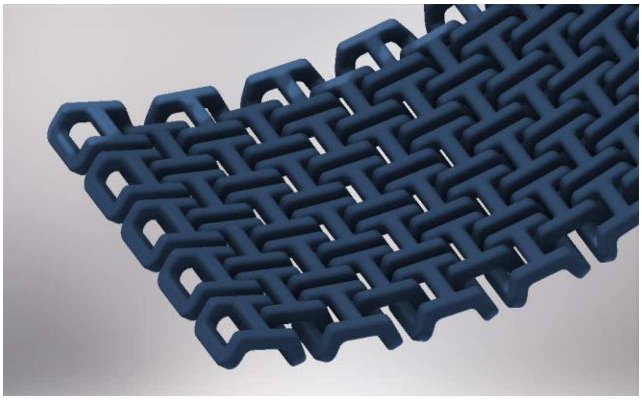


Figure 5.16 Curved model straight side

5.3.3 Third concept solution

One side of the third solution reminds the honeycomb. The other side consists of spirals which are attached to cone. Both sides are visible in Figure 5.17. The cone lacks material from inside to make it lighter since the other solutions seemed to have more air between the links. Comparison of all the concepts' masses is brought in Table 5.2. All the spiral beams for concept 3 are interlocked. Due to the complexity of spirals (close-up in Figure 5.18), the gaps between links are minimal, and limiting the movement.

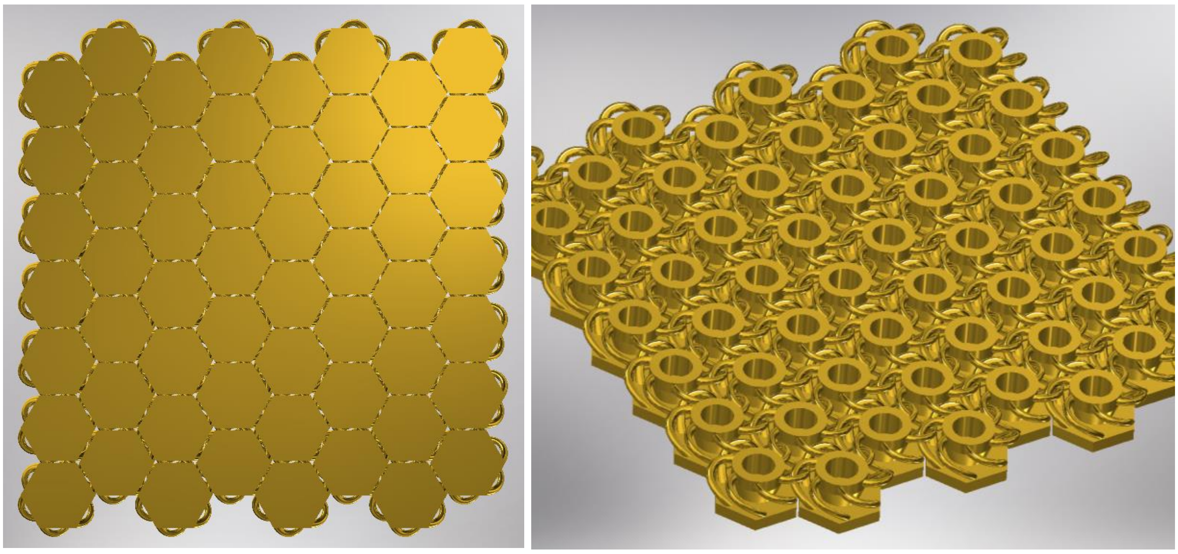


Figure 5.17 Concept solution 3, straight

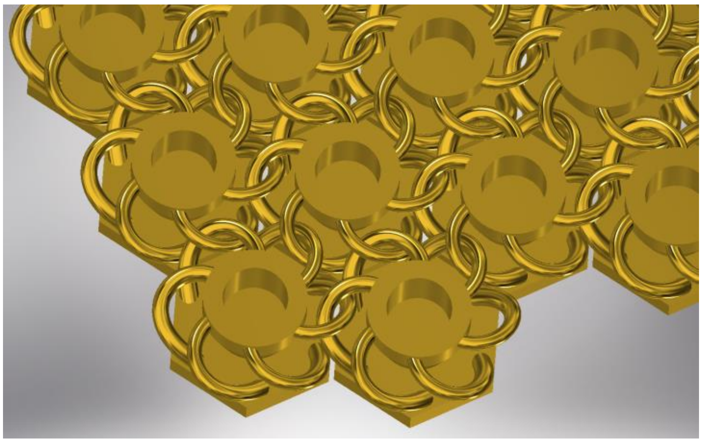


Figure 5.18 Interlocked spirals from the backside

Based on 3D model, it can be stated that the model is bendable only to one side (Figure 5.19). The hexagon is limiting the movement to the other side.

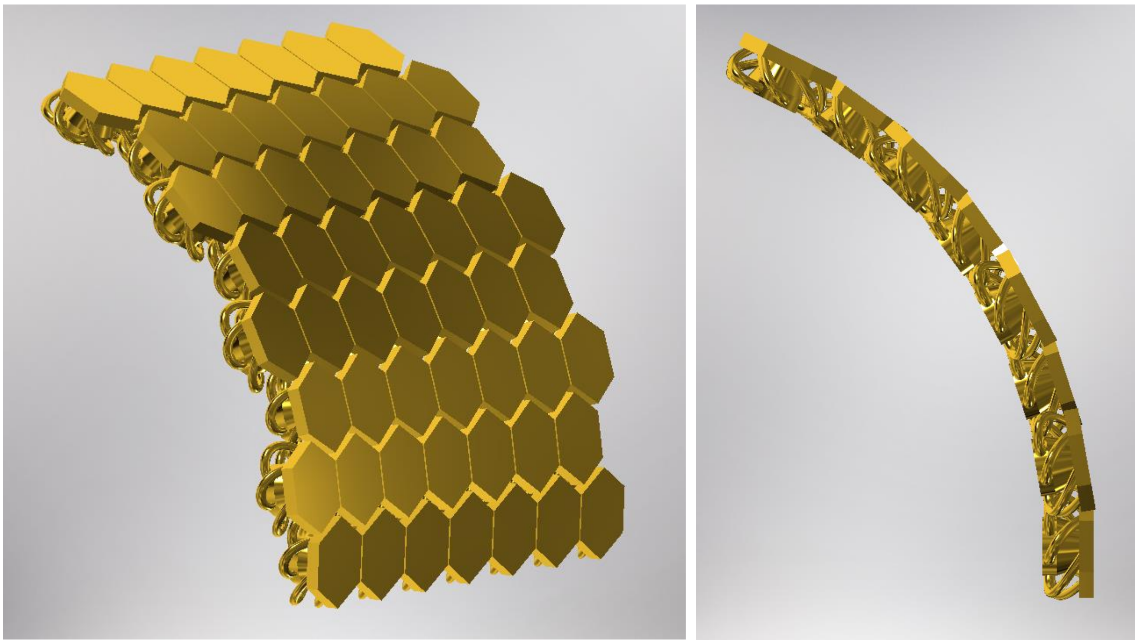


Figure 5.19 Concept solution 3, curved

5.3.4 Fourth concept solution

The fourth concept, visible in Figure 5.20, has the easiest shape. It is a rectangle with two sides cut under a 45 degrees angle to be able to print it as interlocked system. The rectangles are interlocked so that the second one is reversed 180 degrees. The isometric (Figure 5.21) and side view (Figure 5.22) are good examples for this.

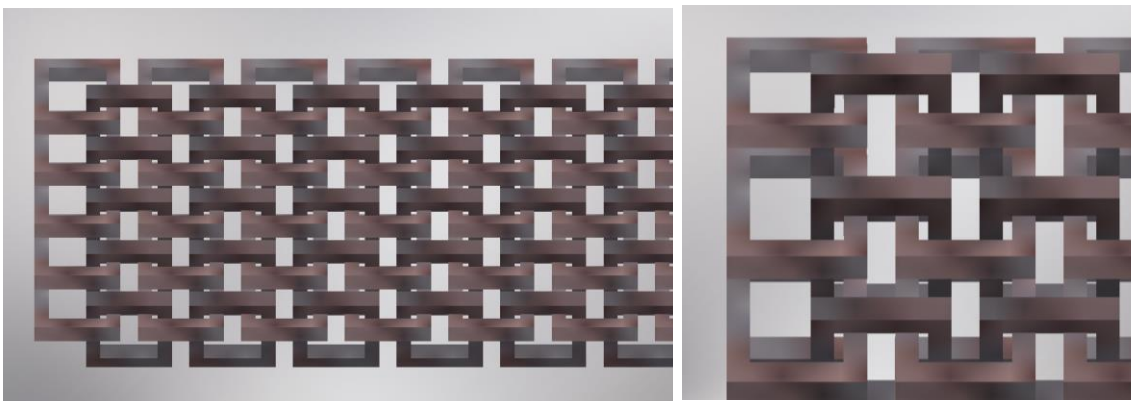


Figure 5.20 Concept solution 4, straight

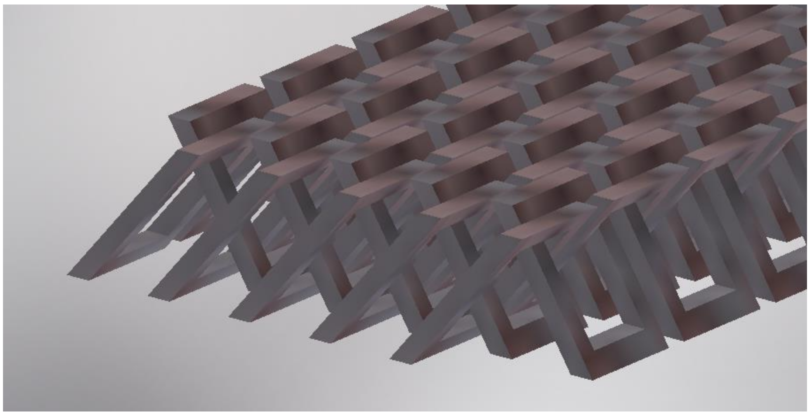


Figure 5.21 Isometric view of concept 4

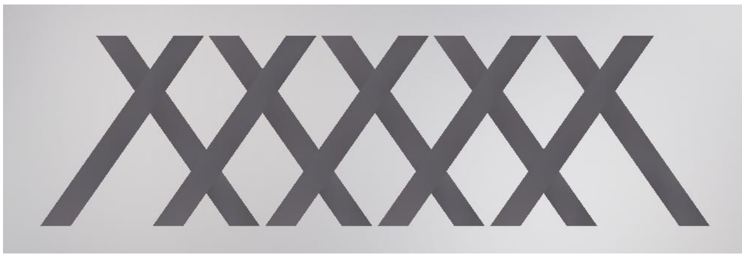
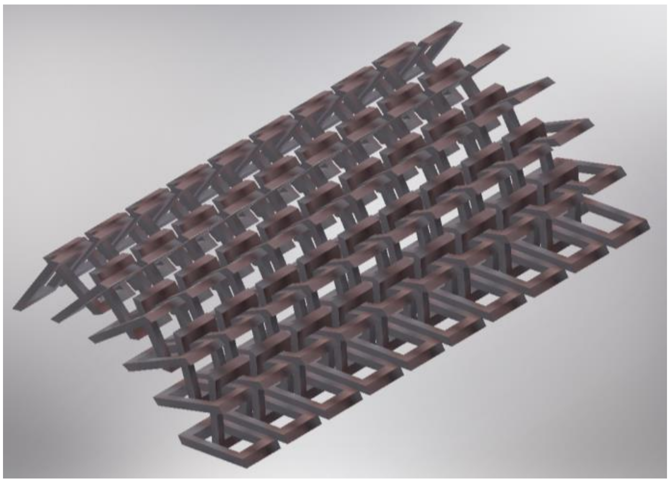


Figure 5.22 Side view of the concept 4

The curved solution for concept 4 was a bit complicated to understand in Inventor. To realise the full potential how rectangles can move and follow the curve, 3D printed solution is better. However, from Figure 5.23 it at least shows that the radius can be achieved although the links are sparsely apart and would not act like this in reality.



