CLOSING THE LOOP

RECYCLING PLASTIC WASTE

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NOTES

- All the work in this thesis is that of the authors, unless stated otherwise
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KEYWORDS

Additive Manufacturing, Freeform 3D printing, 3D Printing, Recycled Filament, Plastic, Design, Architecture, Parametric, Waste, Sustainability, Recycling, Recycling Waste, Waste Plastic

ABSTRACT

New Zealand is ranked among the top nations in waste production, including a million tonnes of plastic waste. Currently, there are methods for recycling plastic within New Zealand but these methods can be expensive and time-consuming, resulting in most of the plastic being thrown into the landfill. Because plastic does not fully degrade, it ends up in the ocean and other waterways, poisoning the water with toxins.

The purpose of this research is to provide a solution to reducing plastic waste by creating an alternative method of recycling that utilises new technologies such as additive manufacturing, to create a building material that fits into the concept of the circular economy.

The findings of this research explored the recycling of plastic by collecting plastic waste such as PLA (Polylactic Acid) from old 3D printed models. The plastic was recycled into filament for additive manufacturing (AM) and used to print building tile, establishing an initial proof of concept for the use of recycled plastic as a potential building material.

CONTENTS

CHAPTER ONE

1

INTRODUCTION

1.1. INTRODUCTION

New Zealand creates 3.6 kilograms of waste per person every day. This equates to 6.28 billion kilograms of waste per year for the entire nation (Newshub, 2018). Amongst this there is 220,000 tonnes (about 60 kg/person) of plastic waste a year (MfE, 1997). According to Thompson, Moore, vom Saal, & Swan (2009), current reliance on plastic is simply not sustainable. The reserves where raw materials such as ethane are taken to make plastic are declining. The short-lived one-use products created are accumulating. Since 1950 to 2015 only 9% of waste was recycled, 12% incinerated and the rest either ended up in landfills or the natural environment (Rhodes, 2018). This resulted in physical problems for wildlife and humans' through ingestion, entanglement in plastic, the leaching of chemicals from plastic products and the transfer of chemicals to natural habitats (Thompson et al, 2009).

Current methods for recycling plastic have flaws. Laura Parker (2018) states that 'of the 8.3 billion metric tons (of plastic) that have been produced, 6.3 billion metric tons have become plastic waste. Of that, only nine percent has been recycled'. This is where adopting a circular economy model for plastic waste is critical. If waste plastic was designed with its end use in mind, then products can be reused, and recycled efficiently. This eventually reduces or eliminates the use of raw materials and waste sent to the landfill by relying on the material already in circulation.

Plastic waste has become an object of research to help people find solutions to the issue. Previous studies have reported that there are possible solutions, some easier to achieve than others. These include material reduction, design for end-of-life recyclability, increased recycling capacity, development of bio-based feedstocks, strategies to reduce littering, and revised risk assessment approaches (Thompson et al, 2009).

New methods such as additive manufacturing can play an important role in addressing how waste materials such as plastic can be recycled. It has become a tool for creating designs that were not possible with traditional tools. Using materials ranging from concrete, resins, clay, plastic, and even biomaterials. Entire buildings, walls or elements, such as facade panels or bricks can be printed (e.g. XtreeE, 2017).

The thesis investigates how an alternative recycling system can be created for waste plastic to create a circular economy using additive manufacturing.

1.2. RESEARCH

HOW CAN AN ALTERNATIVE RECYCLING SYSTEM BE CREATED FOR WASTE PLASTIC TO CREATE A CIRCULAR ECONOMY USING ADDITIVE MANUFACTURING?

QUESTION

1.3. THE AIM

The aim of this research is to develop a circular economy (lifecycle) for waste plastic through recycling it utilizing additive manufacturing

1.4. OBJECTIVES

- Research the types of plastics that can be recycled and reused for printing filament
- Produce recycled printing filament
- Identify a building element that could be rethought or replaced by a recycled plastic printing system
- Generate a systematic printing workflow from design to production
- Produce iterative test objects
- Prototype full-scale model of a tile

1.5. SCOPE

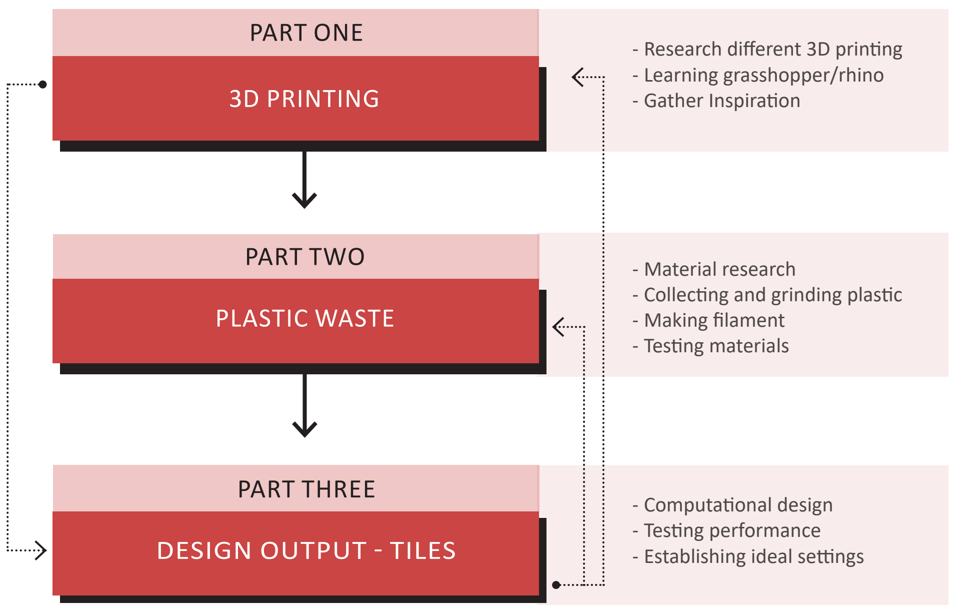


Figure 1: Scope Diagram 1

This thesis focuses on three key parts. These parts make up the chapters of this thesis. Each chapter relates to the next with information from one helping to develop the next.

Part one was the learning and gaining knowledge of computational design. Research was conducted on current additive manufacturing and the materials used. This part of the thesis is non-sequential and ran alongside the last two parts. Part two and three are closely linked and also reflect back on findings from each part. Part two of this thesis focuses on plastic and how it can be recycled and turned into 3D printing filament. Then part three is about how this can be tested by using a design output such as a tile.

When the circular economy is discussed this thesis focuses on the specifics of one part of it. Expanding the research to follow the full circular economy would dilute the research.

If this research is continued following this thesis, more time will need to spent printing and making the filament and experimenting with other material. However challenges such as availability of materials and aspects outside the scope such as running costs and emissions will need to be evaluated especially if this system is to considered against current recycling systems. The availability and accessibility of current manufacturing tools today may be different to that in years to come, therefore this will affect the development of future research in this area.

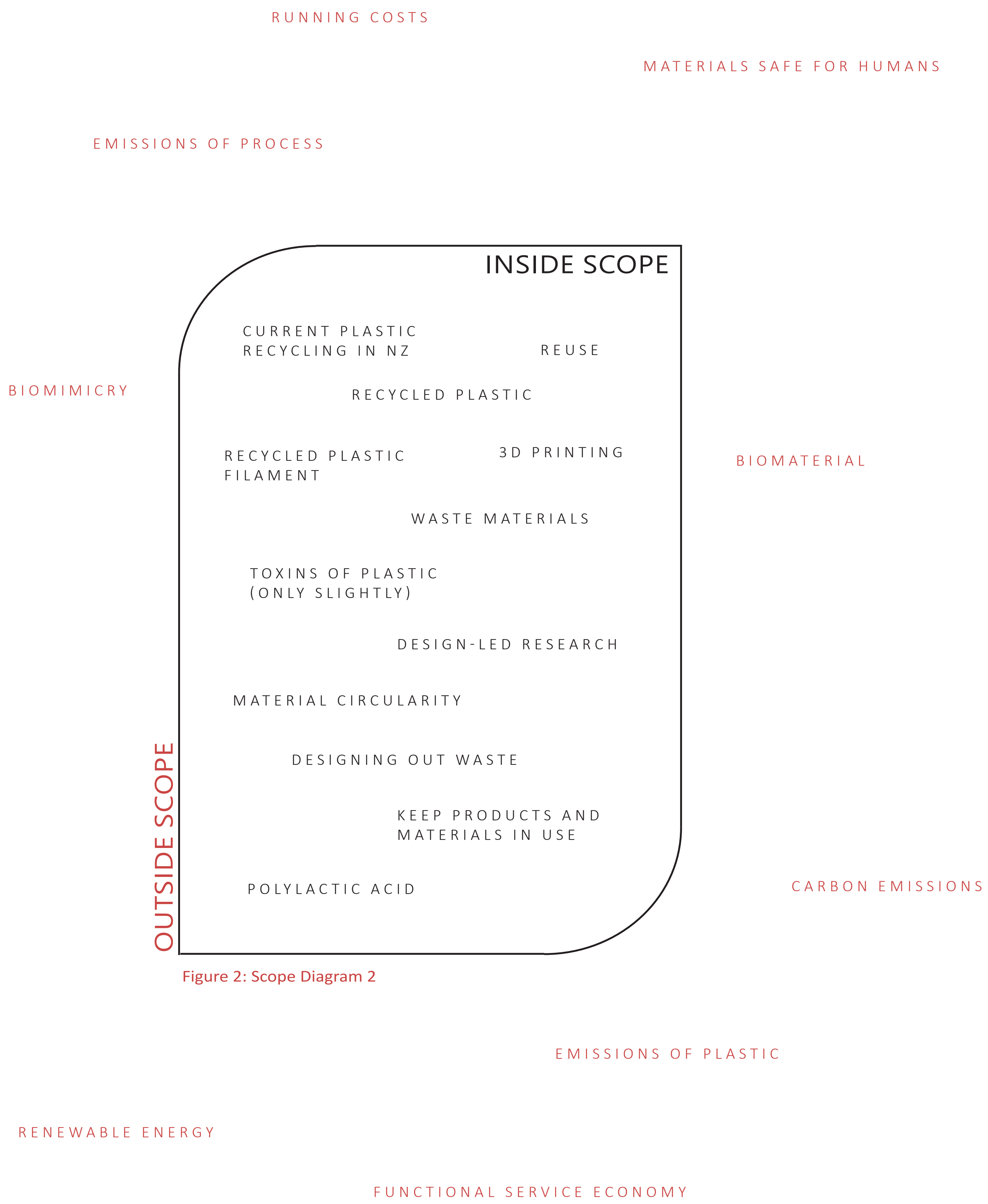


Figure 2: Scope Diagram 2

1.6. METHODOLOGY

The research proposal will primarily be design-led research. The methodology will utilize four phases of 'Design Thinking' to help answer the research question. These phases are define, ideate, prototype and test.

