Development of a Demountable Connector: Increasing the Circular Potential of Additive Manufactured Mono-Material Facade Blocks

10-04-2024

DEVELOPMENT OF A CONNECTOR THAT IS DESIGNED-FOR-DISASSEMBLY TO INCREASE THE CIRCULAR POTENTIAL OF ADDITIVE MANUFACTURED MONO-MATERIAL FACADE BLOCKS

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April 2024

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Summary

The building sector is a big contributor to environmental problems. It is responsible for the extraction of 24% of earths raw materials, it generates 40% of total waste and 40% of the total energy use comes from the built environment. The building industry focusses on production rather than lifespan, leading to materials not being separable. This means a shift towards a circular economy is necessary.

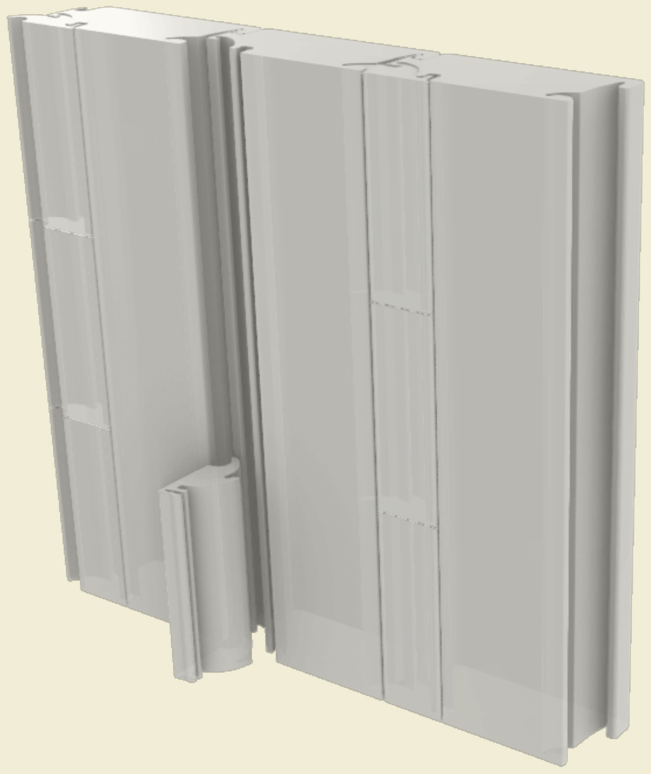
This thesis aims for improving the circular potential of additive manufactured mono-material façade elements through the design of a demountable connector. This was achieved through both circular analysis of an additive manufactured façade element, Spong3D, and research through design of a demountable connector.

Through literature it was found that additive manufacturing has the potential to produce circular building products. Through reducing material use with shape optimization, and the ability to make mono-material elements. And the ability to make complex shapes, which allow for demountable connectors and thus reuse.

The Spong3D panel was analysed on its circular potential and compared to the circular building product Hempcrete. It was found that the Spong3D element was not designed with circularity in mind. However, the current design can be improved upon to improve its circular potential. It is already mono-material, which allows for reusing and recycling. Further improvements include using recycled materials, and optimizing the shape, thus reducing the raw materials used. Lastly, a demountable connector adds reusing potential.

This connector was designed in the prototyping stage of this thesis. Multiple designs were made and evaluated in a decision model consisting of circularity requirements for the entire lifespan of a product. The final design, C-cure, consists of the Spong3D panel and a locking element, two sides of the panel connect together, and the locking element rotates into a recess, locking the panels into place. The design fulfilled all circular requirements.

The C-cure connector uses little energy to produce. It allows the Spong3D to assemble and disassemble and is a reliable connector in use.



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APPENDIX

1. Introduction

1.1. Background

The built environment is a main contributor to the extraction of raw materials and the production of greenhouse gasses (Joensuu et al., 2020). Non-renewable materials are used that also have a high environmental impact. Besides, materials are often discarded at the end-of-life state, accounting for more than one third of all waste in the EU (Construction and Demolition Waste, N.D.), with a total waste generation in 2020 of 2154 million tonnes (Eurostat, 2023). In the Netherlands, the percentage of construction and demolition (C&D) waste is even higher at 40% of total waste (Koutamanis et al., 2018). Even materials that are recycled are downcycled and still end in landfill. For example, concrete, brick, and asphalt waste is used as a base material for roads by crushing it (Mulder et al., 2007).

Up to 24% of the raw extracted materials are used for the building industry, this extraction causes great reduction in earth's exergy (Valero et al., 2008). The embodied energy of building materials makes up between 6 and 20% of the total energy needed for residential buildings (Moazzen, 2022). The total energy used by the built environment comes to a total of 40% of the world's energy (Turkyilmaz et al., 2019).

1.2. Problem statement

As addressed in the previous paragraph, serious issues exist regarding the use of raw materials and energy within the built environment. Besides, substantial amounts of construction and demolition waste are generated and cause environmental damage.

The current economy has a linear system, this goes for our entire economy as well as the built environment, which causes the issues addressed above. Buildings are designed to be used only once or with a specific purpose in mind. Therefore, buildings use raw materials that deplete sources, are consumed until at the end of life they lose value, and the materials are seen as waste. Although some materials are recycled, in most cases they end up in landfill.

To resolve these problems, the building sector needs to shift towards a circular economy, where materials are seen as valuable, and products are designed to maintain the quality of the materials. This is done by keeping products in the cycle, by for example reusing them. Besides, the circular economy aims to restore nature. (Ellen Macarthur Foundation, n.d.)

1.3. Objectives & Design assignment

Specifically with building façades often multiple materials are used, they are needed for different functions like strength and insulation. These layers often are connected in such a way they cannot be separated or will be damaged at the end of life.

Recently research is conducted into the use of additive manufacturing for mono-material façade elements where functions are combined into one component. These show potential for application in practise (Leschok et al., 2023; Ghasemieshkaftaki et al., 2021; Sarakinioti et al., 2018).

Until now, the focus has not been on circularity, but great potential lies in this area. The printing method allows for the use of waste materials like rPET. Besides, additive manufacturing allows for building on location, modular mono-material components with integrated functionalities and connections Designed for Disassembly. Design for Disassembly can only be realized through the design of demountable connectors between elements. Although there are designs that proof the concept of mono-material façade elements, additive manufacturing of PET connectors is still under-explored, and only few examples can be found that still show limitations.

In this thesis research is conducted into connectors Designed for Disassembly through additive manufacturing with PET. Prototypes will be assessed on their functionality for a circular design.

The design assignment within this thesis is the Design for Disassembly of a modular connector between blocks, based on the Spong3D façade block. The connector should aim to meet circular requirements for the manufacturing, assembly, in-use, and disassembly phases.

1.4. Research Questions

The main research question of this thesis is:

How to design a Mono-Material demountable connector for a Circular Façade system using PET through Additive Manufacturing?

The research question will be supported by the following sub questions:

How can Additive Manufacturing be used to produce Circular Building Products?

How can the Design for Disassembly method be used for the design of Circular Building Products?

What is the circular potential of the Spong3D building block?

What are the requirements for a demountable Additive Manufactured connector?

1.5. Research Method

The main methods used in this thesis are literature study, analysis, research through prototyping and evaluation.

The context will be set through literature study into additive manufacturing, circular product design and Design for Disassembly. This will be supported by analysing case studies about facade elements produced via additive manufacturing and connectors designed for disassembly.

More detailed research is done by analysing the circular potential of the Spong3D block, to evaluate its possibility to use as the base of the design of the connector. Practical tests are also performed into the context of the prototyping, by doing preliminary tests and setting the 3D printer settings.

The last method used is research through design. Three rounds of prototypes are made, evaluating each to inform the next round of prototypes. The evaluation requirements are formed through the research conducted with the first two methods.

1.6. Structure of the thesis

The thesis consists of four parts, divided by their methodology.

The first part, Literature study, sets a context for the thesis. It researches the state of the art for additive manufacturing in the built environment, circular building products and the use of additive manufacturing to create circular building products. It also researches the use of Design for Disassembly to increase the circular potential of a product.

In the second part, the focus is on analysis. The spong3D facade block is analysed on circular potential on the domains of material, manufacturing, design, and management to show its use as a base for the design. On top of this, the 3D printing constraints and capability are tested and set. Lastly, a set of requirements is made, based on the research for analysing the prototypes with.

The third part is the practical part of this thesis where designs are prototyped and evaluated. They go through three loops of refinement.

In the last part the results are discussed and concluded, and a reflection of the process is given.

1.7. Assumptions, scope and limitations

This thesis builds on the "living in a bottle" lab, where continual research is conducted into the possibility of 3D printed PET housing. It focuses on the possibilities 3D printers create for producing optimized, translucent mono-material building elements.

This lab uses tiny houses as a context, because within a small footprint they have all functionalities normally found in a home.

In this thesis, the Spong3D panel is extensively analysed. This is a mono-material façade panel that mainly focuses on insulation, through closed cells and water cooling. It is part of the lab and is currently in its proof-of-concept stage. For the thesis, the focus lies on the cell's insulation part, and it is assumed the cells also fulfil a semi structural role.

The research also focuses on creating a proof-of-concept connector, with the main focus on circularity and Design for Disassembly. Extensive testing of the connector lies beyond the scope of the project.

LITERATURE STUDY

2. Additive manufacturing for circular building products

2.1. Introduction

This chapter explains the definitions Additive Manufacturing (AM) and Circular building product (CBP). It is explained how AM can be used to create CBP's.

Circular economy

Kirchherr et al. conducted a literature review into the definitions used for Circular Economy (CE). For their study they analysed 114 definitions, to create transparency on how CE is understood and used. According to this research because CE is used so often and different people give their own meaning to the concept, the definition has become vague. (Kirchherr et al., 2017)

They state that the CE is an economic system where a fundamental and systemic change caused the 'end-of-life' to be replaced by reducing, reusing, recycling or recovering. Although a systemic change is needed the concept can be applied to both small and large scale (Kirchherr et al., 2017). The aim of CE is: "to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017, p.229).

With the analysis of the definitions Kirchherr et al. found a wide range of interpretations and strategies to accomplish CE. The most common strategy found for CE is through the 3R's: reuse, reduce, recycle. Although reduce is often left out and a majority of the definitions studied did not speak about the importance of a waste hierarchy. The authors state that this can lead to companies claiming to follow CE, while only applying minimal strategies like recycling. Besides, the connection between CE and sustainable development is not often mentioned, but the definitions rather had an economic focus. Even though the CE concept is often used with different meanings, it is still shows promise since it has started movement within the economy towards sustainable development. (Kirchherr et al., 2017)

Besides the definition of Kirchherr et al., the definition of the Ellen Macarthur Foundation is also used in this paper. They state: "The circular economy is a system where materials never become waste and nature is regenerated" (Ellen Macarthur Foundation, n.d., What is a circular economy section). They argue that the main strategies for a circular economy are to extend the lifespan of products and when this is not possible, use the materials at their highest value. Nature should be restored and taken inspiration from. And lastly waste should be designed out and pollution eliminated. (Ellen Macarthur Foundation, n.d.)

Additive manufacturing

Additive Manufacturing (AM) is the process of creating objects from a digital model, usually made layer by layer (ISO/ASTM, 2021). It is used for different industries, one of which is the built environment. There are several methods for AM, the one used most for the built environment is Fused Deposition Modelling (FDM). With this technique, a 3D model is sliced into layers which are then extruded from a nozzle from bottom to top. Materials used for AM in the built environment are concrete, clay and plastic (Leschok et al., 2023). Products made include entire houses, façade elements and beams among others (Al Rashid et al., 2020). This thesis focuses on thermoplastic, specifically PET, façades.

Thermoplastic façade elements have not yet fully been applied in the industry, but full scale elements have been produced and are functional for use. Using AM for architecture has many advantages. The production method allows for the design of intricate infill of façade elements, which can decrease weight. Besides, multiple functionalities can be integrated and optimized within mono-material elements, improving performances of for example thermal comfort, structural strength and how much material is needed. With this technique low embodied energy and recyclable materials can be used. (Leschok et al., 2023)

Printing with PET also knows some limitations. PET has a limited fire safety, the end product may show limited watertightness, because air cavities can form between the printing layers. The structural strength of the product varies depending on the direction because of the weaker bonds between layers, the material can also show reduced properties after long exposure to UV radiation and lastly, printing time is still a limiting factor, although the ability for localized production can also reduce fabrication time. (Tse, 2020)

These limitations can partly be reduced. The fire safety and watertightness can be improved with coatings and epoxy, which then potentially makes the material harder to recycle. For fire safety and structural strength, design optimization can also greatly reduce the limitations. (Tse, 2020)

2.2. Case studies

Spong3D

Spong3D is a façade prototype, made in the Netherlands in 2018 (figure 2.2). The panel is printed using PETg and its structure is formed to have optimal insulating properties (4TU.Federation, 2023). It also has channels for active cooling and heating. The dimensions are 0.75 X 0.5 X 0.36 meters, it weighs 20 kg and the total printing time is 296 h (Sarakinioti et al., 2018).

Urban cabin

The Urban Cabin is a 3D printed prototype of a tiny house. It is made in 2015 and is located in Amsterdam, the Netherlands, see figure 2.3 and 2.4. Printed with bio-based materials, it uses shape optimization for the strength of the structure. Concrete is integrated into the floor. (DUS Architects, n.d.-b)

According to the makers of the cabin, the plastic can be recycled and used again as filament (Frearson, 2016). Although it should be questioned whether the integrated concrete won't prevent recycling, since separating the two different materials might not be possible.

Canal House

The 3D print Canal House project started in 2013 in Amsterdam, the Netherlands (figure 2.5 and 2.6). The goal was to print a canal house in elements in a living lab where people can witness the production process (DUS Architects, n.d.-a). Components are printed using the "KamerMaker" (or: chambermaker, see figure 2.7) FDM printer, with a maximum size of 2 by 2 meters in depth and width and a height of 3,5 meters. Although components have been printed the project never finished (Arcam, 2021). The components were to be connected together by filling them with a hardening foam (Sterling, 2014). This will reduce the possibilities of reusing or recycling the components and materials.

Aectual

Aectual is a company that makes 3D printed elements specific to events and locations (see figure 2.8). They make temporary façade systems and have a take-back system, where Aectual takes the elements after use and recycles them into new products. They use a biobased plastic based on plant oils. Their panels have a maximum size of 5 by 1,8 meters. (Aectual, 2023)

Fluid Morphology

Fluid Morphology is a prototype of a façade panel, made for the Deutsches Museum in Munich, Germany in 2019, see figure 2.9. It is made from PETg and the panels are to be reused. The aim of the façade element is to make a mono-material panel with insulating properties due to closed air ducts. Besides, the wave like shape will provide acoustic properties. (3F studio et al., 2019)

Conclusion

From the examples there are several findings. Successful prototypes have been made and although most projects have not reached practice yet, Aectual shows that additive manufactured façade elements can be effectively applied in the building industry.

The projects used extrusion or FDM as their printing method, and most used either PETg or a biobased plastic, with the possibility of recycling at the end of life. Although for the Urban Cabin and Canal House different materials were added, preventing recycling.

The maximum printing size was 2 X 2 X 3,5 meters, which allows for the printing of components. It was noticed that the printing time for one panel within the Spong3D project was almost 300 hours, which should be significantly reduced if it is to be implemented in practice.

Multiple projects aimed for mono-material façade elements with a focus on thermal and structural properties, although strength has not been extensively tested.

Almost none of the projects focused on making a circular product. The focus was on the possibility of AM for the structure of an element and the for making mono-material panels. Although Aectual has a take-back system for their panels, where they recycle the materials used.

None focused on connectors or modularity, which would improve the circularity, because it allows for reusing the elements. No material source focus or material optimization.

2.3. Additive Manufacturing for Circular Building Products

According to previous research AM has a large potential to be used as a fabrication technique for circular façade elements.

Çetin et al. state several reasons for using AM, it can be used to reduce use of resources and construction waste by optimizing designs, creating light weight building structures, the transportation of large elements can be minimized and recycled and waste materials can be used. Connections can be designed for reuse and elements can be made through modular design. (Çetin et al., 2021)

According to Oberti & Plantamura AM can be used to minimize material use and using local materials, waste can be eliminated during construction, less air pollutants will be emitted and components are easily reused at end-of-life. (Oberti & Plantamura, 2015)

Name	**Product**	**Dimensions**	**Product phase**	**Material and source**	**Production technique**	**Load-bearing**	**Connector/ additional material**	**Circular strategy**
Spong3D [1,2]	Curtain wall element - adaptive thermal system	H: 0.75m W: 0.50m T: 0.36m 20kg	Proof-of-concept	PETG	FDM	Withstand wind load and transfers to main structure	No connector designed	Recycling material
Urban Cabin [3]	Temporary-housing - components	Area: $8m^2$ H: 3m	Proof-of-concept	Linseed oil based 3D filament	FDM	Stands on itself, wall shape provides stability	Concrete (for floor), openabe surfaces, connections are not known	Recycling partly, concrete is integrated
Canal House [4, 5, 6, 7, 8]	Housing element system	Max: 2 x 2 x 3.5m 180kg	Proof-of-concept - stopped before completion	Biobased filament	FDM		Pieces are slotted together, hardening foam is added to secure connection	Recycling
Aectual [9]	Temporary façade elements	Max: W: 5m H: 1.8m $13\text{-}20kg/m^2$	In industry	Bio Polyamide based on plant oils	Fused Granular Fabrication (extrusion)			Recycling (max x7), return service after use
Fluid Morphology [10, 11, 12]	Facade element	W: 1.6m H: 2.8m t: 0.06m 10-15kg	Proof-of-concept	PETg	FDM	Shape provides possibilities for being load bearing	No connector designed	Reusing panels

Figure 2.1: Data 3D printed building products. (1: 4TU.Federation (2023), 2: Sarakinioti et al. (2018), 3: Frearson (2016), 4: DUS Architects (n.d. -a), 5: Archello (n.d.), 6: Amsterdam Smart City (2016), 7: Sterling (2014), 8: Arcam (2021), 9: Aectual (2023), 10: Benedict (2017), 11: Vialva (2019), 12: 3F studio et al. (2019))

Figure 2.2: Spong3D (Mohsen, 2017)

Figure 2.3:Urban Cabin (Van Den Hoek, 2016 -a)

Figure 2.4: Urban Cabin concrete detail (Van den Hoek, 2016 -b)

Figure 2.5: Canal House Render (DUS architects, n.d.)

Figure 2.6: Canal house (Archello, 2013)

Figure 2.7: KamerMaker 3D Printer (Honka, 2013)

Figure 2.8: Aectual Temporary Facade (Aectual, 2023)

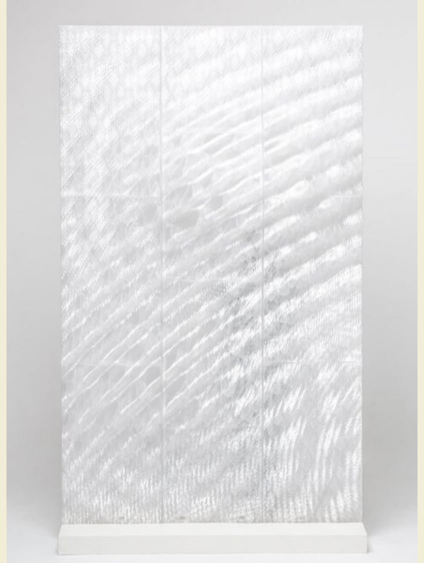


Figure 2.9: Fluid Morphology (Technical University of Munich, 2017)

Hager et al. say that, because the printer can be mobile, the transport and storage of materials can be reduced, low embodied energy materials can be used and wet construction processes are minimized, creating less dust at the fabrication site. (Hager et al., 2016)

Tse argues similarly the reduction of embodied energy, construction waste involved in the production and transportation of large parts because of print at point of assembly. Recyclability will be improved with mono-material elements. (Tse, 2020)

Leschok et al. explain the possibility of high performance façade elements that are site specific, but also mono-material components that are easily reused. (Leschok et al., 2023)

In several papers the additional advantages of using AM for the built environment are mentioned. It creates a safer working environment, faster and accurate construction for lower labour costs, even with complex design shapes. (Çetin et al., 2021; Oberti & Plantamura, 2015; Hager et al., 2016)

2.4. Summary

In summary, AM has the potential to produce circular building products. As seen in the prototypes it is possible to make FDM printers that allow for the manufacturing of component size building products. Although most of the example products did not focus on circular design, the circular potential could be improved on.

It is possible to reduce material use through shape optimization, the printer allows digital design techniques that calculate where more material or less material is needed relative to the forces on the product. Besides, the product can be mono-material, which reduces the amount of different materials needed and the internal connectors. Lastly, the use of virgin materials can be reduced by the use of recycled PET.

Besides, the transportation can also be reduced with the use of local materials, rPET for example is collected throughout the Netherlands, these thermoplastics are relatively lightweight compared to other building materials, reducing the weight of the transport. And FDM printers could even be set up at or near the building location.

FDM printing also allows for reuse, because complex shapes can be printed, which allows for making demountable connectors and thus Design for Disassembly (see chapter 3. Circular design strategies). Because printing files are made in a digital model, it is possible to make modular designs and to store data about the product, allowing for reusing of the products.

With AM, replacement prints can be made for the repair of a product and because of the materials used and the option for mono-material elements, it can be recycled.

3. Circular design strategies

3.1. Introduction

In this chapter, circular strategies used in this thesis will be explained. First, the R-strategies will be explained and then the four Domains of circularity as a method for analysing the circular potential of a building product. Lastly Design for Disassembly as a concept will be explained and the link to circular building products will be made.

3.2. R-strategies

In order to keep a product in circulation, the R-strategies should be applied as seen in figure 3.1. It shows 10 different strategies, that include the wider known strategies: Reduce, Reuse, Recycle. Not all strategies are as effective in a circular economy and thus should be applied from top to bottom. It is best to refuse a product, so no longer using it, however this is hard to achieve since most building products have a function or are ingrained into the industry. So, in that case move one step down to rethink, where the use of a product is intensified, and if this is not possible, move down until a suited strategy is found. It is seen that the lowest strategy is recovery, here the value of the product is largely reduced by incinerating it for energy. It is possible to apply multiple R-strategies to a product, either at the same time or after each other (first repair a product during its first life, then reuse it in a second cycle).

3.3. Four Domains

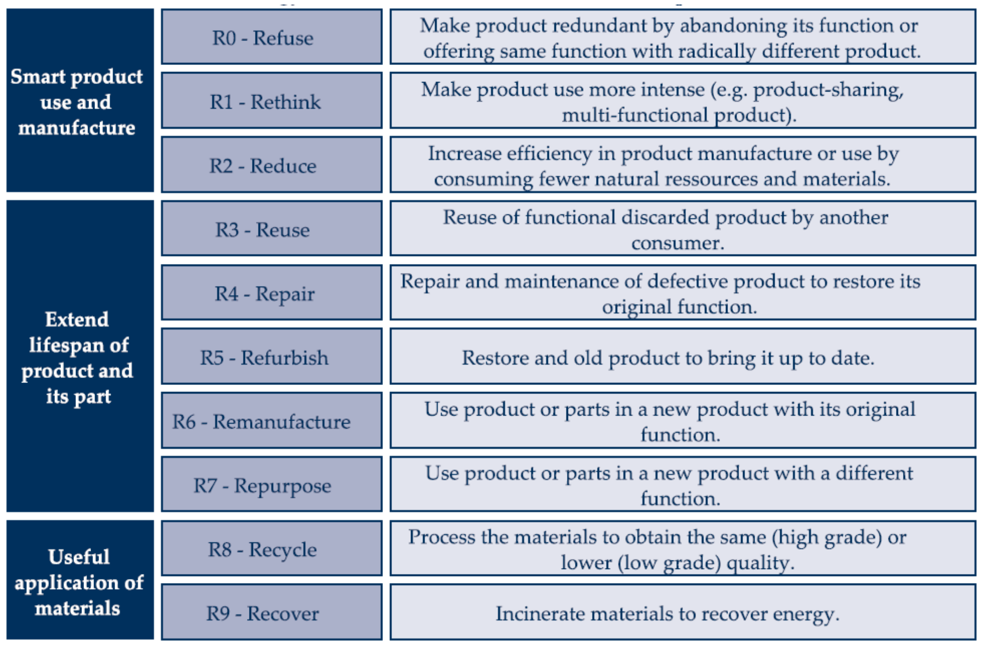
A Circular Building Product (CBP) should apply circular strategies over the entire lifespan of a product. One way of analysing the circularity of a product is through dividing it into four domains: materials, design, manufacturing and management. These expand beyond the contact the user has with the product, or the design. In stead it looks at all the stages of production and management and through this way a product can be analysed with all life stages in mind.

For materials the focus lies at the origin of the materials, whether they are biological or technical and how many different materials are used. The aim is to reduce the effect the materials have on the environment, by choosing materials that cannot be depleted and have a short transport distance.

With design it is aimed at how the different product layers relate to each other and the rest of the building and how they are connected, with a goal of having demountable connections.

Manufacturing should support the other domains, be low in energy consumption and at the same time not be labour intensive.

Lastly, management focuses on who is involved in the product and what system it is sold or leased in. (Ioannou, n.d.)



Smart product use and manufacture	R0 - Refuse	Make product redundant by abandoning its function or offering same function with radically different product.
	R1 - Rethink	Make product use more intense (e.g. product-sharing, multi-functional product).
	R2 - Reduce	Increase efficiency in product manufacture or use by consuming fewer natural ressources and materials.
Extend lifespan of product and its part	R3 - Reuse	Reuse of functional discarded product by another consumer.
	R4 - Repair	Repair and maintenance of defective product to restore its original function.
	R5 - Refurbish	Restore and old product to bring it up to date.
	R6 - Remanufacture	Use product or parts in a new product with its original function.
	R7 - Repurpose	Use product or parts in a new product with a different function.
Useful application of materials	R8 - Recycle	Process the materials to obtain the same (high grade) or lower (low grade) quality.
	R9 - Recover	Incinerate materials to recover energy.

Figure *3.1: R-strategies (Kupfer et al., 2022)*

3.4. Design for Disassembly

Design for Disassembly (DfD) is a design strategy that aims to decrease waste production, material depletion and pollution. This is a broad strategy that can be applied many design categories, including building design. According to Guy et al.: “DfD is the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials.” (Guy et al., n.d., p.3) With DfD, the end-of-life is taken into account from the design stage on. It aims to keep a high quality of materials throughout its lifespan. Principles are focused on separating layers of different materials, not integrating them, having simple designs with clear documentation and having connectors that can easily be demounted. (Guy et al., n.d.)

DfD as a strategy for CBP

DfD works as a strategy to reduce environmental impacts and in its principles could be used as strategy for circular building products. DfD allows multiple R-strategies to be applied in order to extent the life of a product. These strategies are reuse, repair, refurbish, remanufacture and repurpose, which each need the product to be able to be taken apart with minimal chance of breakage.

When a product is Designed for Disassembly it is important multiple aspects are taken into account over the entire lifespan of a product. Specifically for the end of life stage several criteria need to be followed in order to create a product that can easily be taken apart. Since, if it is too complex or expensive, the choice of discarding it and starting something new would be the easiest. However, it is also important to look at the assembly and in-use, for only if a product is easy to assemble and has good quality during use, it will actually be used.

Examples

The focus on DfD lies on demountable connectors. A few examples are given. In woodworking demountable connectors are often made. This is seen in more traditional woodworking, with mortise and tenon joinery, two wooden parts are fitted together and locked with a third element in the shape of a wedge. This wedge can be removed again by applying force in the opposite direction as how it is assembled (see figure 3.2). In the figure 3.3, a more novel woodworking technique using a CNC is applied. Here a connection is made by moving the pieces into multiple directions, first one piece is placed into the slot of the other piece, then it is wedged together by the shape of the pieces. They can be disassembled by applying force in the opposite direction.

In injection moulding, demountable connectors are often made out of plastic. As seen in the image (figure 3.4), it is possible to recreate using 3D printing. A buckle is shown, that can be used to connect two straps together, it is a snap-fit connector were parts slide into a recess and locking the element until force is applied to push the parts together. This works well with the elasticity of the material.

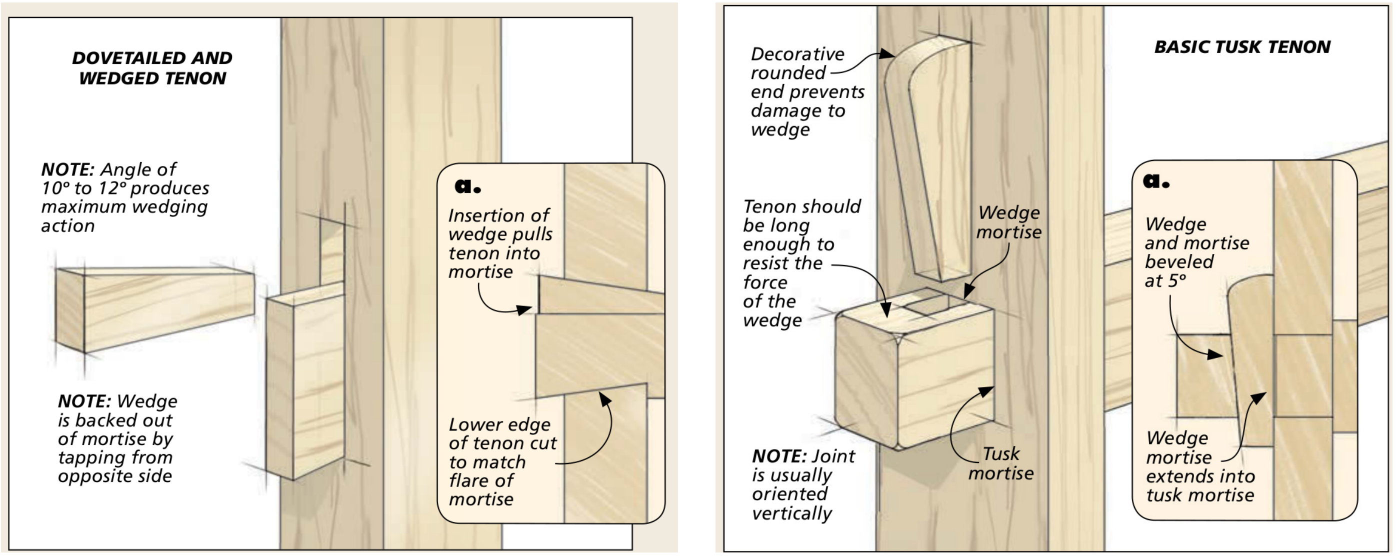


Figure 3.2: *Mortise & Tenon wood joinery (Raife, n.d.)*

Figure 3.3: *Demountable wood connection (Davis, n.d.)*

Figure 3.4: *Snap Fit connector (Maker’s Muse, 2019)*

ANALYSIS

4. Circular potential of Spong3D

4.1. Introduction

In this thesis connectors are designed to increase the circularity of AM mono-material facade elements. As researched in chapter 2: Additive manufacturing for circular building products, AM has the potential to create circular products. For this thesis the Spong3D element is used as a base for the connectors, it is however not known whether this is a circular product and if its circular potential can be improved.