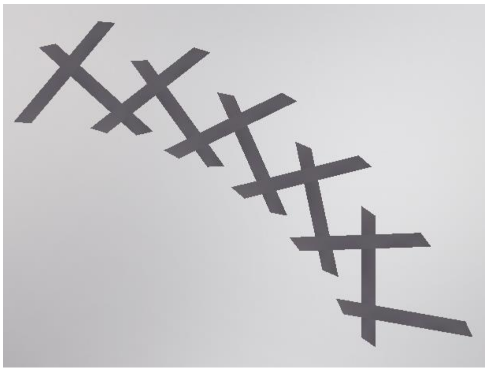


Figure 5.23 Concept solution 4, curved

5.3.5 Fifth concept solution

One side of the fifth solution represents triangle. The other side consists of beams angled so that the links go through each other. The front and backside are visible in Figure 5.24. The gaps between links rather large compared to other solutions.

The fifth solution is extraordinary from others, since it uses two different links. The first one has three beams coming from one centre beam and the second one has three separate loops on each side (Table 5.1). The beams from first one go through the loops of second one. The close-up is in Figure 5.25.

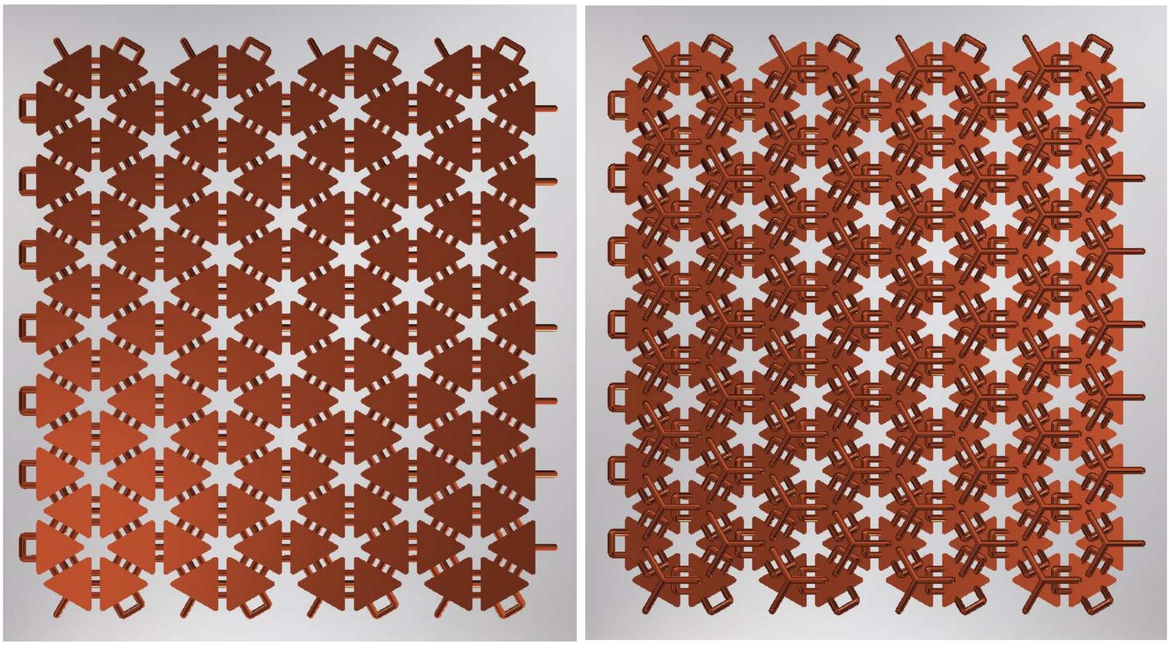


Figure 5.24 Cocept solution 5, straight

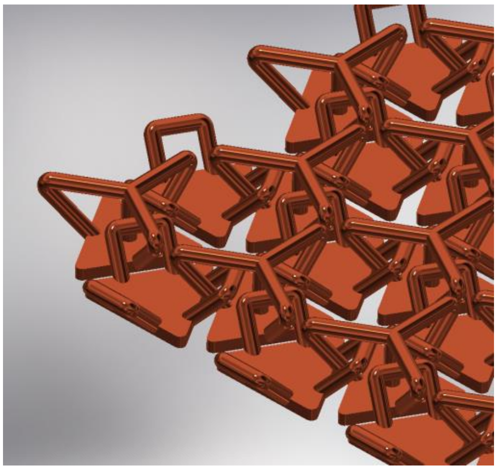


Figure 5.25 Close-up of concept 5

The curved form of this concept is depicted in Figure 5.26. One side is more flat than the other. Compared to concept 3, the links should be able to curve both ways due to the big gaps in between segments. The side with beams seems, at least from CAD model, a bit fragile.

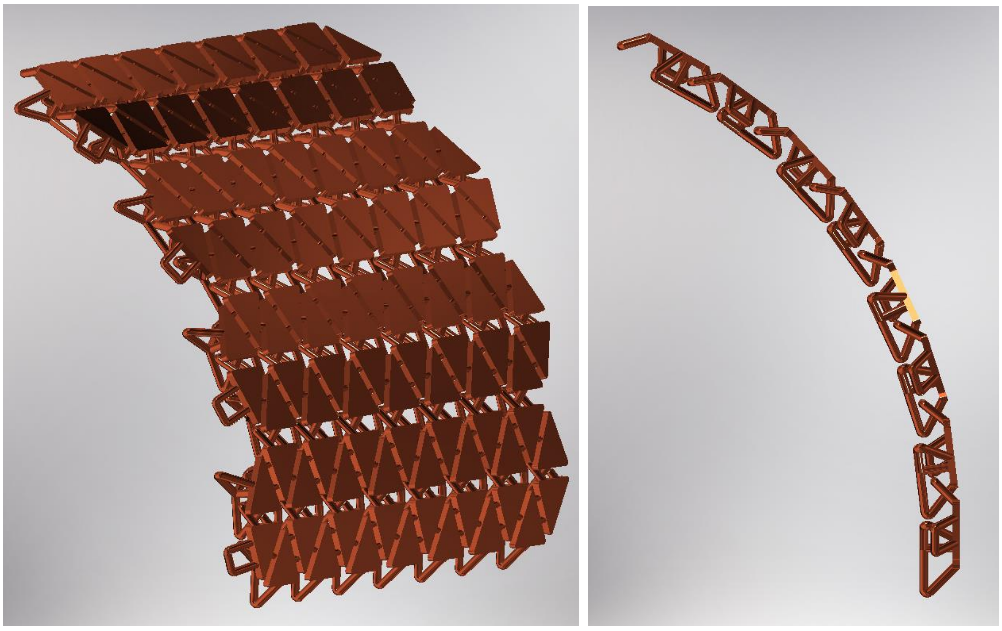


Figure 5.26 Concept solution 5, curved

5.3.6 Further steps for digital concepts

Given concept solutions are meant as internal structure replacement for aluminium honeycomb. The regular process of building the formula car monocoque remains similar.

Carbon fibre fabric is layered to the form and aluminium honeycomb to the places, where it is needed. The curved parts are left free for the suitable concept. Since the honeycomb thickness is greater than that of the 3D printed concepts, a smooth transition needs to be designed as well. It is left for further developments. For this thesis, only the formation logic for rounded parts is described.

The build plate size of 3D printer must be considered when designing suitable parts for formula car. Since the build plate might be smaller than that of the necessary structure size, modularity was also considered when designing the concepts. The 3D models can be patterned the way needed, but the connecting pieces for them had to be designed separately.

In following Figure 5.27 the possible connecting piece for concept 1 can be seen. For concept 2 and 3 the open links are brought in Figure 5.28. All the details were 3D printed and tried out on the concepts. The feedback is brought in 5.3.7 3D printed concepts. The fixation to aluminium honeycomb could be achieved in two different ways. All the concepts have gaps and therefore, a simple wire, thread, or cable tie could be used to attach the 3D printed parts to existing aluminium honeycomb. Another method would be to make a design change to the existing custom-made insert the FS team Tallinn places in the honeycomb layer to attach necessary equipment afterwards. It would simplify the process when inserts are close to curved edges. When all the previous ideas do not work, then, adhesives, like with the regular honeycomb-carbon fibre connections, could be used as well.

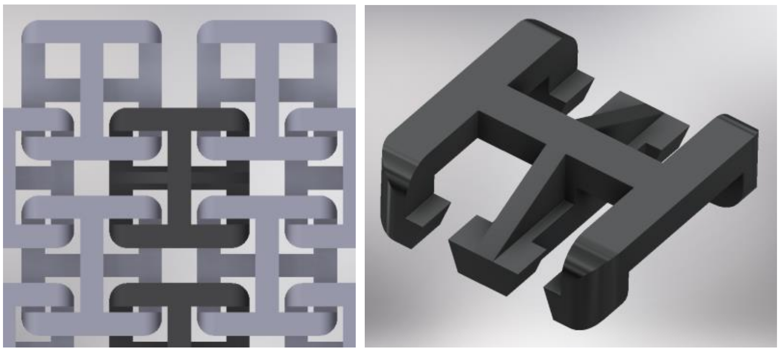


Figure 5.27 Concept 1 connecting piece

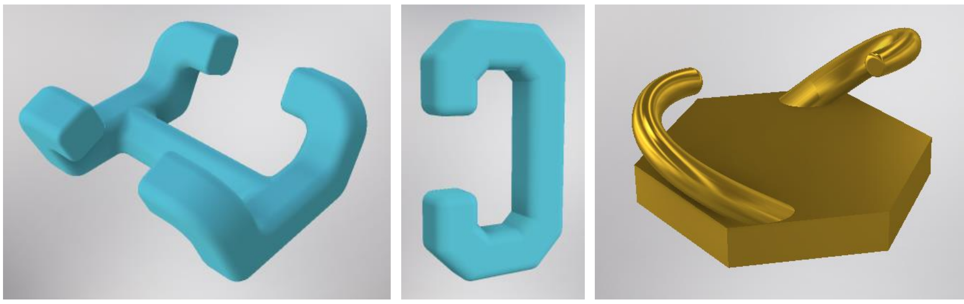


Figure 5.28 Concept 2 open links in blue and concept 3 open link in gold

Comparing the masses of structures enables us to compare the results to the aluminium honeycomb FS team uses now. All the parts are made of material PA6, which density (1,14 g/cm^3) is inserted to Autodesk Inventor where all the parts are 3D modelled. Since the details are very small, the program does not even calculate the mass for one detail. That is the reason for assembly, and this given assembly then shows the mass. Single piece mass is calculated from there. Volumes are taken from Inventor. Due to the fact that concept 5 was designed with two different pieces, the single piece mass can be calculated through density formula 5.1:

$$\rho = \frac{m}{V}, \tag{5.1}$$

where ρ is density,

m is mass,

V is volume.

Mass was derived from formula 5.1: $m = \rho \cdot V$.

$$m\ (1) = \rho \cdot V = 1{,}14\ g/cm^3 \cdot 0{,}093 cm^3 = 0{,}11\ g$$

Table 5.2 Volumes and masses of concepts

Concept nr	Single piece volume (mm^3)	Single piece mass (g)	Assembly volume (mm^3)	Assembly mass (g)
1	199,1 = 0,1991 cm^3	0,22	8164,6	9
2	174,5 = 0,1745 cm^3	0,20	10646,1	12
3	482,4 = 0,4824 cm^3	0,56	17365,7	20
4	289,9 = 0,2899 cm^3	0,33	14209,4	16
5	(1): 92,9 = 0,093 cm^3 (2): 90,7 = 0,091 cm^3	(1): 0,11 (2): 0,10	7710	9

The conversion to g/ cm^3 must be made to compare the density to aluminium honeycomb and for the first concept the calculation is shown as following:

$$\frac{1cm^3 \cdot 0{,}22g}{0{,}1991\ cm^3} = 1{,}10\ g/cm^3$$

Table 5.3 Concepts' densities

Concept	Density (g/cm^3)
Concept 1	1,10
Concept 2	1,15
Concept 3	1,16
Concept 4	1,14
Concept 5	(1): 1,18 (2): 1,10

Compared to aluminium honeycomb density (0,0769 g/cm^3), the concepts are heavier and the goal of making the parts even lighter could not be achieved. However, the further improvements to concepts can reduce the density as well. For the moment, FS team should decide if the gain in mass exceeds the manufacturing convenience and time-efficiency or not.