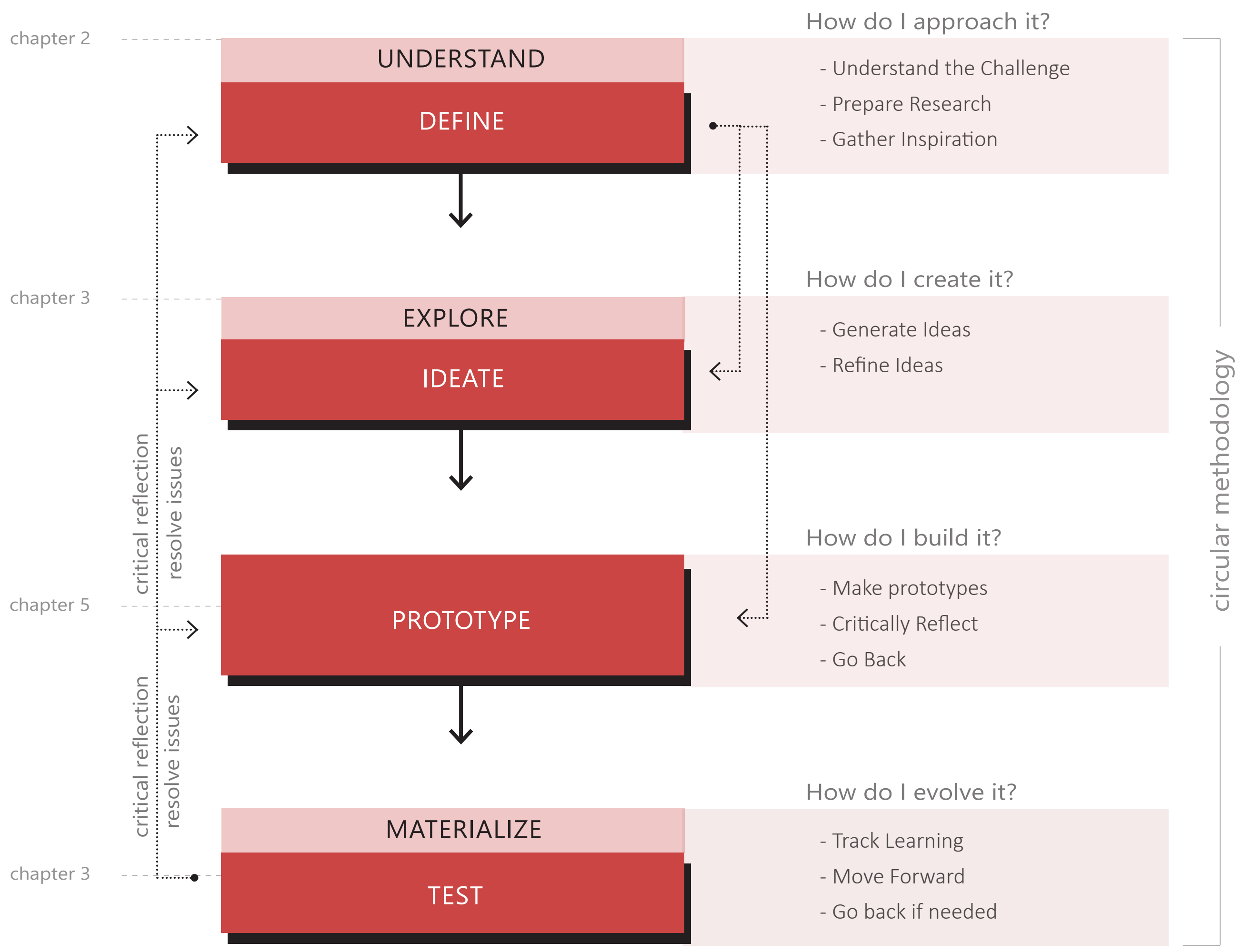
Stage one of this thesis will start with a literature review to investigate current construction and industry practices and examples in order to clearly define the problem. A precedent analysis will be part of this stage to acknowledge leading examples of freeform printing in architecture and reflect upon their strategies. Finally, further research into what types of plastic can be recycled and extruded into a useable filament will conclude this stage.

Stage two, ideation, will involve an exploration into recycling waste plastic. Innovative models such as the circular economy will be researchconsidered . that will best support an answer to the research question

The prototyping phase will produce a range of iterations that can be recorded, analysed and critically reflected upon. The prototypes will start off with creating a recycled plastic filament. This filament will then be used to create simple structures to test the limitations and constraints of the freeform 3D printer and the recycled plastic. Designs of building elements and/or components will be created and printed. This leads to the test phase, where rigorous tests are completed on the end product using the best solution from the prototypes. These tests can then create new and exciting ideas drawing us back to the ideate phase, or even taking us back to the define phase as tests reveal insights that redefine the problem.

Design thinking is a non-linear process (shown in the diagram below), it serves as a guide where knowledge gained at one stage can be passed to another stage. (Dam & Siang, 2019)

1.7. DESIGN THINKING PHASES



CHAPTER TWO

2

LITERATURE REVIEW

Figure 3: Plastic waste on the side of the road

2.1. INTRODUCTION

This chapter of the thesis introduces plastic and discusses current recycling methods and their limitations. It introduces additive manufacturing and precedents related to it. These precedents are compared and evaluated to establish what has been done previously. Current recycled plastic examples are discussed. Then the chapter is summarised with a reflection of the findings.

Chapter Overview:

- Introduction to plastic
- Current plastic recycling
- Additive manufacturing
- Different 3D printing materials and techniques
- Current recycled plastic examples

2.2. PLASTIC

Plastic is something people use in their day to day lives. Refrigerators, coffee cups, and cables are lined with it. Plastic is everywhere. Since its invention in 1920, the myriad of uses and benefits of this material boomed after WW2. Plastic is a desirable material as it is lightweight, durable and cheap. Benefits for its uses are its chemical resistance, ductility, melting point, recycling, weather resistance, and weight. (Chanda, 2017)

Plastic may seem like a game-changer but its use of raw materials such as cellulose, coal, petroleum and natural gases has a detrimental effect on the environment. Obtaining these raw materials to produce the plastic creates greenhouse gases, contributing to climate change. New Zealand releases 80 million tonnes of greenhouse gases into the atmosphere every year (MacManus & Nadkarni, 2019).

Waste plastics are thrown into landfills following a linear, single use approach to waste instead of a circular model. In the UK alone 3.7 million tonnes of plastic are thrown away each year. A single-use water bottle can take 400 years or more to degrade, and these pieces do not fully degrade but instead get smaller and smaller (Parker, 2018). Not all plastics thrown into landfills are easily recyclable. PET (1) and HDPE (2) are the easiest, unless they are contaminated with food waste which makes them harder to recycle. Then there are other plastics such as PVC (3), polyethylene (4 & 5), polystyrene (6) and everything else (7) (Recycle.co.nz, 2018).

***1* TON OF PLASTIC = *1.25* TONS OF ETHANE**

(PAPREC GROUP, 2014)

Figure 4: Plastic waste on the side of the road

2.3. CURRENT PLASTIC RECYCLING

The idea of recycling first came about in 1994 when plastic packaging was seen as a waste product (Hita, Pérez-Gálvez, Morales-Conde, & Pedreño-Rojas, 2018) . Recycling the materials meant extending the life cycle of it.

Currently, in New Zealand the most popular plastics recycled are PET (clear soft drinks bottles); and HDPE (milk bottles). There are two main types of plastics, thermoset plastics which will only char and break down and thermoplastics which can easily be melted down and recycled.

> ***"OF THE 8.3 BILLION METRIC TONS THAT HAS BEEN PRODUCED, 6.3 BILLION METRIC TONS HAS BECOME PLASTIC WASTE. OF THAT, ONLY NINE PERCENT HAS BEEN RECYCLED"***
>
> *PARKER, 2018*

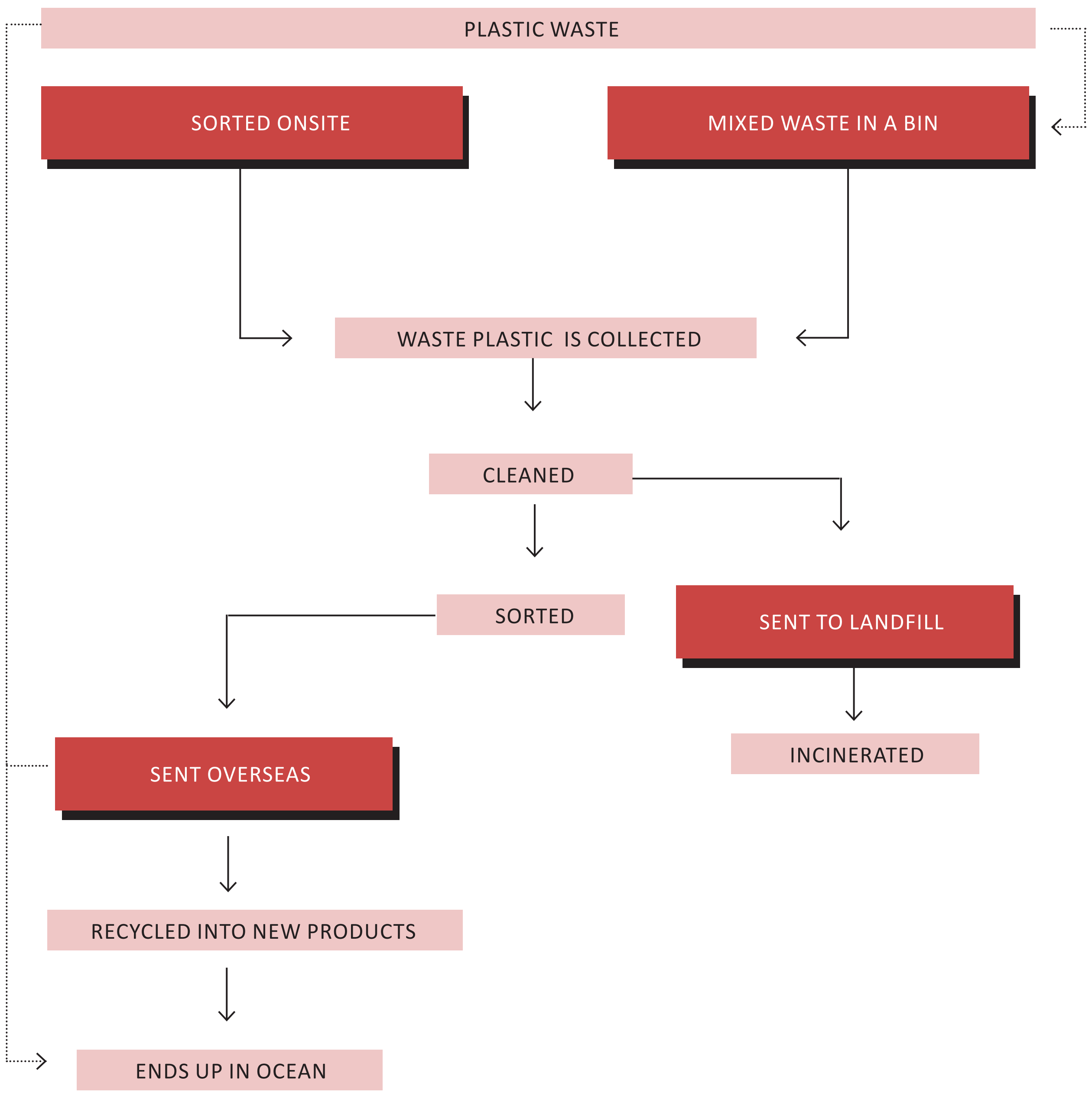
In 2017 New Zealand sent 41 million kilograms of plastic waste to overseas countries to be processed. China received 7 million kilograms of NZ plastic, Hongkong accepted 13.5 million kgs and 19 million tons sent to Thailand, Indonesia, Vietnam, and Malaysia although since January 2018 China is no longer accepting this waste. This forces the recycling companies to send the majority of their waste to facilities in south-east Asia, some of this waste is illegally imported as other countries now send their waste limiting capability of the faculty. (Reidy, 2018)

Transporting this waste can also contribute to climate change, NZ currently produces approximately 8507kt of greenhouse gases a year (MacManus & Nadkarni, 2019). Although there are facilities in New Zealand that collect plastic waste (Reclaim, Green Gorilla, EnviroWaste), they only clean it, sort and send it elsewhere, sometimes even to landfill. Facilities such as Astron Plastic Group and Flight Plastic are turning this plastic waste into new products. Unfortunately there is a limited number of companies for the amount of waste produced.