Therefore the circular potential of the Spong3D element is researched in this chapter. This is done through analysing the block on the four circularity domains: Material, Manufacturing, Design and Management. First, the block is analysed, and then it is compared to an alternative building block, hempcrete. Lastly, based on the analysis a summary is given.

Spong3D

Spong3D (see figure 4.1) is a façade element panel that: "integrates insulating properties with heat storage in a complex, mono-material geometry" (Sarakinioti et al., 2018).

It is a prototype that is designed to optimize shape for insulation and also applies active cooling and heating using water through integrated pipes. It is one of the only examples of a mono-material facade panel that has actually been 3D printed on a one to one scale and has available data.

For this element Fused Deposition Modelling (FDM) was used because of the form freedom it allows. The design went through multiple iterations that mostly focused on the insulating properties and heat storage. It also went through time/shape optimization by adjusting the design to have minimal sharp corners and mostly curves. Besides, the nozzle size and slicing settings were optimized. (Sarakinioti et al., 2018)

The design resulted in a successful mono-material PETG prototype with low thermal conductivity. Although there also were several challenges found during testing, namely with watertightness and time efficiency, since printing a single element took 296h. (Sarakinioti et al., 2018)

Throughout this paper a cut-out of 1 by 1 meter is used for analysis, with an Rc of 4,7 m^2K/W, this means it has a thickness of 470 mm. The properties can also be found on the schematic, figure 4.4.

In the following paragraphs, the circular properties are analysed, and compared to hempcrete.

Hempcrete

Hempcrete (see figure 4.2) is a mono-material façade block, made from biological materials, namely hemp and lime. It can be considered partially load-bearing (Jami et al., 2019). It has a high strength and flexibility, works insulating and regulates indoor temperature and humidity and can be formed into blocks (Amziane & Sonebi, 2016). It is a circular product that functions much like concrete. Although the function is similar to Spong3D, the strategies used are opposite.

In order to compare this block to Spong3D, the same cut-out of 1 by 1 meter is used with an Rc of 4,7 m^2K/W as well. This means the thickness used is 329 mm. Properties can also be found in figure 4.4.

4.2. Materials

Domain comparison

Spong3D is a mono-material block, made out of PETG. The prototype in it's current form is made from raw plastic, which is produced using crude oil. Crude oil is a fossil fuel and not renewable. Alternatively, it could be made out of recycled PET, which would mean a locally available waste stream could be turned into a building material.

It is not yet possible to replace the material by a biological material, but promising research shows there is a potential to replace it by a lignin based material in the future. This material would also be suited for AM. (Bierach et al., 2023)

Hempcrete on the other hand is made from biological materials. Namely lime, hemp, water and a pozzolanic material, which improves the properties of the mixture (Jami et al., 2019). Even though lime is biological, it is a non renewable material. The materials are mixed like a concrete. Lime is the binder of the mixture. Hemp fibres add insulating properties to the blocks, it is a fast growing plant that can get up to 4 meters high (Yadav & Saini, 2022). After harvesting the hemp straw is broken down into small pieces, called hemp shivs and dried as a preparation for mixing the materials.

Figure 4.1: Spong3D (Mohsen, 2017)

Figure 4.2: Hempcrete (Isohemp natural building, n.d., Raife, n.d.)

Both lime and hemp can be locally sourced. In the paper by Arrigoni et al. (2017) a lifecycle analysis was done into hempcrete produced in Italy. It was found that the hempcrete was sourced from 245 km away, and the lime from 320 km. Even though the material absorbs more CO_2 during its lifespan than is emitted for its production, it was found that lime is the largest factor in CO_2 emission (Arrigoni et al., 2017).

Hempcrete is recyclable, at the end of life the blocks can be broken down and the materials can be mixed with water and additional binder to be used again. Besides, the waste generated during production can also be recycled (Yadav & Saini, 2022).

As seen in figure 4.4, the weight of a Spong3D is almost half of a hempcrete panel (54kg vs 98kg). This is due to the internal structure of the Spong3D which reduces weight. This allows fore easier transport and installing compared to hempcrete.

GWP

The Global Warming Potential (GWP) is used to calculate the carbon footprint of a product or material. It is measured in CO_2 as an equivalent for greenhouse gasses. This creates the possibility for comparing different products. (CINARK, n.d.)

The GWP of the spong3D element is compared to several alternative façades. To make a fair comparison, all elements are set to the minimum requirement for insulation in the Netherlands according to the BENG regulation, 4,7 (m^2K)/W and were compared on a cut-out of 1 by 1 meter.

For Spong3D the data for both virgin and recycled were calculated from the GWP per kg, for the GWP for $1m^2$. These came out as 149,29 $kgCO_{2eq}$ for virgin, and 48,87 $kgCO_{2eq}$ for recycled (Franklin Associates, 2018).

Hempcret has a negative GWP of about 25 $kgCO_{2eq}$ depending on the mixture contents (Arrigoni et al., 2017).

Besides hempcrete, the Spong3D element is compared to a traditional facade and the WEBO element. The traditional element is one with materials often used in the Netherlands: gypsum-limestone, mineral wool and brick (SBR, 2015). De dimensions are calculated with the Kingspan Rc tool and with an Rc of 4,7 it has a thickness of 440mm (Kingspan, n.d.; also see Appendix A). The GWP is calculated using the Material Pyramid calculator by CINARK and came out to be 99 $kgCO_{2eq}$ (CINARK, n.d.). The calculation can be found in appendix A.

The WEBO element is a prefab timber frame construction element. It forms a more novel building method compared to the traditional facade (WEBO, 2024). Just as the traditional façade, its GWP is calculated using the calculator, and came out to be -22 kgCO2eq for a square meter and Rc of 4,7 m2K/W (CINARK, n.d.; for the calculation, see appendix A).

Using virgin PET for a facade has the highest value, meaning it is the worst for the environment. The traditional façade is somewhat better, still has a high GWP, it also is very heavy, meaning more energy is used for installation. The circular WEBO element has a negative value, which is achieved because it uses a wooden construction. The Spong3D panel has a low positive value, which can possibly be outweighed by other positive properties of the product.

Hempcrete is CO_2 positive because of the materials used. While Spong3D has a low GWP, still energy is used for cleaning and recycling.

4.3. Manufacturing

Domains comparison

The Spong3D building block is manufactured using FDM printing. This method allows for automatic fabrication and material optimization. Spong3D is not optimized to be material and time efficient. FDM printing with thermoplastics is a novel manufacturing method for the built environment, only few other façades have been designed to be produced using FDM.

Using FDM as the manufacturing method is at the base of the design of the block. It is used for its possibilities in automation while at the same time allowing for complex shapes. It dictates plastic filament is used for the building block, in this case PET. This manufacturing method also allows for the building block being mono-material.

The design can be optimized to minimize the amount of support and material use during the manufacturing phase. The most energy efficient method of printing this block is using an industrial robot FDM printer (see sub-paragraph production energy), this does ask for a starting investment. Although the printer is automated, it still requires a skilled person to solve problems that may arise during production and to set the printer to the right starting settings, as this requires some tweaking.

Hempcrete has the opposite approach compared to the Spong3D block. While Spong3D uses novel building technologies, the manufacturing process of Hempcrete blocks is similar to that of concrete. Hempcrete uses a novel combination of materials: hemp, lime and water. Hemp is grown, then harvested and broken down into small pieces called hemp shivs. These shivs, the lime and water are mixed and cast into a block form, the curing process takes 28 to 45 days. During the assembly they are fixed together permanently using lime mortar, alternatively dry stacking is also possible for some designs (Jami et al., 2019).

Contrary to the Spong3D block, where the manufacturing

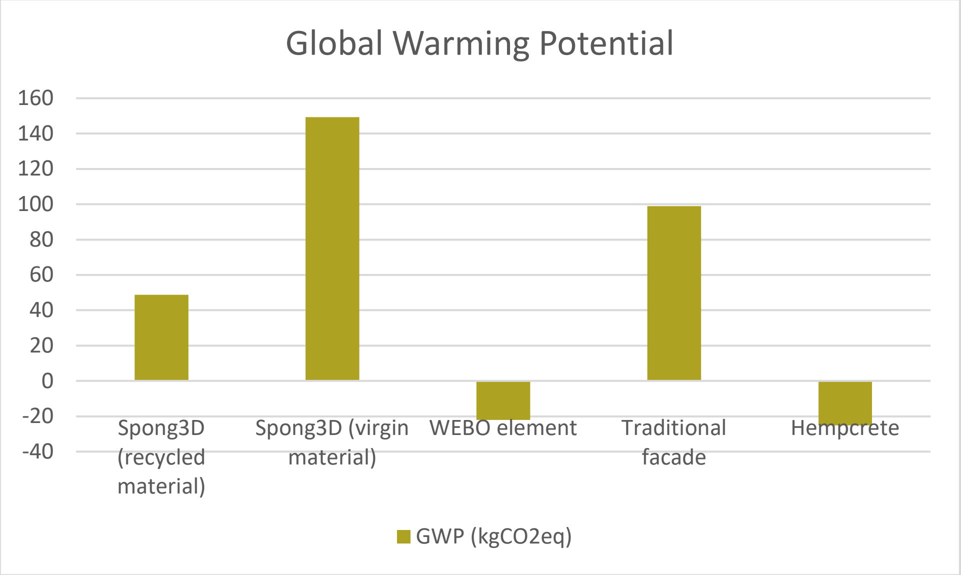
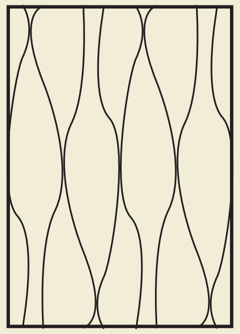


Figure *4.3: Global Warming Potential comparison (Own figure)*

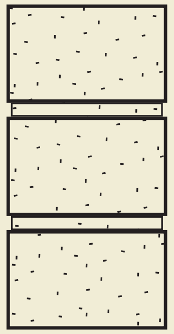
Spong3D

Materials:	PET
Thickness:	470 mm
Hight * Width:	1 * 1 m
Weight:	53,7 kg
Insulation/Rc:	4,7 m^2K/W
$GWP_{recycled}$:	48,87 $kgCO_2{}^{eq}$
Production $energy_{recycled}$:	14,8 MJ/kg
GWP_{virgin}:	149,29 $kgCO_2{}^{eq}$
Production $energy_{virgin}$:	70 MJ/kg



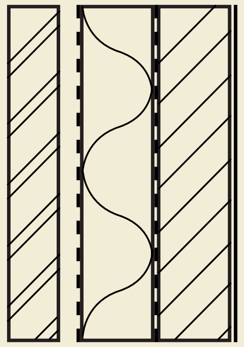
Hempcrete

Materials:	Hemp + Lime + water
Thickness:	329 mm
Hight * Width:	1 * 1 m
Weight:	98,7 kg
Insulation/Rc:	4,7 m^2K/W
GWP:	-25 $kgCO_2{}^{eq}$
Production energy:	10,34 MJ/kg



Traditional Facade

Materials:	
Thickness:	440 mm
Hight * Width:	1 * 1 m
Weight:	452 kg
Insulation/Rc:	4,7 m^2K/W
GWP:	99 $kgCO_2{}^{eq}$



WEBO

Materials:	gypsum-limestone, mineral wool, brick
Thickness:	284 mm
Hight * Width:	1 * 1 m
Weight:	77,09 kg
Insulation/Rc:	4,7 m^2K/W
GWP:	-22 $kgCO_2{}^{eq}$

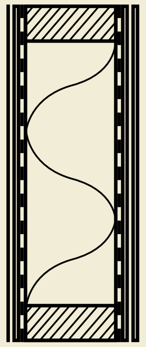


Figure *4.4: Data façades (Own figure)*

process stands at the base of the product, for hempcrete the materials mainly determine the manufacturing process (see materials chapter). The mixture forms a slurry that then needs to be dried to harden, much like concrete. Possibilities are to either let them dry in a mould, which creates a prefabricated block or to cast it in situ. This thesis focusses on the prefab block, since this form is the closest to the mono-material Spong3D panel.

Hempcrete does not require elaborate equipment, but is based more on manual labour for pouring and moulding the blocks. It is a relatively low tech building method, but still, especially with pre-cast blocks need some equipment for breaking the hemp shivs, mixing and casting (Jami et al., 2019).

Production energy

Production energy is an important part of how sustainable the manufacturing process is. For FDM printing it is possible to minimize the energy use by optimizing the setup of the printers. This takes into account the extruder, the printer/robot, cooling system and pellet feeder. All data is collected from the production companies. The comparison is made for the energy use per volume. The set-ups can be found in figure 4.5 and the results in figure 4.6.

From the comparison the industrial robot came out first, with relatively comparable the printfarm second.

The optimized setup for Spong3D is relatively energy efficient compared to hempcrete.

		Spong3D	**Hempcrete**
Weight	kg	53,7	98,7
Energy	MJ/kg	2,7225	10,34
Total energy	MJ	146,19825	1020,558

It should be noticed that whatever setup is used has a large impact on the design of the building block. While the industrial robot is able to produce large panels with minimal connections, with the printfarm producing blocks with maximum dimensions of 400X400X400mm, where additional connections are needed between blocks.

On the other hand, the printfarm would be more commercially available and thus easier to work on a consumer level, while the robot setup would only work on an industrial scale.

4.4. Design

Domains comparison

Spong3D forms both the internal and external face of the building. Meaning it is both the skin and the internal finish. It is connected to the other panels and floor and roof, and forms the skin this way. It also is connected to the structural layer of the building and the service layer should be connected to it. Besides, it is related to the site of the building, since it forms a specific visual.

The material of the building block, PET, determines the look, making it translucent and futuristic, something not commonly seen in buildings today.

PET allows for a mono-material building block with multiple functions integrated into one. Since everything is integrated, there are no different parts to be demounted. If the block breaks, it needs to be replaced in its entirety. Since the block is still in its prototype phase, no external connectors have been designed so far. In this thesis it is aimed to design a demountable connector to improve the circular potential of the Spong3D panel.

Just like Spong3D, Hempcrete is a mono-material block, with multiple functions. It has the possibility to be both the internal and external face of a building, although it is also possible to add an additional finish. The block has both insulating and structural properties, meaning it forms part of the skin and the structure of the shearing layers. It connects to the service layer and the site.

The material choice of hemp and lime has a large impact on the aesthetic of the block, by giving it a very rustic and textured look with natural colours.

The blocks are fixed together and to the rest of the structure using a mortar of the same material. This means the blocks cannot be demounted in their original form, thus do not allow reusing.

4.5. Management

There are several possible strategies for circular product management. As stated in the article by Atasu et al. (2021) there are three main strategies:

- Leasing or renting a product out to allow for maintenance and reuse of products.
- Extending the lifespan of a product by making it high quality, reducing the amount of products needed to sell.
- Taking back the product at the end of life for recycling or remanufacturing.

They should be applied based on the material value and the ease of retrieving the product. (Atasu et al., 2021)

For example, leasing hempcrete would not be the ideal circular strategy because it is not easily retrieved. The product is integrated into the building once it is installed. If a demountable connector is added to the Spong3D panel, it would be very much suitable for a leasing system, since the product and material has a high value and it is demountable and lightweight.

Figure 4.5: 3D printers, from left to right, top to bottom: Printfarm (Anycubic, 2018), leapfrog (pick3dprinter, 2022), robot arm (Comau, n.d.), scara (3D potter, n.d.)

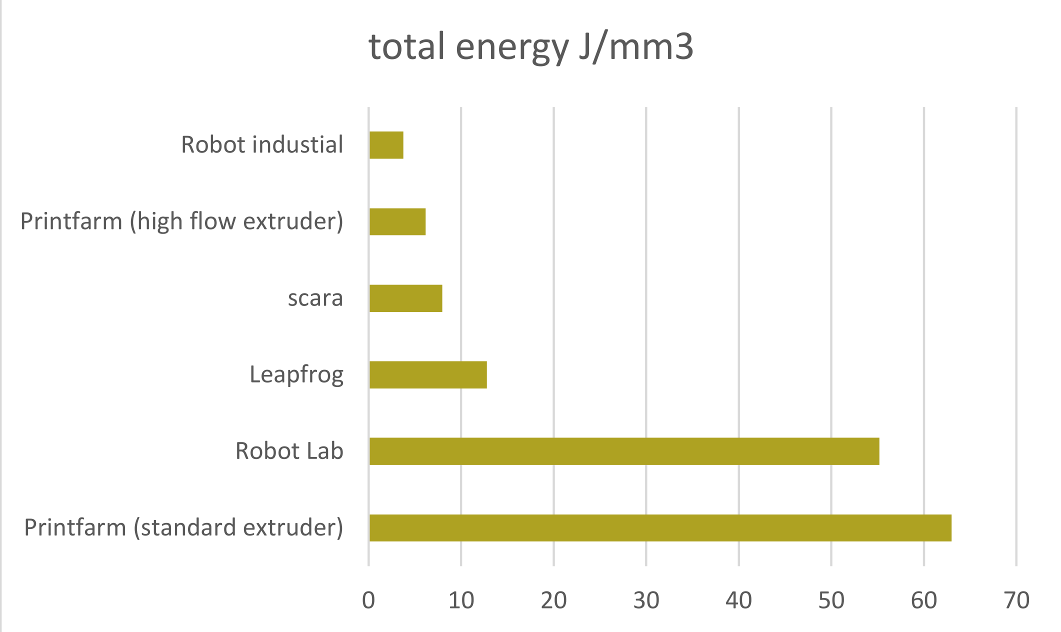


Figure 4.6: Energy comparison printer set-ups (Anycubic, 2018; E3D-online, 2019 a and b; pick3dprinter, 2022; DyzeDesign, 2022; 3Dpotter, n.d.; ceadgroup, n.d.)

4.6. Summary

As Spong3D is a proof-of-concept made to focus mostly on insulating properties, it is not yet designed to apply circular strategies. Although as seen in the domain analysis some elements of the design are already in line with R-strategies. The most important being that it is mono-material which combines multiple functions in a single product, reducing the materials needed. It also simplifies the design into needing no internal connections, this allows for the potential of it being reusable. Besides, it also allows for recycling. Lastly it is lightweight, lighter than hempcrete. This means that for transport energy is reduced.

With further development the circular potential can be improved upon. Spong3D has a lamella structure that is optimized for insulation, it could be optimized for strength as well, to add material where needed and reduce where it is not needed. To reduce the use of virgin material, locally recycled PET can be used. If the prototype is designed to be modular and have integrated demountable connectors, it could also be reused.

Although Hempcrete and Spong3D have the same approach regarding their mono-materiality. However, because of the different materials used, their strategies are quite different. The material informs the design and manufacturing method. While Hempcrete uses a biobased material, Spong3D is made of a technical one. This means that the two can be compared on their strategies, but the most circular method for one of the panels is not the best for the other.

Using a technical material, it is important to keep the material value of Spong3D as high as possible, while this is less important for Hempcrete. Especially since PET has a global warming potential for the production of materials.

Since Hempcrete asks for intense labour, with a low starting cost, it is best used on a small scale. On the other hand, Spong3D is more profitable when scaled up, with a more intensive use of the 3D printers you can easily get a return on the initial investment.

Because of the quality of the material for Spong3D, if a connector is added, the circular potential will be increased, while this is not possible for hempcrete.

Figure 4.7: *Hempcrete wall (Hemp build magazine, 2021)*

Figure 4.8: *Spong3D (Mohsen, 2017)*

5. Design parameters

5.1. 3D printer setup

Printing settings

For prototyping multiple Anycubic Chiron FDM printers were used. This 3D printer has an extruder that can move along 3 axis, so it extrudes layer by layer. The extruder heats material that is fed from a filament spool, the heating makes it melt, so it can be extruded in specific dimensions. It also sticks to the layer below. With this printer a SuperVolcano extruder was used, this allows for faster printing than a regular extruder since it has a longer area for heating, namely with a maximum of 6600 mm3/min (E3D-online, 2019).

Prints are made on top of a heated print bed, which has a 400 by 400 mm area and the height of the product can have a maximum of 450 mm (Anycubic, 2018). Meaning that small scale prototypes are possible, but from 1:2 or 1:1 prototypes should be made in multiple pieces. This does not cause trouble, since up to 5 printers can be used at the same time.

For 3D printing, 3D models need to be transferred into a model with properties the printer can read. This is done with slicing software, Simplify3D in this case. It divides the model into layers and allows you to set the properties of the walls, top, bottom and infill among other things.

Before each round of prototyping some tests were done to find the optimal settings in simplify3D for that round.

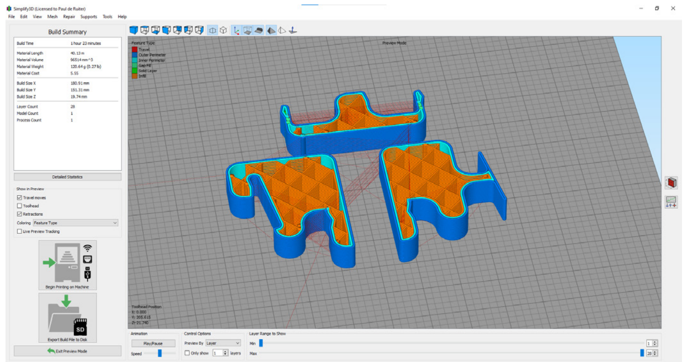


Figure 5.1: *3D slicing software (Own figure)*

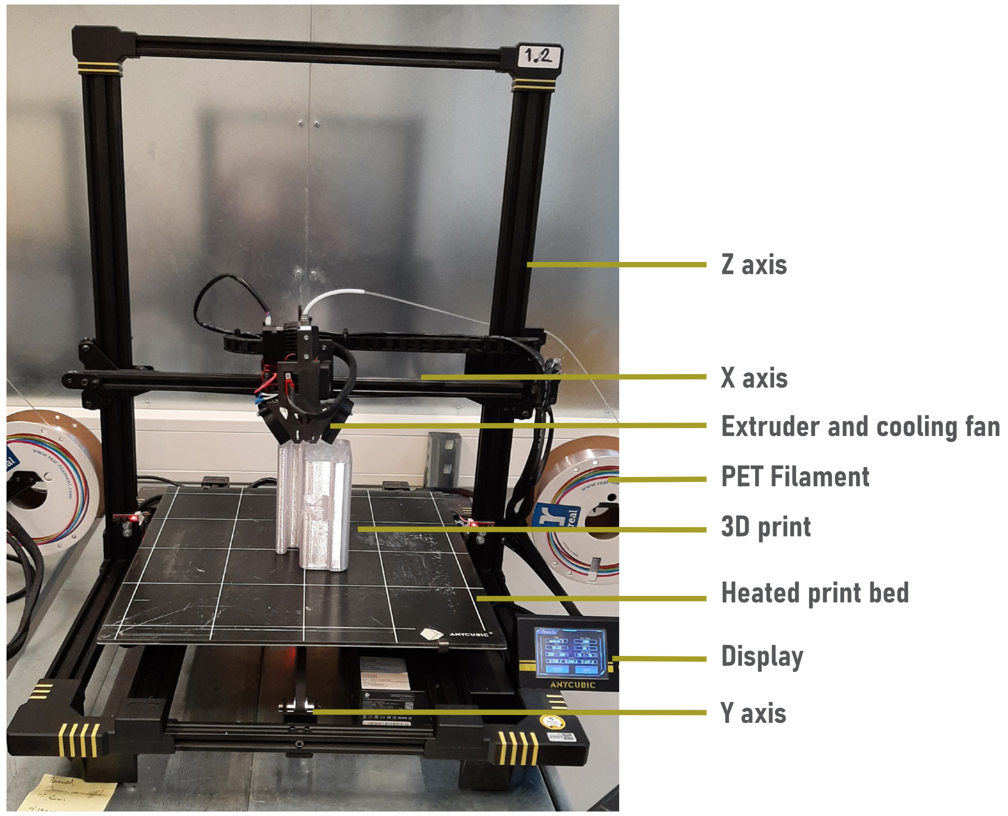


Figure 5.2: *FDM printer (Own figure)*

Concept prototypes

For the concept prototypes each print took one hour or less, so in a short time different options could be printed. The end goal of this round was to see whether the prototypes had potential for further development.

Some tests were needed to get the printer to the right settings. This was done by printing small cylinders of 40mm in diameter and 20mm in height (see figure 5.3 and 5.4). It was found that having a levelled print bed is important for the quality of the print, if the bed is too low compared to the extruder, the bottom layer will not form one whole, but stay in separate extruded lines. If the bed is too high, the opposite happens and material oozes out on the sides.

For the first tests a gap was formed in the wall, this happened because not enough material was extruded at the end of the layer. So the retraction distance was reduced and the restart distance was increased. Retraction distance determines when the extrusion stops, this should be before the end of the layer, since molten material oozes a little afterwards. Restart distance determines where the starting point of the new layer is.

Another problem found was the bottom layers and walls were not connecting properly. In order to solve this problem the first layer width and height were lowered. This made the lines print closer together and closer to the edge.

Bubbles in the prototypes formed because of the filament attracting moisture and it being boiled in the extruder, leaving air gaps. This can be prevented by drying the material in a low temperature oven, however it was chosen to accept the bubbles as it did not compromise the quality of the concept print. This way energy use and time needed for printing were reduced.

It was found that with a low infill percentage the top layer was sagging, but with more infill the printing time takes longer, so for the prototypes where it was not needed to have a high rigidity, prints were made without infill and top.

In the end prototypes were printed using 2 bottom layers and 1 wall with a thickness of 1.2mm and a height of 0.7mm. For some no infill was used and for others an infill of 20% with 2 top layers. The material was extruded at a temperature of 230°C for the extruder and 70°C for the heat bed. The speed used was 1800 mm/min. For more details, see Appendix B.

Improved prototypes

The goal of this prototype round is to test the working of the connectors and to compare them. This meant high quality prints with more stiffness than the previous rounds. To accomplish this, an infill of 10% and 2 in stead of 1 wall layers were used.

Most problems were already solved for the first prototyping round. Tests were only performed (see figure 5.5) to increase the strength of the first layer, the width and height were increased to 120% and the print bed was set higher. The two walls were not connecting, so the extrusion multiplier was increased to 1, resulting in a wall thickness of 1.44 mm. With an infill of 10% the top layers will sag, so to prevent this the 4 highest layers below the top layers had an increased infill percentage of 40%. All settings can be found in appendix B.

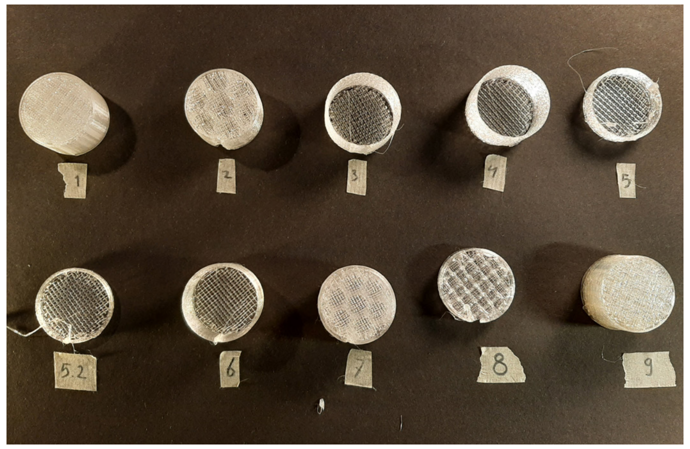


Figure 5.3: Concept prototypes printing tests overview (Own figure)

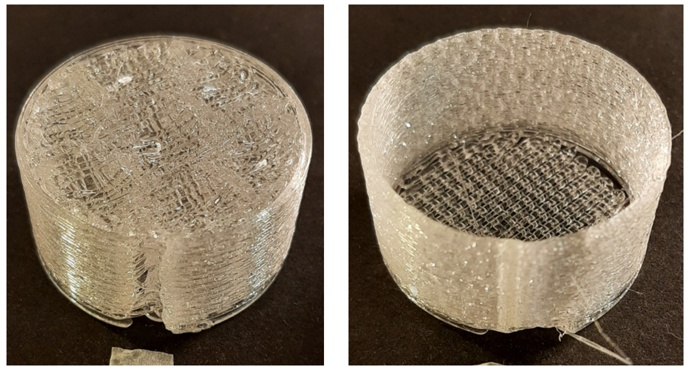


Figure 5.4: Printing problems. Left: gap and sagging. Right: disconnected bottom and bubbles (Own figure)

Figure 5.5: Improved prototypes printing tests overview (Own figure)

Additional test

It was also tested if an overhang was possible in the print (see figure 5.6). It was found that 45° is possible with one wall. It was later found during prototyping that this only sometimes works, since in one instance the overhang started sagging. It was solved by using 2 wall layers next to each other since this adds stability.

It was also tried to print an oval and circular overhang, this was not found possible, since the overhang got too large.