Figure 5.29 shows how difficult it was to shape the concepts exactly to one edge on the formula monocoque. This was the reason to 3D print the solutions and get real understanding how these concepts act and follow the form in reality.

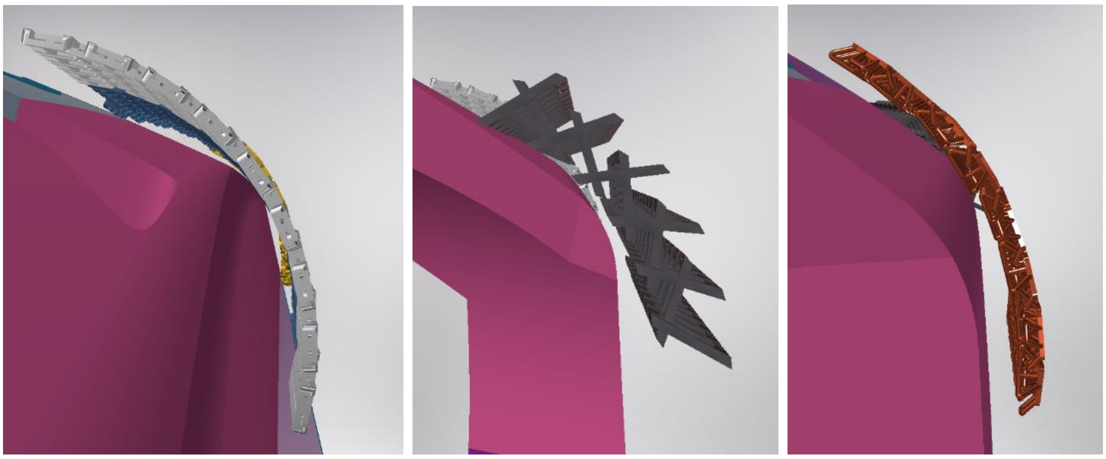


Figure 5.29 Curved 3D models on the edge of monocoque

5.3.7 3D printed concepts

All the concepts described previously were 3D printed with SLS machine from polyamide (PA6) at TalTech. Due to doubts in measurements and whether the parts would print nicely, some concepts were enlarged and printed additionally.

Photos of 3D printed concepts and small observations are given below.

As a one conclusion for all the concepts, the surface quality is the same and overall, very good. They all feel smooth under hand. However, the printed concepts leave a residue of PA6 powder on the hands even after thorough cleaning. On the positive side, the small beams are strong and have not broken after multiple dropping tests.

Concept 1 was printed in two sizes (Figure 5.30) and the smaller one was easier to form. It was able to curve more than the one with larger elements (Figure 5.31). Both had a bit of struggle to stay in their original shape – when it was messed up into a ball then the elements did not want to untangle themselves effortlessly (Figure 5.32). This concept can be bent in any direction, although one direction works better than the other due to 'H' shaped link. The minimum radius achieved for the smaller-sized concept was 7,5 mm, for larger concept 22,5 mm. Elongation and compression work well with these concepts. For this solution, open links were modelled and printed as well (Figure 5.33).

They proved to be a success since it was rather easy to attach them – just press a bit – and they could be removed as well. The most positive effect about them was that they did not fall off when moving or shaking the printed concept.

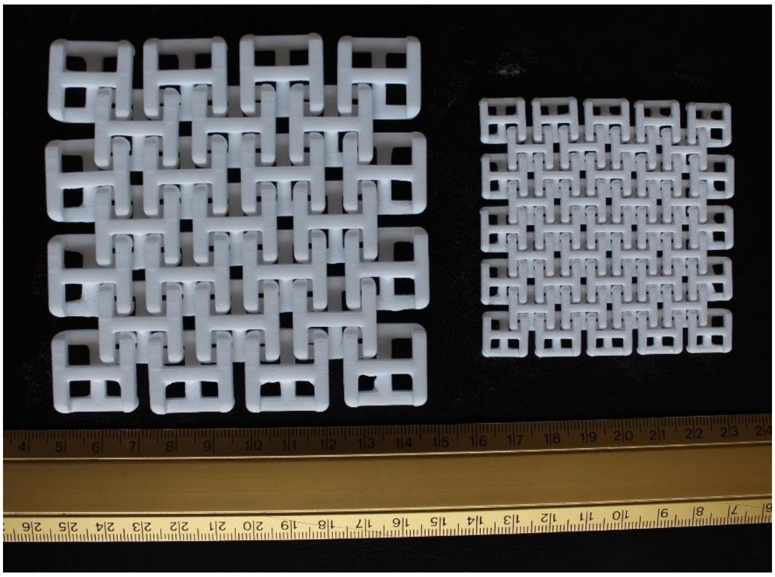


Figure 5.30 Concept 1 3D printed versions

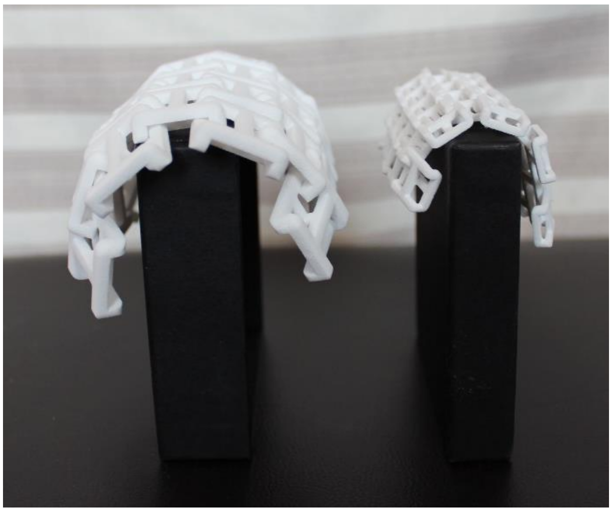


Figure 5.31 Concept 1 larger vs smaller curve

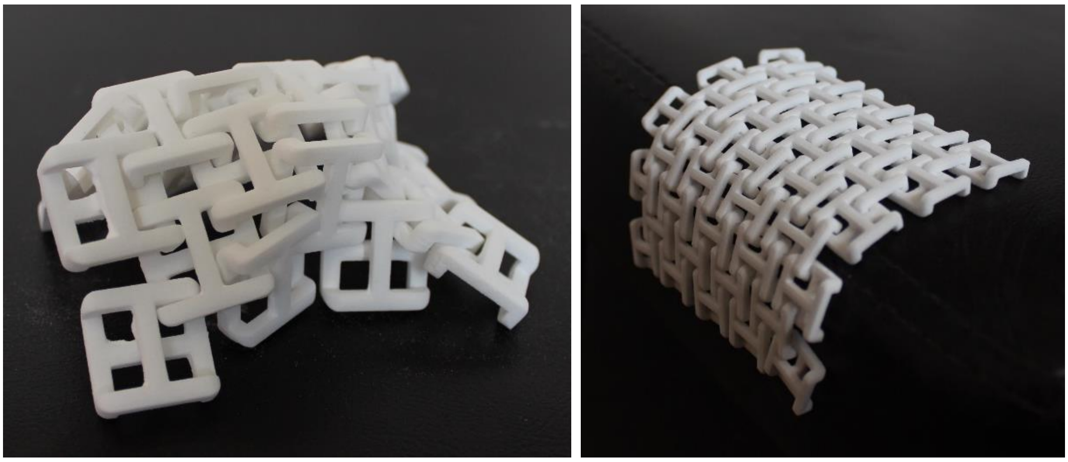


Figure 5.32 Concept 1 tangled and untangled

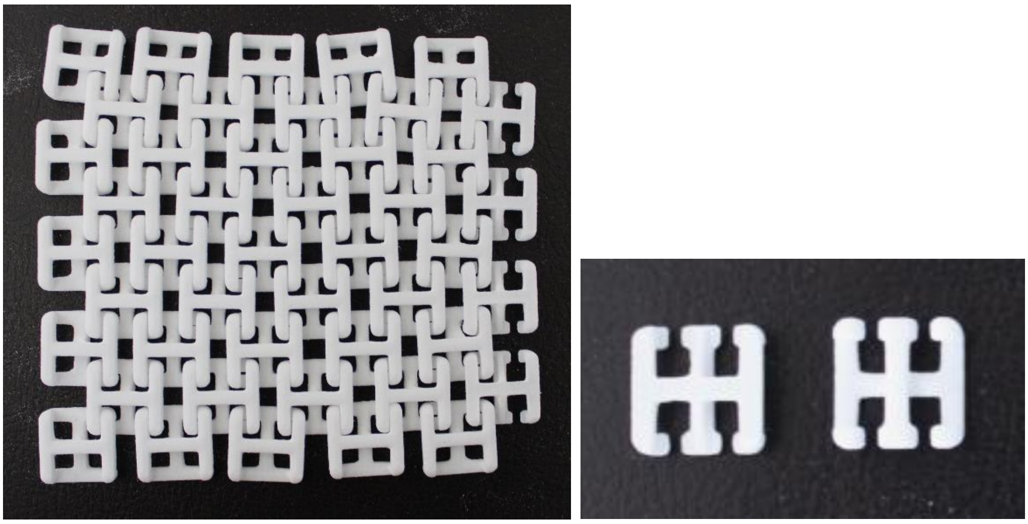


Figure 5.33 Concept 1 with added open links on the right side

Concept 2 “Wave” was printed in two sizes as well (Figure 5.34) and they both were equally flexible. Smaller one with smaller links was understandably able to curve with smaller radius as well (Figure 5.35). Shape preservation was easier than with concept 1. The elements could be even folded on top of each other (Figure 5.36) or formed into cylinder shape and easily be shaken into its’ original form. This concept can be bent in any direction, although some directions work better than the others. The minimum radius achieved for the smaller concept was 5 mm, for larger concept 7,5 mm. Both can be elongated and compressed along the beam direction, the other direction does not allow as much movement. For this solution, open links were modelled and printed as well (Figure 5.37). They were rather difficult to insert, fell off almost immediately, and could not withstand even small movements.