Economic limitations are what is forcing us to send this waste overseas as it is the cheaper option, "the problem is, recycling is a low margin business built on the economies of scale." If there was money to be made from recycling facilities then more companies would do it, in 2017 we shipped $13.2 million of waste, with a kg of waste earning just 25 cents. (Reidy, 2018)

Therefore the main barriers with recycling plastic seem to be associated with money. There are costs for the plastic to be collected and sorted, and then costs for it to be made into new products or shipped overseas. This is why a lot of it ends up in landfills or reaches waterways. This thesis will propose an alternative recycling method, this is just one solution and the economics of it will not be calculated. Although they will be considered as it will be a local recycling system it will provide jobs for locals and can provide products for them made from their waste. This then counteracts carbon emissions as less transportation is needed.

Figure 5: How current recycling system works



2.4. ADDITIVE MANUFACTORING

The Economist (Kafka, 2012) is calling additive manufacturing the third industrial revolution. It is a 'game-changer' and has energized the world of manufacturing (Badiru, Valencia, & Liu, 2017). Each method of additive manufacturing has its own capabilities, advantages, and limitations that are driven by the materials and qualities of the process involved. Researchers have spent almost a decade investigating and refining 3D printing technologies.

A common advantage and major incentive to many industries who have adopted additive manufacturing is the increase in freedom of design. The technology has the ability to bring complex forms to life suggesting that 'if you can't build it, print it' (de Laubier, Wunder, Witthoft, & Rothballer, 2018). This new technology can provide capabilities beyond that of traditional builders. Digital models of the designs allows designers to get an idea of what the object will look like before it is printed, as the printed model is nearly identical to the virtual version.

3D printers are semi-autonomous, requiring little human surveillance and allows them to work 24/7 speeding up projects. There are multiple companies that have started to engage with additive manufacturing (e.g. Ai Build, 2016). The outputs from many of them have been related to extruding concrete or small scale/low volume projects.

There are many different methods of 3D printing, such as Inkjet binding, or traditional 3D printers (3DP) which print layer by layer with support material and 3-axis of movement. Whereas freeform 3D printing has 6-axis of movement. Allowing it to print complex geometries with no support material. This thesis will utilize additive manufacturing techniques for recycling waste plastic.

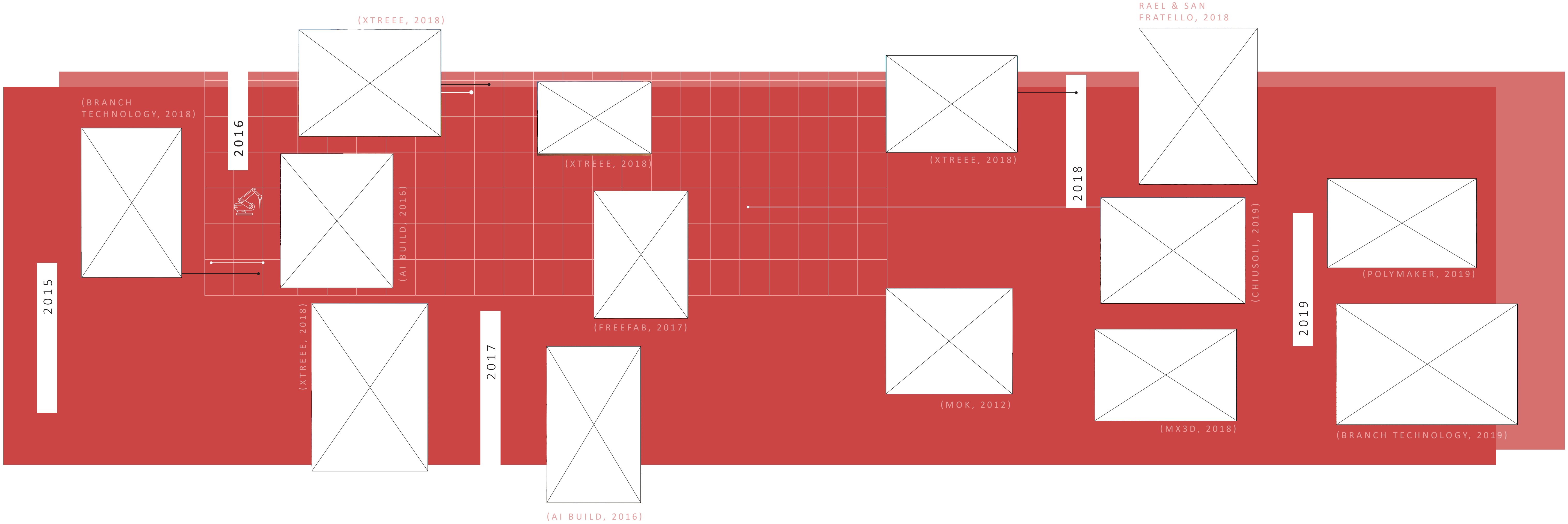
OPTIMIZING THE MATERIAL VISCOSITY, FLOW RATE, ARE IMPORTANT FACTORS FOR A SUCCESSFUL PRINT,"

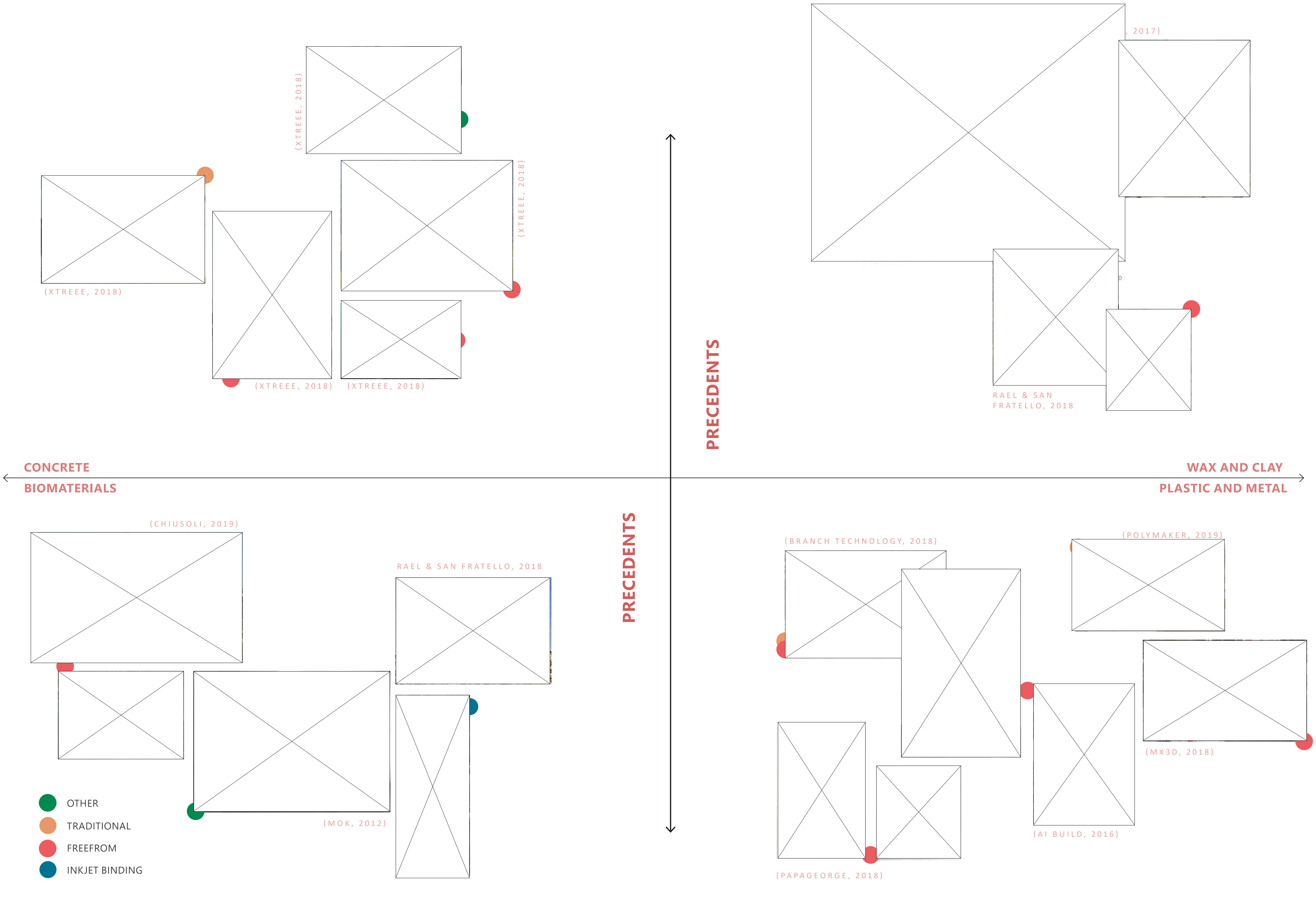
TOM DRYE, TECHMER PM

1. Filament
2. Extruder attatchment
3. Air flow for cooling
4. Acrylic print surface

ABB 6-AXIS INDUSTRIAL ROBOT
WITH EXTRUDER ATTATCHMENT

2.5. PRECEDENT TIMELINE




(XTREEE, 2018)
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RAEL & SAN FRATELLO, 2018
PRECEDENTS
CONCRETE
BIOMATERIALS
WAX AND CLAY
PLASTIC AND METAL
(CHIUSOLI, 2019)
RAEL & SAN FRATELLO, 2018
PRECEDENTS
(MOK, 2012)
(BRANCH TECHNOLOGY, 2018)
(POLYMAKER, 2019)
(MX3D, 2018)
(AI BUILD, 2016)
(PAPAGEORGE, 2018)
OTHER
TRADITIONAL
FREEFROM
INKJET BINDING

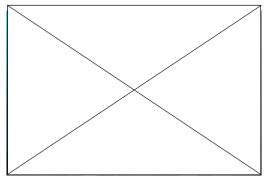


Figure 7: (XtreeE, 2018)

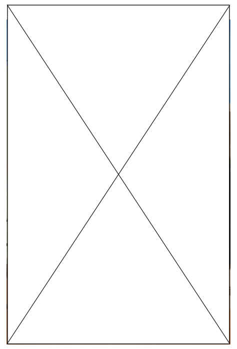


Figure 9: (XtreeE, 2018)

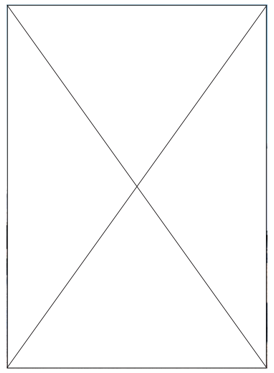


Figure 10:(XtreeE,2018)

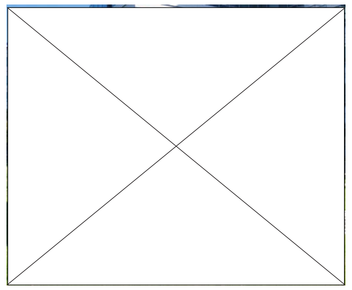


Figure 6: 3D Pavilion (XtreeE, 2018)

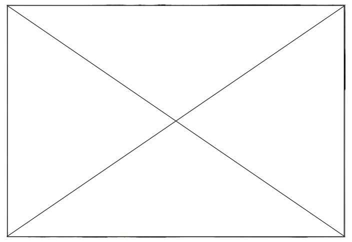


Figure 8: Facade Panel (XtreeE, 2018)

2.6. CONCRETE

3D printing with concrete (3DCP) is a form of additive manufacturing that has the possibility to create shapes that were not possible with traditional concrete formwork. ("3D Concrete Printing," 2018)

XtreeE is a leading example of the possibilities that can be created using this new technology. They have created projects:

- Rexcord artificial reef (Fig.07)
- Facade panels (Fig.08)
- Columns (Fig.09)
- Pavilions (Fig.06)
- Sinusoidal wall (Fig.10)

Concrete 3D printing provides the possibility of large scale prints. There are multiple companies that are printing whole houses while some are printing building elements. Concrete 3D printing also allows the possibility for onsite printing and offsite assembly, saving time and money.