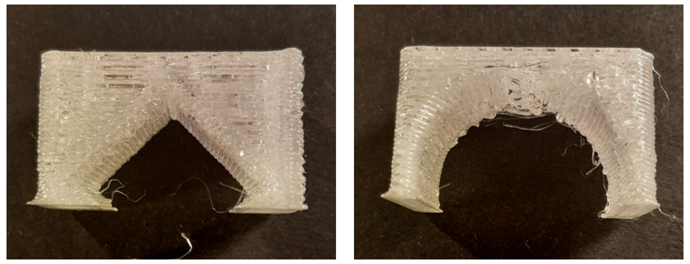


Figure 5.6: Overhang tests (Own figure)

5.2. PET filament

PET is a thermoplastic, when heated it becomes soft and when it cools down it hardens again, this makes it suitable for 3D printing. It is either provided in a spool or as granulate. Between layers it has a reduced strength because it bonds on a smaller area, compared to along the layers. This causes the printed material to have different properties depending on the direction, this is called anisotropic behaviour. Properties from the company BASF can be found in the table (BASF FORWARD AM, 2023).

Printing direction	**Flat**	**Upright**
Density	1287 kg/m3	1287 kg/m3
Young's modulus	1640 MPa	1334 MPa
Yield strength	66,9 MPa	30,2 MPa
Tensile strength	38,6 MPa	14,7 MPa

PET waste

PET is a high-quality material that is often used for single-use packaging products. A total of 8.3 billion metric tonnes of it have been produced and 6.3 billion metric tonnes have become waste, although there are recycling systems in place, less than 10% of the total waste is recycled (Parker, 2021). This waste either ends up in landfills or is incinerated. In the Netherlands alone, the plastic packaging production in 2016 amounted to 10 million tonnes (Plastic Waste and Recycling in the EU: Facts and Figures, 2018).

The fact that 90% of the plastic ends up as waste after a single use, costs a large amount of energy, since it is a technical material that costs a lot of energy to produce, namely 70 Mj/kg (Franklin Associates, 2018). Part of this waste is incinerated, releasing toxic chemicals (Alabi et al., 2019). While plastic also ends up in nature as micro and macro plastics, causing risks for biodiversity (Li et al., 2016).

This mismatch in the amount of plastic produced and recycled is caused by the difficulty of recycling and the reluctance in making the changes needed. While this mismatch ideally will be solved, it takes time to make such a systemic change. Finding alternative solutions for plastic waste in the mean time, will prevent it from ending up in nature or landfill, keeping the value of the material as high as possible.

Waste reduction during 3D printing

With making models, waste is also generated (see figure 5.7). The material needs to be heated and to make sure it has the right temperature and consistency, an extra line is extruded before the start of the actual print. When the filament runs out it has to be changed, this always leads to some material being lost. Lastly, sometimes the print fails, due to having a design that does not work with the printer, not having the right printer settings, or malfunctioning of the printer.

All of this waste can and should be recycled. The amount of waste created should also be reduced. For the misprints this can be done either by stopping the print as soon as possible after it becomes clear that it won't come out as intended. Or if the print can still be used for its function, for example a prototype where the aesthetics or strength are

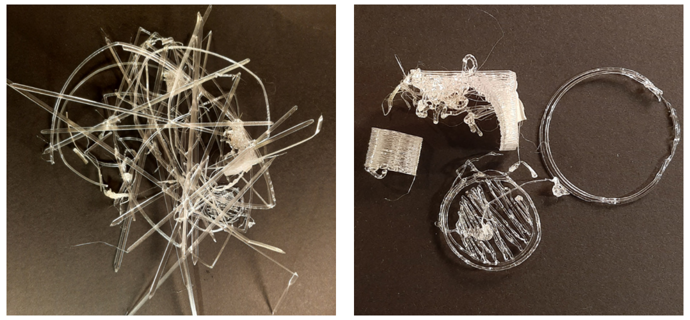


Figure 5.7: Print waste: starting and testing, and misprints (Own figure)

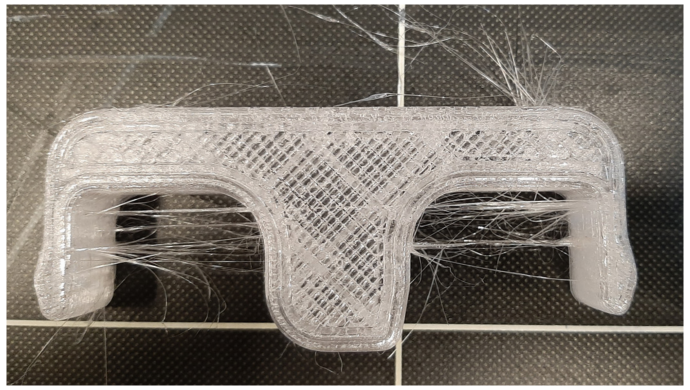


Figure 5.8: Print waste: stringing (Own figure)

not important can still be used if the surface has bubbles.

Another type of waste created are plastic strings where the extruder stops and starts again, as seen in figure 5.8. This happens often when multiple parts are printed at the same time, when a small bit of plastic is still oozing from the extruder. This does not create a large amount of waste, but it is hard to collect and recycle. In stead it breaks off from the print and gets lost. (As found out after printing the prototypes, since strings of plastic were found on random places throughout my room)

This stringing can be reduced with the right settings from the slicing software. Increasing the retraction distance will cause the printer to stop extruding earlier on, so no material is left to string. It should be noted that this can cause gaps in the walls of the print, so the retraction should not be too large and it can be chosen to have the start and stop locations at random places compared to each other, so it does not form a line, but the layers on top can compensate for the lack of material.

5.3. Examples AM connectors

Shading system

Among other things this system is designed for ease of assembly (figure 5.12). The printed panels are slit onto a separate steel substructure. For this end the panels are designed with an indentation on their sides. (Grassi et al., 2019)

Non-orthogonal snap-fit façade connection

The design of complex façade elements including connections out of PLA (figure 5.9 and 5.10). Several iterations were done, the findings were a snap-fit connection. A tolerance of approximately 1-2 mm is needed and a hierarchy between the horizontal and vertical connections. Several aspects need to be researched: wind loads, airtightness, aging and deformation. (Taseva et al., 2020)

Façade panel connections

The objective of this research was the design of connections that use snap-fit assembly, low air permeability, no water infiltration, material infill, vertical gap that allows for vertical movement, see figure 5.11 and 5.13. Successful prototypes were produced that include this. They suggest further research into the types of barriers, air permeability, watertightness, mechanical strength from structural loads, with special focus into the cross-section between the vertical and horizontal connection. (Cheibas et al., 2022)

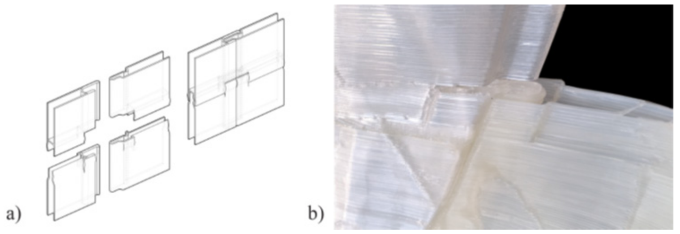


Figure 5.9: Non-orthogonal snap-fit façade connection. a) Assembly system, b) Crosspoint of connections (Taseva et al., 2020)

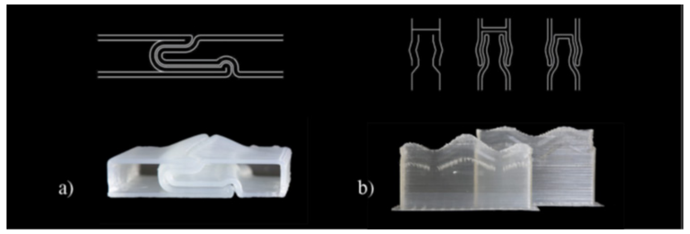


Figure 5.10: Non-orthogonal snap-fit facade connection. a) Vertical connection, b) Horizontal connection (Taseva et al., 2020)

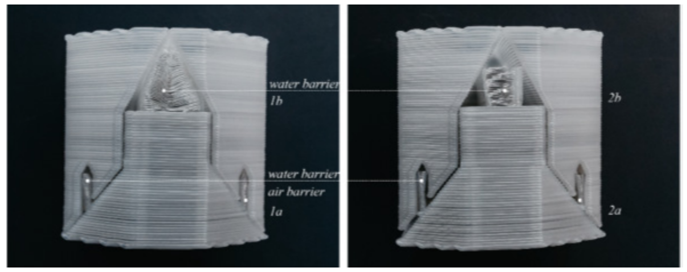


Figure 5.11: Façade panel connections, hybrid connection study for the vertical direction (Cheibas et al., 2022)

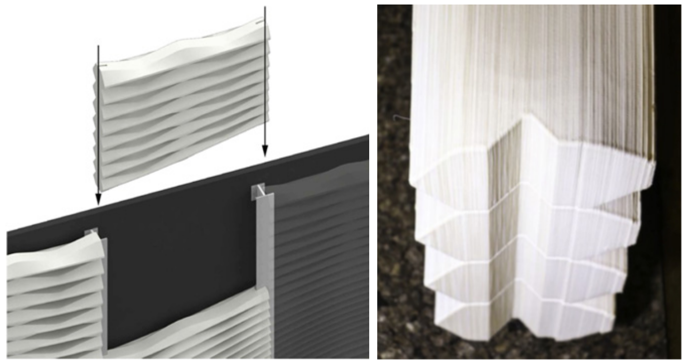


Figure 5.12: Shading system (Grassi et al., 2019)

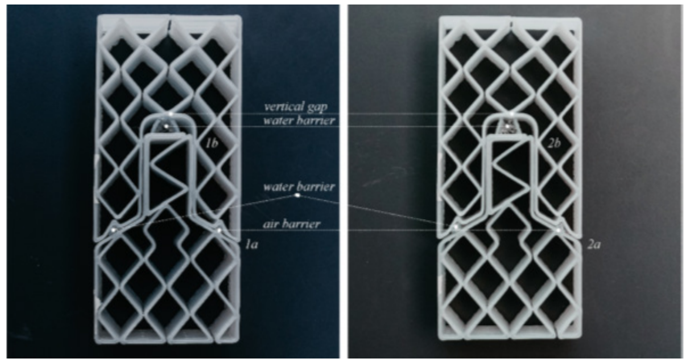
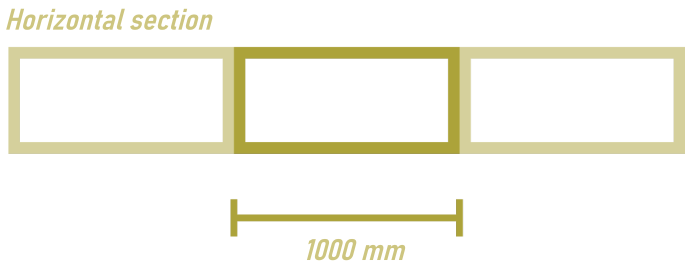


Figure 5.13: Façade panel connections, hybrid connection study for the horizontal direction (Cheibas et al., 2022)

5.4. Modular facade system

The context of the connector is a modular façade system, with elements that all have the same size, as seen in figure 5.15. The elements are based on the Spong3D prototype, however, since that does not have a specific size it is chosen to have elements of 1000mm width, by 2700 mm hight and 470 mm depth (see figure 5.14). This is floor to ceiling height, and the depth is determined by a standard insulation value of R=4,7m2K/W. It should be connected to the main structure on the top and bottom of the element.

The focus of the design lies on the vertical connector, in a wall. Corner solutions and connectors for elements on top of each other should either be designed separately or based on the connectors designed in this report.



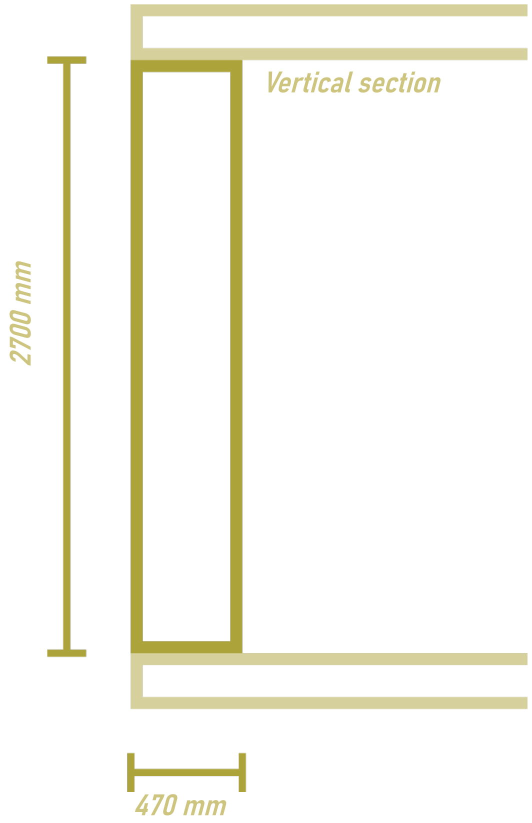


Figure 5.14: Panel dimensions (Own figure)

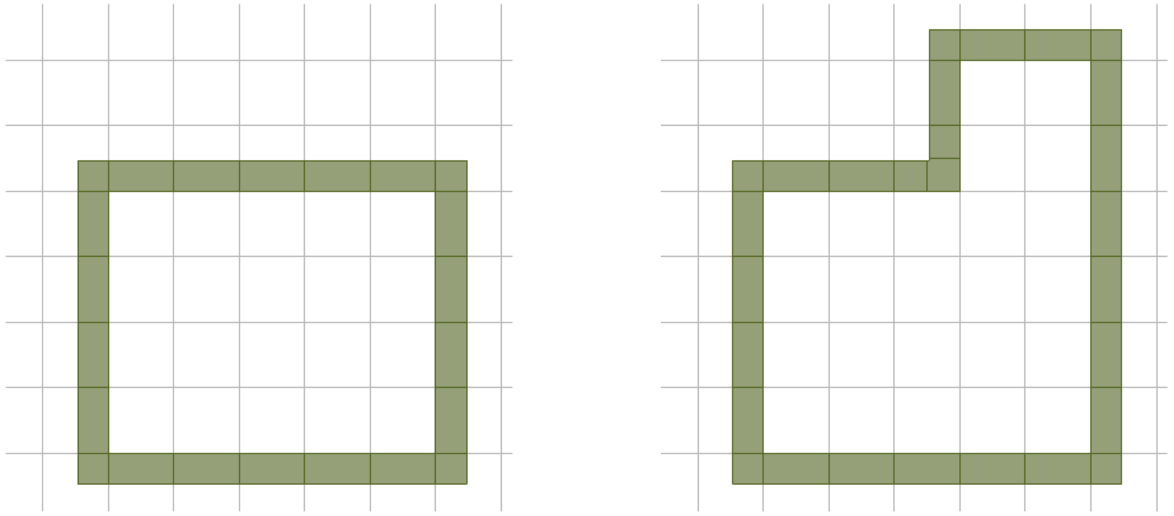


Figure 5.15: Modular façade system (own image)

5.5. Design principles

The base of the connector design is Design for Disassembly, so the element should be demountable. Besides it should be possible to take one single element out of a wall and place one between others (figure 5.16). This is needed for placing the last element, changing the layout and for replacement. To allow this, elements should be demounted in the horizontal plane and a third element should function as a lock to prevent the element to come loose on itself and prevent opening from the outside, see figure 5.16). The connector should be integrated in the mono-material element and be made from the same material. Lastly, the connection should not let water through. Although it does not lie within the scope of the project to test it, watertightness should be accomplished by making the way from outside to inside as long as possible.

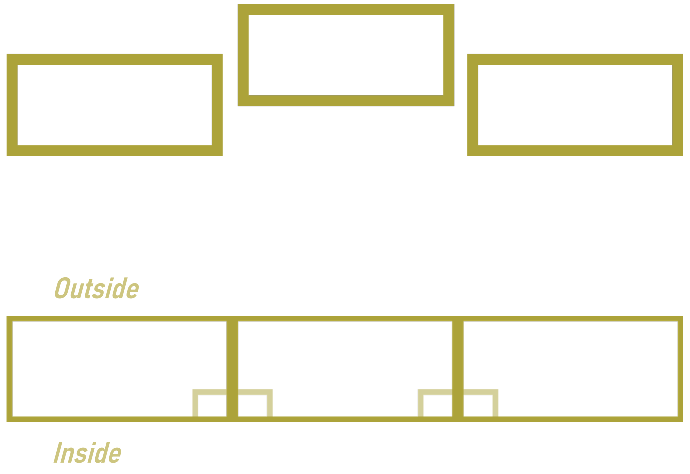


Figure *5.16: Principles, top: take one out. Bottom: locking element (Own figure)*

5.6. Decision matrix

In this thesis a decision matrix is used for evaluating the prototypes made. The model used here is based on the model by Güngör (2005), this can be found in appendix C. All categories from their model are used and the requirements are heavily inspired on Güngörs model. Since Güngörs model is more complex than needed for the purposes in this thesis, the rest of the structure is simplified into a matrix. The weights being chosen based on importance specifically related to circular building products made through AM.

In their paper, Güngör (2005) developed a decision model for making products designed for disassembly. They argue that all main stages of a life cycle should be taken into account in order to avoid negative effects of the design related to cost, assembly and performance of the product. Through a literature study, issues (or requirements) are selected that form the evaluation criteria for the designs. The issues are divided between clusters, which are formed based on the life cycle stages: Assembly concerns, in-use-period concerns and disassembly concerns. The clusters are weighted to each other on importance to the product. The issues are also weighted to each other within and between the clusters. This is done to ensure that scoring of each issue is counted correctly related to each other. (Güngör, 2005)

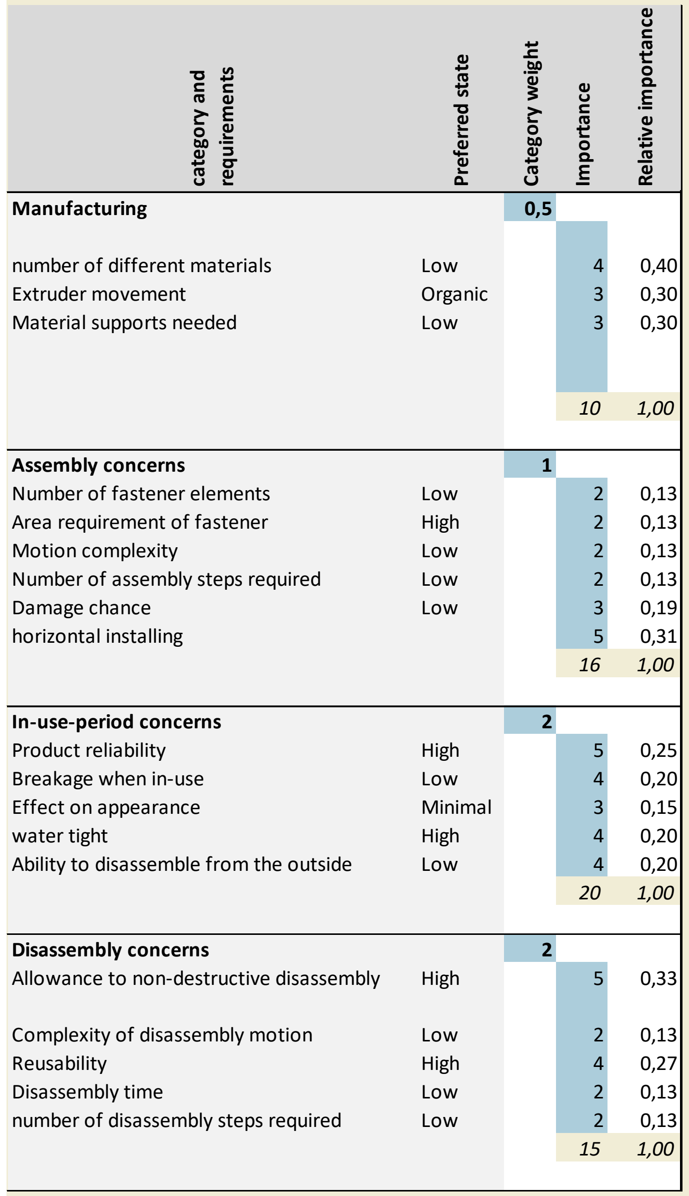
The version of the decision matrix used in this report is made to evaluate as clearly as possible the circular potential of the connectors and to be able to compare the prototypes to each other and choose the connector with the highest potential. It also shows where exactly the strengths and weaknesses of the connectors are, so improvements can be made in the design variants.

Although the model by Güngör is aimed at DfD, the model in this report is used for circularity, which is possible because the aims are quite similar (see chapter 3. Circular design strategies). The issues are adapted to be specific to AM for circularity. The clusters of life stages are used as categories for the requirements of the connector design. Since manufacturing plays a large role in the design for the connectors, it is added as a new category.

The categories manufacturing, assembly, in-use and disassembly all are weighted to each other, based on their importance for circularity. This can be found in the figures 5.17 and 5.18. The prototyping is done in two rounds, the concept round and the improved prototypes. The concept round is about making different designs with a low detail level and the second is about improving and happens on 1:5 scale. So less criteria are used for the first round and specific criteria are added for the second round, where the prototypes can be accurately compared to each other. Since most criteria are added to the manufacturing category, for the first round this is weighted 0,5 while in the second round it is weighed 1. Since the assembly is closely related to the manufacturing criteria, assembly is weighted a 1. In-use and disassembly both are weighted with a 2, since they are the most important to circularity.

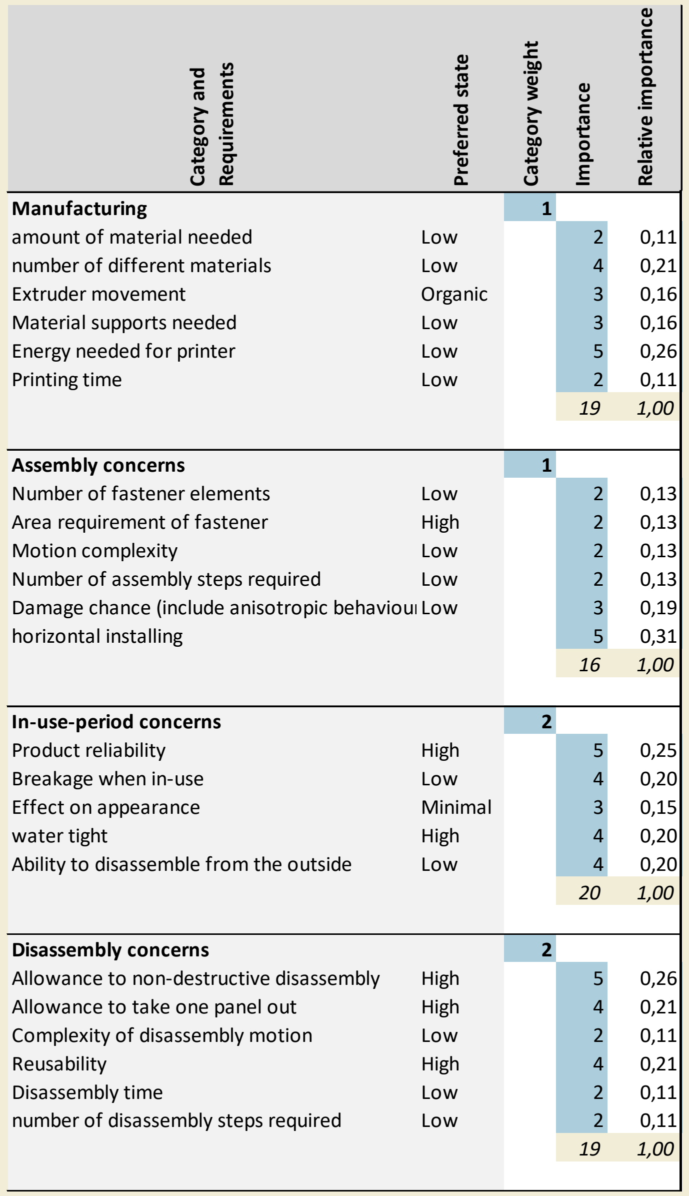
All requirements within the categories are also weighted on importance related to each other, as can be seen in the figures. They receive a score from 1 to 5 based on their relative importance, where 1 is not important and 5 is very important. To make each category weighted fairly to each other, a relative importance is calculated, where all requirements add up to 1 for each category. When a design is scored, it is multiplied by the relative importance of each requirement, added within the category and multiplied by the importance of the category.

When a connector is evaluated on its circular potential it is scored on each of the requirements on a scale of -3 to 3. This is shown in the table:



category and requirements	Preferred state	Category weight	Importance	Relative importance
Manufacturing		**0,5**		
number of different materials	Low		4	0,40
Extruder movement	Organic		3	0,30
Material supports needed	Low		3	0,30
			10	*1,00*
Assembly concerns		**1**		
Number of fastener elements	Low		2	0,13
Area requirement of fastener	High		2	0,13
Motion complexity	Low		2	0,13
Number of assembly steps required	Low		2	0,13
Damage chance	Low		3	0,19
horizontal installing			5	0,31
			16	*1,00*
In-use-period concerns		**2**		
Product reliability	High		5	0,25
Breakage when in-use	Low		4	0,20
Effect on appearance	Minimal		3	0,15
water tight	High		4	0,20
Ability to disassemble from the outside	Low		4	0,20
			20	*1,00*
Disassembly concerns		**2**		
Allowance to non-destructive disassembly	High		5	0,33
Complexity of disassembly motion	Low		2	0,13
Reusability	High		4	0,27
Disassembly time	Low		2	0,13
number of disassembly steps required	Low		2	0,13
			15	*1,00*

Figure *5.17: Decision matrix: concept prototypes (Own figure)*



Category and Requirements	Preferred state	Category weight	Importance	Relative importance
Manufacturing		**1**		
amount of material needed	Low		2	0,11
number of different materials	Low		4	0,21
Extruder movement	Organic		3	0,16
Material supports needed	Low		3	0,16
Energy needed for printer	Low		5	0,26
Printing time	Low		2	0,11
			19	*1,00*
Assembly concerns		**1**		
Number of fastener elements	Low		2	0,13
Area requirement of fastener	High		2	0,13
Motion complexity	Low		2	0,13
Number of assembly steps required	Low		2	0,13
Damage chance (include anisotropic behaviou	Low		3	0,19
horizontal installing			5	0,31
			16	*1,00*
In-use-period concerns		**2**		
Product reliability	High		5	0,25
Breakage when in-use	Low		4	0,20
Effect on appearance	Minimal		3	0,15
water tight	High		4	0,20
Ability to disassemble from the outside	Low		4	0,20
			20	*1,00*
Disassembly concerns		**2**		
Allowance to non-destructive disassembly	High		5	0,26
Allowance to take one panel out	High		4	0,21
Complexity of disassembly motion	Low		2	0,11
Reusability	High		4	0,21
Disassembly time	Low		2	0,11
number of disassembly steps required	Low		2	0,11
			19	*1,00*

Figure *5.18: Decision matrix: improved prototypes (Own figure)*

3	Excels at requirement
2	Achieves requirement
1	Barely achieves requirement
-1	Barely does not achieve requirement
-2	Does not achieve requirement
-3	Fails at requirement

This scale of scoring is used so there is a clear difference between the numbers, it is clear how high a prototype scores. If more numbers are used it will not be clear which score fits the prototype best, leading to errors. If less numbers are used it might not be clear which prototype scores best, because the final scores will be more similar to each other. Negative scores are used to create a clear indicator of when a prototype fails on its requirement.

Designs are scored on the working of the prototype, not on the concept of the design, to make a clear distinction between how it works versus how it was intended to work.

5.7. Design requirements

These are the requirements used for both the first and second round of prototyping. The definition is explained, as well as the preferred state.

Manufacturing

Number of different materials – The aim of the design is to make a mono-material connector, it is therefore preferred to have as little different materials as possible.

Extruder movement – An organic extruder movement uses less time and thus energy than sharp corners.

Material supports needed – Using supports means creating waste material, and thus also using more energy, so it is preferable to use no supports.

Assembly

Number of fastener elements – A small number of elements is preferred (Güngör, 2005). If many separate elements are used, they are more prone to being lost and it takes longer to assemble.

Area requirement of fastener – According to Güngör (2005) a minimal area is required for the connector. However, for 3D printed PET the opposite is true, since the material creeps over time, a maximal area is preferred, this is used for the decision model.

Motion complexity – This has to do with the ease of assembly. The more complex the assembly motion is, the more time it takes to install the product (Güngör, 2005).

Number of assembly steps required – The more steps required for installation, the more time it takes, so it is preferable to have less assembly steps (Güngör, 2005).

Damage chance – If the assembly of the connector causes it to damage, it needs to be replaced, which is not desirable. It is preferred to have a low damage chance (Güngör, 2005).

Horizontal installing – For the functionality of the product it is needed to install only using horizontal movement.

In-use

Product reliability – The connector should work according to its purpose (Güngör, 2005).

Breakage when in-use – If the connector brakes during the use phase, it loses its product value, therefore the product should have a low risk at damage during use (Güngör, 2005).

Effect on appearance – A good appearance has a positive effect on the length a product is used and increases the possibility of being used (Güngör, 2005).

Watertight – The connector should not allow water to get inside the walls.

Ability to disassemble from the outside – The building should be safe and locked from people on the outside.

Disassembly concerns

Allowance to non-destructive disassembly – In the 2001 studies by Güngör and Gupta (as cited in Güngör, 2005) it is stated that this is one of the most important requirements in Design for Disassembly, since it determines whether a product can be reused.

Complexity of disassembly motion – A low complexity of disassembly is preferred, to improve the chance it is disassembled and reused (Güngör, 2005).

Reusability – A good reusability is desired (Güngör, 2005).

Disassembly time - The less time the disassembly takes, the greater the chance it is disassembled without destruction at the end of life (Güngör, 2005).

Number of disassembly steps required – With less steps to take, the chance improves for disassembly without destruction.