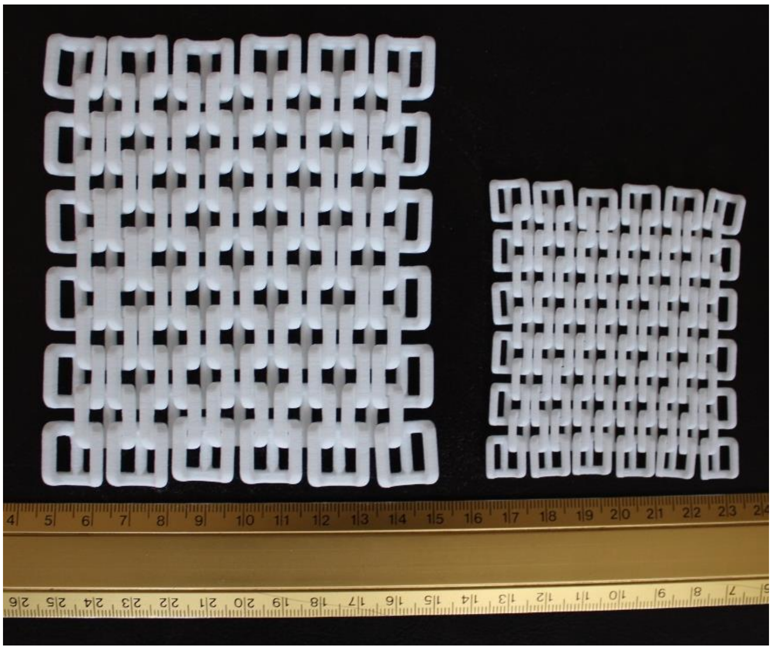


Figure 5.34 Concept 2 3D printed versions

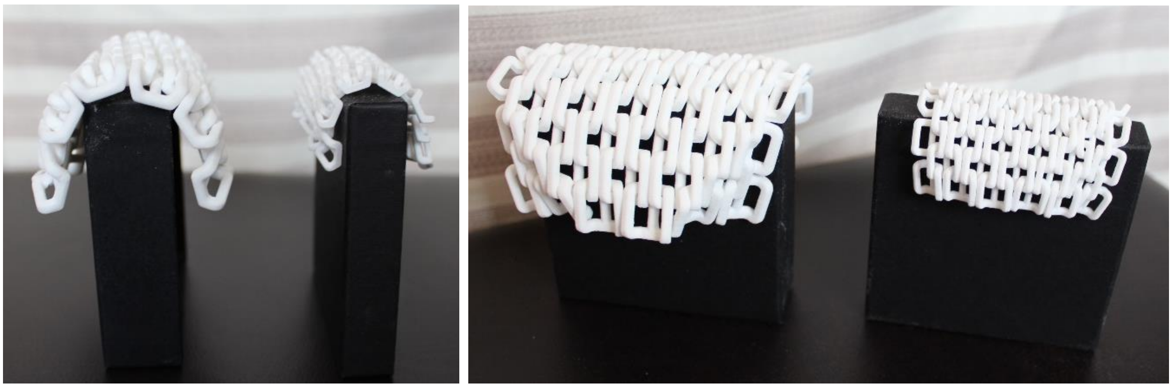


Figure 5.35 Concept 2 larger vs smaller curve

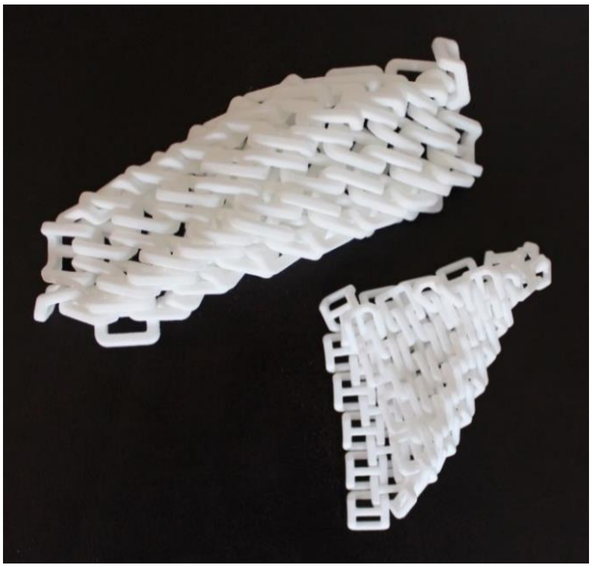


Figure 5.36 Folded concept 2

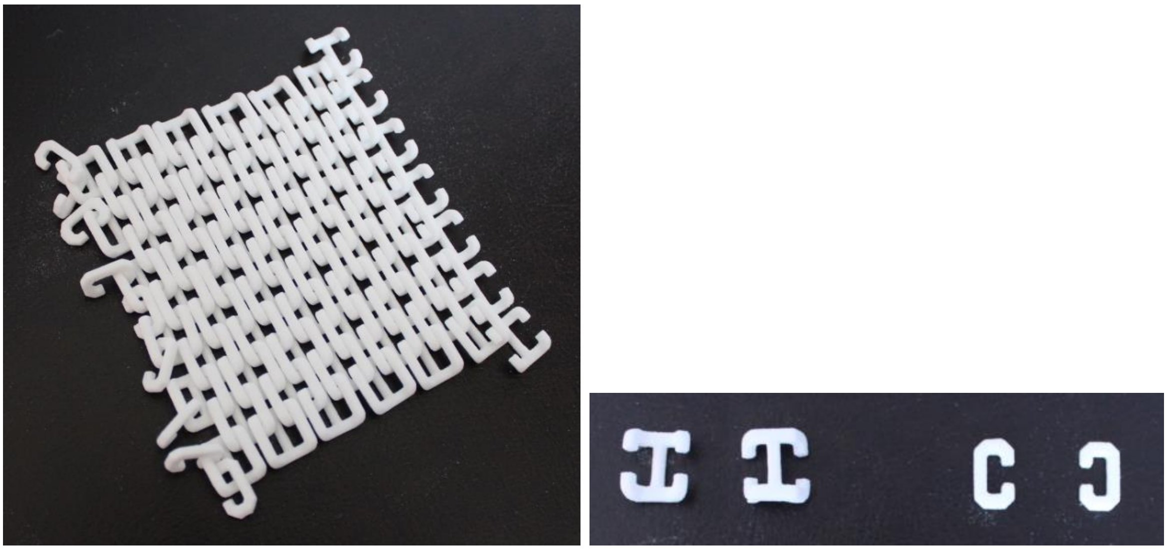


Figure 5.37 Connecting links for concept 2

Concept 3 was printed only in one size (Figure 5.38). So far, it is the most convenient prototype. It has a nice aesthetic look and the edges are not as loose as for all the other concepts, including the 4th and the 5th. The backside has a mesmerizing visual effect and the spirals allow for the surface to bend practically on top of each other (Figure 5.39). However, the gaps between honeycomb shapes are minimal and this is preventing the flexibility in the reverse direction (on the right in Figure 5.39). The minimum radius achieved for the concept was 3,5 mm. Elongation and compression were practically impossible.

An open link was designed to combine two units together (visible in Figure 5.40). It was easy to insert but it fell off just as easily. One additional concept could have been printed to try out the attachments. It seems that it might even hold the links together, but nothing can be assured before trying this out.

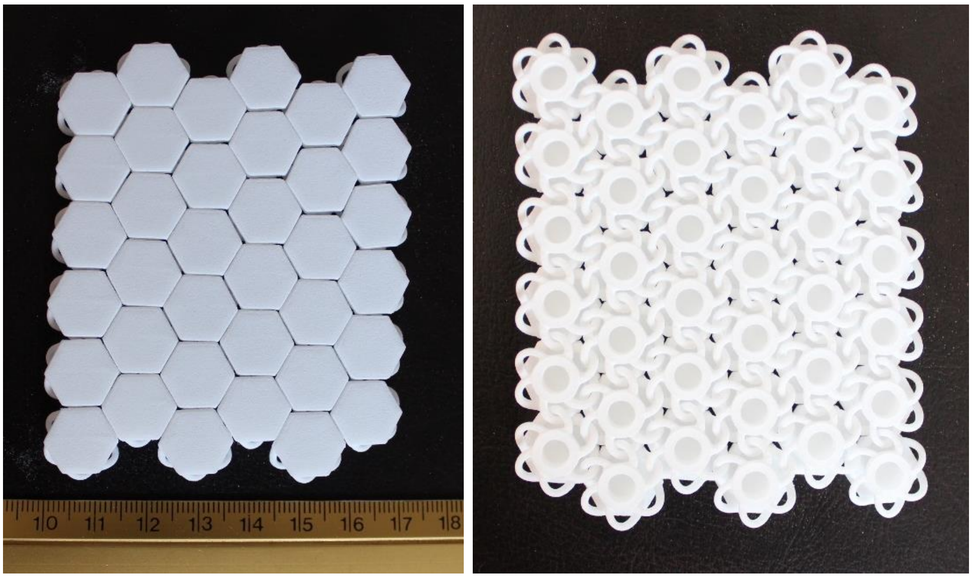


Figure 5.38 Concept 3

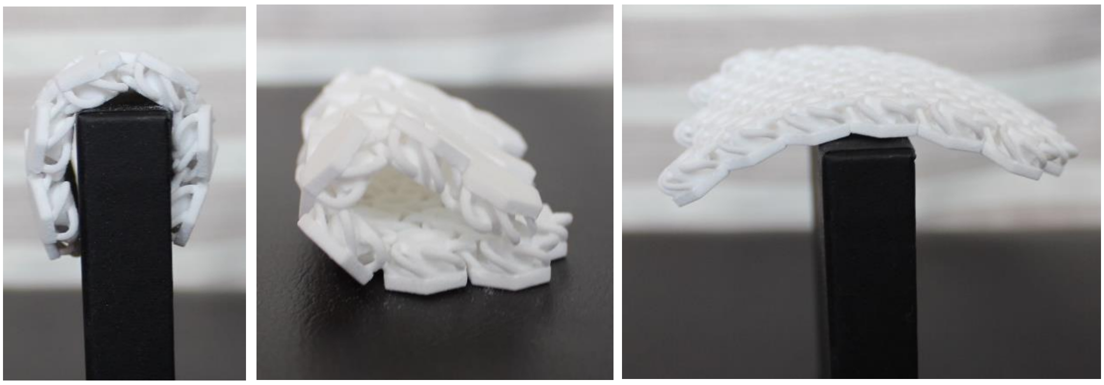


Figure 5.39 Concept 3 curve possibilities

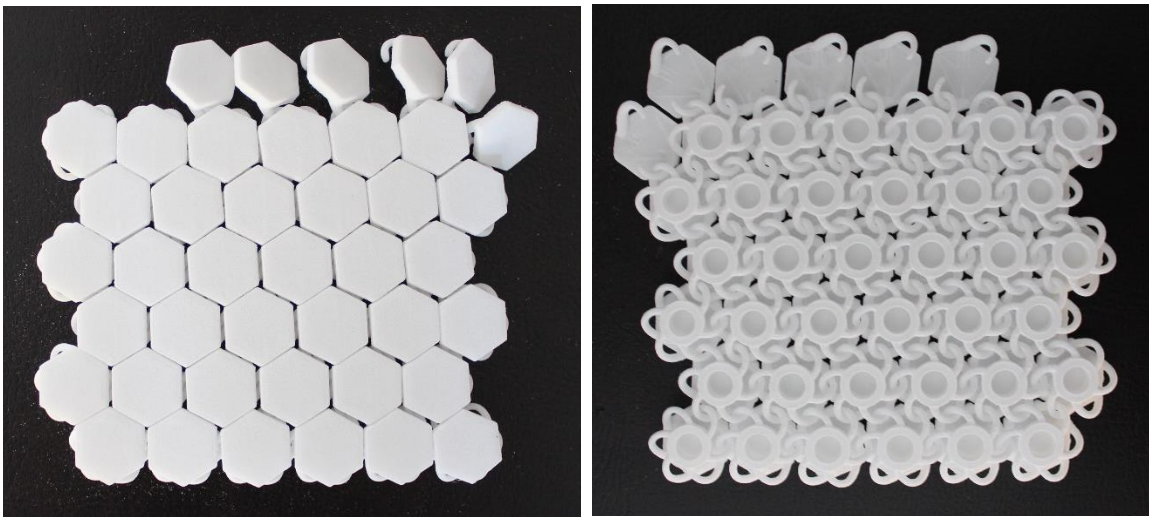


Figure 5.40 Open links attached to concept 3

Concept 4 was printed in two sizes (Figure 5.41) and they both were equally flexible. Nothing very certain for the radius can be said – both seemed quite similar (Figure 5.42). Shape preservation was very difficult. All the rectangles twisted and turned within each other, not preserving the shape and it could be formed into very angular ball (Figure 5.43). This concept can be bent in any direction, there does not seem to be difference with bend directions. For this solution, open links were not modelled because from the 3D model it already seemed that this option could be the least favourable due to large gaps. The flexibility is good and minimum radius is around 5 mm for both prints. Elongating is easier than compressing since with the latter, the structure will start deforming.