Although this material has potential it cannot follow a circular economy therefore this makes it an unsustainable option for 3D printing compared to other materials.

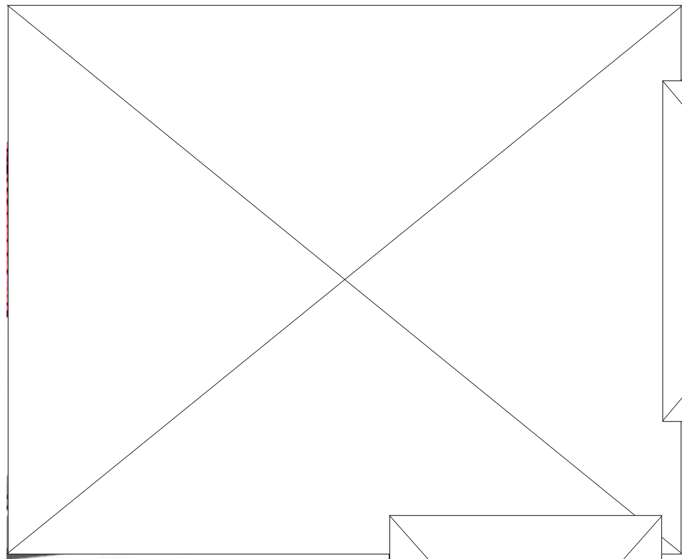


Figure 12: (FreeFAB, 2017)

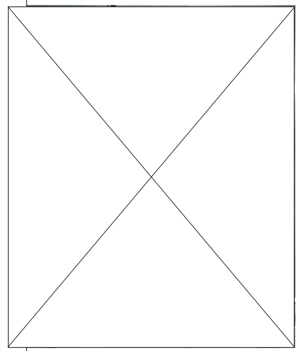


Figure 11: (FreeFAB, 2017)

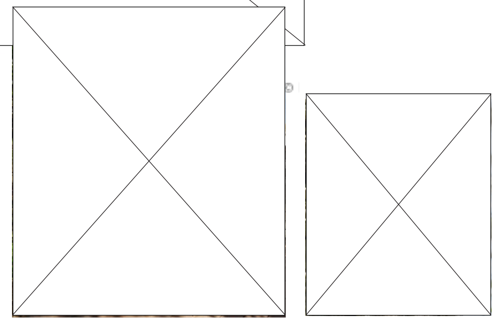


Figure 13: (Rael & San Fratello, 2018) 2017)

2.7. WAX AND CLAY

Examples:

- Cabin of curiosity (Fig.13)
- Wax facade (Fig.11-12)

Other materials used in additive manufacturing are wax and clay. The company FreeFAB 3D prints with wax like resin to create a mould for concrete facade panels to be cast in. The wax can then be removed once the concrete is set and reused or recycled. Clay 3D printing is done by a company called Emerging Objects who developed the 'Cabin of Curiosity' which boasts 3D printed clay tiles on the exterior. These are printed using a freeform technique which allows for a unique design, "The surface of each ceramic tile visually emulates a knitting technique called the seed stitch" (Rael & San Fratello, 2018). Although unlike the wax, clay cannot be reused once it is baked.

'FreeFAB™ Wax offers significant benefits over conventional mould production, as the wax from moulds is filtered and re-used directly, recovering more than 90% of materials. This result in dramatically less waste, lower embodied energy in each product and reduced material consumption. This benefit supports the sustainability agenda of Laing O'Rourke & FreeFab, and reduces the carbon footprint of both production and products.' (FreeFAB, 2017)

Both of these elements are produced off site. The resin example can print large elements in one go, whereas the clay prints are limited by scale. Lots of small prints are made and assembled to make a larger element.

This project influenced the use of tiles as a choosen testing system for waste plastic.

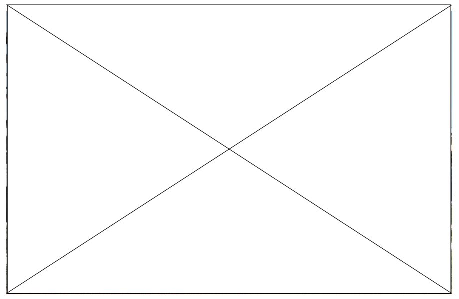
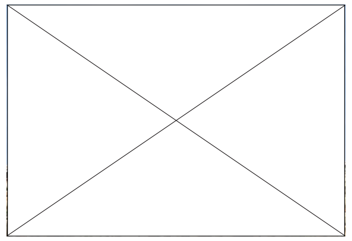


Figure 15: (Rael & San Fratello, 2018)



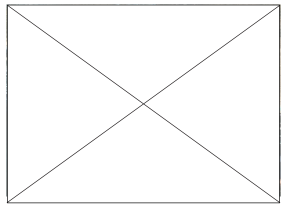


Figure 14: (Chiusoli, 2019)

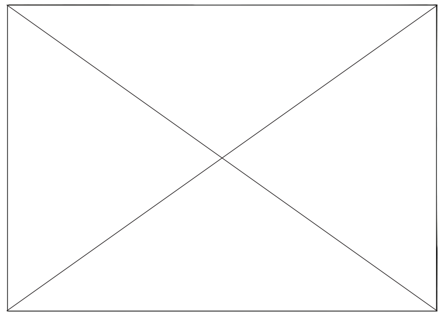
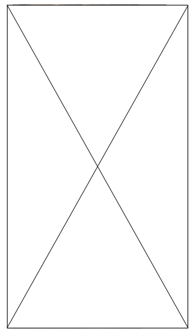


Figure 16: (Mok, 2012)



2.8. BIOMATERIALS

Examples:

- Earth house (Fig.14)
- Mycotecture (Fig.16)
- Cabin of curiosity (Fig.15)

Biomaterials are material or composites that are derived from nature (Edvardsson, 2018). They are mainly used for medical purposes but architecture has adopted this technology as an alternative to harmful and wasteful materials. We are now starting to focus on material-based approaches to architecture while also focusing on form and geometry. Therefore new techniques in fabrication have become apart of the design workflow as they are made more accessible.

The mycelium bricks by Mycologists Phil Ross are an example of a bio-integrated design which uses a living system such as mushrooms/fungi to produce a material to be integrated into a design. Another example is by Rael & San Fratello, (2018) who use waste materials to produce wall tiles. These tiles are constructed with materials such as chardonnay grape skins and sawdust. They are also additive manufacturing other element using materials such as salt, chocolate, sand and tea. It is not clear if all of these materials can be bio-degraded once additives are used to glue particles together. These ideas are revolutionary, but are outside the scope of research for this thesis.

Figure 20: (Polymaker, 2019)

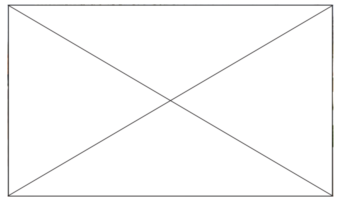
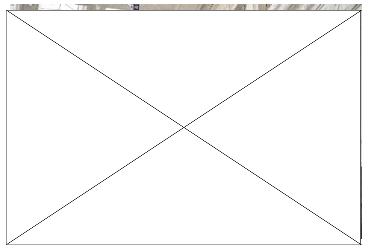
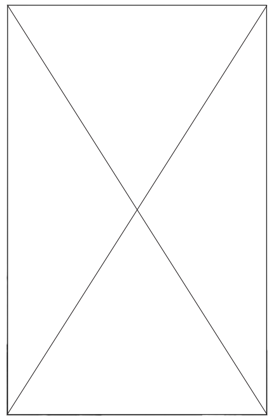


Figure 17: (Branch Technology, 2018)





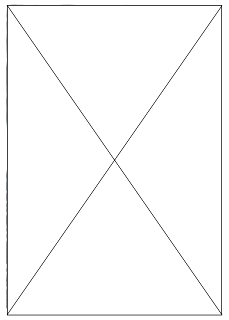


Figure 19: (Ai Build, 2016)

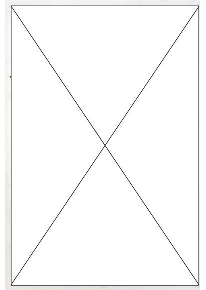


Figure 21: (Papageorge, 2018)

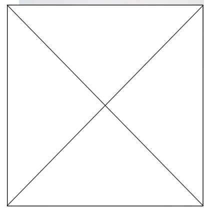


Figure 18: (Papageorge, 2018)

2.9. PLASTIC

Examples:

- Nature clouds and lattice structure wall (Fig.17)
- Concrete reinforcing (Fig.19)
- Plastic bridge (Fig.20)
- Structures (Fig.18-21)

Plastic is a common material used for additive manufacturing. It has desirable properties which make it easy to print designs with. Branch Technologies is a company who are taking plastic to freeform 3D print large scale building elements, such as walls, chandeliers and pavilions. Another example is Ai Build, who also use freeform 3D printing techniques to create concrete formwork, chairs and interior fixtures. Each of these designs are contributing towards the knowledge of additive manufacturing technique, but there is little contribution towards knowledge of what happens to these designs at the end of their lifecycle.

2.10. TOOLS, MATERIALS AND PROCESS/APPLICATION

Additive manufacturing includes a range of different devices for a range of 3D printing styles. Freeform 3D printers are used by companies such as Branch Technology and AI Build. These companies are redefining a typical wall through freeform 3D printing with plastic. Branch creates a lattice structure that replaces a traditional stud element. The lattice structure is fitted with 'low cost, traditional construction materials', such as insulation foam, drywall and external elements such as brick. AI Build has a similar approach although they are printing using freeform but with a layer by layer method. Similar to that of a traditional 3D printer. They have created a system where they can freeform 3D print concrete formwork. This increases design flexibility and zero waste material is produced. In 2016 the initial research about affordable large-scale additive manufacturing where they produced a wall prototype. This wall scaled 1.5x2.3x0.5m and only weighed 15kg. Freeform allows large scale objects to be printed in one print due to it having a large range of movement.