These requirements are added for the second round:

Manufacturing

Amount of material needed – The connector should be optimized to use a minimal amount of material, more material means more energy is needed for the production of both the material and the product.

Energy needed for printer – Less energy is preferred.

Printing time – Less time means less energy being used, it also improves the usability of the product.

Disassembly

Ability to take one element out – This is desired so maintenance can be done and layout can more easily be changed.

DESIGN

6. Concept prototypes

6.1. Introduction

The design of the connector is made through prototyping on the 3D printfarm. This is done through three rounds of prototyping.

The first round is used to create different concepts, they are small and low in detail to be able to reduce the time and material needed for them. At the end of the first round, the concepts are compared to each other with the matrix as described in the previous chapter. The three highest scoring concepts are then chosen and further developed in the second round.

6.2. Dovetail

The dovetail connector is designed to form the starting point of the designs, to start to understand the behaviour of the material and the translation from digital model to object (figure 6.1). It is based on a dovetail connection in wood which connects on friction. It was made to slide together vertically, and be locked in horizontal direction by the shapes.

A tolerance of 1 mm is used between the elements and it is noticed that this is too small for a tight friction connector, since it slides apart easily.

It is also noticed that small details in the model can disappear in the 3D printed object, and that all corners come out slightly rounded. Since the extrusion width is 1.2 mm, details should be at least larger than that.

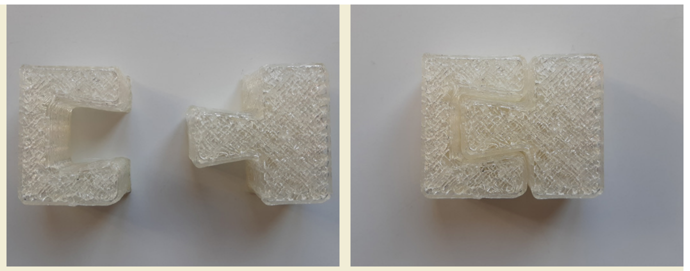


Figure 6.1: *Dovetail connector prototype (own image)*

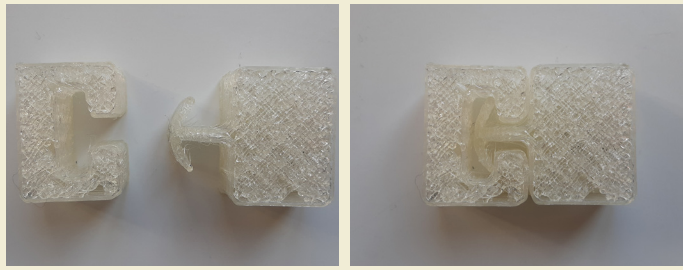


Figure 6.2: *T-spring 2 elements connector prototype (own image)*

The dovetail could only be designed to connect with a vertical sliding movement, which does not comply with the design principles. Because of the printing method a horizontal slot with this shape is not possible without adding support material, which should be avoided.

Since this design does not work within the principles and the design variant shown next has a similar principle, but shows more potential for further development, this design is not evaluated in the matrix.

6.3. T-spring

For the T-spring connector the flexible properties of the PET are used to form a clamping connection, see figure 6.2. One part of the connector forms a curved T shape, that slides into a recess located on the other side of the block.

Recycled plastic was used for this print, and it is observed to be less flexible than the virgin PET, this can be taken into account when designing with rPET.

The tolerances are tight enough to provide a sturdy connection that can be assembled and disassembled, and it also is reliable to stay connected throughout the use. However, similar to the dovetail connector, this connector can only be installed vertically, which prevents it from being used.

6.4. T-spring with locking element

The concept of this connector is to use the T-spring to clamp the blocks into place, but to install it horizontally through an extra opening made on one side of the recess, the spring can snap into place as seen in figure 6.3. A third element is used to lock it permanently into place.

This prototype does not function as expected, since the third element fails to lock the other elements into place. This would mean that the wall could collapse. Since it does show potential for assembly and disassembly, with some adaptations it could work properly. Because only one locking element is needed and its mechanism is hidden on the inside of the block, only a few seams can be seen, and it has a calm effect on the appearance of the block.

6.5. Hinging

The hinging connector is inspired on the T-spring design with locking element, but has another locking principle (figure 6.4). Two facade elements connect together through a snap fit and a third element can be twisted into place to form a lock that prevents movement of the block. The locking element works on a hinging principle, where a small force is needed to take out the third element if meant. But a large force is needed for the blocks to release on themselves, so that it is nearly impossible to break apart unintentionally.

Due to there being a delicate balance between the tolerances needing to be tight enough for it to snap together, but not so loose it falls apart on its own, the prototype does not fit together precisely. Even though, the locking mechanism does fulfill its purpose.

Since this connector only requires one locking element, like the previous prototype, assembly and disassembly can be done with little steps and in a short time frame. It also has a positive effect on the appearance of the wall. On the other hand, the connector area is relatively small compared to the other connectors.


Figure 6.3: *T-spring with locking element connector prototype (own image)*


Figure 6.4: *Hinging connector prototype (own image)*

6.6. Mortise and tenon

The mortise and tenon connector is inspired by wood joinery based on friction, just like the dovetail (figure 6.5). Two building blocks overlap and a tapered hole through both of them, the mortise, leaves space for a wedge, the tenon. This can then be locked with another wedge. As can be seen in the figure, two variants of the design have been printed.

This prototype showed the limitations of size and shape, because there were elements that were relatively small and had sharp corners, the precision was reduced. It has a large hole through the entire block, which makes it hard to make watertight, and also needs a large amount of elements, which makes the ease of assembly and disassembly low. Besides, it has a low surface area for the connection and because the material is susceptible to creep, it cannot be relying on this form of friction, since the connection will get looser over time.


Figure 6.5: *Mortise and tenon connector prototype. Left: variant 1. Right: variant 2 (own image)*

6.7. Clips

With this connector the two sides of the panel slide together, they have aligning slots, to place clips in that lock them in place, see figure 6.6. The prototype is made with infill to provide the right support for the shapes. It makes it more solid than the other prototypes.

The connector has a large contact surface and is made of robust shapes that do not break easily. It does however consist of a large number of components, which have a negative impact on the appearances and the ease of assembly and disassembly.

6.8. Snap fit

For the snap fit connector two panels snap together and because of a lip, temporarily lock into place, a third element stops the panels from being disassembled, see figure 6.7. Once the extra element is removed, this is possible again.

The prototype does not yet function as intended, since the locking element does not stop the panels from being disassembled. It does however show potential otherwise, since it is easily assembled and disassembled because of the single locking element.

6.9. Evaluation

After prototyping the designs were evaluated with the decision matrix, as seen in figure 6.8. The three highest scoring prototypes from round one will be chosen for the second round of prototypes, where they will be improved upon. The highest scoring prototypes are the Hinge, Snap Fit and Clips connectors. These also have the highest potential to be improved into working prototypes.

The Hinge and Snap Fit have a similar principle where the panels snap together and a third element, which spans from floor to ceiling is used to lock the elements together. Compared to the other elements they score high on assembly and disassembly, with a minimal amount of different elements and steps to take into account and a high ease of movement. They can both improve on the extruder movement during manufacturing and the product reliability during use.

The Clips connector scores lower than the two mentioned before. Although it is a sturdy connection that is reliable during use, multiple clips are needed along the length of the panel, adding time and complexity to the assembly and disassembly stage and having a large impact on the appearance of the wall. Since this can be improved upon, it is taken to the next stage.

The T-spring and the mortise and tenon connectors are not taken to the next round of prototyping, since the T-spring cannot be used for this design, the T-spring with locking element does not work as intended and the Mortise and Tenon has a low product reliability, would not be watertight and has a large impact on the appearance of the prototype.

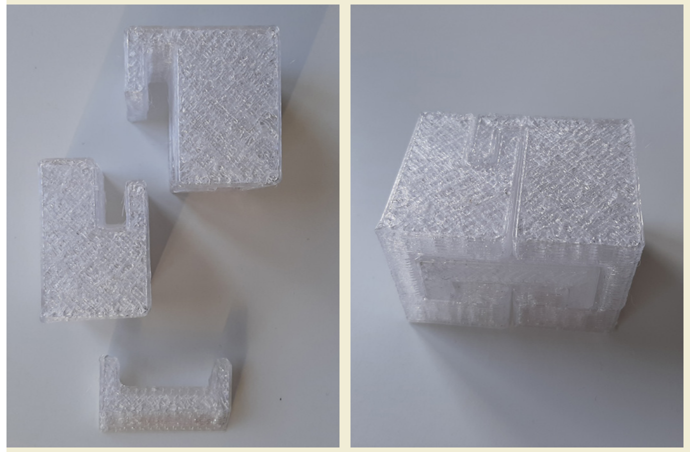
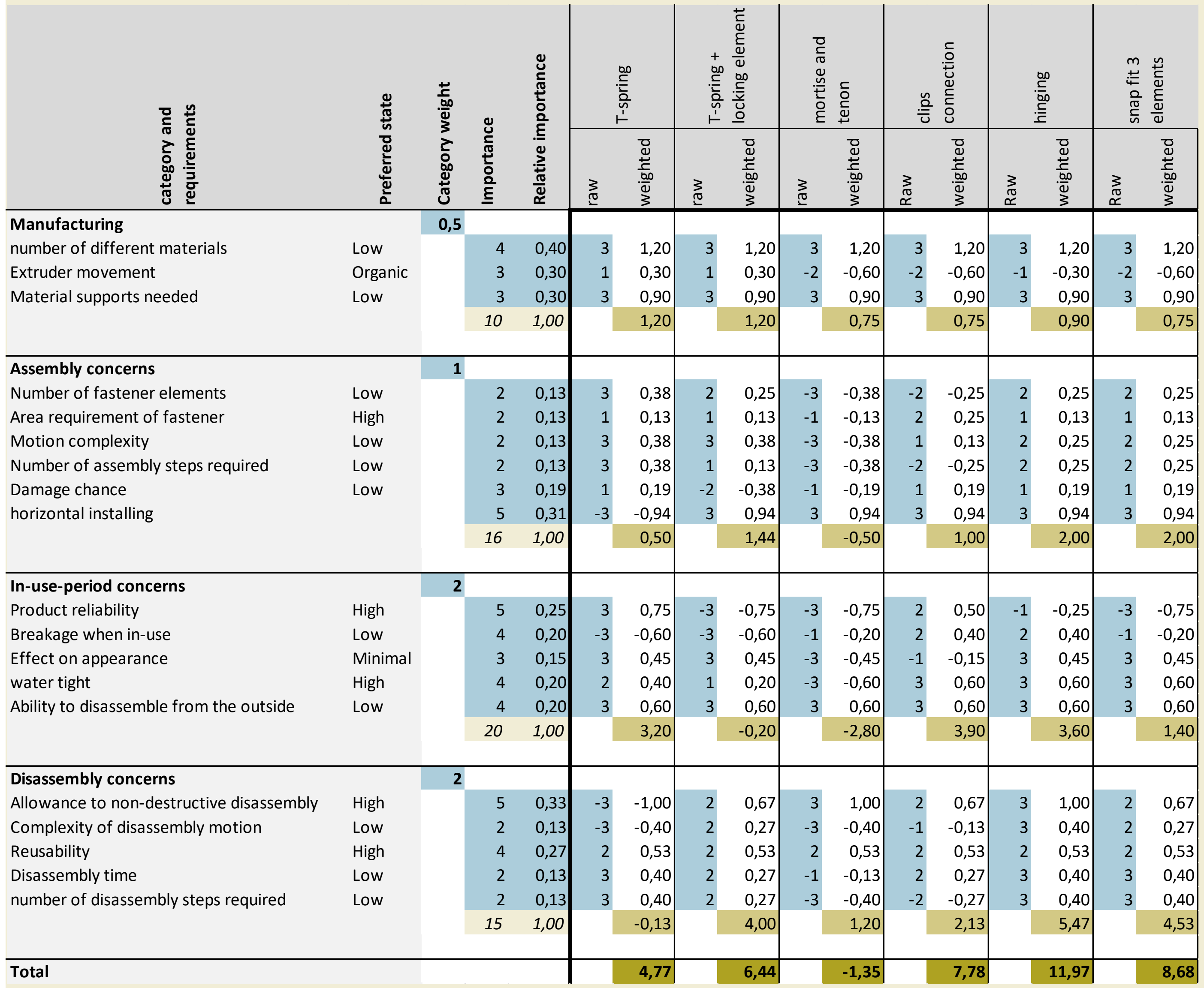


Figure 6.6: Clips connector prototype (own image)


Figure 6.7: Snap Fit connector prototype (own image)



category and requirements	Preferred state	Category weight	Importance	Relative importance	T-spring		T-spring + locking element		mortise and tenon		clips connection		hinging		snap fit 3 elements	
					raw	weighted	raw	weighted	raw	weighted	Raw	weighted	Raw	weighted	Raw	weighted
Manufacturing		0,5														
number of different materials	Low		4	0,40	3	1,20	3	1,20	3	1,20	3	1,20	3	1,20	3	1,20
Extruder movement	Organic		3	0,30	1	0,30	1	0,30	-2	-0,60	-2	-0,60	-1	-0,30	-2	-0,60
Material supports needed	Low		3	0,30	3	0,90	3	0,90	3	0,90	3	0,90	3	0,90	3	0,90
			10	*1,00*		1,20		1,20		0,75		0,75		0,90		0,75
Assembly concerns		1														
Number of fastener elements	Low		2	0,13	3	0,38	2	0,25	-3	-0,38	-2	-0,25	2	0,25	2	0,25
Area requirement of fastener	High		2	0,13	1	0,13	1	0,13	-1	-0,13	2	0,25	1	0,13	1	0,13
Motion complexity	Low		2	0,13	3	0,38	3	0,38	-3	-0,38	1	0,13	2	0,25	2	0,25
Number of assembly steps required	Low		2	0,13	3	0,38	1	0,13	-3	-0,38	-2	-0,25	2	0,25	2	0,25
Damage chance	Low		3	0,19	1	0,19	-2	-0,38	-1	-0,19	1	0,19	1	0,19	1	0,19
horizontal installing			5	0,31	-3	-0,94	3	0,94	3	0,94	3	0,94	3	0,94	3	0,94
			16	*1,00*		0,50		1,44		-0,50		1,00		2,00		2,00
In-use-period concerns		2														
Product reliability	High		5	0,25	3	0,75	-3	-0,75	-3	-0,75	2	0,50	-1	-0,25	-3	-0,75
Breakage when in-use	Low		4	0,20	-3	-0,60	-3	-0,60	-1	-0,20	2	0,40	2	0,40	-1	-0,20
Effect on appearance	Minimal		3	0,15	3	0,45	3	0,45	-3	-0,45	-1	-0,15	3	0,45	3	0,45
water tight	High		4	0,20	2	0,40	1	0,20	-3	-0,60	3	0,60	3	0,60	3	0,60
Ability to disassemble from the outside	Low		4	0,20	3	0,60	3	0,60	3	0,60	3	0,60	3	0,60	3	0,60
			20	*1,00*		3,20		-0,20		-2,80		3,90		3,60		1,40
Disassembly concerns		2														
Allowance to non-destructive disassembly	High		5	0,33	-3	-1,00	2	0,67	3	1,00	2	0,67	3	1,00	2	0,67
Complexity of disassembly motion	Low		2	0,13	-3	-0,40	2	0,27	-3	-0,40	-1	-0,13	3	0,40	2	0,27
Reusability	High		4	0,27	2	0,53	2	0,53	2	0,53	2	0,53	2	0,53	2	0,53
Disassembly time	Low		2	0,13	3	0,40	2	0,27	-1	-0,13	2	0,27	3	0,40	3	0,40
number of disassembly steps required	Low		2	0,13	3	0,40	2	0,27	-3	-0,40	-2	-0,27	3	0,40	3	0,40
			15	*1,00*		-0,13		4,00		1,20		2,13		5,47		4,53
Total						**4,77**		**6,44**		**-1,35**		**7,78**		**11,97**		**8,68**

Figure 6.8: Decision matrix concept prototypes (own image)

7. Improved prototypes

The improved prototypes will be 3D printed on the same scale so a fair comparison can be made, again with the decision matrix.

In each paragraph the prototypes are first improved to the criteria in the matrix, and then a 1:5 prototype is printed. These 1:5 all have the same dimensions and infill, so they can accurately be compared to each other. Of each design variant a cross section was made to test the ability to take out a panel or to be able to place the last panel in between the already standing ones.

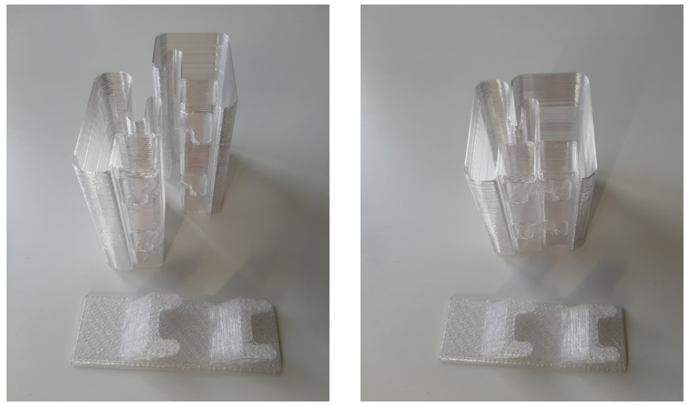


Figure 7.2: Clips test prototype (own image)

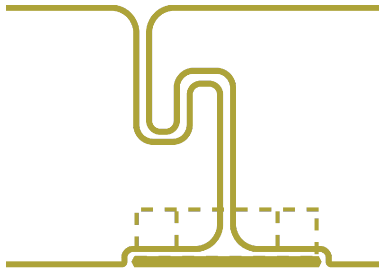


Figure 7.1: Clips design (own image)

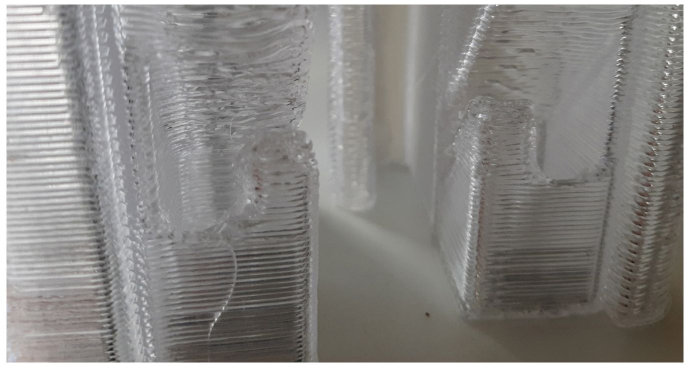


Figure 7.3: Clips tear detail (own image)

7.1. Clips

The design of the Clips connector was first changed by connecting the clips to a strip, this improves both the appearance and the ability to assemble and disassemble. Although visually the design is a lot simpler than before, it still has an impact on the entire design, since the strip has a different printing direction.

Some observations were made in relation to the printing process and material. Although an overhang angle of 45 degrees was tested before, on this print, it was too steep and the material started to sag. This is probably caused by an increased layer height and the use of only one wall layer, without infill, which is less stable. Because of this, the slot became too small for the clips, and the angle of the clips changed slightly, so that they could not fit together, see figure 7.2.

Because it did not fit well, the material cracked, this happened simultaneously along a layer bond and perpendicular to the layers (figure 7.3), suggesting that the material is actually as strong on both directions, contrary to the research suggesting anisotropic behaviour.

Taking into account the lessons learned from the prototype, a 1:5 prototype was printed with infill, which solved the inaccuracies in the print. The 1:5 actually has tolerances that are too loose, since there is some movement possible. The assembly steps can be found in figures 7.4 and 7.5. The cross section made showed that even with loose tolerances, it is not possible to take out one single panel, see figure 7.6 and 7.7.

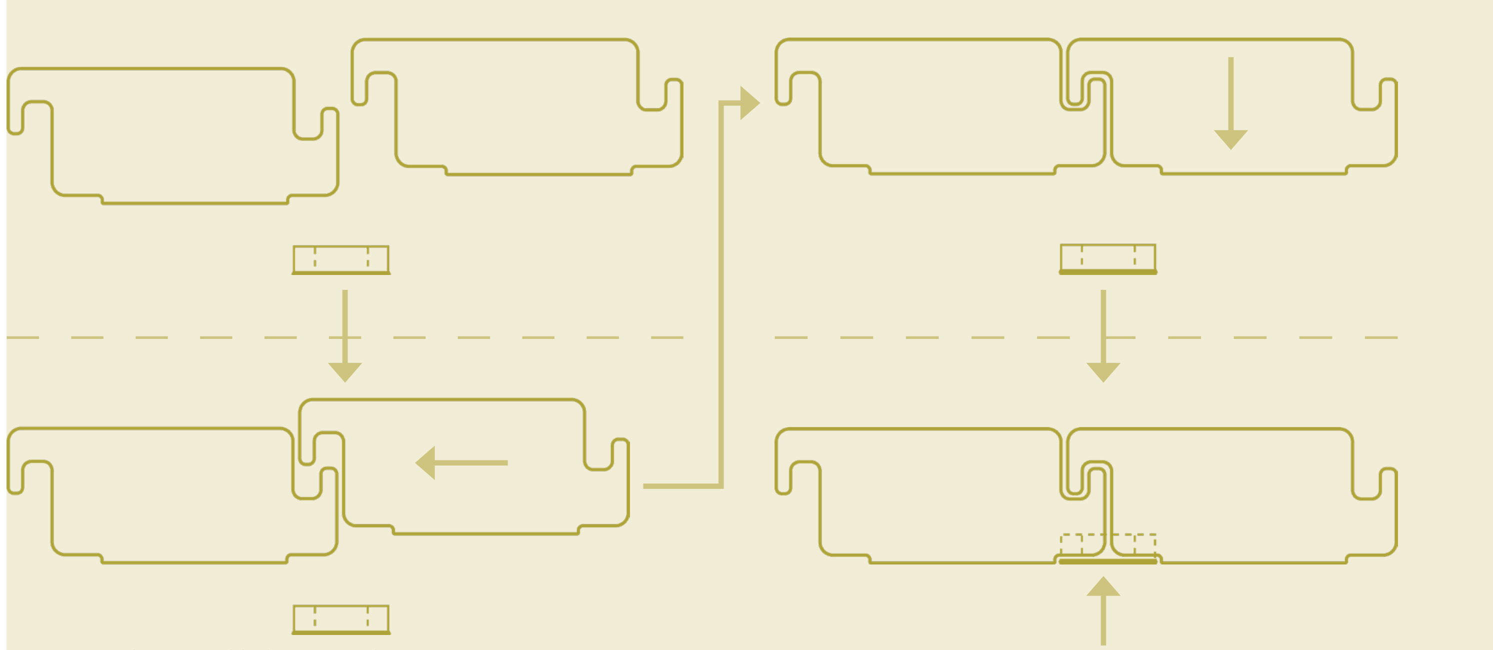


Figure 7.4: Clips assembly (own image)

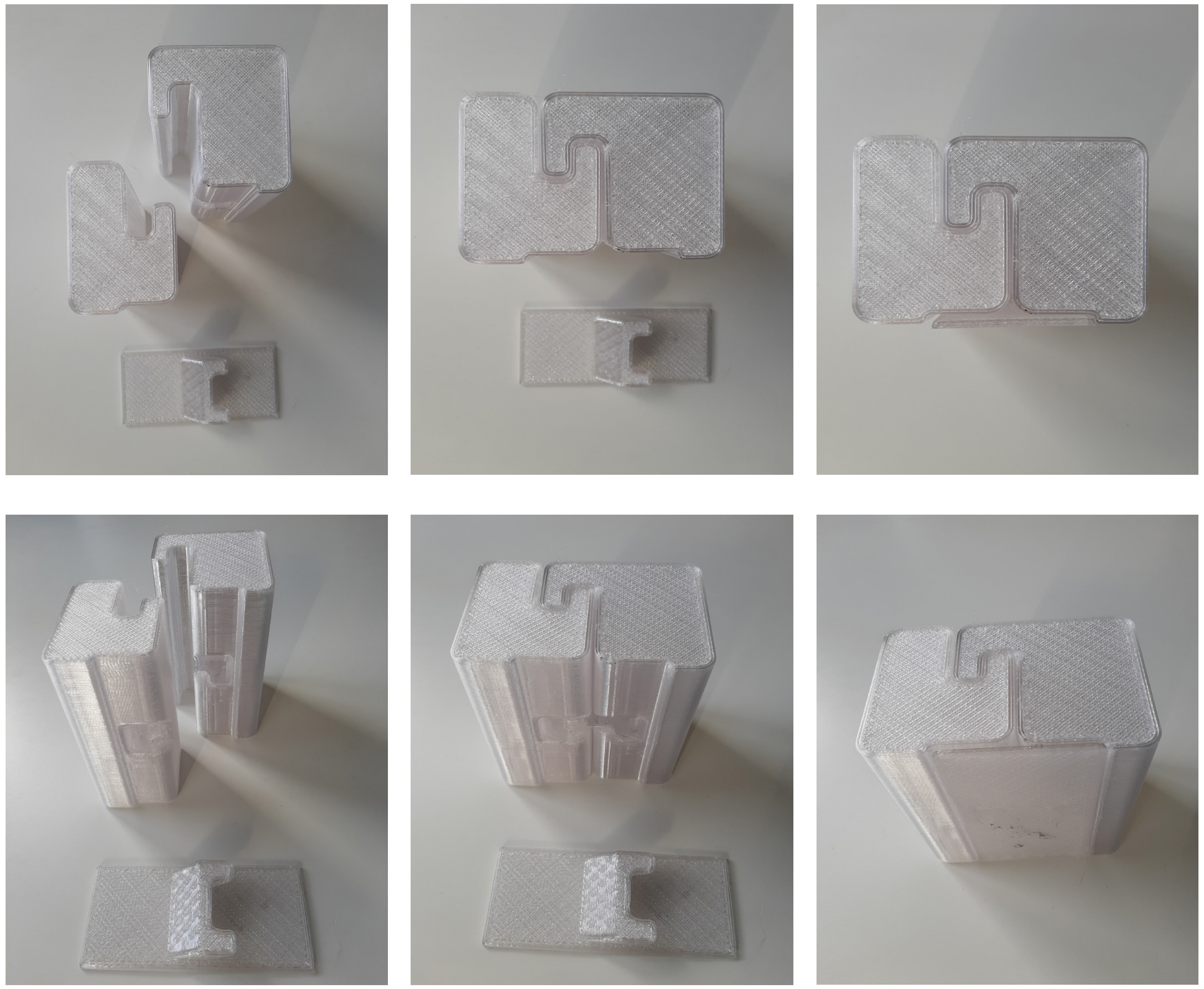


Figure 7.5: Clips final design assembly (own image)

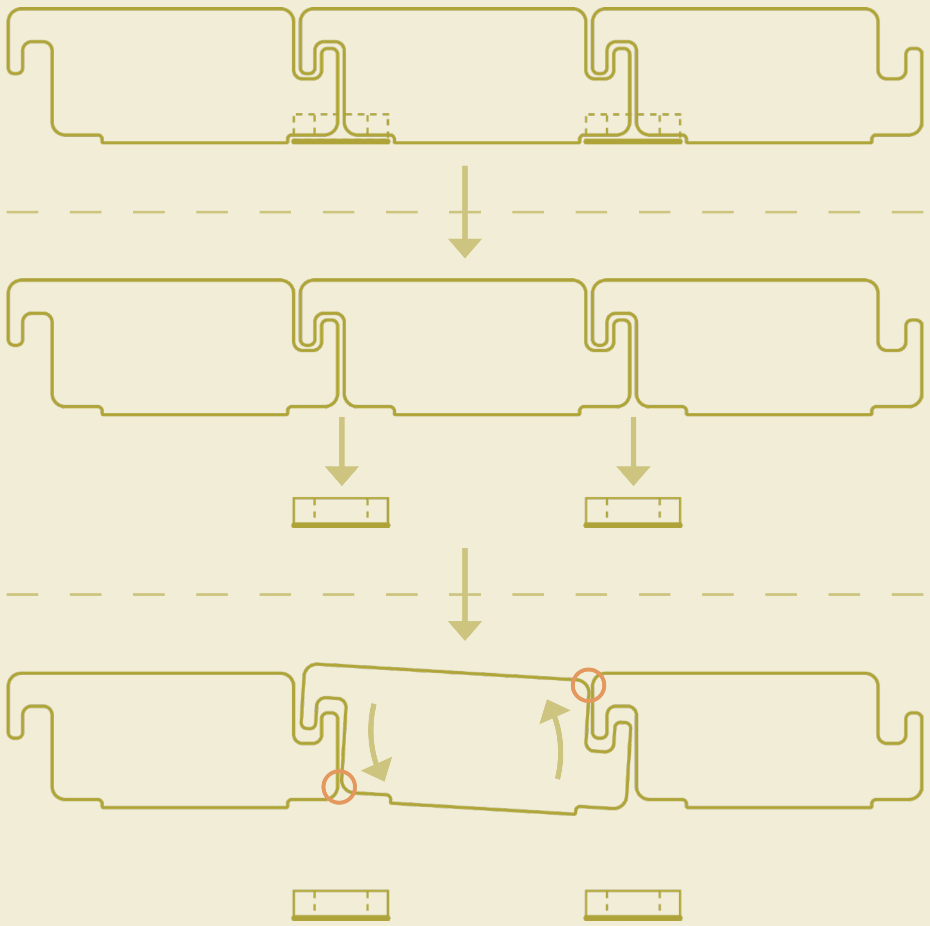


Figure 7.6: Clips disassembly (own image)

Figure 7.7: Clips final design 3 panels (own image)

Figure 7.8: Hinging design (own image)

7.2. Hinging

For the Hinging connector the tolerances and the shape are changed in the next prototype. The tolerances became too tight, because the snapping elements broke on both sides (figure 7.11). This also showed a weak point in the connector. With improved tolerances and more hight in the connector it is expected not to form any problems.