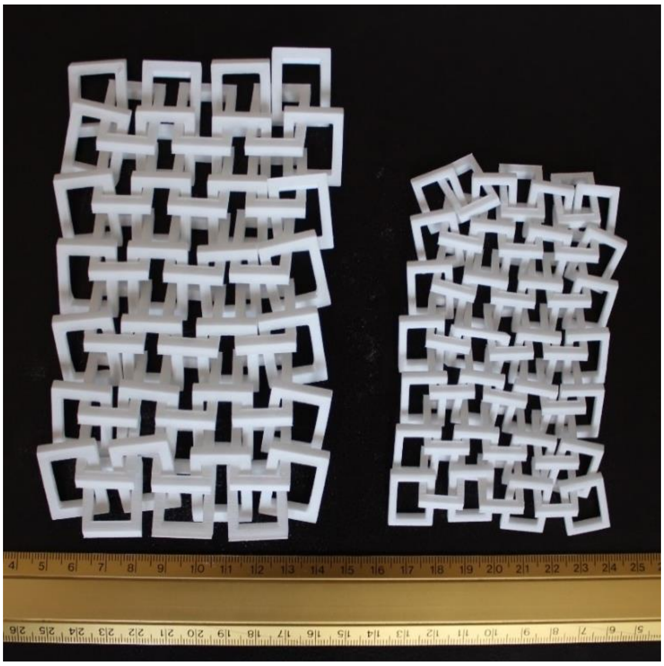


Figure 5.41 Concept 4 3D printed versions

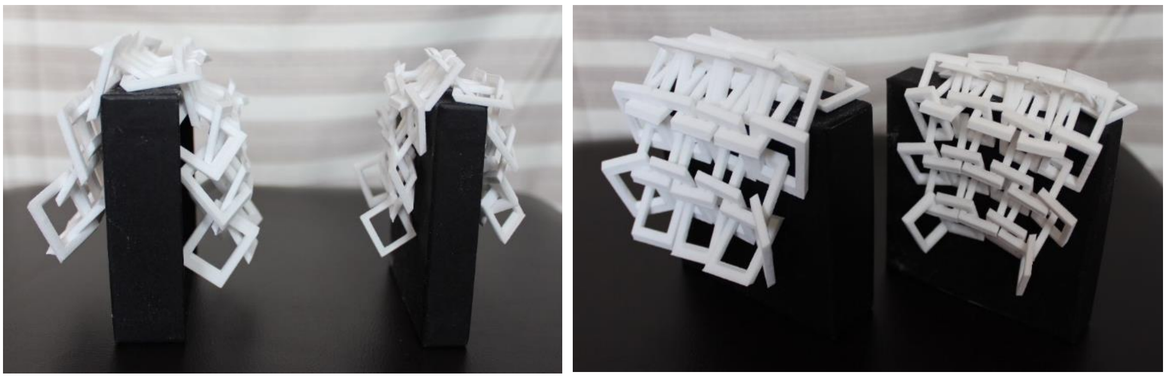


Figure 5.42 Concept 4 larger vs smaller curve

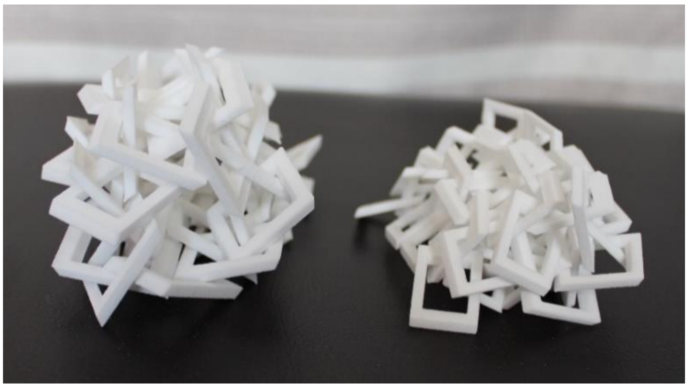


Figure 5.43 Concept 4 shape formation

Concept 5 was printed in two versions (Figure 5.44). Similarly, to concept 3, the element has a flat surface, which in this case is triangle. As previously showed in Table 5.1 the triangular element has two different beam options. This is required to be able to connect the parts through each other. It can be seen on the Figure 5.44 that the edges are not straight. It was because of beam connections. The one in Table 5.1 5.(1) had very sharp angles and therefore got stuck with connecting elements. It was difficult to have the parts nicely flat. The links have large gaps between each other, enabling very sparse structure and good elongation. Compressing the printed structure together will eventually change the shape of structure. It was able to bend in any direction but shaken to original form with difficulties. As with concept 4, this one as well could be practically formed into a ball and therefore the minimum radius for this concept does not exist. The open link was not specially designed for given concept, but the loops enable various other connections (e.g., thread, wire).

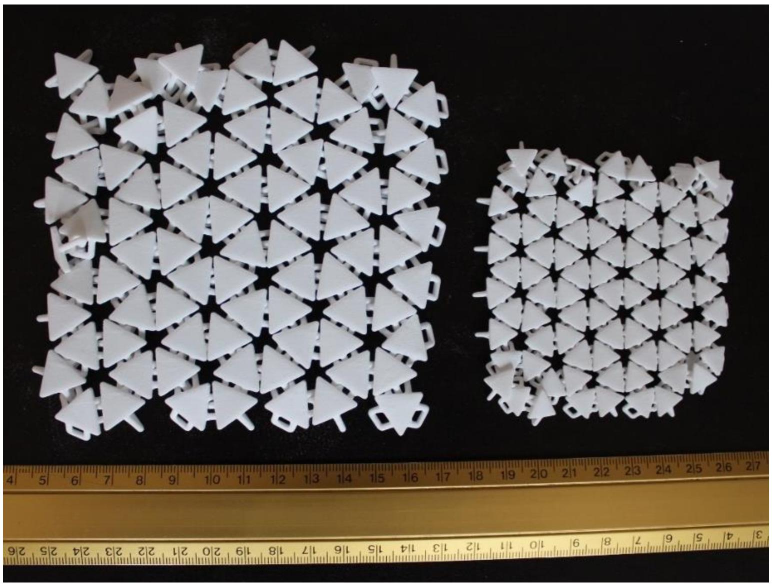


Figure 5.44 Concept 5 3D printed versions

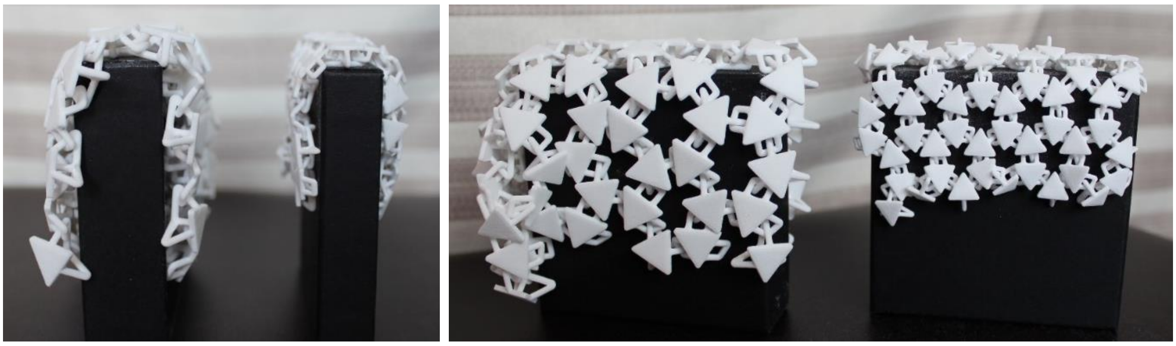


Figure 5.45 Concept 5 larger vs smaller curve

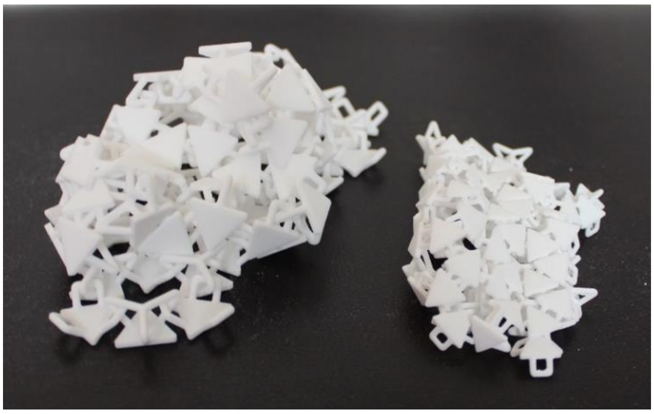


Figure 5.46 Concept 5 shape formation

The Table 5.4 concludes beforementioned concepts' measurable values (density and minimum radius) and ease of use. Based on the latter, concepts 1-3 are more promising. When comparing their density and min. radius, nr 2 seems to be the best option. If the issue of bending only in one direction is not that important, then nr 3 is even better.

Table 5.4 Comparative table of concepts 1-5

Concept	Density (g/cm3)	Minimum radius (mm)	Ease of use
1	1,10	7,5	+ bends in any direction, open links work - gets tangled
2	1,15	5	+ takes original form well, bends in any direction, aesthetical look +/- has open links, but do not work well
3	1,16	3,5	+ takes original form very well, aesthetical look +/- has open links, but do not work well, bends in one direction
4	1,14	5	+ bends in any direction - large gaps, very sharp corners, shape preservation is extremely poor, no open links
5	(1): 1,18 (2): 1,10	Does not exist; 0	+ bends in any direction - large gaps, shape preservation is poor, no open links

6. VALIDATION

Every year the FS team builds a new formula car and the team consisting of students changes each year. The valuable knowledge from previous team might not reach the current team. In the light of that, given thesis is important to preserve the information found and give guidance to the next team of FS. The CAD models are provided to the current FS team and the main ideas and principles were explained to the chief engineer Kaarel Haavajõe.

6.1 Feedback on the concepts

All the five concepts in the form of 3D printed parts were presented to FS team Tallinn chief engineer Kaarel, who provided very thorough feedback on all the solutions.

He eased the author’s concerns about attachment to the carbon fibre and aluminium honeycomb parts – all the solutions looked like they will stick to the resin adhesive. Overall, the main manufacturing process will remain the similar, just corner pieces are to be replaced with 3D printed concepts.

When asking about the attachments of printed parts, Kaarel said it would be better if the concepts could be attached to themselves beforehand when assuming that the 3D printed parts will be separate and act as modules. The attachment should be enough to temporarily attach them and place onto the carbon fibre layer. It would be a great advantage. Based on this information, only the first solution open link would fit the requirements. On the other hand, the concepts could be printed in larger pieces so that the attachments are not needed. It is a possibility that needs further research and consultations with 3D printing specialist. Since the parts can be folded, they could be also printed in folded form.

The main reason for the structure between carbon fibre fabrics is to hold them at certain distance. Carbon fibre is like a fabric that can basically fall in between the gaps of the structure. For this reason, the gaps between links need to be there to allow the flexibility but at the same time they cannot move as much to create large hollow areas. The movement between links defines how well the carbon fibre will lay on top of it and how well the structure really works. Too wide gaps were his main concern for concepts 4 and 5. Some other comments from Kaarel on the concept 5: “the gaps are too wide, all the structure gets too scattered, links move too much, the links at the edges get stuck and are difficult to form into the desired shape".

The comments on concept 4 were not that great as well because it had similar issues like nr 5 – gets stuck, too wide gaps, unstable structure. It probably cannot be used as a structure between carbon layers at all. Besides, the edges and corners are too sharp. "At first it was very difficult to even understand how this structure looks like or works due to the unsteadiness of shape." Kaarel thought that if the link was a square instead of a rectangle, then the orientation for the link would not matter and it could be a bit easier to understand the shape of it.

All the other concepts (1-3) left a better impression to him. The gaps were good, and structures could be bent but at the same time, they did not allow so many hollow spaces like concepts 4 and 5. The first and second concept (Wave) were rather similar to him in the looks and characteristics. They both could be bent in every direction and gaps were with good distance. However, the second concept seemed to be the best in his opinion. The aesthetical look of it was a bonus as well. The third concept felt a bit heavier than the rest and therefore a proposal from Kaarel was to reduce the mass. "Maybe the top flat surface could be thinner? All the corners of hexagon feel a bit sharp as well. They could have radiuses."

For further developments he suggested to try different sizes of the concepts 1-3 and play around with the radiuses for corners or edges as well as different angles for the concept 2 links. The heights could be changed as well. Additionally, for the third solution, it became clear that the hexagon defines the movement, and it could be smaller or larger to see the various options.

If the minimum radius for each concept is known, then the designing and planning of the formula car monocoque would be simpler. "You could count on it."