Whereas Emerging Objects is freeform printing with clay using the same layer by layer approach as AI Build. Emerging Objects has a different approach to the way they design and print. Instead of printing the whole object in one go, they print each part and then assemble it. This can be seen in their 'Cabin of Curiosity' where pieces of the facade are printed and then assembled.

A key precedent for this research is the Cabin of Curiosity, it shows how a facade of a building can be redesigned incorporating waste materials. It is unclear what happens to these elements at the end of their lifecycle. Another element to the facade tiles created is how they can hold plants bringing life to the wall.

Branch Technologies 'Nature Clouds' installation was another key precedent. It shows the potential of freeform 3D printing to create a building element that is unique, organic and modular. The 'nature clouds' are a combination of a man made material used to house and bring nature back into a space. The contrast between these elements is eye catching and symbolic of the bioplastic used to hold the plants. The Cellular Fabrication technique and the material provide a lightweight yet strong design. (Branch Technology, 2018)

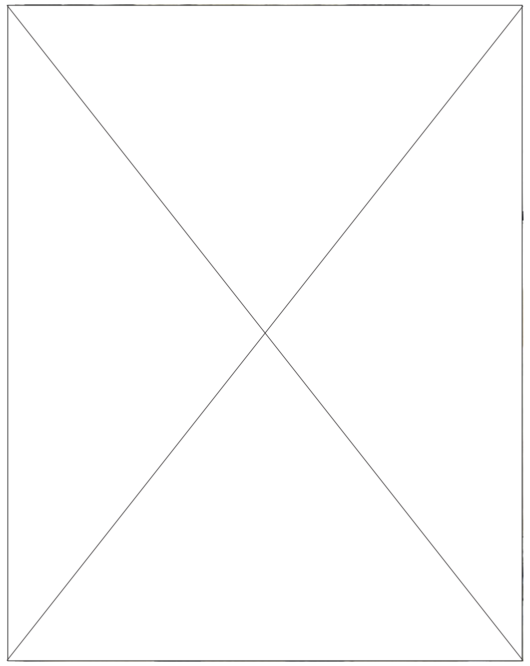


Figure 22: (Ai Build, 2016)

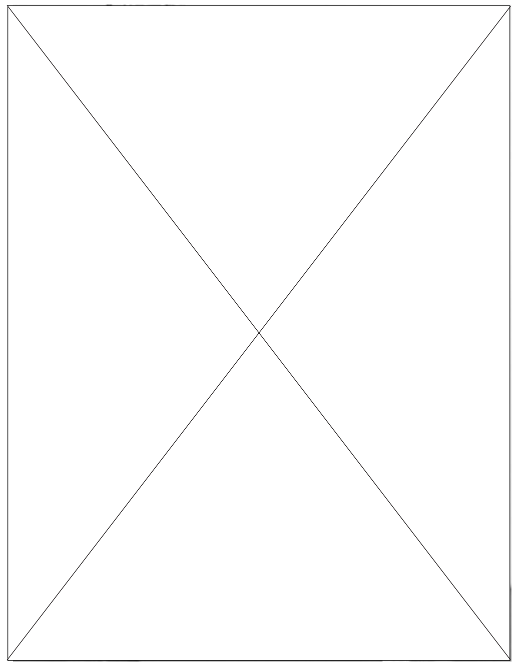


Figure 23: (Branch Technology, 2018)

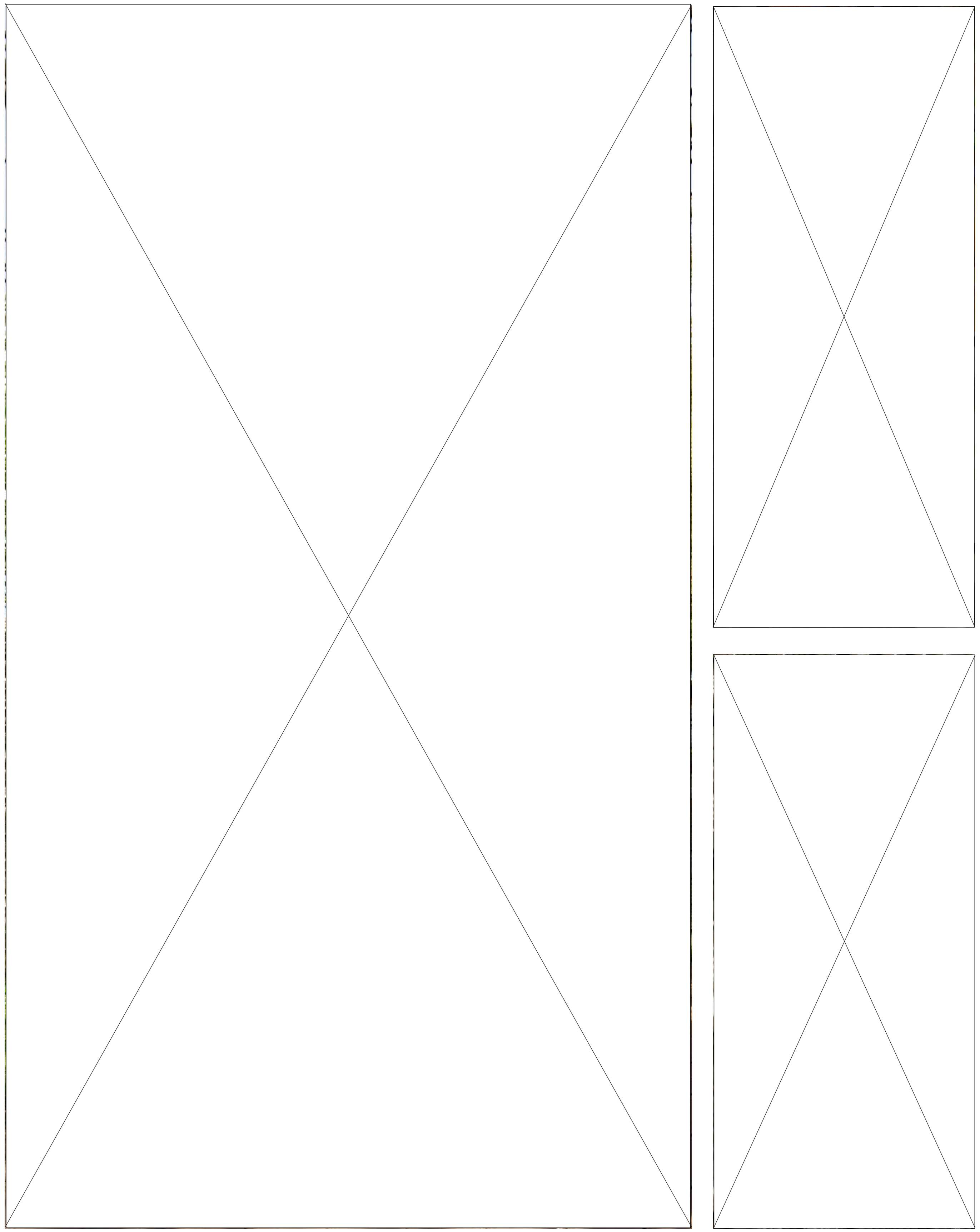
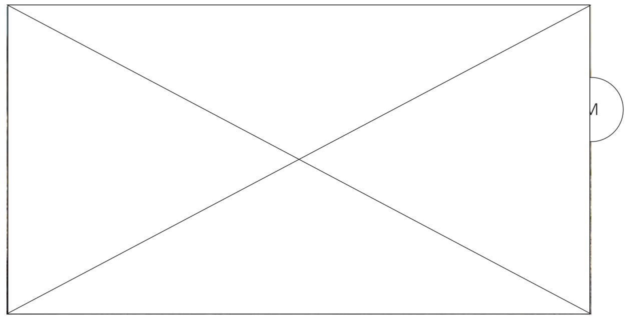


Figure 24: CABIN OF CURIOSITY - (Rael & San Fratello, 2018)

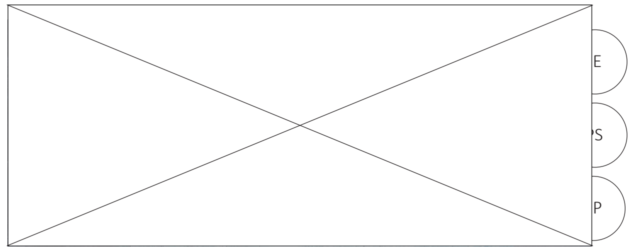
2012 - SEA CHAIR

Figure 25: (“Sea Chair,” 2012)



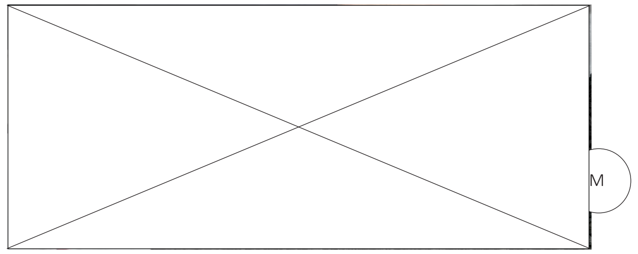
2013 - PRECIOUS PLASTIC

Figure 26: (“Precious Plastic,” 2017)



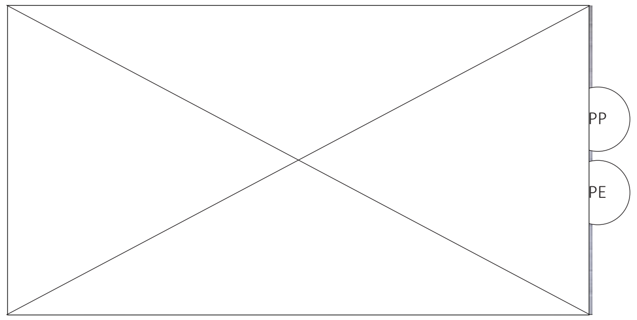
2013 - ENVIROPLAZ

Figure 27: (Penman, 2018)



2019 - TINY PLASTIC FACTORY

Figure 28: (Snell, 2019)