The next prototype made for the Hinging connector was the 1:5 with infill (figure 7.12). Larger tolerances were used compared to the previous prototype, which makes the connector reliable. It was able to assemble, see figure 7.9. However, disassembly of the hinging element was not possible because the added length made the snapping elements stiffer and the location of the snap locked itself in. With this design it is possible to take out a single panel in between others (figure 7.13).

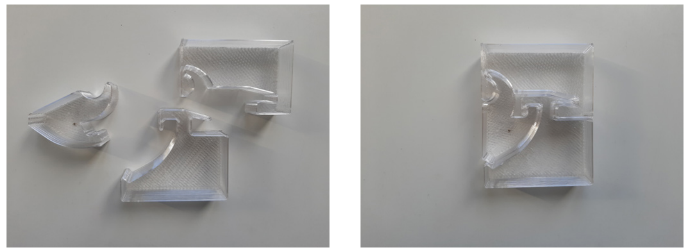


Figure 7.10: Hinging design variant 1 (own image)

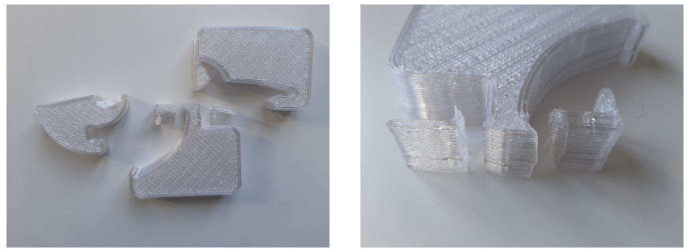


Figure 7.11: Hinging design variant 2(own image)

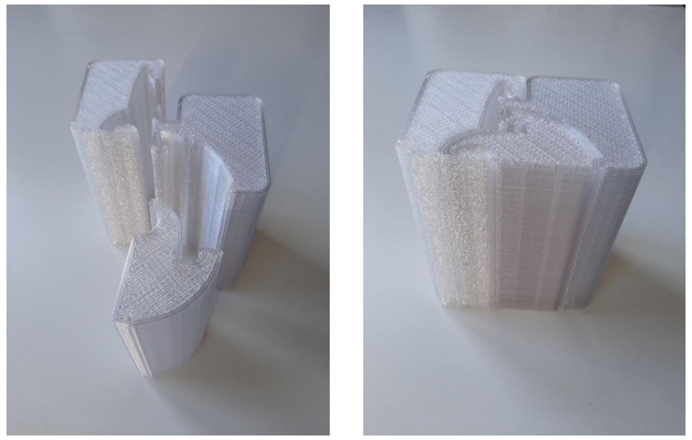


Figure 7.12: Hinging final design front view (own image)

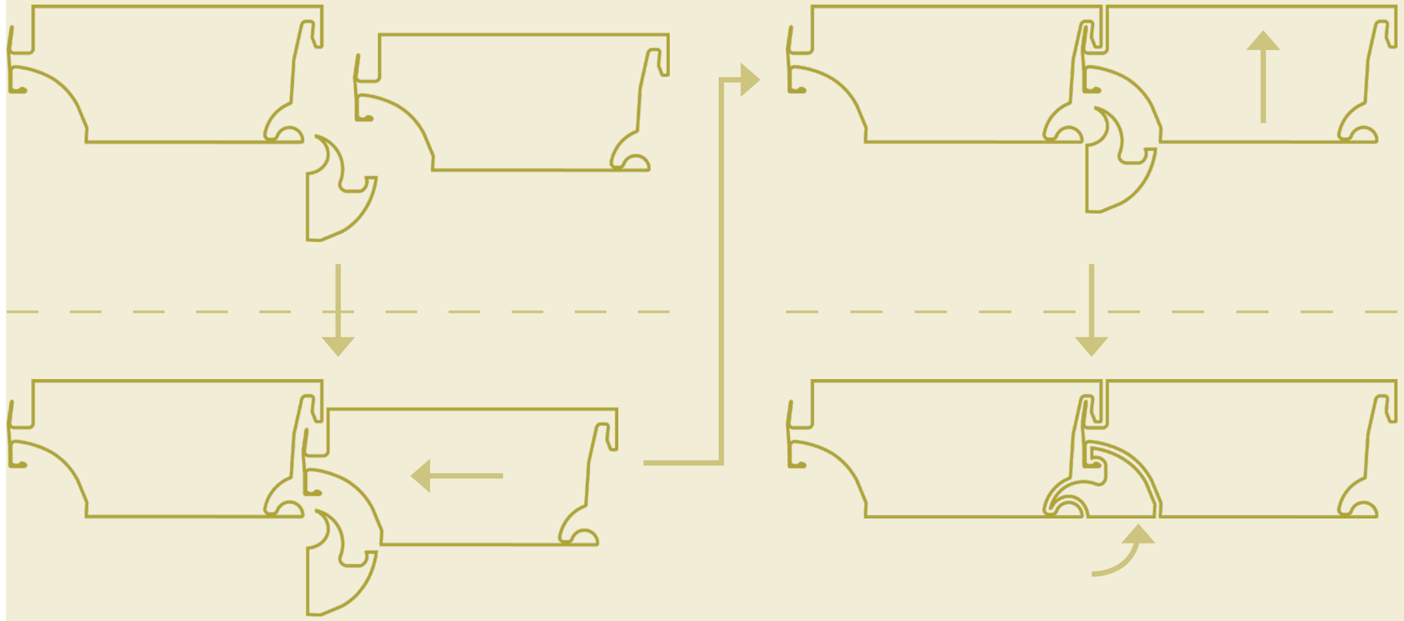


Figure 7.9: Hinging assembly (own image)

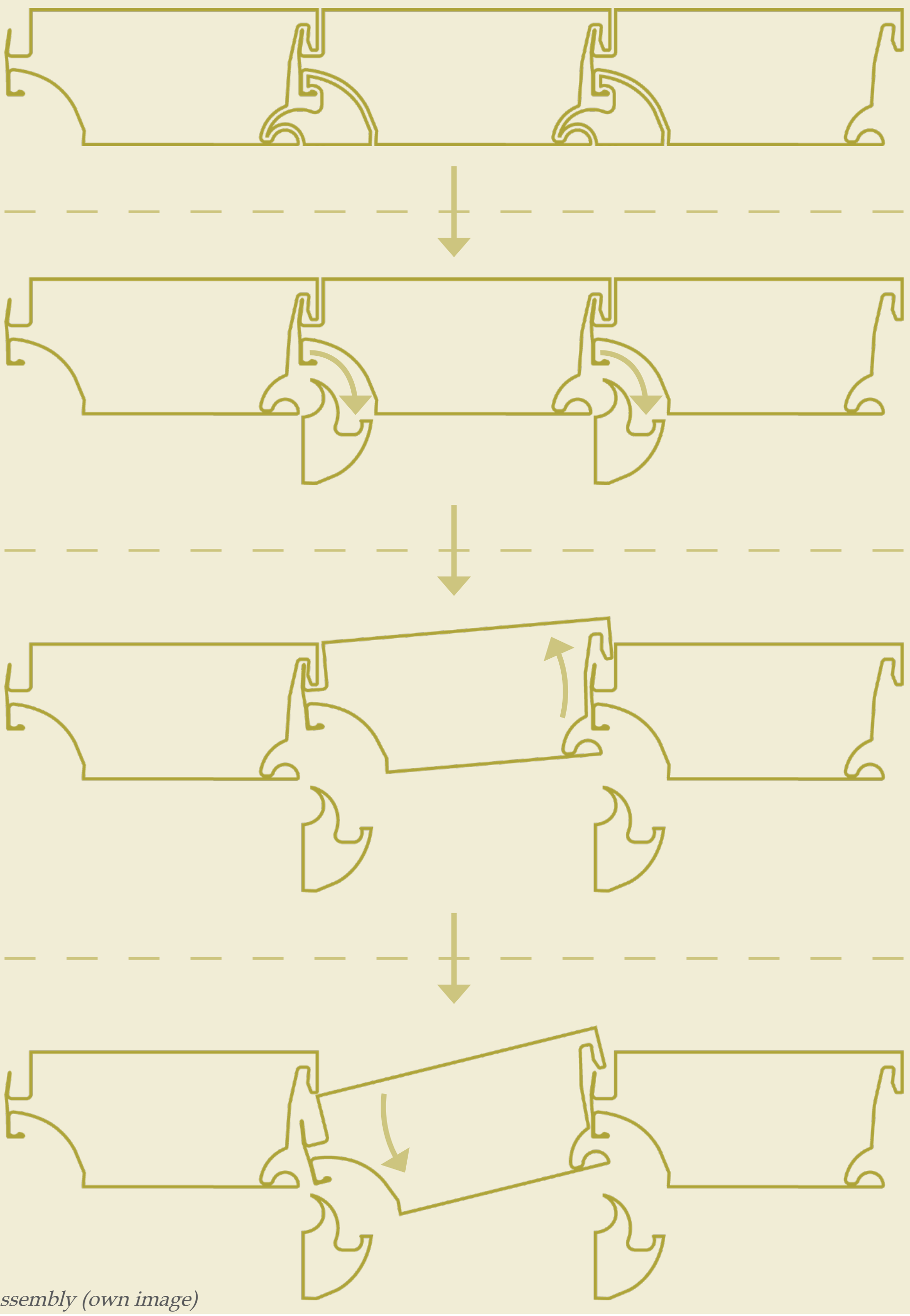


Figure *7.13 Hinging disassembly (own image)*

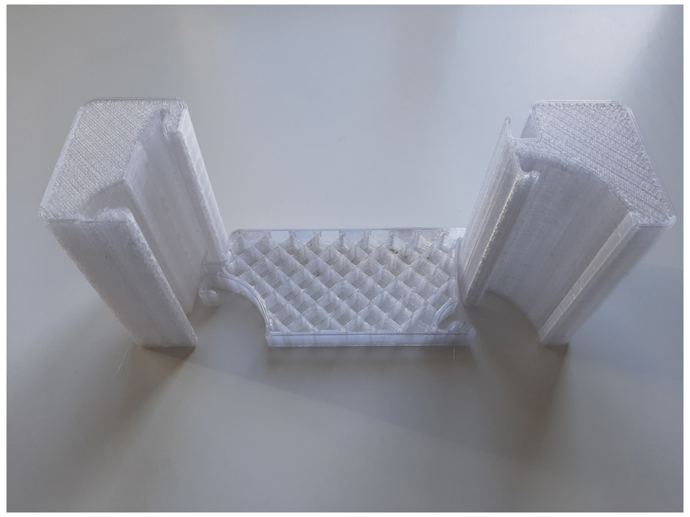


Figure *7.14: Hinging final design three panels (own image)*

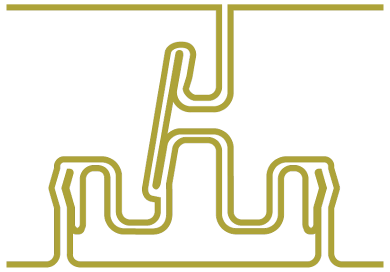


Figure *7.15: Snap Fit design (own image)*

7.3. Snap Fit

The Snap Fit connector needed to be changed to improve the reliability of the connector. The design of the lip on the panel where another panel snaps into needs to be adapted so that it locks into place, and the locking element needs to lock the two together and take the force from the fragile parts of the design.

Multiple versions were made to test the locking element, see figure 7.19. The first version clamps only on one side, the prototype clamps on the wrong side, making it non functional. Even if it was clamping on the other side, all the force would be on the snap, it also was not easily disassemblable, since the material is not flexible enough to snap into place. For the next version a locking element was made with three protrusions that were flexible, so they could snap into place. However, too much material was taken away for this element, so the clamping effect did not work. For the last test version, extra material was added for the protrusions, so the element did clamp the panels together. Again, the tolerances were slightly too tight.

For the final 1:5, the tolerances were changed and it fits together (figure 7.16 to 7.18). The assembly can be found in figure 7.20. It was found that when disassembling, the locking element cannot simply snap out, but needs to be pulled from one side, releasing bit by bit. The longer the element is, the more space is needed for taking it apart, causing problems in small spaces. It was also noticed that the element is almost symmetrical, making it hard to know what is the right way to assemble it, this can be easily solved however by making it fully symmetrical. It was also found not possible to take out only one panel out, at least when the two panels next to it remain in the same position, because it locks itself into place. When the locking elements of 3 elements are removed, the middle panel could be taken out by shifting the outer panels slightly (figure 7.21).

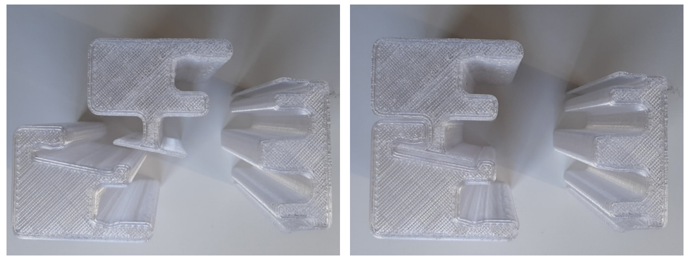


Figure *7.16: Snap Fit final design assembly (own image)*

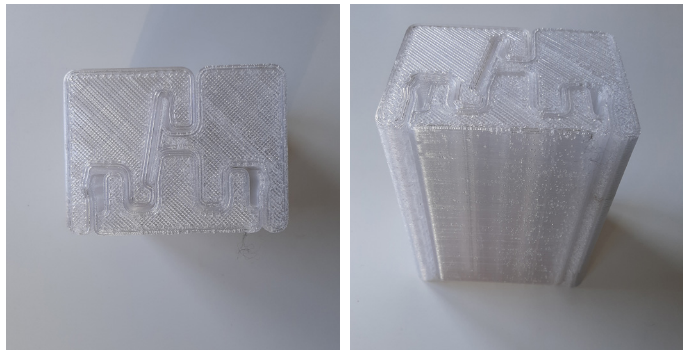


Figure *7.17: Snap Fit final design top and front view (own image)*

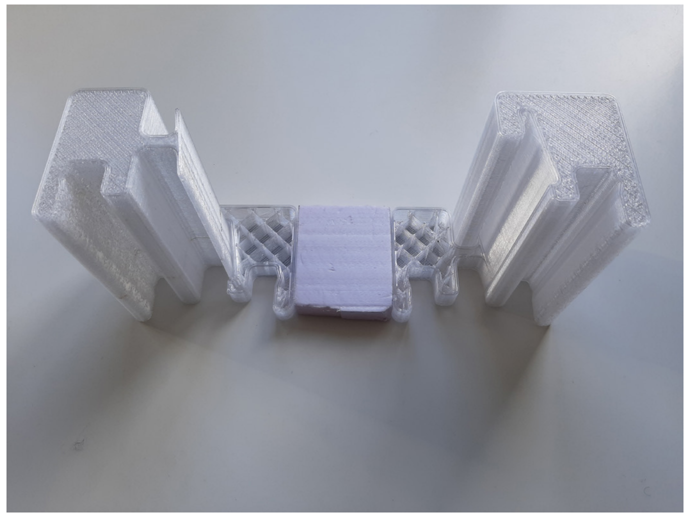


Figure *7.18: Snap Fit final design three panels (own image)*

Figure*7.19: Snap Fit design variants (own image)*

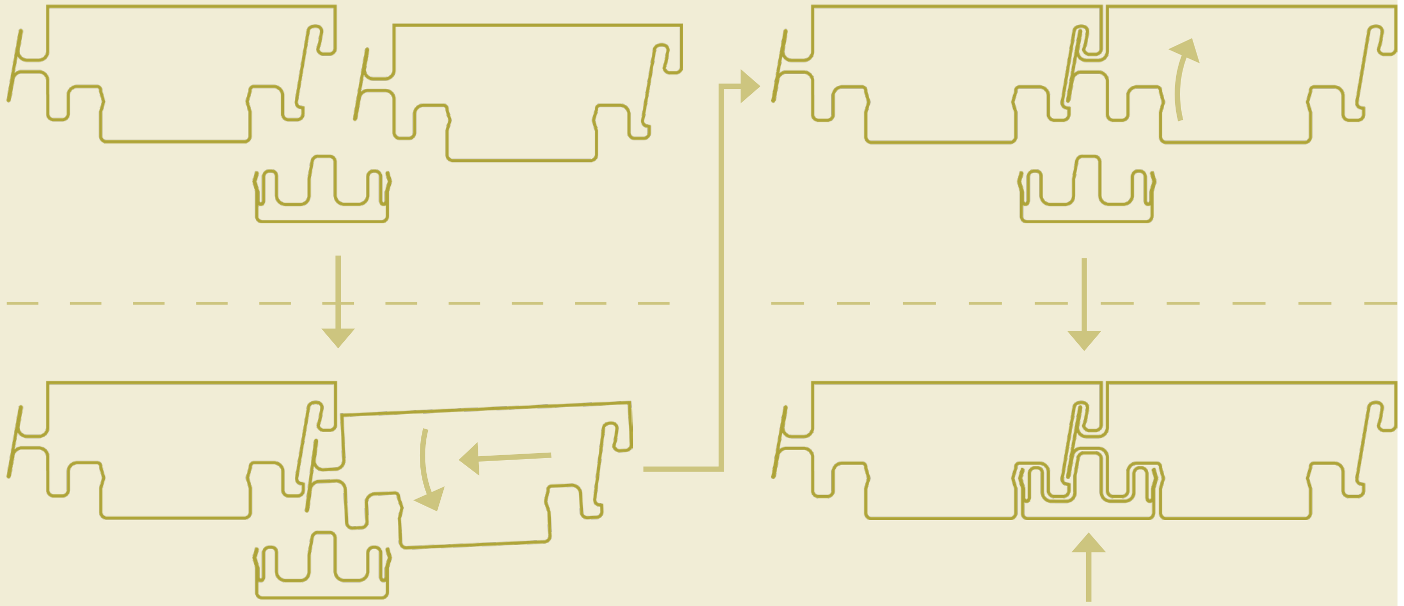


Figure *7.20: Snap Fit assembly(own image)*

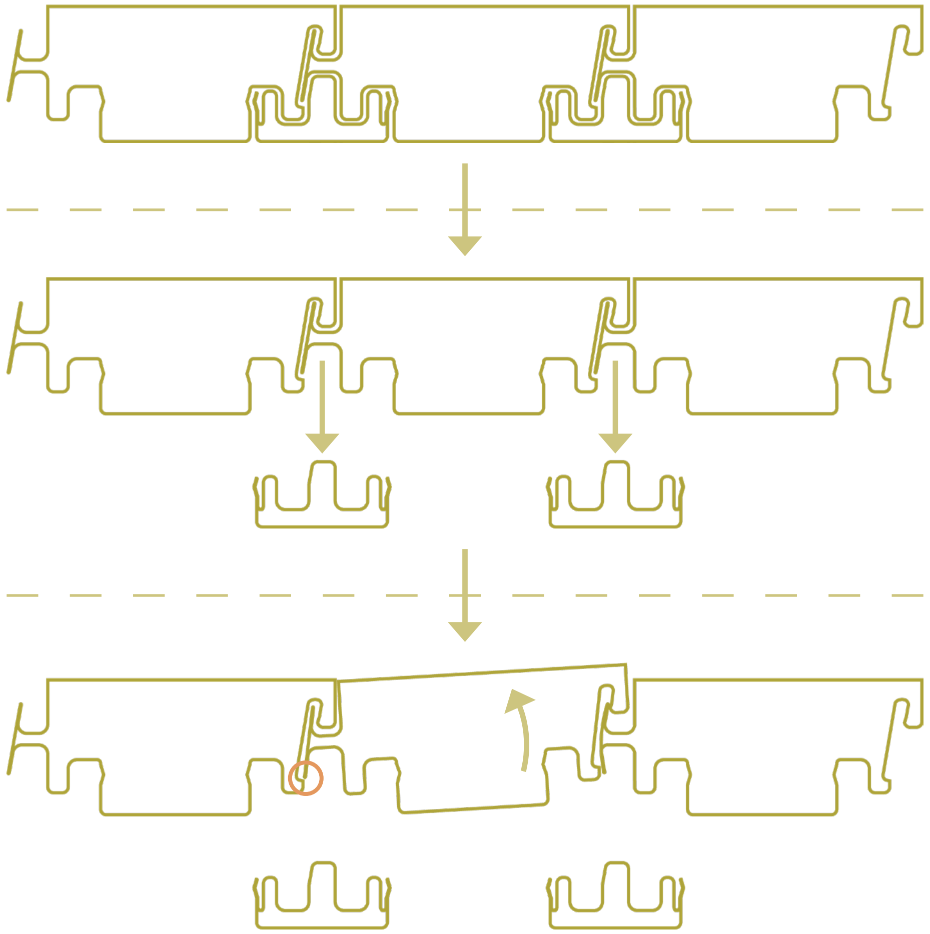


Figure *7.21: Snap Fit disassembly (own image)*

7.4. Evaluation

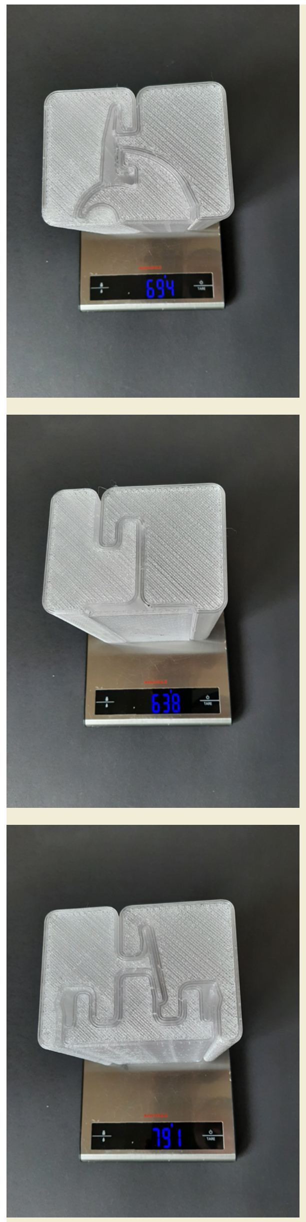
When comparing the connector prototypes, in the decision matrix, a similar final score is found. With a few exceptions they score high on all requirements. They each have a few weaknesses and for choosing which panel should be taken to the next round it is analysed which weaknesses are most easily solved.

The Clips connector has a low area for connecting, and because there will be multiple clips on one strip, the panels need to be exactly aligned in all directions and all clips need to be assembled together. With the current tolerances the clips are also not permanently locking the wall together, making it less reliable than the other elements. And lastly, it is not possible to take out only one panel. The tolerances and removing of a panel can be changed with a new prototype, but the other flaws are more inherent to the design.

The Snap Fit connector has the worst printing settings, it takes long to print and the extruder movement is not organic. Because there are more thin elements to the connector than the designs it is also slightly more prone to damage during assembly or disassembly. And lastly, it is harder to take apart, because of the locking element and because taking one panel out cannot be done easily. Although the printing settings and damage chance could be slightly improved, the main weaknesses are not easily addressed.

The Hinge connector does not get the highest score for the manufacturing, since the shapes are quite complex. The product reliability and the allowance for disassembly score somewhat lower, because the tolerances are not exactly right, so it is both loose and hard to take apart, which can be changed in a next design variant.

Since the Hinge can be improved upon more easily than the others and shows the greatest potential in the concept, it is chosen for further development.



Category and Requirements	**Preferred state**	**Category weight**	**Importance**	**Relative importance**	Clips		Hinge		Snap Fit	
					raw	weighed	raw	weighed	raw	weighed
Manufacturing		**1**								
amount of material needed	Low		2	0,11	3	0,32	2	0,21	1	0,11
number of different materials	Low		4	0,21	3	0,63	3	0,63	3	0,63
Extruder movement	Organic		3	0,16	3	0,47	1	0,16	-1	-0,16
Material supports needed	Low		3	0,16	3	0,47	3	0,47	3	0,47
Energy needed for printer	Low		5	0,26	3	0,79	2	0,53	1	0,26
Printing time	Low		2	0,11	3	0,32	2	0,21	-1	-0,11
			19	*1,00*		3,00		2,21		1,21
Assembly concerns		**1**								
Number of fastener elements	Low		2	0,13	3	0,38	3	0,38	3	0,38
Area requirement of fastener	High		2	0,13	-1	-0,13	2	0,25	3	0,38
Motion complexity	Low		2	0,13	1	0,13	3	0,38	3	0,38
Number of assembly steps required	Low		2	0,13	3	0,38	3	0,38	3	0,38
Damage chance (include anisotropic behaviou	Low		3	0,19	2	0,38	2	0,38	1	0,19
horizontal installing			5	0,31	3	0,94	3	0,94	3	0,94
			16	*1,00*		2,06		2,69		2,63
In-use-period concerns		**2**								
Product reliability	High		5	0,25	-1	-0,25	1	0,25	3	0,75
Breakage when in-use	Low		4	0,20	3	0,60	2	0,40	3	0,60
Effect on appearance	Minimal		3	0,15	1	0,15	3	0,45	3	0,45
water tight	High		4	0,20	3	0,60	3	0,60	3	0,60
Ability to disassemble from the outside	Low		4	0,20	3	0,60	3	0,60	3	0,60
			20	*1,00*		3,40		4,60		6,00
Disassembly concerns		**2**								
Allowance to non-destructive disassembly	High		5	0,26	2	0,53	-1	-0,26	1	0,26
Allowance to take one panel out	High		4	0,21	-3	-0,63	2	0,42	-1	-0,21
Complexity of disassembly motion	Low		2	0,11	3	0,32	3	0,32	3	0,32
Reusability	High		4	0,21	2	0,42	2	0,42	2	0,42
Disassembly time	Low		2	0,11	3	0,32	3	0,32	3	0,32
number of disassembly steps required	Low		2	0,11	3	0,32	3	0,32	3	0,32
			19	*1,00*		2,53		3,05		2,84
Total					**48**	**10,99**	**53**	**12,55**	**48**	**12,68**

Figure *7.22: T-spring 2 elements connector prototype (own image)*

8. Final Design: C-cure

For the final design the hinge connector is improved into the C-cure connector. The principle is kept the same, only a few changes are made to the design. For the Hinge connector had some trouble staying closed on itself, and to disassemble. So the C-cure has an extra snap fit to the locking element and locks in a different position. Besides, for the panel the locking recess is moved somewhat for ease of disassembly. (See figure 8.1)

In the figures 8.9 and 8.10 it can be seen how it is assembled and disassembled. This element has only been sketched and should be tested with a print.

The figures 8.3 and 8.4 show how the connector looks within the wall. A pattern of vertical and horizontal lines is created from the inside of the building. On the outside only vertical lines can be seen. To prevent the locking element from getting so high it cannot stay stable when printed, each element is about a meter high.

Recesses should be added as a handle for opening the locking element. See figure 8.7 and 8.8.

The name of the final design should be explained shortly. C-cure (secure) is chosen because of its purpose: to secure two panels together. The C stands for the fact that it is a circular product. Besides, this is the movement that is made when installing the locking element.

Watertightness

One main function of façades is to keep rainwater out of the building, but since the additive manufactured façade element in this thesis is mono-material, there aren't any sealing materials to stop the water at the edges of the panels. Although testing the watertightness would be too early in these stages of prototyping, watertightness was still aimed for in the design. Two design elements will prevent water leaking inside. The first being having a long path the water has to take in order to travel inside. The other has to do with capillary action, with two sides of the plastic close together and the plastic attracting moisture, the water will travel horizontally through the connected sides. To prevent this, a gap is created where the water will run down and in this way, the façade can be drained (figure 8.2).