For one further opportunity, Kaarel suggested to design a link for smoother transition between concept structure and aluminium honeycomb. It derives from the fact that the concepts now were a lot thinner than the honeycomb they usually use. This could be a 3D printed piece that can be cut to the required shape – an idea is sketched in Figure 6.1. The blue color indicates the material and it could be smooth or with steps, the white color represents the removed part. The transitions could vary from 5 mm to 10 mm or from 5 mm to 15 mm and so on. The unnecessary part can be removed, and the link should suit the aluminium honeycomb height as well as the concept height.

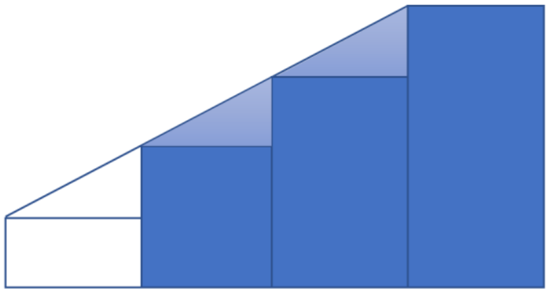


Figure 6.1 Idea of transition part between aluminium honeycomb and 3D printed structure

6.2 Further opportunities

In this thesis, five concept solutions for the internal structure of the FS car body were designed with the manufacturing process simplification in mind.

Further opportunities for each solution would be to see whether the pieces could be designed for the exact purpose or the location of formula car to have even better characteristics. The single element could already have radiuses in the right areas, forming a smooth base for the carbon fibre. The cell sizes need to be tested on the formula car to see whether they should be smaller in some locations or larger in other locations. Ultimately, structure with variable thickness, height, or size could be 3D printed. The mass should be lessened to compete with the aluminium honeycomb. The surface of the printed objects could be rough to adhere better to the resin in use. The open links between printed pieces need to be developed further to provide full design solution. Additionally, the connecting links to existing structures could be designed and developed.

This thesis proposed concepts can be taken as an example to use such flexible structures for a different purpose. Their main goal in given thesis context was to offer alternative solution for aluminium honeycomb core. The ultimate positive effects about them are the 3D printing readiness, possibility to be attached to one another, and the maintain of the flexibility.

As a result of all the discussions with the team's chief engineer, one additional possibility that could be further researched and designed as a part of the solution is, how the production process and all the know-how from team members is handed over to new team members.

7. CONCLUSION

From the research objectives, current 3D printing field situation was analysed, and the lattice structures in various fields were introduced. As a result of all the analysed fields, fashion industry gave inspiration to propose a different concept from the known lattice structures, which are offered by many computer software.

The main objective of designing a lattice structure concept solution for Formula Student monocoque internal structure, is fulfilled. Five concept solutions for the internal structure of the monocoque were designed, 3D printed, analysed, and validated. The most suitable solution in chief engineer's opinion seemed to be the concept 2. This choice coincided with the result achieved on the basis of the criteria.

The more precise goals set in chapter 5.1 were achieved partially. With chosen concept 2 "Wave" (seen in Figure 7.1) the manufacturing of formula car is more convenient and faster due to the shape formation possibilities on curved surfaces (Figure 7.2). The other concepts to be considered are nr 1 and 3.

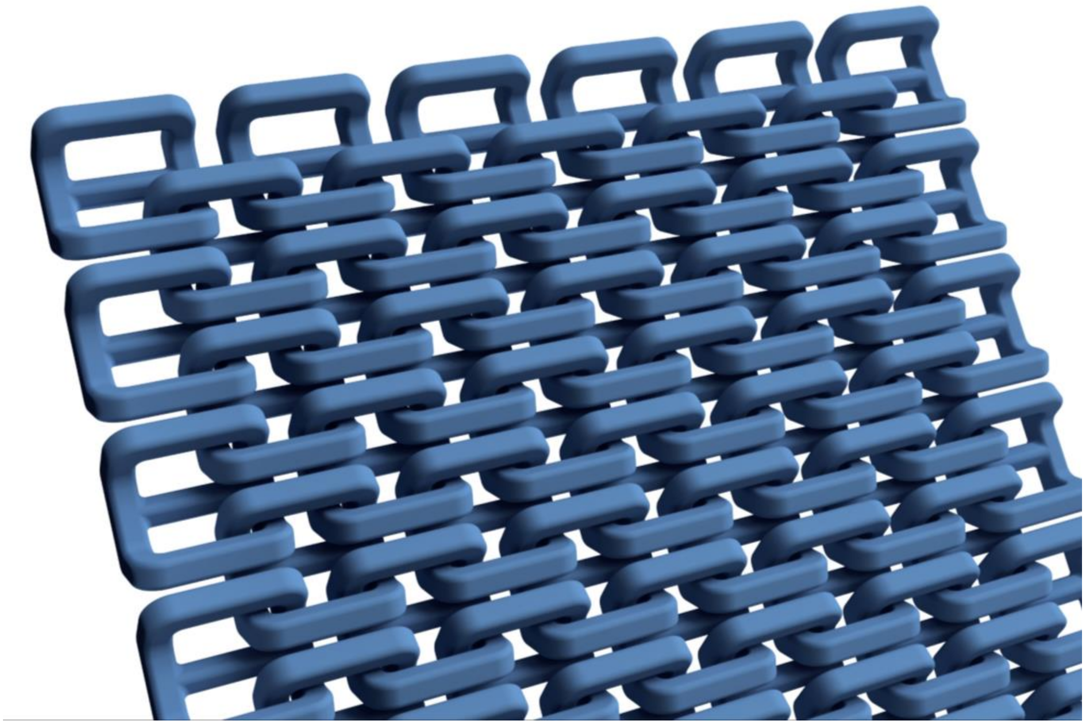


Figure 7.1 Concept 2 "Wave"

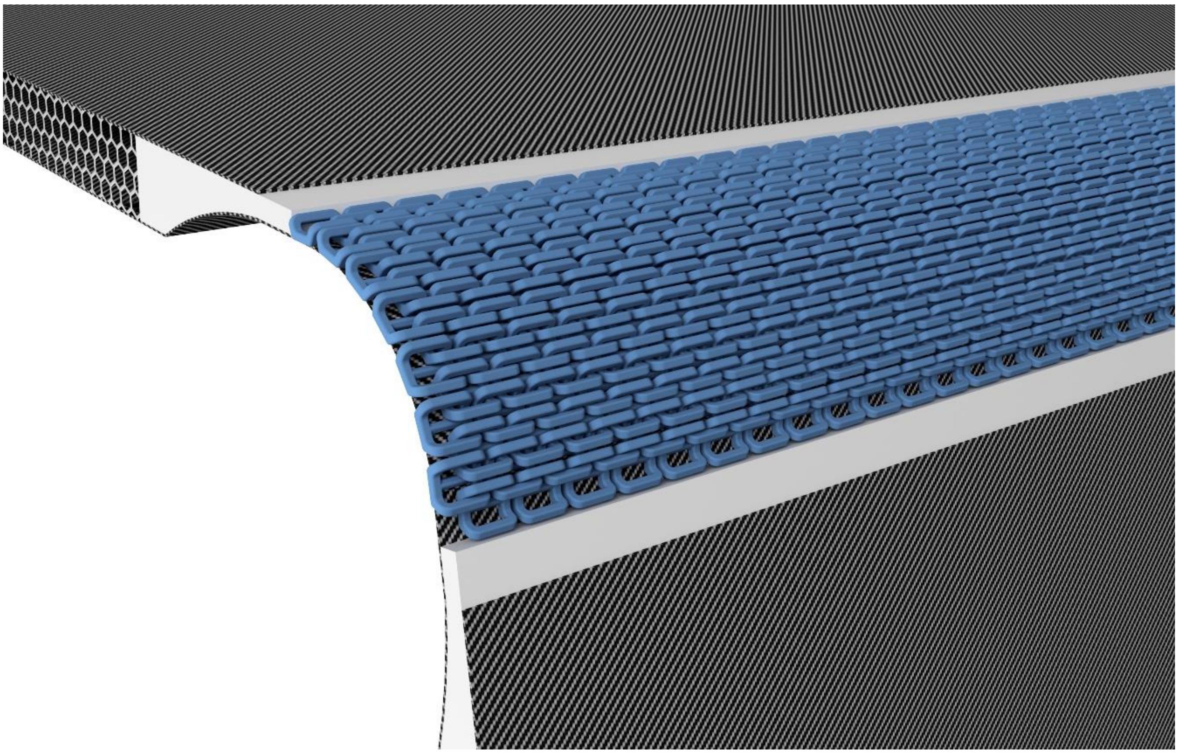


Figure 7.2 Curve with concept 2

The formula car body surface is large and requires modular parts which have the possibility to be attached together. As a solution, open links were designed. The open links designed for concept 2 were not very effective and either an improved solution needs to be designed or as an alternative, wires, threads, cable ties or adhesives could be used to attach the modules together. The best open link solution was designed for concept 1.

One set goal that did not prove to be a success, was the mass optimisation. All the concepts were heavier in density than the aluminium honeycomb. Mass could be optimised with further developments e.g., remove the unnecessary surfaces or make thinner walls. The technology is constantly improving and will offer even better solutions in the future. For now, however, further decision must be made by the FS team whether they concede to the mass or choose more time-efficient and convenient manufacturing method. Given the fact that the time for building the car is very limited, it would enable them to start testing the car sooner and be more competitive.

Final shape of the structure needs to be rigid, and it should not interfere with the airflow - this thesis did not deal with the outside form design and therefore the aerodynamic factors remain the same, which means that the structure does not interfere with the airflow. On the other hand, the added weight might change the body centre of gravity and needs a more thorough analysis. Rigidity is guaranteed with the distance the structure creates in between carbon fibre fabric layers. The lattice structures will be fixed with adhesives to the carbon fibre fabrics and to the surrounding structures.

One additional discovery that was realised through the interviews, was the information and the know-how complicated passing on to new team members. Often the new members are just showed once how the monocoque is manufactured and after that they are left on their own. All the questions must be solved amongst the new team.

SUMMARY

This master thesis aims to design a 3D printed alternative solution to Formula Student team Tallinn formula car body internal structure. Given thesis is only focusing on the form formation of internal structures not the outside form design.

The methodology is based on the constructive design research and comparative experimentations. The research involves literature overview of AM, bringing out the contrasts between additive and conventional manufacturing. AM processes, mainly SLM and SLS are concentrated on, to show the capabilities of 3D printers in creating lattice structures.

Through interviews and studying the current manufacturing method, the problems regarding manufacturing of FS team Tallinn formula car were discovered. The main one was addressed, and the rethought car body structure solutions were designed accordingly.

In this thesis, five concept solutions for the internal structure of the FS car body (monocoque) were designed with the manufacturing process simplification in mind. To fully understand the potential of proposed concepts, 3D printed versions were used during validation. In order to test the solutions, a feedback session with FS team chief engineer was conducted.

The main objective of designing a lattice structure concept solution for Formula Student monocoque parts to accelerate the manufacturing process and to make it more convenient for the FS team, is fulfilled. The more precise goals set in chapter 5.1 were achieved partially and are more closely explained in concluding chapter. Many of the proposed concepts were successful and enhance the body structure manufacturing process, enabling the FS team to start testing the car sooner and be more competitive. The most optimal solution selected on the bases of the criteria and by the chief engineer coincided. The selected one is concept 2.

Even though, the concepts were designed for FS, they could be improved and find a way to other means of transport: cars, buses, airplanes, self-driving cars etc.

One additional problem, that was discovered through the interviews, but was left out of this thesis scope, was the information and the know-how complicated passing on to new team members. Although, it is a topic to be considered in the future, author finds that given thesis is a base for the information passing in written form in the scope of 3D printed internal structures.

KOKKUVÕTE

Selle magistritöö eesmärk on disainida 3D prinditud alternatiivne lahendus Tudengivormeli Tallinna meeskonna vormelauto kere sisestruktuurile. Antud lõputöö keskendub ainult sisestruktuuride vormi moodustumisele, mitte välisele vormikujundusele.