M MIXED PLASTIC
PP POLYPROPLENE
PE POLYETHYLENE
PS POLYSTYRENE

2.11. RECYCLING PLASTIC PRECEDENTS

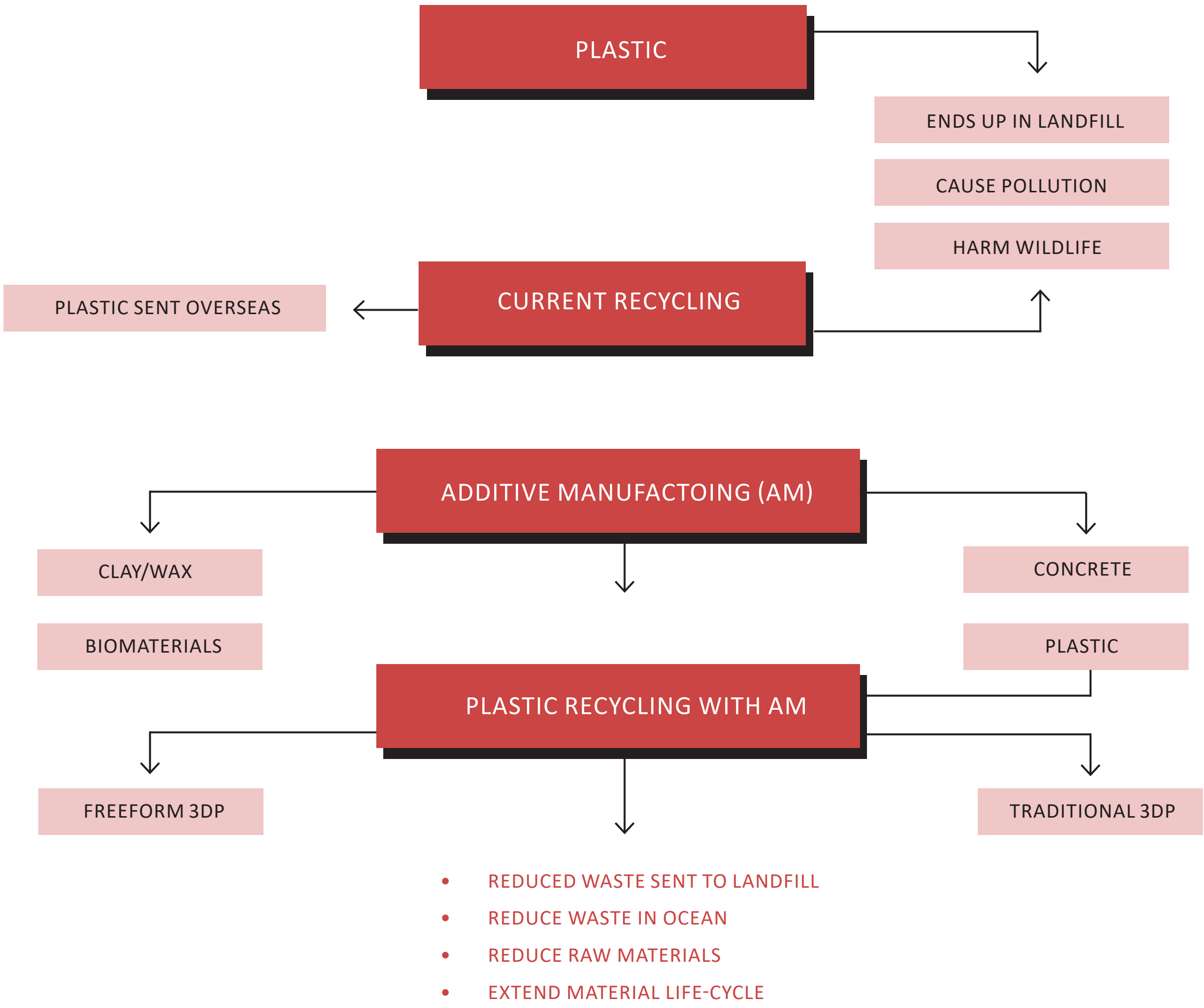
There are a multitude of companies that are working to raise awareness, and help contribute to solving the worlds plastic waste problems.

The ‘Sea Chair’ by Studio Swine focuses on collecting waste plastic from the ocean and turning it into a stool. They also have projects such as ‘Can City’ which collect aluminium objects and also cast plastic into stools.

Precious plastic was established by Dave Hakkens to help work towards a solution to plastic pollution. The company has created machines that ‘enable anyone to recycle plastic’. They have a range of videos on their website that talk about plastic waste and how you can turn it into valuable products.

A local recycling project in New Zealand is the Tiny Plastic Factory. They focus on creating a circular economy for plastic by manufacturing pellets and selling them back to manufacturers. They offer a plastic collection service for businesses, starting by collecting Polyethylene and Polypropylene. They use equipment to produce plastic pellets which they then sell to companies to make into recycled plastic products. (Snell, 2019)

Another company focusing on reducing plastic waste from the waste stream is Enviroplaz. They use plastic waste as an aggregate in concrete. This is called Plazrok, it creates a lightweight and strong concrete while also helping with plastic disposal problems. Peter Barrow the founding director of the company says “it had been a dream of his for the past 20 years to turn plastic waste into something useful rather than dumping it at the landfill.” (Penman, 2018) This scheme does not create a circular economy for a product, but it does repurpose a material that would end up in landfill. Giving it a new life as a new product.



2.12. SUMMARY OF PRECEDENTS

Research has shown that the adaption of additive manufacturing is being used within architecture. Although the implication of the idea of using recycled waste materials is not yet fully recognized. The majority of the case studies use materials that are unable to be recycled at the end of their lifecycle. Consideration of the lifecycle of the elements produced and the materials used needs to be implemented.

Previous examples of precedents that use recycled plastic/or other waste materials to produce an element, mainly produce small scale elements due to the tools used to create them (e.g. "Precious Plastic," 2017). These companies/people are helping contribute to the research of the lifecycle of materials and raise awareness of the issue that societies are facing.

2.13. REFLECTION

Preliminary research into plastics highlighted the growing problem associated with waste plastic and how crucial it is that we start working towards a solution. The literature review highlights the expanding use of additive manufacturing, although this research is only just touching on using it to recycle waste plastic. Within the recycled plastic precedents some deal with only a few plastic types whereas other systems are able to take and recycle all plastics. The issue with companies that use all plastics is these products cannot be recycled again. With Enviroplaz (2018) the aggregate pieces are placed into concrete, removing them from the waste stream and extending their lifecycle but once the aggregate is removed so will the plastic and there is a chance it can end up in the waste stream again. It is unclear what types of plastics are used for the Sea Chair (2012). Research suggests that it is mixed as they collect waste from the ocean and then melt it down. In summary our current recycling system has issues that need addressing. Additive manufacturing has the potential to help with alternative methods of recycling this waste plastic. The plastic waste can be recycled locally to produce products for the surrounding community.

CHAPTER THREE

3

RECYCLING WASTE PLASTIC

3.1. INTRODUCTION

The following chapter focuses on the process of making plastic waste filament. It starts by identifying and explaining the circular economy and how the material of plastic fits within it. The process and steps to making the filament are explained and then different types of plastics are explored. Choosing a plastic to explore further was important in terms of how it would perform. A performance criteria was created for the material to compare how well it could be made into filament and printed with.

Chapter Overview:

- Explaining the circular economy
- Recycled plastic filament process
- Comparing plastics
- Testing the plastic
- Summary and reflection

3.2. CLOSING THE LOOP

The circular economy has been a term that's been used since the late 1970s by academics and businesses, making it difficult to track back to one single date or author. The circular economy model incorporates and integrates ideas from a range of authors to produce principles for this new system. William McDonough and Michael Braungart who established the 'cradle to cradle' model focuses on products and materials that are safe for human health and the environment (Braungart & McDonough, 2002). They introduced the idea of classifying materials as either biological or technical nutrients instead of been thrown to the 'grave'. An example of biological nutrients is when the 'waste' of an animal becomes the nutrients for fungi and plants. Technical nutrients are when a product such as metal and plastic can become 'food' for another product/s. Another author, architect Walter Stahel pursues four main goals of product life extension, long-life goods, reconditioning activities, waste prevention and the selling of services rather than a product. (Winans, Kendall, & Deng, 2017). Biomimicry is an idea that author Janine Benyus defines as 'a new discipline that studies nature's best ideas, and then imitates these designs and processes to solve human problems'. The circular economy takes these ideas and uses nature as a model to follow its processes to help solve ours. Finally, author John T. Lyle suggests an idea of regenerative design, which is said to be the foundation to which the circular economy is built on (Lyle, 1996).

From these key authors and others, three key foundations to the concept of a circular economy have been developed; design out waste and pollution, keep products and materials in use, and regenerate natural systems. (Fig.31.)

While all three foundations are important to the circular economy, this research focuses on using waste plastic to help design out waste. The idea is to keep plastic in use, whether a product is recycled and re-grinded at the end of its use or an element is reused. By using recycled plastic, the need for raw materials to produce new plastic becomes unnecessary.

The circular economy is vast and full of multiple strategies. This thesis only covers a small portion of the circular economy, focusing on the lifecycle of an element. (Fig.2 on page 05, shows which features are outside the scope)

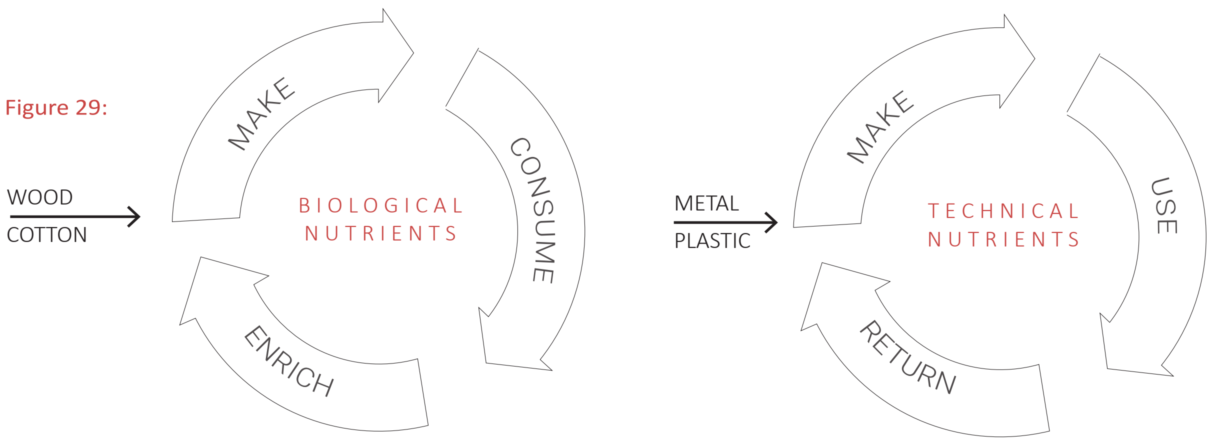


Figure 29:

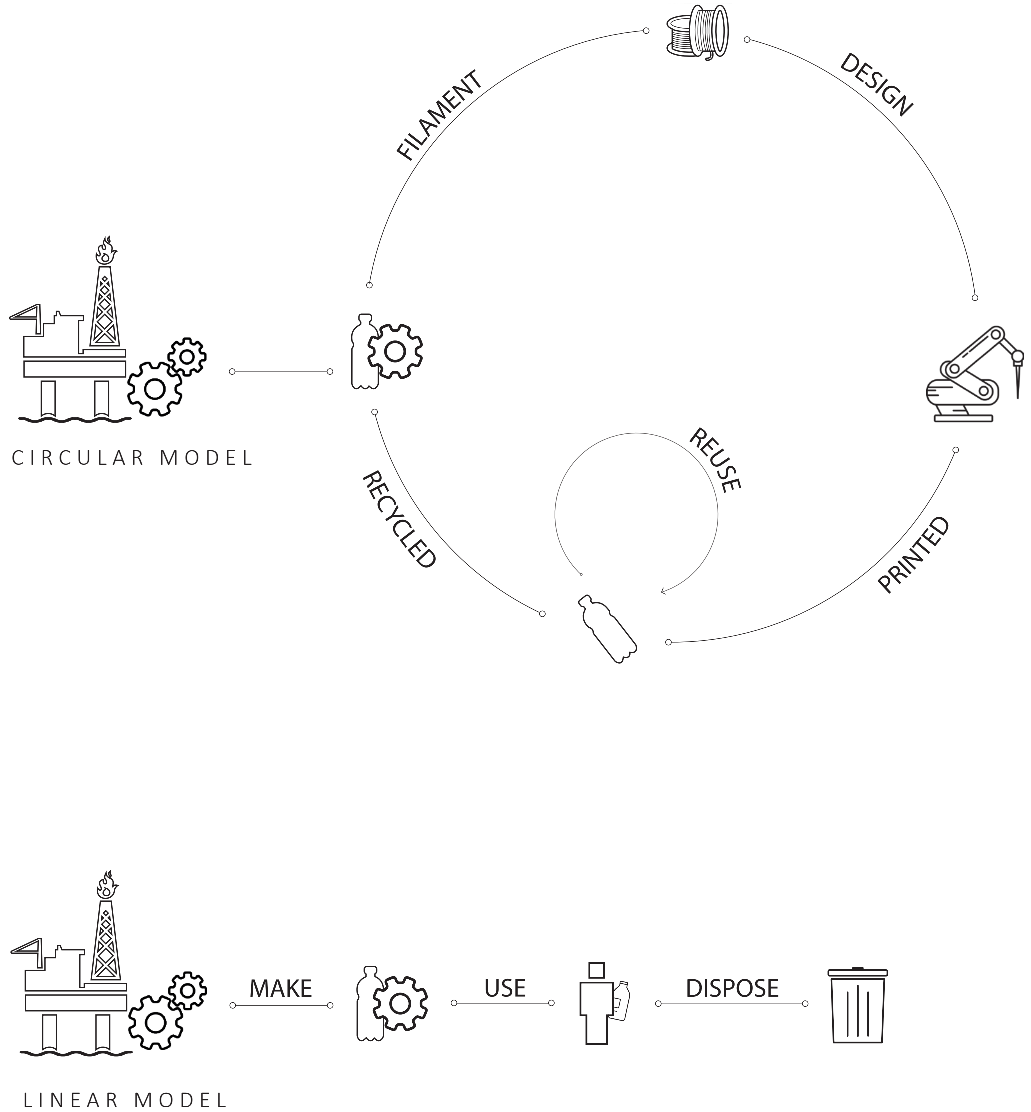
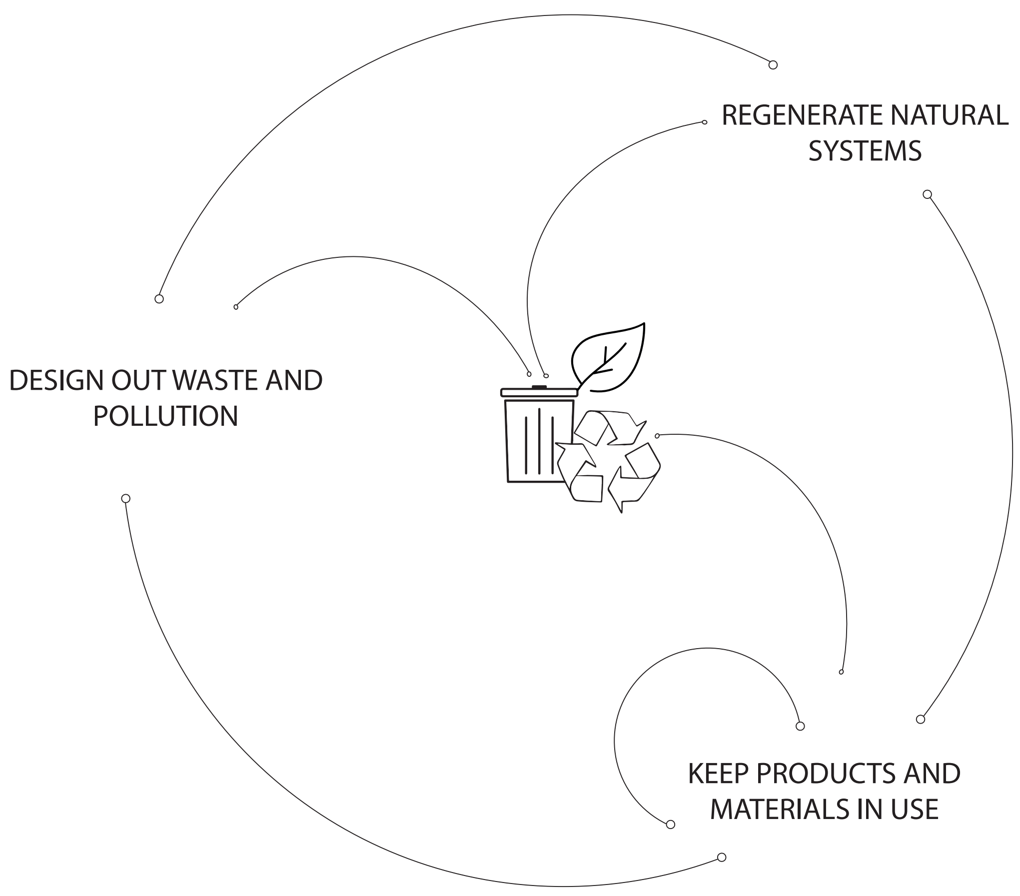


Figure 30: CIRCULAR ECONOMY

Figure 31: CIRCULAR ECONOMY



3.3. MATERIAL CIRCULARITY

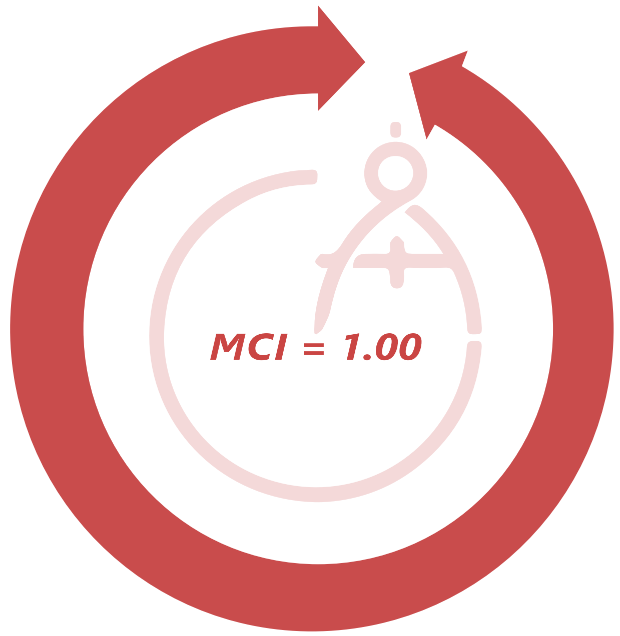


FIG. 01. MATERIAL CIRCULARITY INDICATOR (MCI)

The Ellen Macarthur Foundation strongly follows and advocates for the circular economy system. They have adapted a calculator that allows users to work out the circularity of a material called a Material Circularity Indicator (MCI). As plastic can be recycled and reused it reached an overall MCI level of 1.0.* The MCI calculator follows the assumptions that the material recovered for recycling does not have to go back to the manufacturer. This element is useful to consider as this research does not follow this model. The model also assumes that the recovered material at the end of its use can be processed to a similar quality as the original virgin material. It is also assumed that there is no material loss or damage.

*if something has a MCI of 1, this is equal to 100%. If a material has a MCI of 8 this is 80%.

3.4. RECYCLED PLASTIC FILAMENT

Around 300 million tons of plastic is produced globally each year (Wassener, 2011). Once this plastic has served its purpose/use then it is considered as 'waste', where the 'cradle to grave' model will be adopted. To turn this into a circular model the plastic must be recycled and reused at the end of its life cycle to produce a new product. One example is collecting plastic waste and turning it into usable 3D printing filament.

Currently, there are a limited amount of companies developing recycled plastic filament. The company REFIL in Germany takes plastic bottles, refrigerators and car dashboards, shreds them to be made into 3D printing filament (Refil, 2015). Another company is 3DEVO who strive to 'close the circle' by converting waste plastic into 3D printing filament, "Shred-it, melt it, spool it, and print it" (3devo, 2018). The University of New South Wales has taken a different approach and has created an e-waste micro-factory. They can turn old cellular phones, laptops, and electrical devices into 3D printing filament. They have taken these difficult to recycle materials and created a new life for them (UNSW, 2018).

The scope of this research will focus on the waste material of plastic, and whether it can be upcycled and used to additive manufacture wall tiles.

"SHRED IT, MELT IT, SPOOL IT, AND PRINT IT"

(SDEVO)

Figure 32: Roll of Filament

Figure 33: Twin-screw Extruder

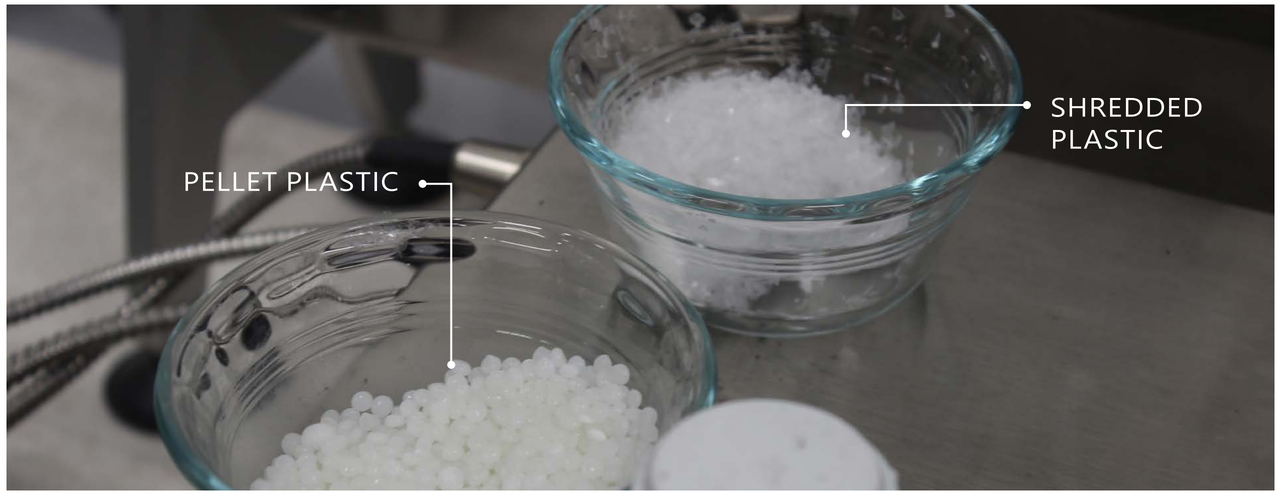


Figure 34: Pellets and Shredded plastic

Figure 35: Recycled Plastic Extruding

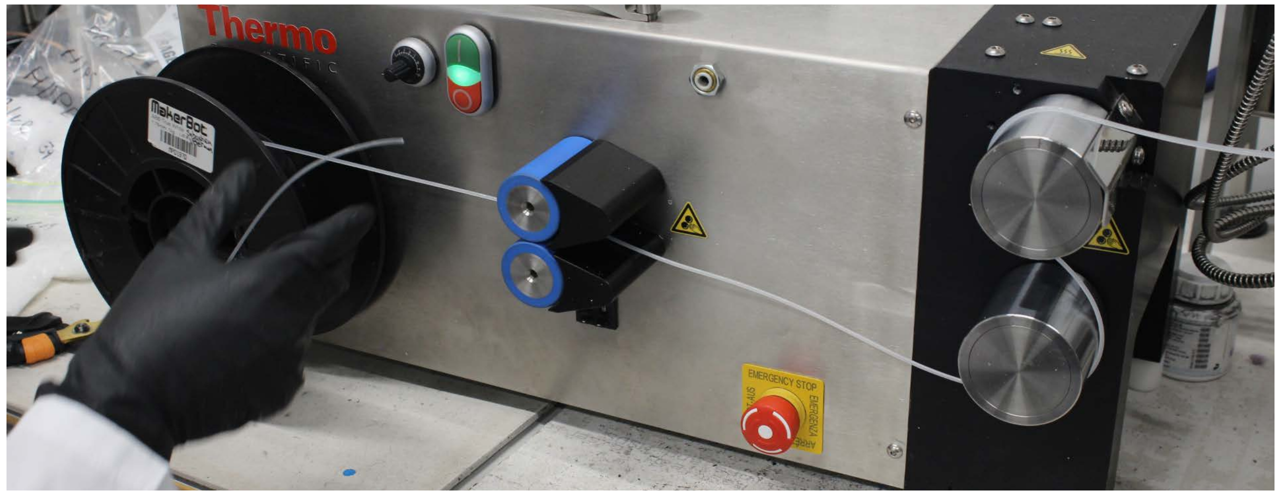


Figure 36: Spooling the Filament

3.5. RECYCLED PLASTIC FILAMENT

THE PROCESS

To begin the process of creating a recycled plastic filament, plastic such as PP and PLA are collected from plastic cups, milk bottles and ice cream containers. These are then cleaned and shredded into tiny pieces, or made into pellets (Fig. 34). The shredded plastic/or pellets are then placed into a machine where they are melted and extruded out the end (Fig. 35). The extrudate is collected and spun onto a spool, where it can then be used to 3D print. (Fig.36)

This process of making the filament is time-consuming and requires a great deal of effort. One issue is finding plastic that can easily be cleaned and sorted. Plastics have to be sorted into like plastic before they are extruded as different plastics have different melting points. Combining different plastics can also reduce the quality, consistency, and colour of the filament. The shredded plastic can also make it hard to produce a consistent diameter filament. Turning the shredded plastic into pellets will help to produce a more consistent filament and overall a better quality print.