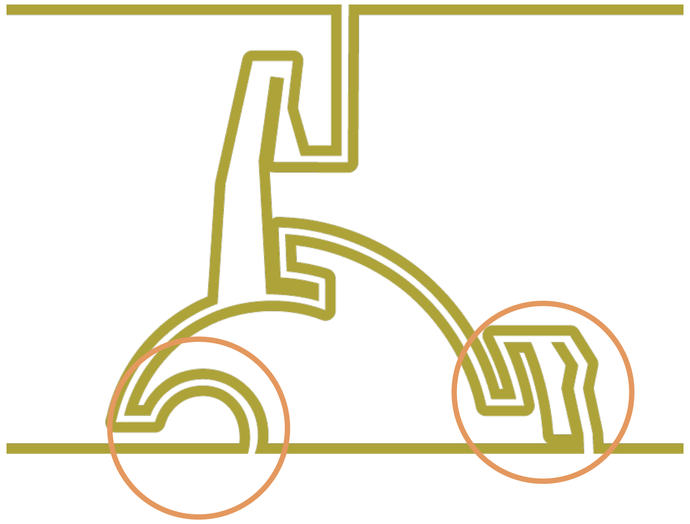


Figure 8.1: Improvements (own image)

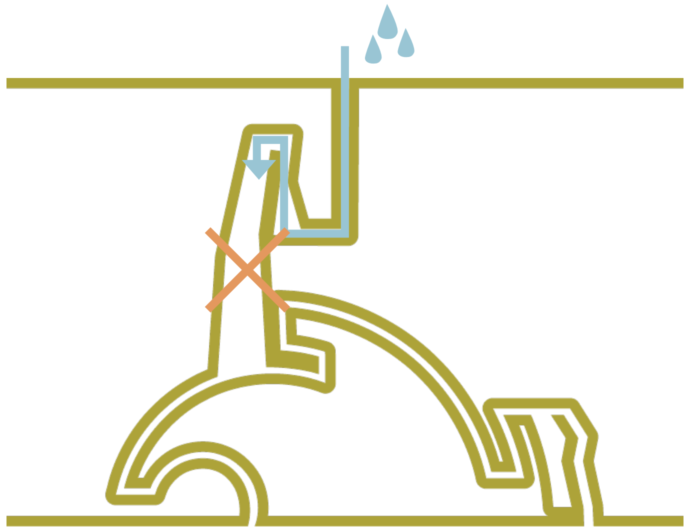


Figure 8.2: Watertightness (own image)

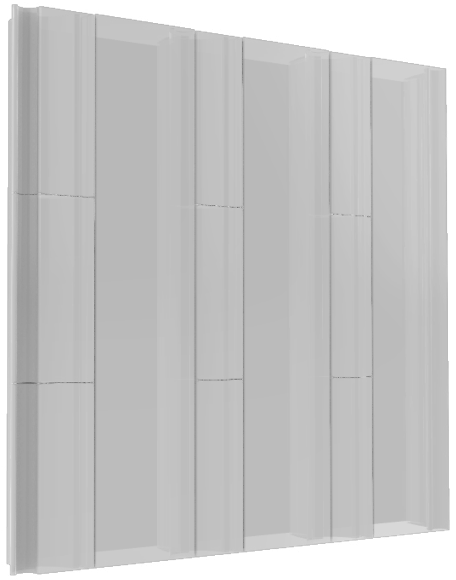


Figure 8.3: Inside (own image)

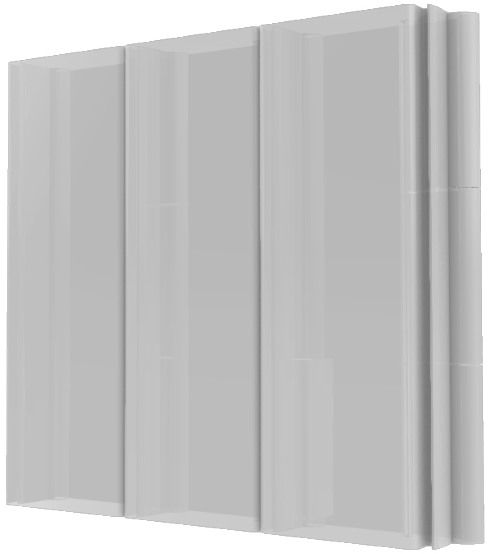


Figure 8.4: Outside (own image)


Figure 8.5: Locking element (own image)


Figure 8.6: assembly and disassembly (own image)


Figure 8.7: Handles design variant inside (own image)

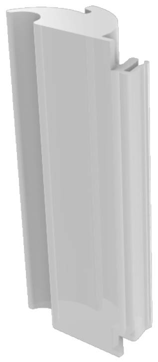


Figure 8.8: Handles design variant locking element (own image)

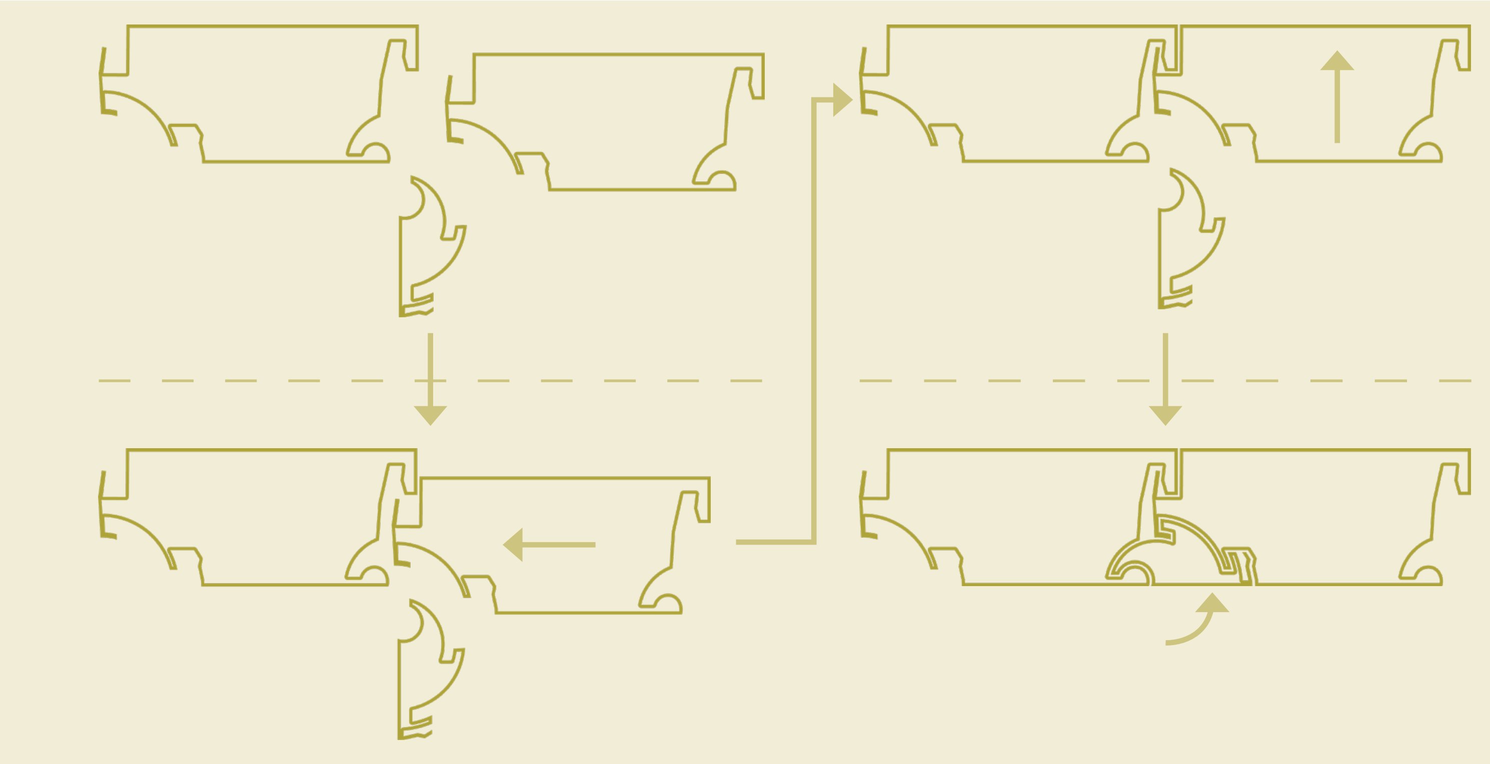


Figure 8.9: *Assembly (own image)*

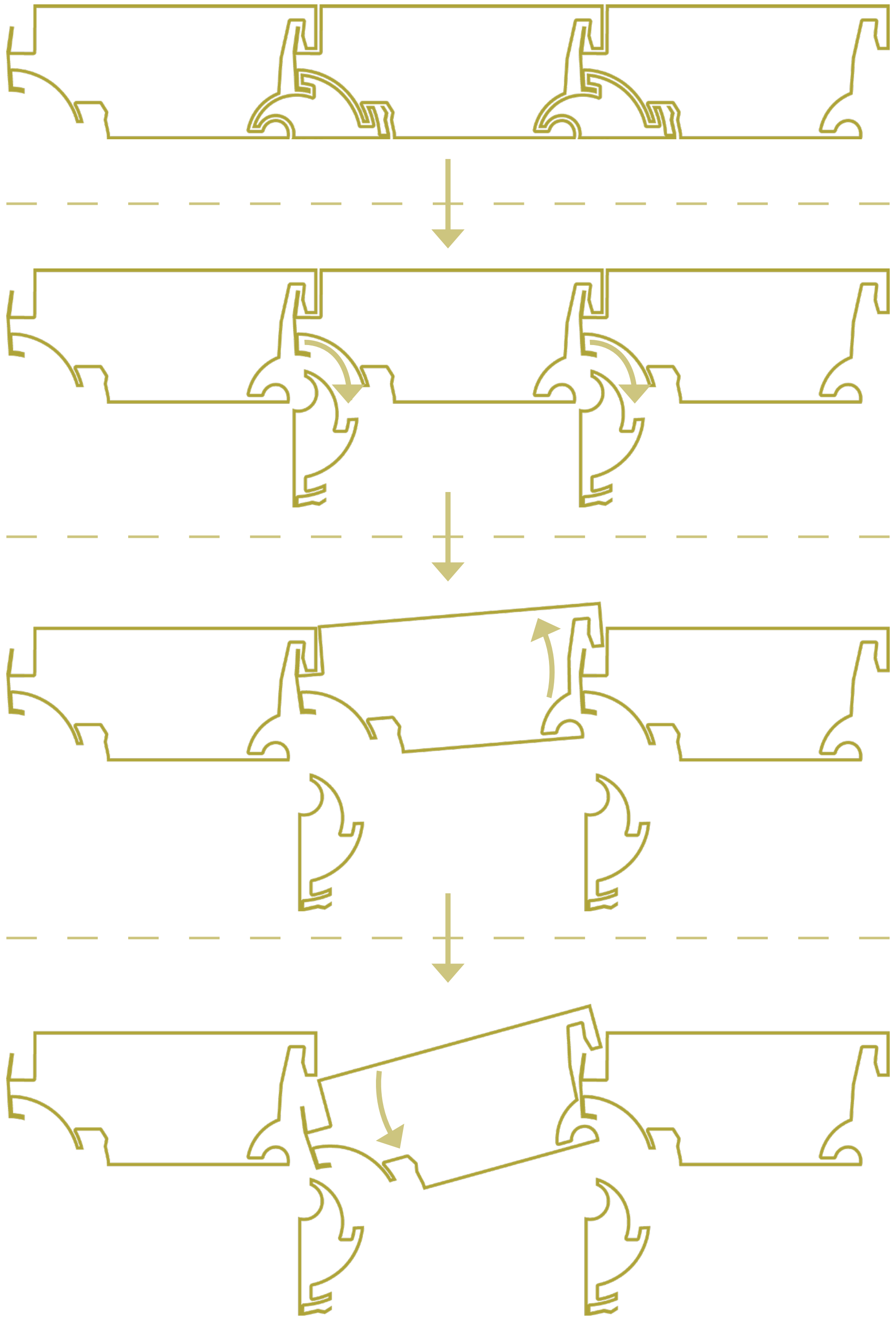


Figure 8.10: *Disassembly (own image)*

CONCLUSIONS

9. Discussion

9.1. Results

In this paragraph, the results from the sub questions and main research questions are summarized.

Through a literature study, research was conducted into the use of Additive Manufacturing (AM) to produce circular building products. It was found that AM has the potential to produce these products.

AM allows for local production, so large parts do not need to be transported and local materials can be used, like PET waste. The shape of a 3D print can be optimized for strength and material reduction, prints can be made specific to the situation, but standardization for modular components is also possible. AM elements can be mono-material and lightweight, and the construction can be done in a clean environment, since no dust is created. Lastly, no or little waste is created during production.

This means that material use, and transport are reduced, components can be reused, and materials can be recycled at the end of life.

Through analysis the circular potential of the Spong3D block was determined. The block was analysed on three circularity domains: Material, Manufacturing and Design and compared to Hempcrete as an alternative mono-material block. It was found that both blocks had a different approach on circularity and thus could not use each others circular strategies.

While hempcrete should be used on a small scale, because of the low initial investment, Spong3D should be used on a larger scale. Besides PET should be kept as high in value as possible because it is a technical material with a high GWP. On the contrary hempcrete can be recycled and composted.

The Spong3D block has a low GWP if it is made with recycled PET. Besides, using PET waste as a material source has added benefits of reducing an excess of waste. The energy used for production can be improved by manufacturing the element with an industrial robot extruder, which is energy efficient and can produce large elements. The element is a mono-material block, meaning it has potential for recycling and is simple in its design with no internal connectors. Overall Spong3D has circular potential if the improvements mentioned above are implemented.

Through the design requirements formulated from the literature study and analysis, a clear framework was developed for a connector that is designed for disassembly. The improved designs fulfilled almost all requirements, and in the final c-cure design the final flaws are improved. In the design the two panel halves snap together, and a third element locks the two panels together and provides extra stability.

The added connector to the Spong3D improves the circular potential of the element. It allows for reusing of the panels, with a high flexibility in layout of the façade panels.

9.2. Discussion

In this thesis it was aimed to find the possibility of designing demountable connectors for AM circular façade panels. It was found that the design of a DfD connector can improve the circular potential of AM thermoplastic façade panels. A connector was designed that meets requirements set through the literature study and analysis of the Spong3D panel.

The development of a decision model for the design process, through the literature study and analysis, provided a structured basis for the prototypes. A clear aim could be found for the design and the different prototypes could be compared to each other through a point system.

The designs all turned out based on the same principle, although the concept designs had variations between them, the three final designs all were based on snapping together, with a third element to lock them. The question arises whether this solution is simply the best with regards to the requirements or if the structure pushed too much toward only one solution.

The final design forms the first of its kind, where the connector allows separate panels to be taken out, is watertight, and demountable. This means that, if this succeeds extensive testing to bring it from a proof-of-concept to a product in the industry it could bring AM façade prototypes like Spong3D on the market as well.

Even though research exists into watertight, demountable connections (Cheibas et al., 2022; Taseva et al., 2020), these all work on a stacking principle, meaning if one panel needs to be taken out, the whole façade needs to be disassembled. The possibility to take one out adds to the flexibility of the design, where a floorplan can be easily changed to suite changing needs.

Although it can be concluded that DfD mono-material AM connectors can be designed, the research also shows some limitations. For this thesis the focus lied on the proof-of-concept for the connectors, no testing was done with regards to the watertightness and strength of the connectors. The designs also focused on one scenario, namely a vertical connector on a straight wall. Even though with the approach of the decision model and clearly set requirements, the hinge connector still shows great potential.

In future research the applicability of the connector could be tested. The watertightness should be assessed through exposing it to water and observing whether water can come through the connector. Besides the strength of the connector could be tested to wind loads, as well as the durability of the connector elements for long term use and how often it can be assembled and disassembled without increasing the damage chance. During prototyping it was noticed that recycled PET behaved slightly differently from the virgin PET, it acted stiffer and seemed more brittle than the virgin material, so it should be tested what exact differences are found and what design changes should be made to consider these differences.

Besides, it could be researched through design what potential the connector design shows in different scenarios like corner solutions and horizontal connectors. Finally, the potential of the connector can be tested by making a full-scale prototype.

10. Conclusion

This thesis aimed to find how to design AM PET mono-material demountable connectors for a circular façade system through research through prototyping. Based on the final hinge design tested to the requirements, it can be concluded that demountable connectors can be designed. The use of an external element that locks two façade elements together was found to align with the requirements for manufacturing, assembly, in-use and disassembly.

The approach of studying the literature related to AM and circular product design, then analysing the Spong3D panel and based on that making prototypes was taken to go from general to specific. First a knowledge foundation was created and then a specific situation was analysed, making it so that in the design phase there was a clear context to build upon. The outcome of the design phase was hard to predict, because it could not easily be observed whether the list of requirements would lead to one design that scored high on all requirements or multiple designs that partly fulfilled requirements. The fact that the final design fulfils all requirements is promising for further development of the connector.

Although the connector fulfils the requirements, further research is needed to determine the applicability of the connector. The strength, durability, and watertightness should be tested as well as the extension of the design into corner solutions and horizontal connectors.

Overall this thesis shows AM can be used as a manufacturing method for circular building products, and that demountable connectors have the potential to improve the circular potential of mono-material façade elements.

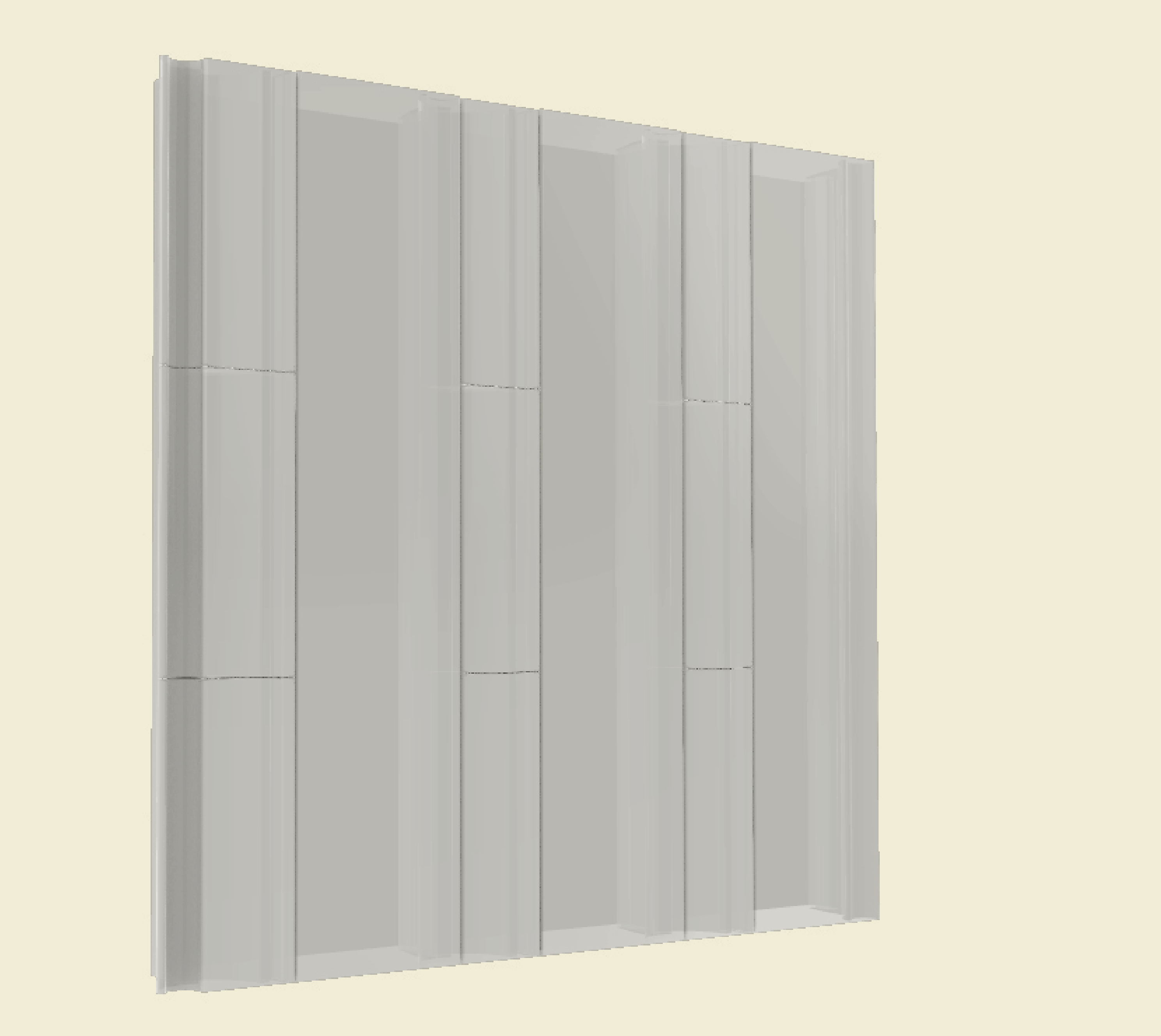


Figure *10.1: C-cure (own image)*

11. Reflection

This thesis aims to find the extent to which rPET and additive manufacturing (AM) can be used to create a connector designed for disassembly. The final product consists of a thesis and a final design. The first stage of the research focused on creating a clear foundation, then the topic was further researched through a literature study, an analysis of the designs within the field was made and based on requirements formulated through the literature study and the analysis a set of prototypes were designed and one was chosen to further optimize.

The literature study creates a clear understanding of the definitions AM, Circular Building Products and Design for Disassembly and relations between them. Within the analysis a clear understanding of the state of the art for additively manufactured circular building products was created and the research gap for circular connectors for additively manufactured circular building products was found. Through research through prototyping, several design variants were developed for connectors designed for disassembly and through a decision model consisting of requirements the prototypes were further improved and one was chosen as final design.

The potential of using AM for the development of circular thermoplastic façade elements has been researched, and prototypes of AM thermoplastic façade elements have been made. However, a gap has been identified in the development of AM connectors that can be disassembled. Research into this topic has the potential to improve the circular potential of AM thermoplastic façade elements. For this reason, this thesis goes into the design of DfD connectors.

The first approach was taken too broad, it aimed to design a circular product, without clearly defining circularity and the criteria related to it. This meant the circularity of the design could not be measured. After researching the different circularity approaches a more rigid structure was worked out in the form of a decision model containing design requirements. This meant the circularity could be tested and the designs variants could be compared to each other.

Since each design variant led to new design problems to solve, the results were not expected. Although for the first round each design led to a new approach for connectors, the improved designs each have a similar approach. Although the form of the designs were different than expected, they did lead to the desired functioning.

The structure of the thesis where a literature study and analysis of a design form the basis for a decision model that informs the design, is an approach that could be used for similar scenarios where a design needs to be improved or used for another field of study, like in this case circular building products.

The research mostly influences the design. The research forms the basis for the requirements that inform the design variants. Although the design principles, which were set at the start of the thesis also influence the direction of design. For example, the use of the Spong3D block at the basis of the connector design informed the structured analysis of the circularity of the block.

The feedback given at the P2 was about finding focus and direction within my work, although this has been slow going since choosing the most relevant approach always asks for more research, I have stayed focused on narrowing down as much as possible. A strategy to attain this focus was to zoom out frequently, this allows for the possibility of reflection and assessment of the relevance of my work and methods.

Decision making in the design process is something I learned from going through the process of making a thesis. A decision is always based on both research and assumption. How a structured decision can be made while also taking into consideration my own judgment is something that has to be learned through experience. While at every design step more unknowns are created by the added knowledge on the topic, it is important to stay focused on the end goal for the design.

The final part of the graduation will be focused on improving the final design to the requirements. New prototypes will be made and sketch designs of the corner and bottom and top solutions will be made. Besides, the literature study of the definitions will be improved.

This thesis topic is part of the ongoing research project 'living in a bottle' into building mono-material translucent building products through AM, it will add relevant information on the circularity of the manufacturing method. The ongoing project has a research method of prototyping, which is in line with the method of this thesis.

This thesis in line with two of the chairs within Building Technology, Façade & Product design and Design Informatics, in that it aims to develop a circular connector for a mono-material façade panel through AM. The design of a circular building product is directly learned from the master track and the ability to learn new skills for design, like in this case 3D printing, is something often taught at the Building Technology track. The relation to the

11.1. Societal impact

The project is still at a proof-of-concept stage, so although it is not yet applicable in practice, it will add to a knowledge base about additive manufactured mono-material façade blocks and AM for circular building products. Although the focus in this thesis lies on the design of a connector, the basis for the design, the Spong3D panel, should be developed further to be more efficient in working and production in order for it to be suitable to take into practice. The connector itself should also be developed to work for corner solutions and horizontal connectors, besides extensive testing into watertightness, strength and durability should be conducted.

As the design of a additive manufactured connector that is designed for disassembly has not been extensively researched, the product achieves a level of innovation. It is a combination of circular building products and AM which should be investigated further, since AM shows clear potential in that it, among other things, allows for standardized products, complex shapes and material optimization. As mentioned in the previous paragraph, the connector design should undergo testing to make a conclusion on the functionalities of the product.

Part of the knowledge base it adds to is in sustainable development. The objective of this thesis is to improve the circular potential of additive manufactured façade blocks, by designing a DfD connector, which has the potential to bring new solutions for circular façade products. It also opens up the possibility for discussion about novel building methods and innovative building resources.

Being about sustainable development a moral dilemma is encountered during the process. The research finds that reduced waste is preferable and for the production of virgin plastic considerably more CO2 is emitted than for recycled plastic. However within the time frame and scope of the project it is not possible to use (only) recycled plastic and create no waste with the production of prototypes. This brings up the question whether this is morally acceptable, however it is important we move to a more sustainable and circular economy as fast as possible. The more solutions are known, the easier it is for people to make sustainable choices, because there are more solutions that fit peoples preference. So by speeding the process up by working less sustainable on a small scale, when the project moves to a larger scale it can have a larger impact.

Although the working on a larger scale should also be discussed. Aesthetically and functionally the building product is not like any other regular façade, so if the product can succeed through testing, the question remains whether it has the potential to be applied in the building industry that remains traditional and is relatively slow compared to other industries. A more proven and used façade material will easily be chosen over a relatively unknown material. Although it also adds a lot of visual interest because of the translucency of the material and the pattern the connectors add to the overall design. Using AM for manufacturing also opens up the possibility of local manufacturing, however this would require restructuring the building process. The combination of different layers in the skin of the building into a mono-material block also has a large impact on the building, it would simplify the building process, but might ask for a different form of maintenance, this would also have a large impact on the building industry.

Overall the value of this thesis lies in the academic field, it mainly adds to a knowledge base on circular building methods and products since the product itself remains at the prototype stage. It still has the potential to add societal value in the future if it can be fully developed into the building industry, this would mean a novel method and façade element is added to the industry.

The final design is easily transferable since all design steps were made based on a structured decision model that was created from the literature study and analysis. Although its design is based on the Spong3D façade block, the connector can be used for other AM thermoplastic façade elements.

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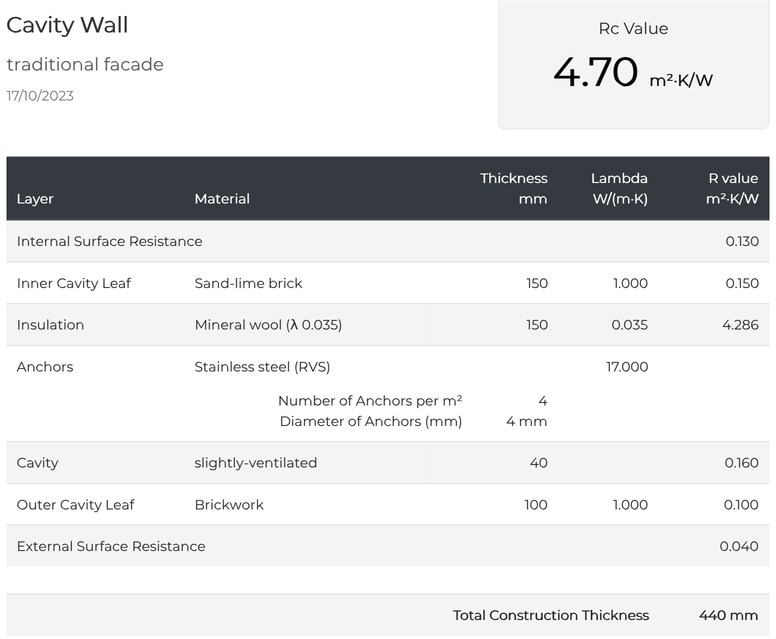
APPENDIX

A. Figures



Cavity Wall

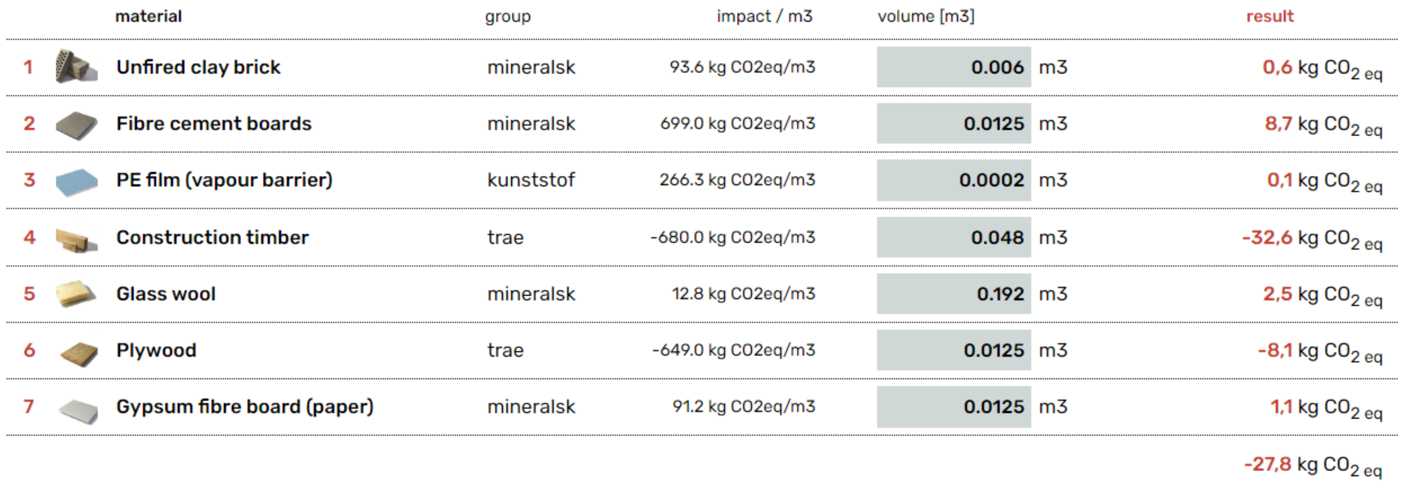
traditional facade

17/10/2023

Rc Value

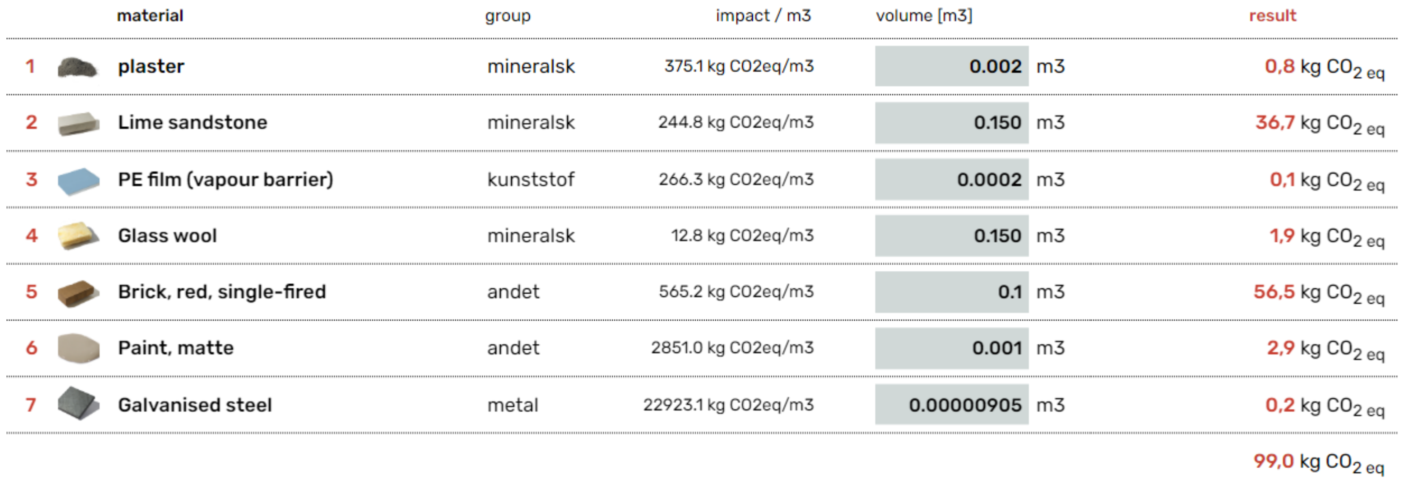
4.70 m²·K/W

Layer	Material	Thickness mm	Lambda W/(m·K)	R value m²·K/W
Internal Surface Resistance				0.130
Inner Cavity Leaf	Sand-lime brick	150	1.000	0.150
Insulation	Mineral wool (λ 0.035)	150	0.035	4.286
Anchors	Stainless steel (RVS)		17.000	
	Number of Anchors per m²	4		
	Diameter of Anchors (mm)	4 mm		
Cavity	slightly-ventilated	40		0.160
Outer Cavity Leaf	Brickwork	100	1.000	0.100
External Surface Resistance				0.040
			Total Construction Thickness	440 mm



	material	group	impact / m3	volume [m3]		result
1	**Unfired clay brick**	mineralsk	93.6 kg CO2eq/m3	**0.006**	m3	0,6 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
2	**Fibre cement boards**	mineralsk	699.0 kg CO2eq/m3	**0.0125**	m3	8,7 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
3	**PE film (vapour barrier)**	kunststof	266.3 kg CO2eq/m3	**0.0002**	m3	0,1 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
4	**Construction timber**	trae	-680.0 kg CO2eq/m3	**0.048**	m3	-32,6 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
5	**Glass wool**	mineralsk	12.8 kg CO2eq/m3	**0.192**	m3	2,5 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
6	**Plywood**	trae	-649.0 kg CO2eq/m3	**0.0125**	m3	-8,1 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
7	**Gypsum fibre board (paper)**	mineralsk	91.2 kg CO2eq/m3	**0.0125**	m3	1,1 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
						-27,8 kg $\mathrm{CO}_{2\ \mathrm{eq}}$