Metoodika põhineb konstruktiivse disaini uurimistööl ja võrdlevatel katsetel. Magistritöö hõlmab kihtlisandustehnoloogia kirjanduslikku ülevaadet, tuues välja kontrastid kihtlisandustootmise ja tavapärase tootmise vahel. 3D printimise protsessid, peamiselt keskendudes SLM- ja SLS-meetodile, on toodud, et näidata 3D printerite võimalusi võrestruktuuride loomisel.

Probleemid seoses FS Tallinna tiimi vormelauto valmistamisega avastati intervjuude ja praeguste tootmismeetodite uurimise kaudu. Keskenduti peamisele ning vastavalt sellele disainiti ümbermõtestatud vormelauto kerekonstruktsioonide lahendused.

Selles lõputöös töötati välja viis Tudengivormeli autokere (monokoki) sisestruktuuri kontseptsioonilahendust, pidades silmas tootmisprotsessi lihtsustamist. Kavandatud kontseptsioonide potentsiaali täielikuks mõistmiseks kasutati analüüsi ajal 3D prinditud versioone. Lahenduste testimiseks viidi läbi tagasiside sessioon FS meeskonna peainseneriga.

Töö peamine eesmärk, tudengivormeli monokokkdetailide võrestruktuuri kontseptsioonilahenduse väljatöötamine, tootmisprotsessi kiirendamine ja mugavamaks muutmine meeskonna jaoks, on täidetud. Peatükis 5.1 seatud täpsemad eesmärgid saavutati osaliselt ja neid on põhjalikumalt selgitatud järelduste peatükis. Paljud pakutud kontseptsioonid olid edukad ja parendavad kerekonstruktsiooni tootmisprotsessi, võimaldades Tudengivormeli meeskonnal alustada auto testimist varem ja olla konkurentsivõimelisemad. Kriteeriumite alusel ja peainseneri poolt valitud optimaalseim lahendus langes kokku. Selleks oli kontsept 2.

Ehkki kontseptsioonid olid mõeldud Tudengivormeli jaoks, saab neid täiustada ja kasutada ka teiste transpordivahendite juures: autod, bussid, lennukid, isejuhtivad autod jne.

Üks lisaprobleem, mis intervjuude käigus avastati, kuid selles magistritöös käsitlust ei leidnud, oli informatsiooni ja oskusteabe edastamise keerukus uutele meeskonnaliikmetele. Kuigi tegemist on tulevikus kaalutletava teemaga, leiab autor, et antud lõputöö on kirjalikul kujul edastatava informatsiooni aluseks 3D printimise sisestruktuuride teemal.

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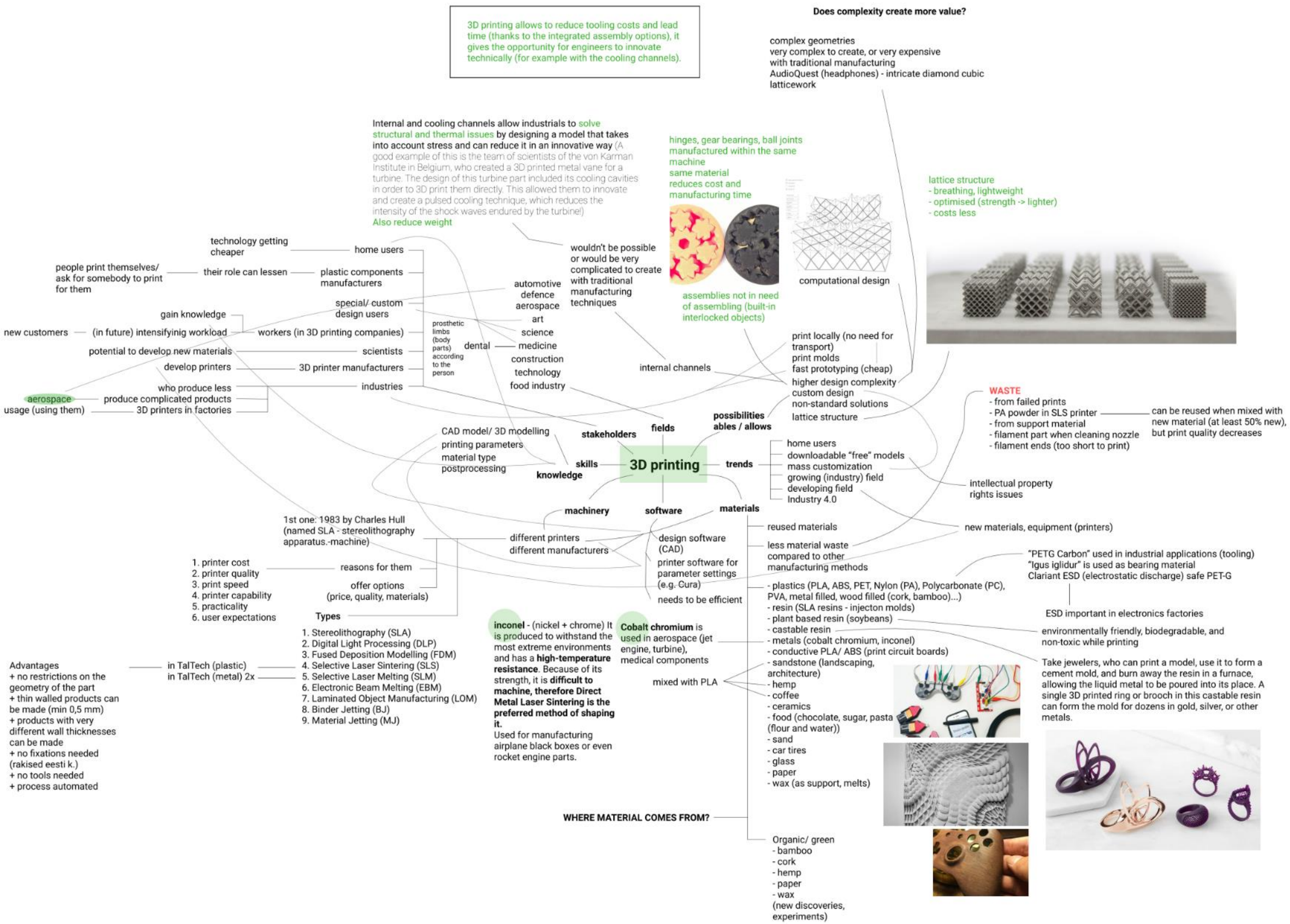
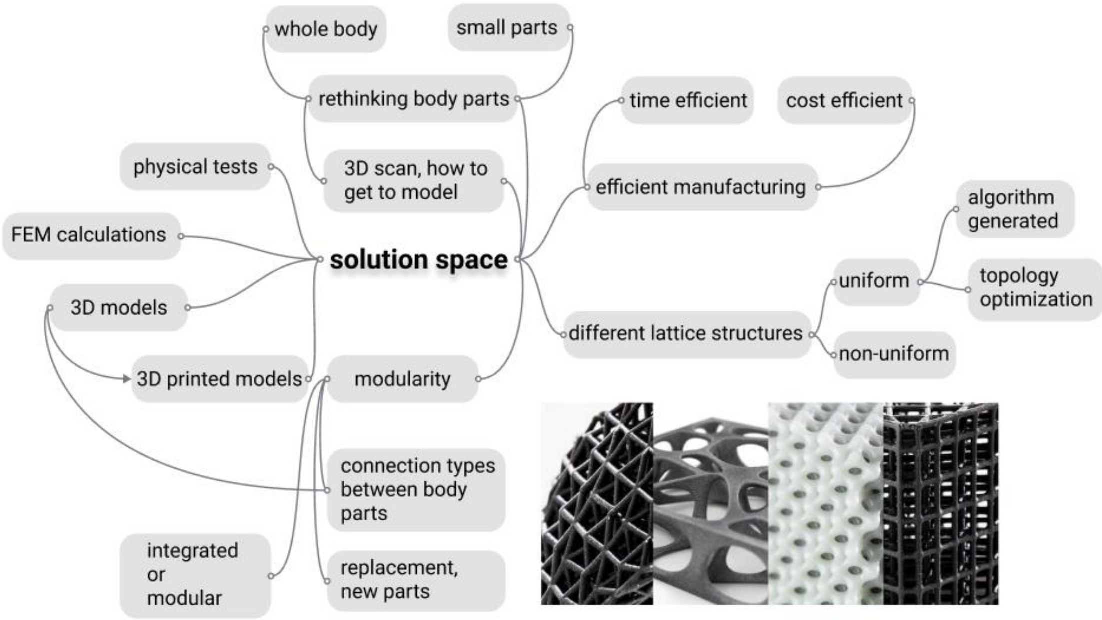
APPENDICES

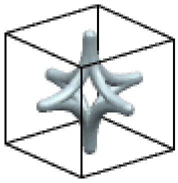
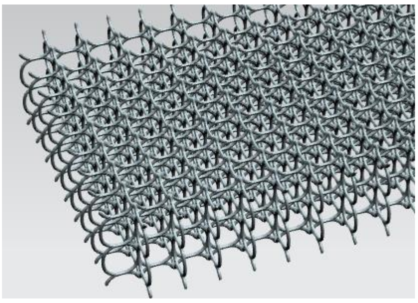
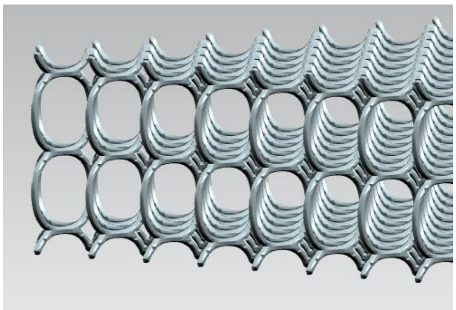
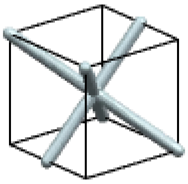
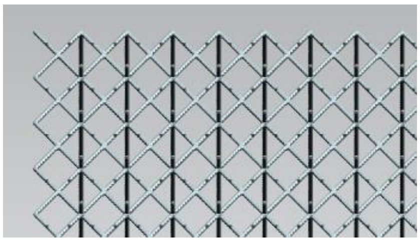
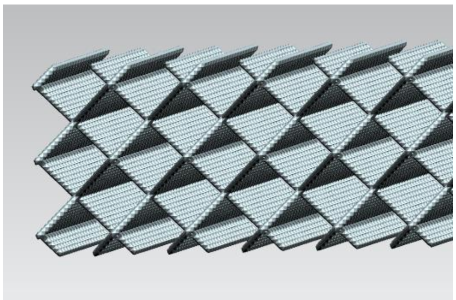
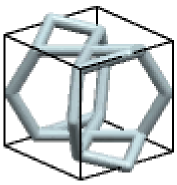
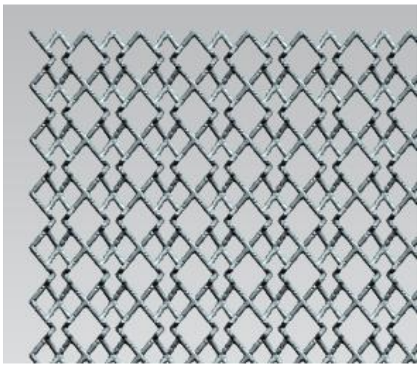
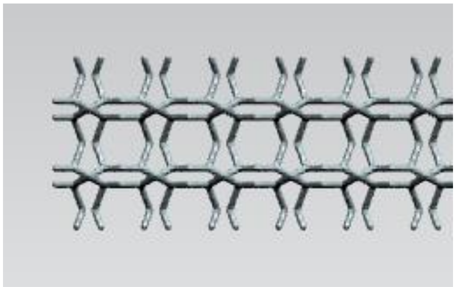
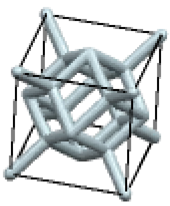
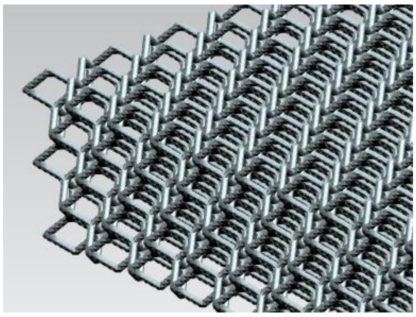
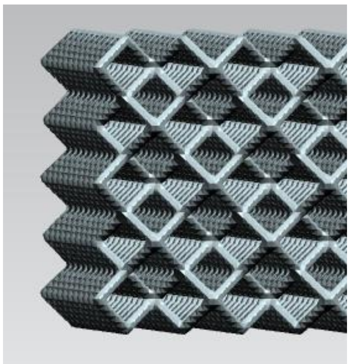
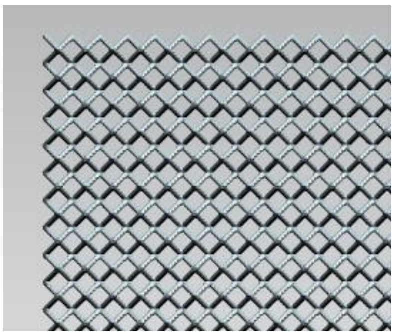
Appendix 1 3D printing mind map