Figure*Global Warming Potential WEBO element (CINARK, n.d.)*

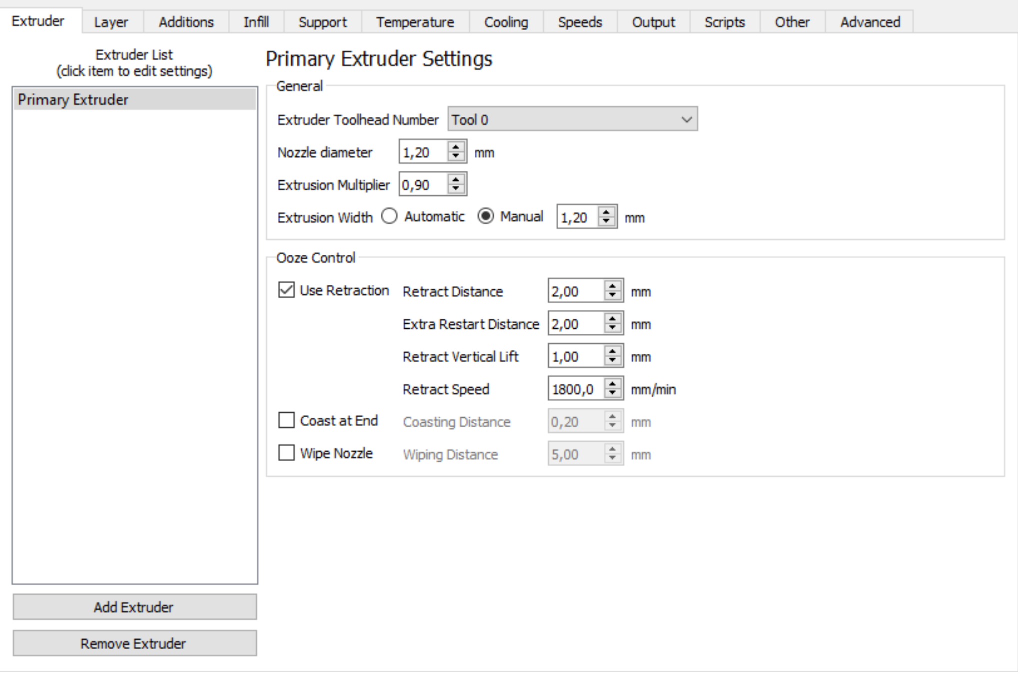


	material	group	impact / m3	volume [m3]		result
1	**plaster**	mineralsk	375.1 kg CO2eq/m3	**0.002**	m3	0,8 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
2	**Lime sandstone**	mineralsk	244.8 kg CO2eq/m3	**0.150**	m3	36,7 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
3	**PE film (vapour barrier)**	kunststof	266.3 kg CO2eq/m3	**0.0002**	m3	0,1 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
4	**Glass wool**	mineralsk	12.8 kg CO2eq/m3	**0.150**	m3	1,9 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
5	**Brick, red, single-fired**	andet	565.2 kg CO2eq/m3	**0.1**	m3	56,5 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
6	**Paint, matte**	andet	2851.0 kg CO2eq/m3	**0.001**	m3	2,9 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
7	**Galvanised steel**	metal	22923.1 kg CO2eq/m3	**0.00000905**	m3	0,2 kg $\mathrm{CO}_{2\ \mathrm{eq}}$
						99,0 kg $\mathrm{CO}_{2\ \mathrm{eq}}$

Figure*Global Warming Potential Traditional Façade (CINARK, n.d.)*

B. Printer settings

Concept prototypes



Primary Extruder Settings

General

Extruder Toolhead Number: Tool 0

Nozzle diameter: 1,20 mm

Extrusion Multiplier: 0,90

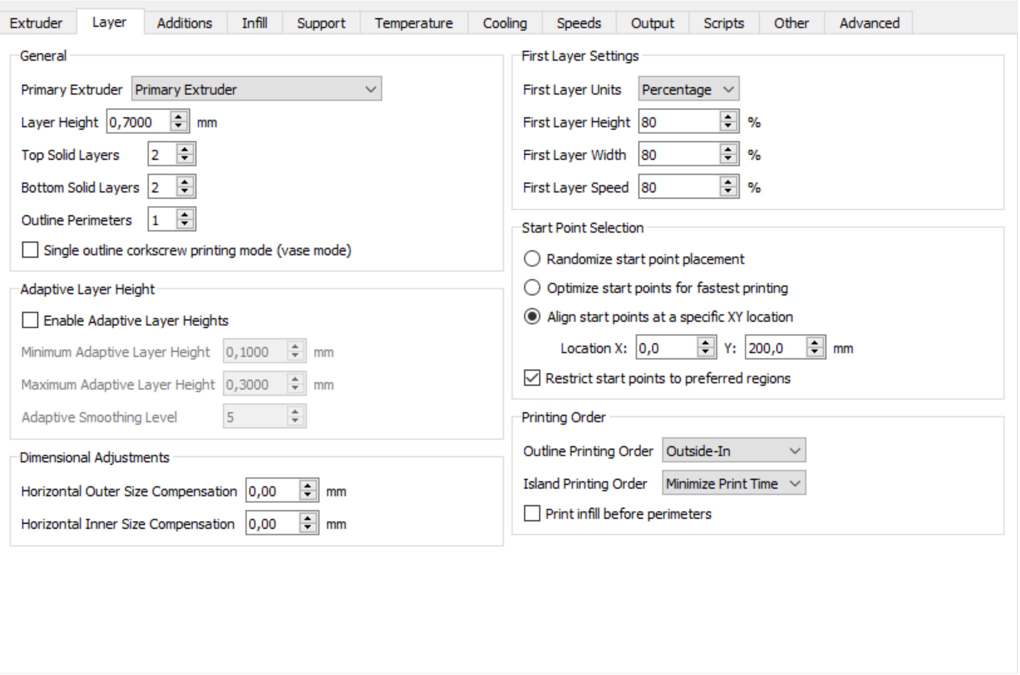
Extrusion Width: ○ Automatic ● Manual 1,20 mm

Ooze Control

☑ Use Retraction
Retract Distance: 2,00 mm
Extra Restart Distance: 2,00 mm
Retract Vertical Lift: 1,00 mm
Retract Speed: 1800,0 mm/min

☐ Coast at End
Coasting Distance: 0,20 mm

☐ Wipe Nozzle
Wiping Distance: 5,00 mm



General

Primary Extruder: Primary Extruder

Layer Height: 0,7000 mm

Top Solid Layers: 2

Bottom Solid Layers: 2

Outline Perimeters: 1

☐ Single outline corkscrew printing mode (vase mode)

Adaptive Layer Height

☐ Enable Adaptive Layer Heights

Minimum Adaptive Layer Height: 0,1000 mm

Maximum Adaptive Layer Height: 0,3000 mm

Adaptive Smoothing Level: 5

Dimensional Adjustments

Horizontal Outer Size Compensation: 0,00 mm

Horizontal Inner Size Compensation: 0,00 mm

First Layer Settings

First Layer Units: Percentage

First Layer Height: 80 %

First Layer Width: 80 %

First Layer Speed: 80 %

Start Point Selection

○ Randomize start point placement

○ Optimize start points for fastest printing

● Align start points at a specific XY location

Location X: 0,0 Y: 200,0 mm

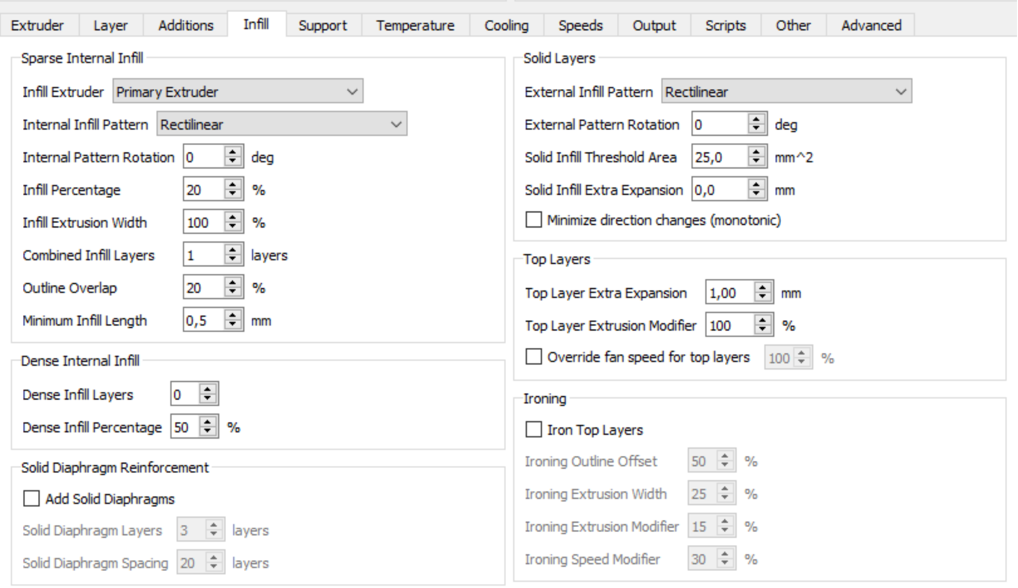
☑ Restrict start points to preferred regions

Printing Order

Outline Printing Order: Outside-In

Island Printing Order: Minimize Print Time

☐ Print infill before perimeters



Sparse Internal Infill
Infill Extruder: Primary Extruder
Internal Infill Pattern: Rectilinear
Internal Pattern Rotation: 0 deg
Infill Percentage: 20 %
Infill Extrusion Width: 100 %
Combined Infill Layers: 1 layers
Outline Overlap: 20 %
Minimum Infill Length: 0,5 mm

Dense Internal Infill
Dense Infill Layers: 0
Dense Infill Percentage: 50 %

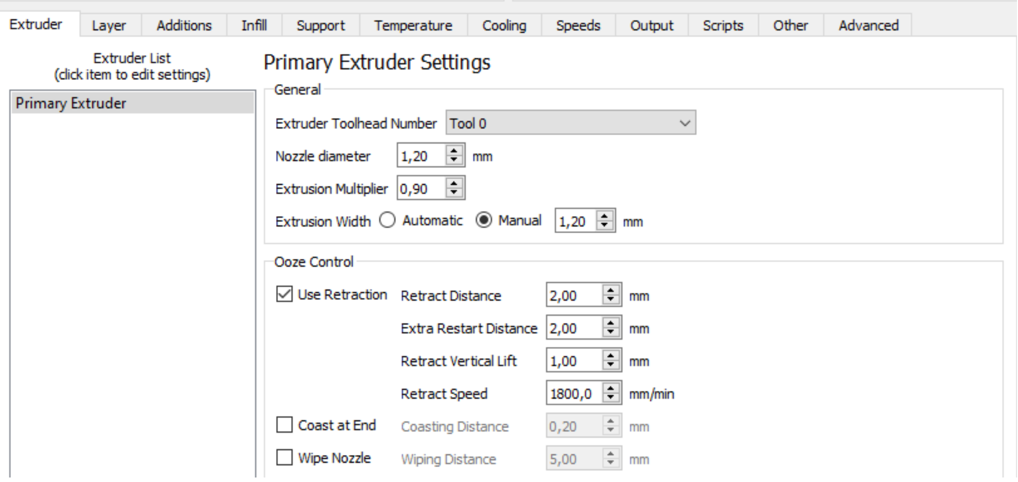
Solid Diaphragm Reinforcement
☐ Add Solid Diaphragms
Solid Diaphragm Layers: 3 layers
Solid Diaphragm Spacing: 20 layers

Solid Layers
External Infill Pattern: Rectilinear
External Pattern Rotation: 0 deg
Solid Infill Threshold Area: 25,0 mm^2
Solid Infill Extra Expansion: 0,0 mm
☐ Minimize direction changes (monotonic)

Top Layers
Top Layer Extra Expansion: 1,00 mm
Top Layer Extrusion Modifier: 100 %
☐ Override fan speed for top layers: 100 %

Ironing
☐ Iron Top Layers
Ironing Outline Offset: 50 %
Ironing Extrusion Width: 25 %
Ironing Extrusion Modifier: 15 %
Ironing Speed Modifier: 30 %

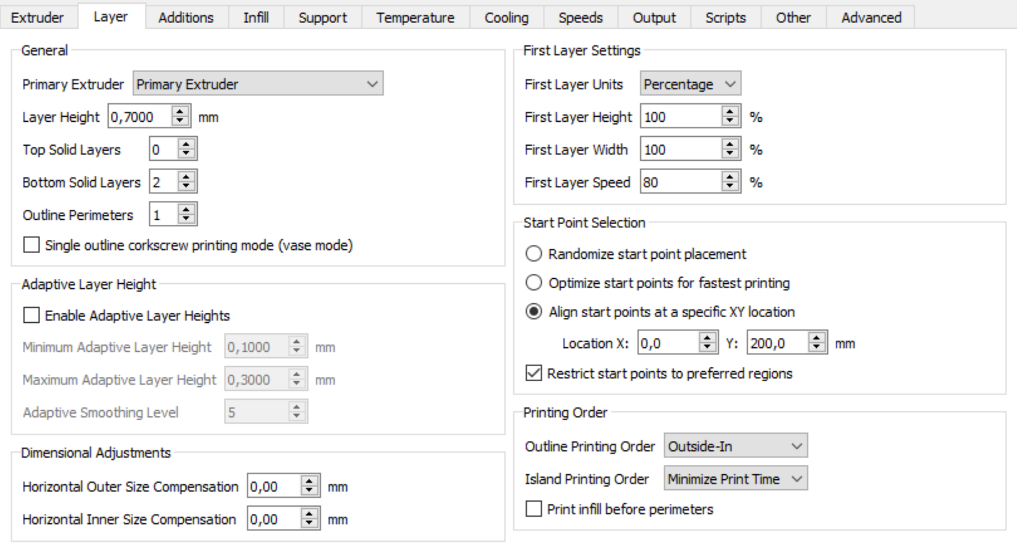
Concept prototypes no infill



Primary Extruder Settings

General
Extruder Toolhead Number: Tool 0
Nozzle diameter: 1,20 mm
Extrusion Multiplier: 0,90
Extrusion Width: ○ Automatic ● Manual 1,20 mm

Ooze Control
☑ Use Retraction
Retract Distance: 2,00 mm
Extra Restart Distance: 2,00 mm
Retract Vertical Lift: 1,00 mm
Retract Speed: 1800,0 mm/min
☐ Coast at End
Coasting Distance: 0,20 mm
☐ Wipe Nozzle
Wiping Distance: 5,00 mm



General
Primary Extruder: Primary Extruder
Layer Height: 0,7000 mm
Top Solid Layers: 0
Bottom Solid Layers: 2
Outline Perimeters: 1
☐ Single outline corkscrew printing mode (vase mode)

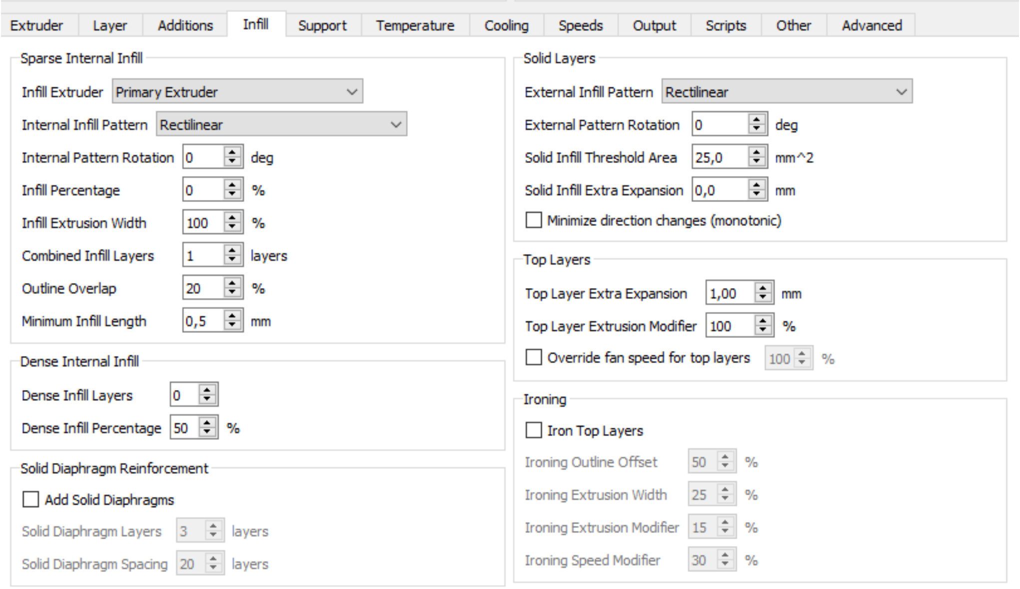
Adaptive Layer Height
☐ Enable Adaptive Layer Heights
Minimum Adaptive Layer Height: 0,1000 mm
Maximum Adaptive Layer Height: 0,3000 mm
Adaptive Smoothing Level: 5

Dimensional Adjustments
Horizontal Outer Size Compensation: 0,00 mm
Horizontal Inner Size Compensation: 0,00 mm

First Layer Settings
First Layer Units: Percentage
First Layer Height: 100 %
First Layer Width: 100 %
First Layer Speed: 80 %

Start Point Selection
○ Randomize start point placement
○ Optimize start points for fastest printing
● Align start points at a specific XY location
Location X: 0,0 Y: 200,0 mm
☑ Restrict start points to preferred regions

Printing Order
Outline Printing Order: Outside-In
Island Printing Order: Minimize Print Time
☐ Print infill before perimeters



Sparse Internal Infill
Infill Extruder: Primary Extruder
Internal Infill Pattern: Rectilinear
Internal Pattern Rotation: 0 deg
Infill Percentage: 0 %
Infill Extrusion Width: 100 %
Combined Infill Layers: 1 layers
Outline Overlap: 20 %
Minimum Infill Length: 0,5 mm

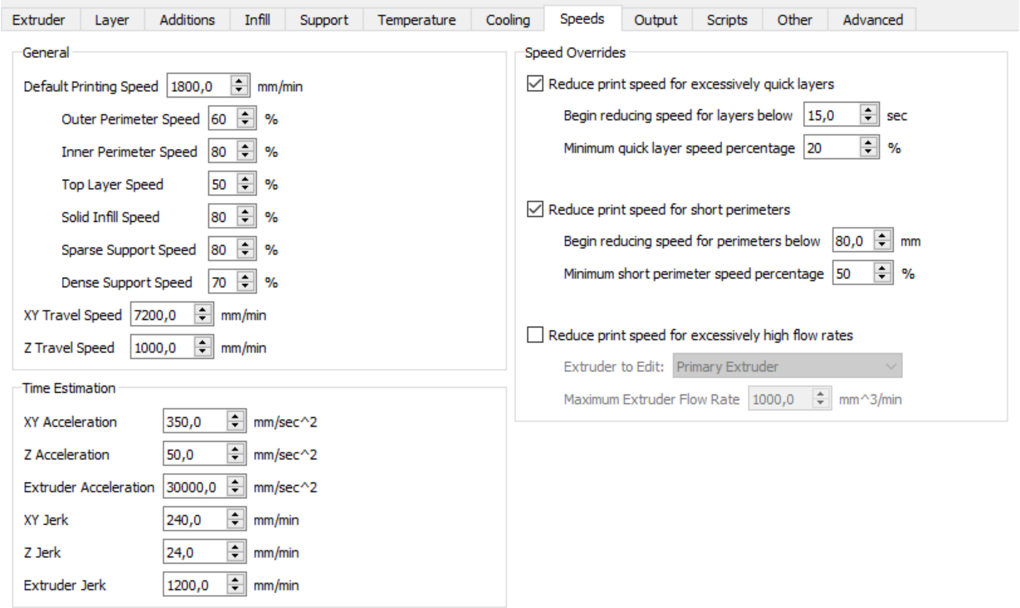
Dense Internal Infill
Dense Infill Layers: 0
Dense Infill Percentage: 50 %

Solid Diaphragm Reinforcement
☐ Add Solid Diaphragms
Solid Diaphragm Layers: 3 layers
Solid Diaphragm Spacing: 20 layers

Solid Layers
External Infill Pattern: Rectilinear
External Pattern Rotation: 0 deg
Solid Infill Threshold Area: 25,0 mm^2
Solid Infill Extra Expansion: 0,0 mm
☐ Minimize direction changes (monotonic)

Top Layers
Top Layer Extra Expansion: 1,00 mm
Top Layer Extrusion Modifier: 100 %
☐ Override fan speed for top layers: 100 %

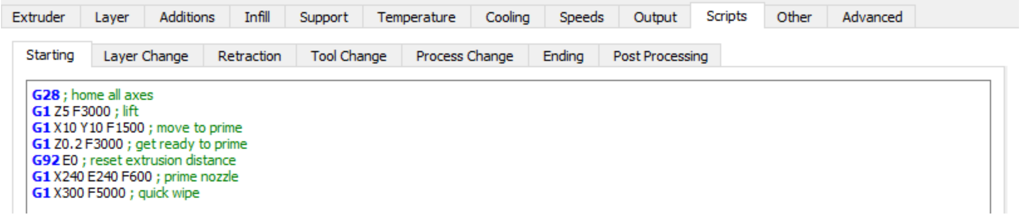
Ironing
☐ Iron Top Layers
Ironing Outline Offset: 50 %
Ironing Extrusion Width: 25 %
Ironing Extrusion Modifier: 15 %
Ironing Speed Modifier: 30 %



General
Default Printing Speed: 1800,0 mm/min
Outer Perimeter Speed: 60 %
Inner Perimeter Speed: 80 %
Top Layer Speed: 50 %
Solid Infill Speed: 80 %
Sparse Support Speed: 80 %
Dense Support Speed: 70 %
XY Travel Speed: 7200,0 mm/min
Z Travel Speed: 1000,0 mm/min

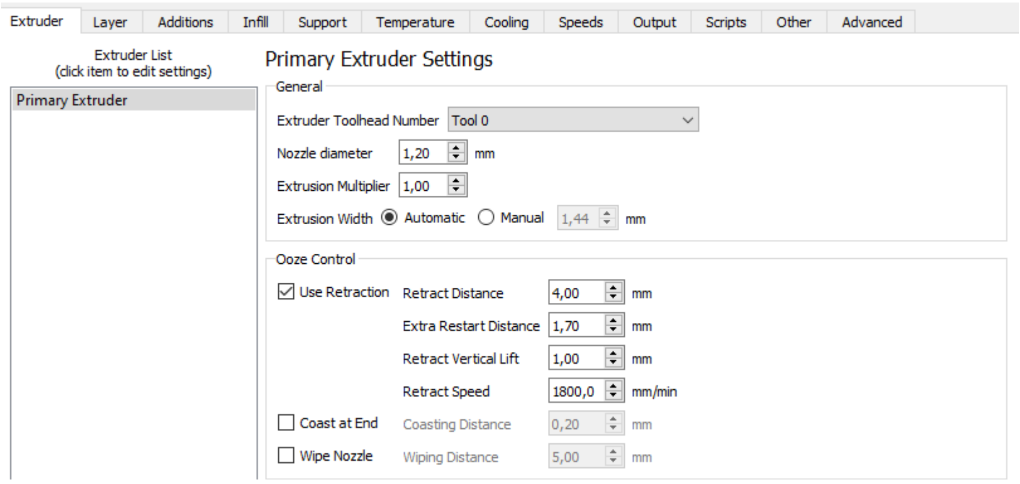
Time Estimation
XY Acceleration: 350,0 mm/sec^2
Z Acceleration: 50,0 mm/sec^2
Extruder Acceleration: 30000,0 mm/sec^2
XY Jerk: 240,0 mm/min
Z Jerk: 24,0 mm/min
Extruder Jerk: 1200,0 mm/min

Speed Overrides
☑ Reduce print speed for excessively quick layers
Begin reducing speed for layers below: 15,0 sec
Minimum quick layer speed percentage: 20 %
☑ Reduce print speed for short perimeters
Begin reducing speed for perimeters below: 80,0 mm
Minimum short perimeter speed percentage: 50 %
☐ Reduce print speed for excessively high flow rates
Extruder to Edit: Primary Extruder
Maximum Extruder Flow Rate: 1000,0 mm^3/min



```
G28 ; home all axes
G1 Z5 F3000 ; lift
G1 X10 Y10 F1500 ; move to prime
G1 Z0.2 F3000 ; get ready to prime
G92 E0 ; reset extrusion distance
G1 X240 E240 F600 ; prime nozzle
G1 X300 F5000 ; quick wipe
```

Improved prototypes

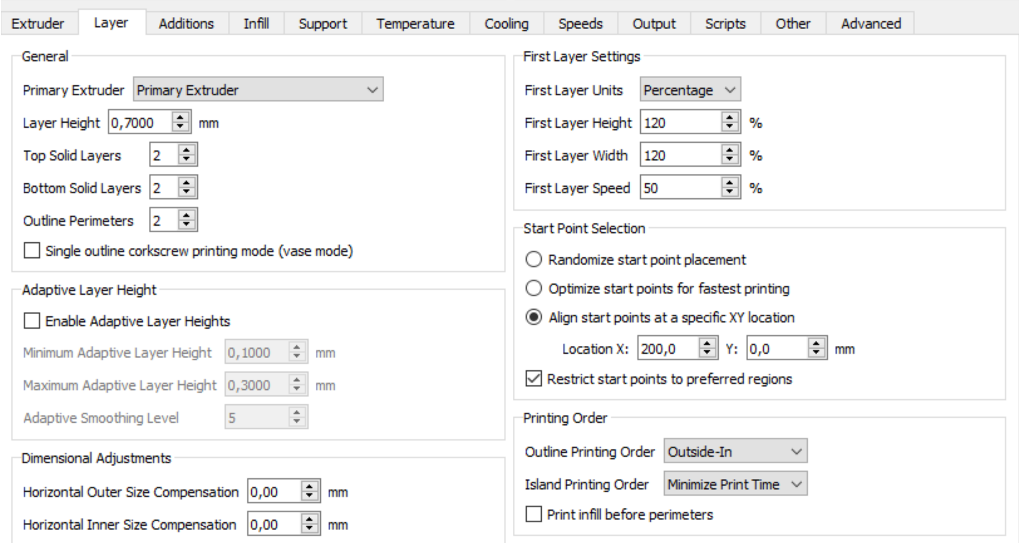


Extruder List
(click item to edit settings)
Primary Extruder

Primary Extruder Settings

General
Extruder Toolhead Number: Tool 0
Nozzle diameter: 1,20 mm
Extrusion Multiplier: 1,00
Extrusion Width: ● Automatic ○ Manual 1,44 mm

Ooze Control
☑ Use Retraction
Retract Distance: 4,00 mm
Extra Restart Distance: 1,70 mm
Retract Vertical Lift: 1,00 mm
Retract Speed: 1800,0 mm/min
☐ Coast at End
Coasting Distance: 0,20 mm
☐ Wipe Nozzle
Wiping Distance: 5,00 mm



General
Primary Extruder: Primary Extruder
Layer Height: 0,7000 mm
Top Solid Layers: 2
Bottom Solid Layers: 2
Outline Perimeters: 2
☐ Single outline corkscrew printing mode (vase mode)

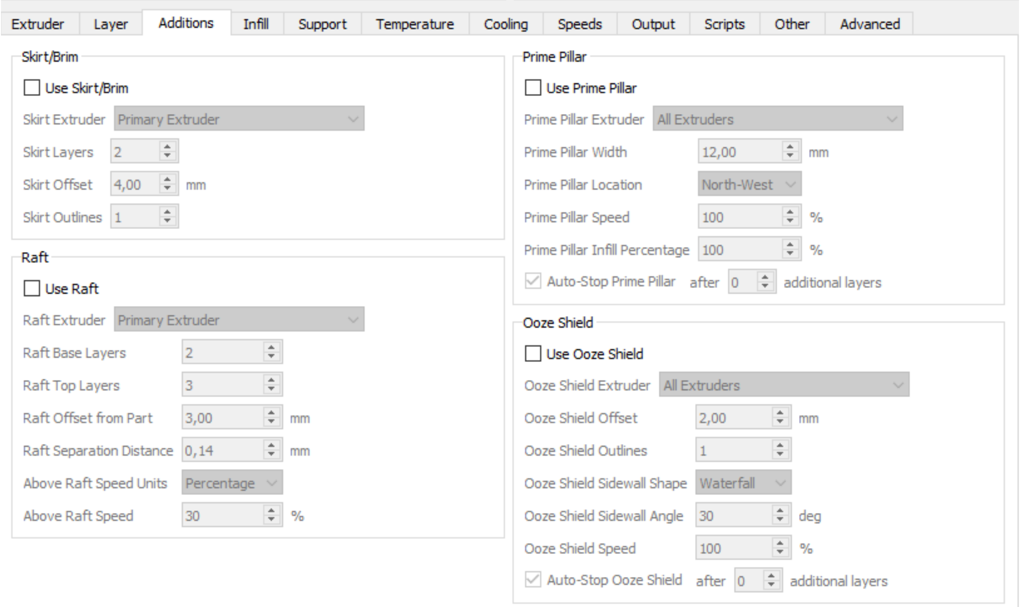
Adaptive Layer Height
☐ Enable Adaptive Layer Heights
Minimum Adaptive Layer Height: 0,1000 mm
Maximum Adaptive Layer Height: 0,3000 mm
Adaptive Smoothing Level: 5

Dimensional Adjustments
Horizontal Outer Size Compensation: 0,00 mm
Horizontal Inner Size Compensation: 0,00 mm

First Layer Settings
First Layer Units: Percentage
First Layer Height: 120 %
First Layer Width: 120 %
First Layer Speed: 50 %

Start Point Selection
○ Randomize start point placement
○ Optimize start points for fastest printing
● Align start points at a specific XY location
Location X: 200,0 Y: 0,0 mm
☑ Restrict start points to preferred regions

Printing Order
Outline Printing Order: Outside-In
Island Printing Order: Minimize Print Time
☐ Print infill before perimeters

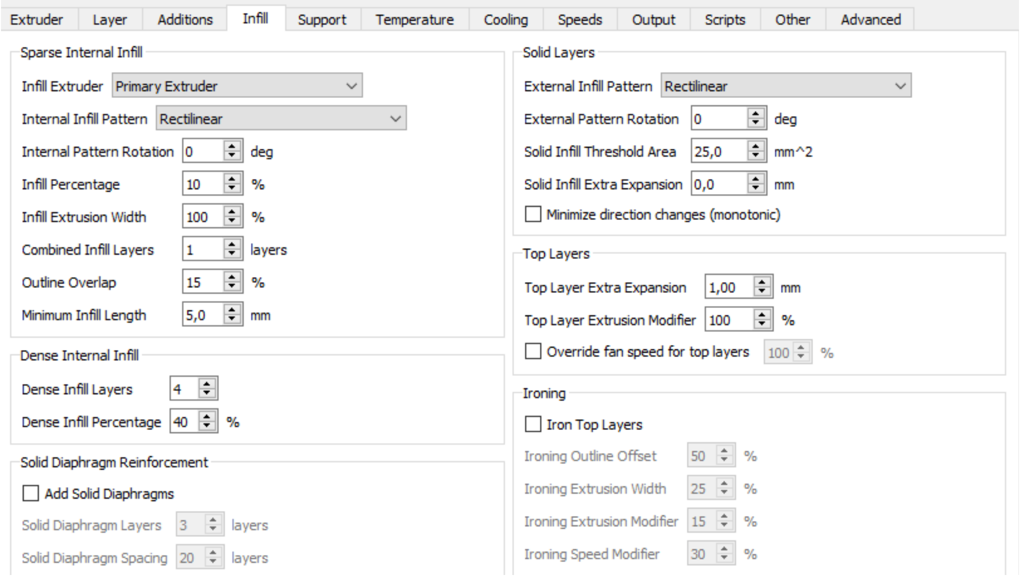


Skirt/Brim
☐ Use Skirt/Brim
Skirt Extruder: Primary Extruder
Skirt Layers: 2
Skirt Offset: 4,00 mm
Skirt Outlines: 1

Raft
☐ Use Raft
Raft Extruder: Primary Extruder
Raft Base Layers: 2
Raft Top Layers: 3
Raft Offset from Part: 3,00 mm
Raft Separation Distance: 0,14 mm
Above Raft Speed Units: Percentage
Above Raft Speed: 30 %

Prime Pillar
☐ Use Prime Pillar
Prime Pillar Extruder: All Extruders
Prime Pillar Width: 12,00 mm
Prime Pillar Location: North-West
Prime Pillar Speed: 100 %
Prime Pillar Infill Percentage: 100 %
☑ Auto-Stop Prime Pillar after 0 additional layers

Ooze Shield
☐ Use Ooze Shield
Ooze Shield Extruder: All Extruders
Ooze Shield Offset: 2,00 mm
Ooze Shield Outlines: 1
Ooze Shield Sidewall Shape: Waterfall
Ooze Shield Sidewall Angle: 30 deg
Ooze Shield Speed: 100 %
☑ Auto-Stop Ooze Shield after 0 additional layers



Sparse Internal Infill
Infill Extruder: Primary Extruder
Internal Infill Pattern: Rectilinear
Internal Pattern Rotation: 0 deg
Infill Percentage: 10 %
Infill Extrusion Width: 100 %
Combined Infill Layers: 1 layers
Outline Overlap: 15 %
Minimum Infill Length: 5,0 mm

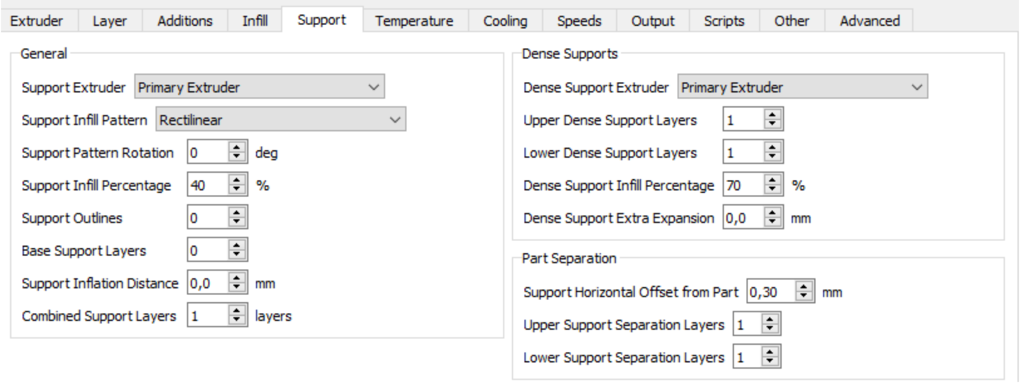
Dense Internal Infill
Dense Infill Layers: 4
Dense Infill Percentage: 40 %

Solid Diaphragm Reinforcement
☐ Add Solid Diaphragms
Solid Diaphragm Layers: 3 layers
Solid Diaphragm Spacing: 20 layers

Solid Layers
External Infill Pattern: Rectilinear
External Pattern Rotation: 0 deg
Solid Infill Threshold Area: 25,0 mm^2
Solid Infill Extra Expansion: 0,0 mm
☐ Minimize direction changes (monotonic)

Top Layers
Top Layer Extra Expansion: 1,00 mm
Top Layer Extrusion Modifier: 100 %
☐ Override fan speed for top layers 100 %

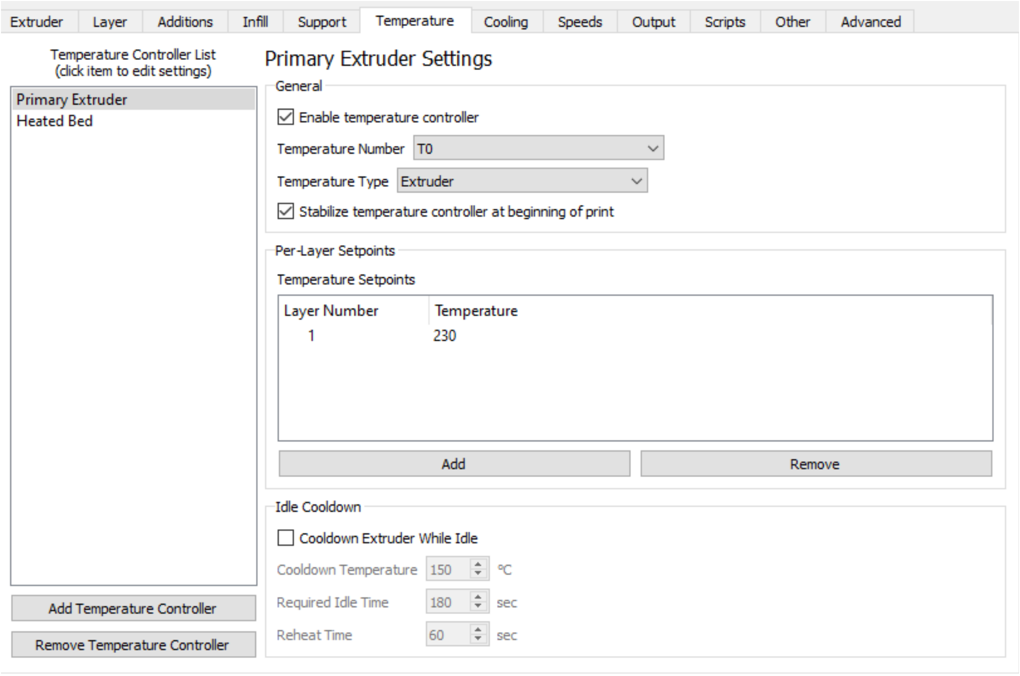
Ironing
☐ Iron Top Layers
Ironing Outline Offset: 50 %
Ironing Extrusion Width: 25 %
Ironing Extrusion Modifier: 15 %
Ironing Speed Modifier: 30 %



General
Support Extruder: Primary Extruder
Support Infill Pattern: Rectilinear
Support Pattern Rotation: 0 deg
Support Infill Percentage: 40 %
Support Outlines: 0
Base Support Layers: 0
Support Inflation Distance: 0,0 mm
Combined Support Layers: 1 layers

Dense Supports
Dense Support Extruder: Primary Extruder
Upper Dense Support Layers: 1
Lower Dense Support Layers: 1
Dense Support Infill Percentage: 70 %
Dense Support Extra Expansion: 0,0 mm

Part Separation
Support Horizontal Offset from Part: 0,30 mm
Upper Support Separation Layers: 1
Lower Support Separation Layers: 1



Temperature Controller List
(click item to edit settings)
Primary Extruder
Heated Bed

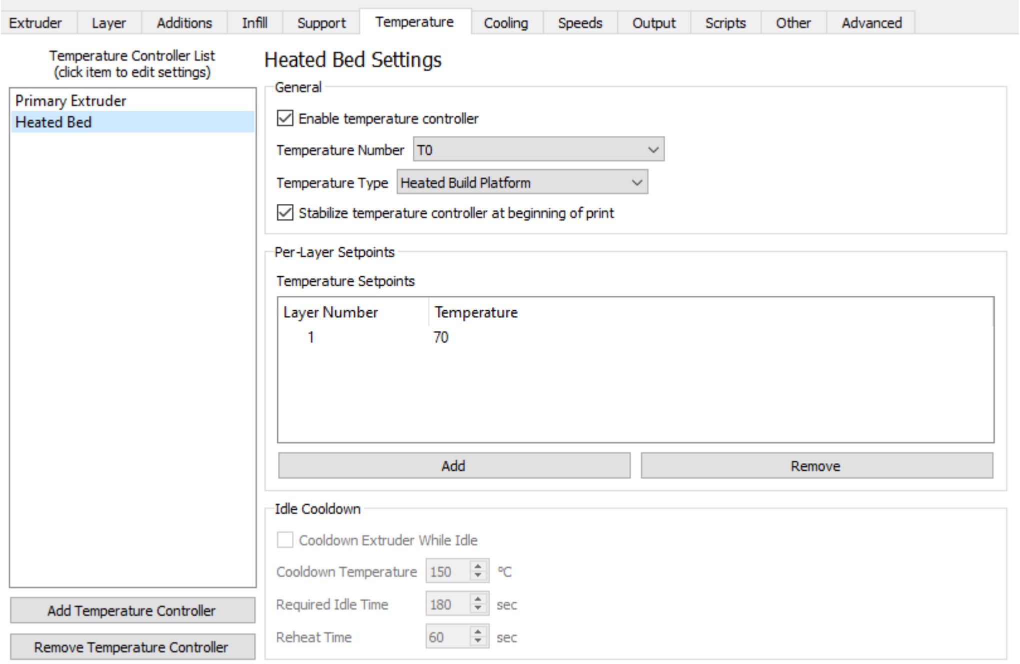
Primary Extruder Settings

General
☑ Enable temperature controller
Temperature Number: T0
Temperature Type: Extruder
☑ Stabilize temperature controller at beginning of print

Per-Layer Setpoints
Temperature Setpoints

Layer Number	Temperature
1	230

Idle Cooldown
☐ Cooldown Extruder While Idle
Cooldown Temperature: 150 °C
Required Idle Time: 180 sec
Reheat Time: 60 sec



Heated Bed Settings

General

☑ Enable temperature controller

Temperature Number: T0

Temperature Type: Heated Build Platform

☑ Stabilize temperature controller at beginning of print

Per-Layer Setpoints

Temperature Setpoints

Layer Number	Temperature
1	70

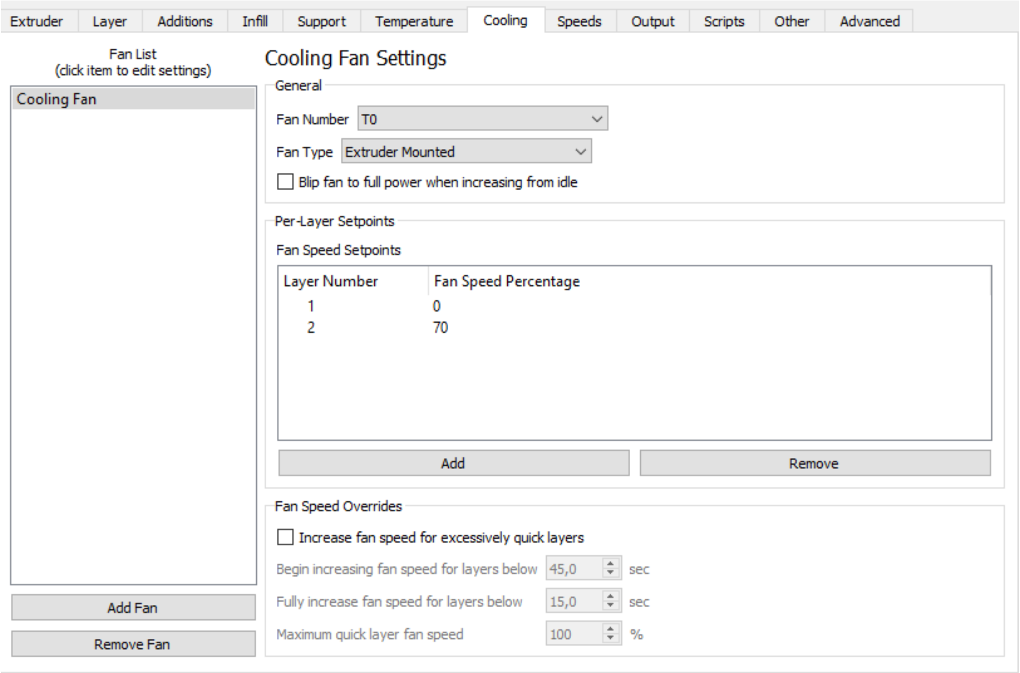
Idle Cooldown

☐ Cooldown Extruder While Idle

Cooldown Temperature: 150 °C

Required Idle Time: 180 sec

Reheat Time: 60 sec



Cooling Fan Settings

General

Fan Number: T0

Fan Type: Extruder Mounted

☐ Blip fan to full power when increasing from idle

Per-Layer Setpoints

Fan Speed Setpoints

Layer Number	Fan Speed Percentage
1	0
2	70

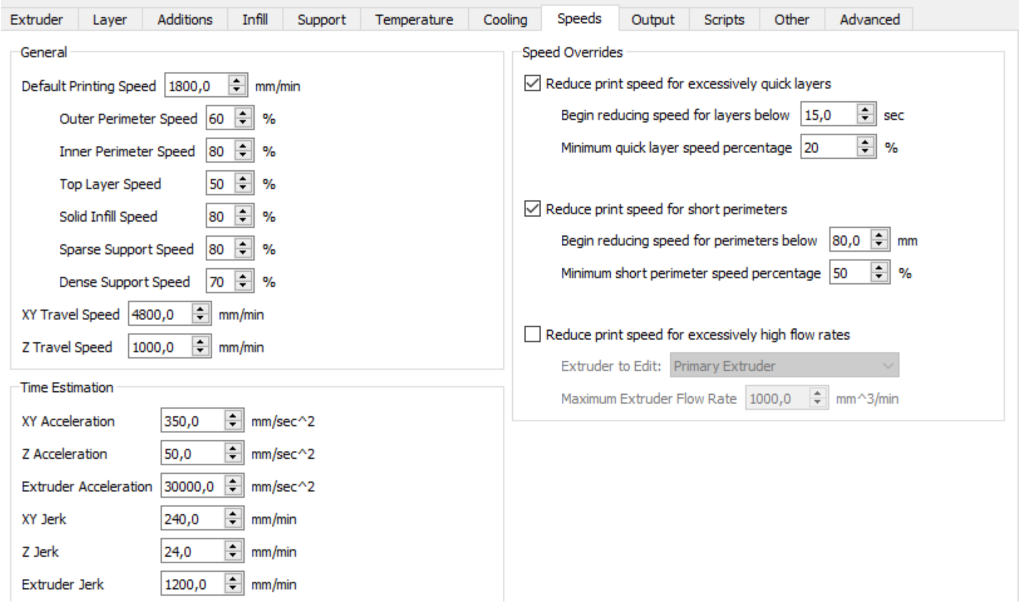
Fan Speed Overrides

☐ Increase fan speed for excessively quick layers

Begin increasing fan speed for layers below: 45,0 sec

Fully increase fan speed for layers below: 15,0 sec

Maximum quick layer fan speed: 100 %



General

Default Printing Speed: 1800,0 mm/min

Outer Perimeter Speed: 60 %

Inner Perimeter Speed: 80 %

Top Layer Speed: 50 %

Solid Infill Speed: 80 %

Sparse Support Speed: 80 %

Dense Support Speed: 70 %

XY Travel Speed: 4800,0 mm/min

Z Travel Speed: 1000,0 mm/min

Time Estimation

XY Acceleration: 350,0 mm/sec^2

Z Acceleration: 50,0 mm/sec^2

Extruder Acceleration: 30000,0 mm/sec^2

XY Jerk: 240,0 mm/min

Z Jerk: 24,0 mm/min

Extruder Jerk: 1200,0 mm/min

Speed Overrides

☑ Reduce print speed for excessively quick layers

Begin reducing speed for layers below: 15,0 sec

Minimum quick layer speed percentage: 20 %

☑ Reduce print speed for short perimeters

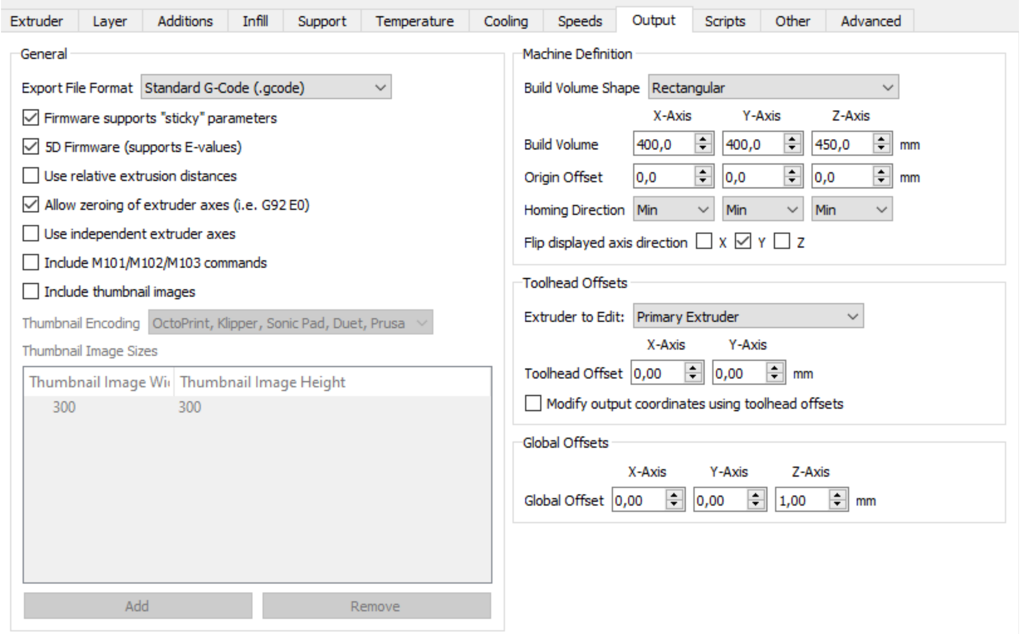
Begin reducing speed for perimeters below: 80,0 mm

Minimum short perimeter speed percentage: 50 %

☐ Reduce print speed for excessively high flow rates

Extruder to Edit: Primary Extruder

Maximum Extruder Flow Rate: 1000,0 mm^3/min



General

Export File Format: Standard G-Code (.gcode)

☑ Firmware supports "sticky" parameters

☑ 5D Firmware (supports E-values)

☐ Use relative extrusion distances

☑ Allow zeroing of extruder axes (i.e. G92 E0)

☐ Use independent extruder axes

☐ Include M101/M102/M103 commands

☐ Include thumbnail images

Thumbnail Encoding: OctoPrint, Klipper, Sonic Pad, Duet, Prusa

Thumbnail Image Sizes

Thumbnail Image Wi	Thumbnail Image Height
300	300

Machine Definition

Build Volume Shape: Rectangular

	X-Axis	Y-Axis	Z-Axis	
Build Volume	400,0	400,0	450,0	mm
Origin Offset	0,0	0,0	0,0	mm
Homing Direction	Min	Min	Min	

Flip displayed axis direction ☐ X ☑ Y ☐ Z

Toolhead Offsets

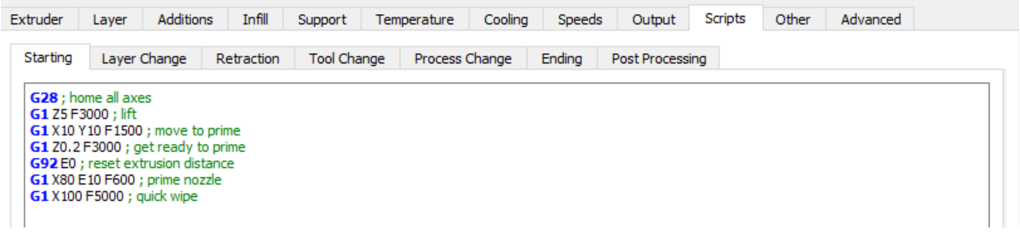
Extruder to Edit: Primary Extruder

	X-Axis	Y-Axis	
Toolhead Offset	0,00	0,00	mm

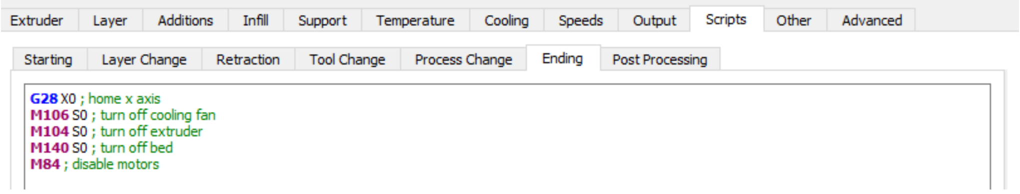
☐ Modify output coordinates using toolhead offsets

Global Offsets

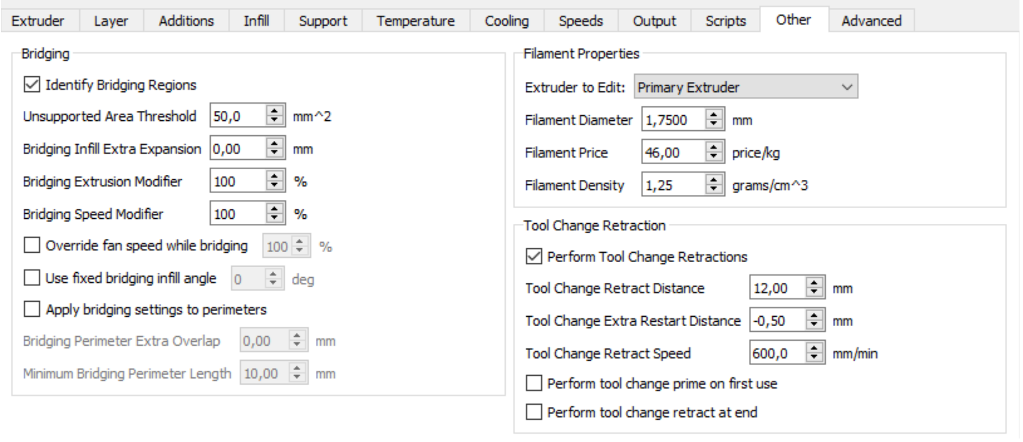
	X-Axis	Y-Axis	Z-Axis	
Global Offset	0,00	0,00	1,00	mm



```
G28 ; home all axes
G1 Z5 F3000 ; lift
G1 X10 Y10 F1500 ; move to prime
G1 Z0.2 F3000 ; get ready to prime
G92 E0 ; reset extrusion distance
G1 X80 E10 F600 ; prime nozzle
G1 X100 F5000 ; quick wipe
```



```
G28 X0 ; home x axis
M106 S0 ; turn off cooling fan
M104 S0 ; turn off extruder
M140 S0 ; turn off bed
M84 ; disable motors
```



Bridging

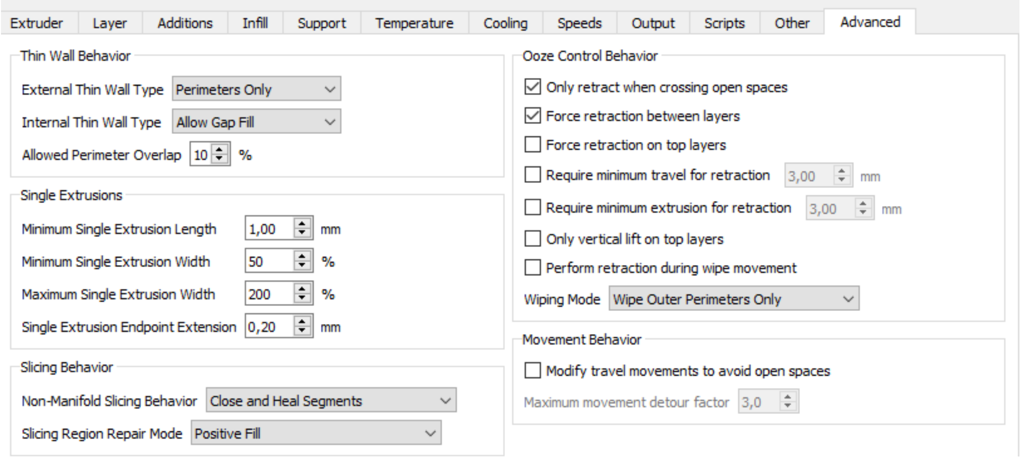
☑ Identify Bridging Regions
Unsupported Area Threshold 50,0 mm^2
Bridging Infill Extra Expansion 0,00 mm
Bridging Extrusion Modifier 100 %
Bridging Speed Modifier 100 %
☐ Override fan speed while bridging 100 %
☐ Use fixed bridging infill angle 0 deg
☐ Apply bridging settings to perimeters
Bridging Perimeter Extra Overlap 0,00 mm
Minimum Bridging Perimeter Length 10,00 mm

Filament Properties

Extruder to Edit: Primary Extruder
Filament Diameter 1,7500 mm
Filament Price 46,00 price/kg
Filament Density 1,25 grams/cm^3

Tool Change Retraction

☑ Perform Tool Change Retractions
Tool Change Retract Distance 12,00 mm
Tool Change Extra Restart Distance -0,50 mm
Tool Change Retract Speed 600,0 mm/min
☐ Perform tool change prime on first use
☐ Perform tool change retract at end



Thin Wall Behavior

External Thin Wall Type Perimeters Only
Internal Thin Wall Type Allow Gap Fill
Allowed Perimeter Overlap 10 %

Single Extrusions

Minimum Single Extrusion Length 1,00 mm
Minimum Single Extrusion Width 50 %
Maximum Single Extrusion Width 200 %
Single Extrusion Endpoint Extension 0,20 mm

Slicing Behavior

Non-Manifold Slicing Behavior Close and Heal Segments
Slicing Region Repair Mode Positive Fill

Ooze Control Behavior

☑ Only retract when crossing open spaces
☑ Force retraction between layers
☐ Force retraction on top layers
☐ Require minimum travel for retraction 3,00 mm
☐ Require minimum extrusion for retraction 3,00 mm
☐ Only vertical lift on top layers
☐ Perform retraction during wipe movement
Wiping Mode Wipe Outer Perimeters Only

Movement Behavior

☐ Modify travel movements to avoid open spaces
Maximum movement detour factor 3,0

C. DfD decision model Güngör