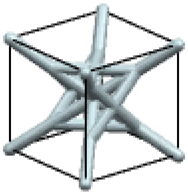
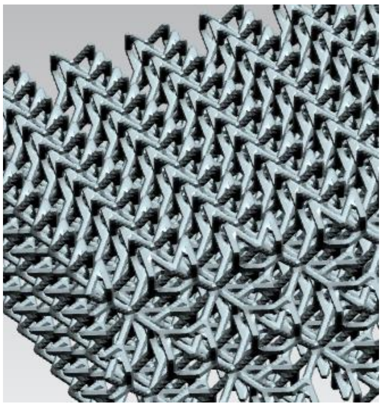
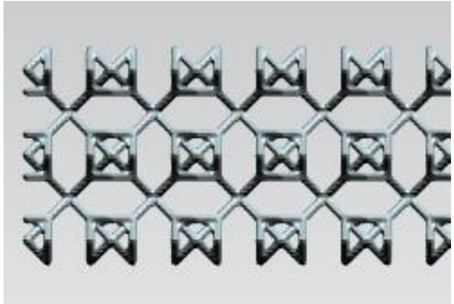
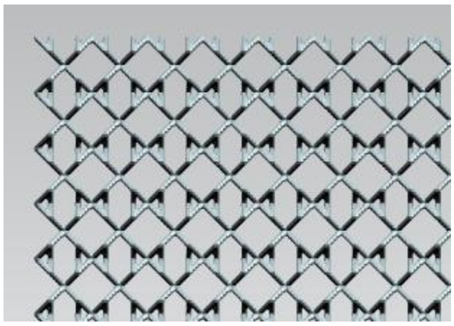


Appendix 2 Solution space

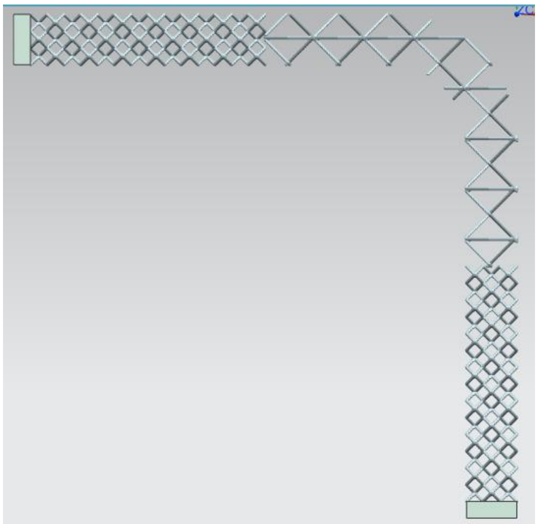
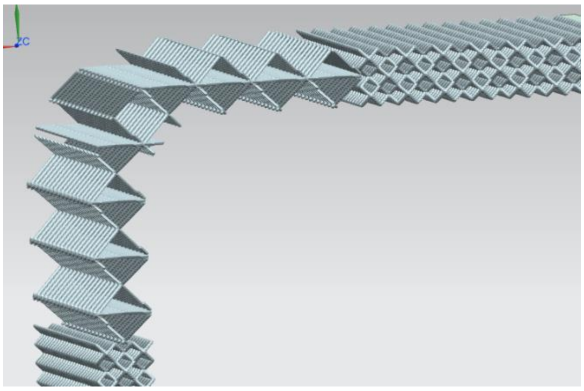
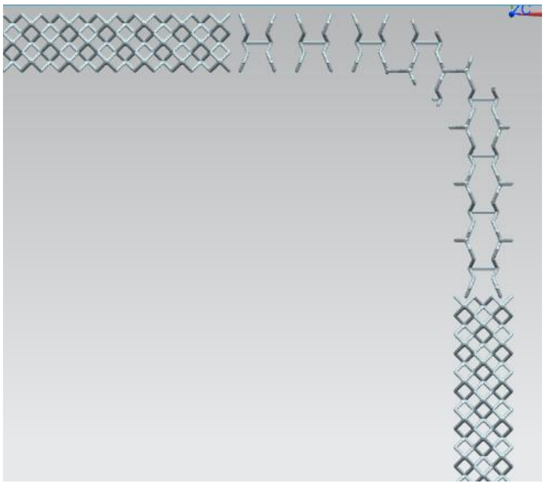
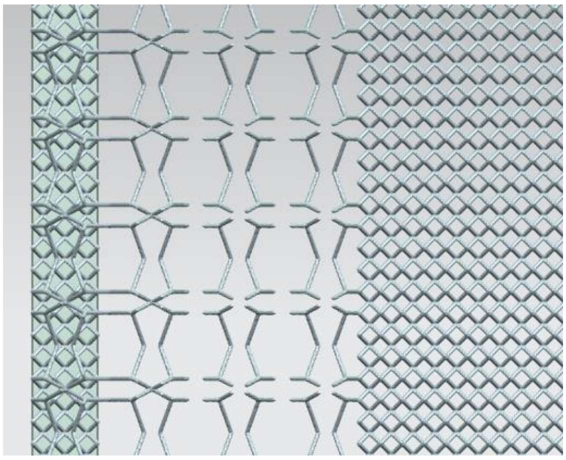
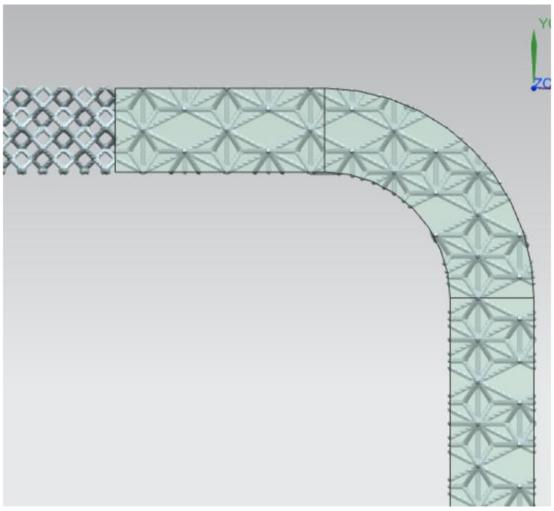
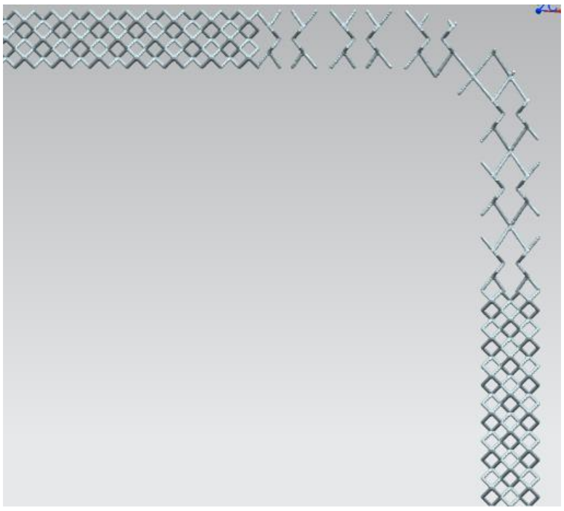


Appendix 3 Siemens NX lattice examples

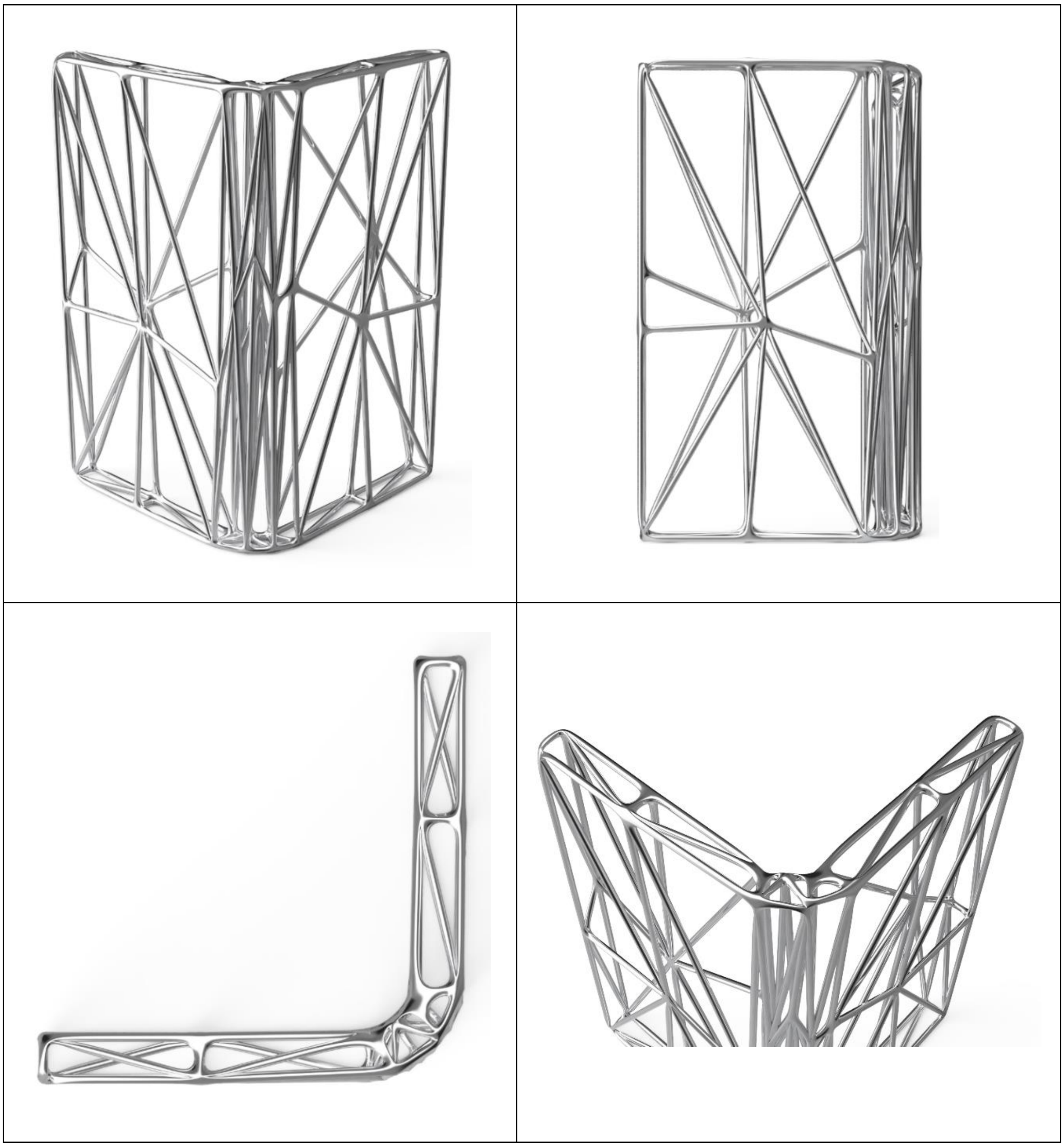
Octapeak 		
TriDiametral 		
HexVaseMod 		
Dodecahedron 	 	

QuadDiametralCross 		 

Appendix 4 Siemens NX 90-degree angle examples

Appendix 5 Fusion 360 90-degree angle examples



Appendix 6 nTopology lattice examples