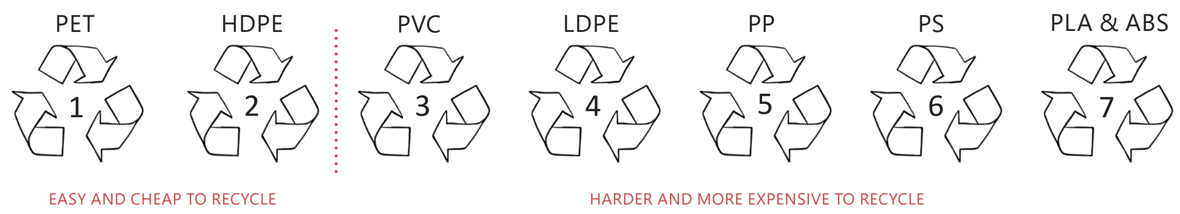
Sometimes downcycling plastics may cause more additives needed to be added than 'virgin' plastic as melting and combining some plastics causes the chains that make it strong and flexible shorten. Chemicals need to be added to create a desired performance for the plastic.

A limitation that needs to be considered throughout this research is that the process of turning the plastic into filament may not be very sustainable at this stage. This thesis will not cover the carbon emissions or energy use of the processes as this is outside the scope of the research.

Mechanical testing has shown that the mechanical properties of specimens printed with recycled PLA were similar to virgin plastic properties. The tensile strength of the recycled filament decreased by 10.9%, shear increases by 6.8% and hardness decreased by 2.4% (Anderson, 2017). This data will have to consider if the filament is being used for structural purposes as the structure may not be as strong as using virgin filament. The multiple reuses of the recycled plastic are also questionable in terms of if it will decrease the quality each time; There is limited mechanical testing done to provide reliable data at this stage.

'WHY CONTINUE TO USE NEW PLASTIC, WHEN THERE'S SO MUCH OLD PLASTIC WE CAN RE-USE'

(REFIL, 2015)



3.6. PLASTICS

IDENTIFY PROPERTIES BEFORE TESTING

MATERIAL	PRODUCTS	PROPERTIES	ADVANTAGES	DISADVANTAGES
PP (5) Polyproplene (C3H6)n	• Take-away Containers • Lunch Containers • Ice Cream Containers • Plastic Cups	• Thermoplastic • Polymerized in 1951 • Melting Point: 130 °C • Tensile strength: 32MPa • Shrink Rate: 1.5- 2.0%	• Chemical Resistant • Can deform without breaking • Retains shape after a lot of torsion and bending • Readily avaliable • Flexible to high heat	• Susceptible to UV degration • Poor binding properties • Highly flammable
PVC (3) Polyvinyl Chloride (C2H3Cl)n	• Pipes • Wall Cladding • Flooring • Interior Fittings • WIndow Frames •	• Thermoplastic • Ideal for industrial application such as construction • Melting Point: 100 - 260°C • Tensile strength: 34- 62MPa	• Very Dense • Readily avaliable and cheap • Extremely good tensile strength •	• Corrosive to 3D printers • Emits hydrogen chloride (HCl) • Poor heat stabiltiy • Subject to fire
PET (1) Polyethylene terephthalate (C10H8O4)n	• Bottles • Packaging • Carpet Fibres • Strapping • Cushion Filing	• First polymerized in 1940s • Melting Point: 260°C • Tensile strength: 152MPa • Shrink rate: 0.1- 0.3%	• Doesn't react with water or food • Strong and lightweight • Doesn't shatter • Transparent • Emits less odor • Easily recycled	• Susceptible to oxidation • Not biodegradable •
ABS (7) Polyethylene terephthalate (C8H8)x· (C4H6) y·(C3H3N)z)	• 3D printing •	• Thermoplastic • Melting Point: 105°C • Tensile strength: 46MPa • Shrink rate: 0.5- 0.7%		• Releases toxins •

(CREATIVE MECHANISMS, 2016)
(ROGERS, 2015)

3.7. PLASTICS

IDENTIFY PROPERTIES BEFORE TESTING

MATERIAL	PRODUCTS	PROPERTIES	ADVANTAGES	DISADVANTAGES
HDPE (2) High-Density Polyethylene (C2H4)n	• Drian pipes • Milk cartons • Garbage bins • Cutting boards	• Thermoplastic • Melting Point: 130 °C • Tensile strength: 20MPa • Shrink Rate: 1.7- 2.9%	• Strong, high density • Resists most solvents	• Expensive
LDPE (4) Low-Density Polyethylene (C2H4)n	• Cling wrap • Plastic bags • Packaging	• Thermoplastic • Melting Point: 110°C • Tensile strength: 7MPa	• Flexible • Lightweight •	• Low tensile strength
PS (6) Polystyrene (C8H8)N	• Solid- medical devices, smoke alarms, yogurt container, plastic cups • Foam- Packaging, styrofoam peanuts, containers for takeaways	• Naturally transparent thermoplastic • Solid- thermoplastic • Foam- thermoset • Comes in a solid plastic ot a rigid foam • Melting Point: 210- 249°C • Tensile strength: 53MPa • Shrink rate: 0.3- 0.7%	• Doesnt reacts to acidic or basic solutuions • Wide range of uses • Inexpensive and readily avalible • Foam is easy to cut, paint and gluye	• Foam is a thermoset • Foam last a long time in the natural environement
PLA (7) Polylactic Acid (C3H4O2)n	• Plastic films • bottles • medical devices • Prototypes • 3D printing	• Bioplastic • Thermoplastic • Melting Point: 157- 170°C • Tensile strength: 61- 66MPa • Shrink rate: 0.37- 0.41%	• Cost efficient to produce • Made from renewbale resources/ biodegradbale	• Not suitable for high tempertures • Brittle •

(CREATIVE MECHANISMS, 2016)
(ROGERS, 2015)

3.8. PLASTIC COMPARISON

SELECTED PLASTIC

After further research into plastic it is evident that many release toxins when they are heated. Exposure to these toxins can be detrimental to our health. This was an important factor considered which choosing which plastic to print with.

Due to the desirable properties of the plastic, PLA (Polylactic Acid) was selected to test further. Other materials such as PP (Polypropylene), and PRO HT (“BigRep PRO HT,” 2017) are also viable materials that can be tested through future research.

Each plastic was collected, shredded, turned into filament and then used to print. The success rate of the print was measured based on the rating scale as shown in Fig.37. Each rating has a set of performance criteria which are used to establish where the results sit on the scale.

Figure 37: Results Rating

0	5	10
poor results	average results	good results
- rough texture	- slightly rough	- smooth texture
- doesnt stick to surface	- sticks to base surface	- sticks to base surface
- doesn’t stick to next layer	- consistant extrusion	- layers stick together

Figure 38: Process

Figure 39: Recycled PLA Filament

Figure 40: Recycled PLA Test Prints

Figure 41: Initail tests of filament

3.9. TESTING POLYLACTIC ACID PLA (7)

Aim:
Collect PLA to shred up and turn into filament to be used for additive manufacturing.

Collection:
The PLA was collected from design student's waste materials.

Grinding:
It was easy to grind up the PLA as a lot of it was small but a large quantity of it was needed to be able to put through the re-grinder.

Once the material is shredded it has to be dried to make sure there is no moisture in it that will affect the quality of the print. The table below shows the different times and temperatures the filament was dried for.

Limitations:
A limitation with the collection of PLA is that it is not as common as PP in everyday items so it may not be as easy to collect.
When grinding the filament not all of it could be used at the end as only pieces small enough to put in the twin-screw extruder were used. The larger pieces would have to be used for another purpose or ground down smaller somehow.

NOTE: The times for drying the plastic was established by an expert in this area

Making the filament:
An issue faced when making the filament was that it was difficult to achieve a consistent profile and would often become too flat (Fig.41). This made it harder to print with as it wouldn't go through the extruder effectively, due to it not having a consistent diameter. This issue was fixed by increasing the space the element shown in Fig.44. as it was too close together and squishing the filament as it was still warm. Cooling the filament before it reached the spool also helped as it hardened causing less deformation in the extrudate. If it cooled too much then it would not coil onto the machine making it hard to spool.

Figure 42: Comparing flat and round filament

NO.	MATERIAL	COLOUR	DRYING	AMOUNT MADE	GRANULATED	ADDITIVE/S	RESULT
1	PLA	Pink	60c for 16hrs	-	yes	HDPE	7
2	PLA	mixed	-	1869.5g	yes	ABS	4
3	PLA	mixed	-	-	yes	HDPE	7
4	PLA	white	60c for 16hrs	-	yes	-	7

3.10.TESTING POLYLACTIC ACID PLA (7)

Testing the white PLA filament multiple parameters such as size, layer height, speed and extrusion rate was undertaken to help find a desirable quality of print for the tiles.

Size:
To test if the size of the tile was a limitation 3 different sizes were selected. These are 100% which is full scale (23cm long), then 70% (16.5cm) and 50% (11.5cm). When scaling down the tiles the measurements for the clips were no longer accurate.

Print and extrusion speed:
The print speed and extrusion speed had to be adjusted so the filament had time to extrude enough filament.

Layer height / Offset:
This is an important parameter as if the layers are too far apart they will not stick together and the tile will fall apart as seen in number 1 in Fig. 43.

Temperture:
TThe extruder was having a problem with overheating so lowering the temperature and having the airflow on a small amount helped to solve this issue.

Reflection:
The main issue discovered through experimenting with size is that as the prints got bigger there appeared to be more defects in the print and layers wouldn't stick together effectively. As the extruder had to go further each layer had longer to cool down, therefore, it did not adhere together effectively. The layer height was another factor that affected the results of the print. The further away the layers the less likely they stick together. If the filament was not extruded fast enough then the layer would not be substantial enough for the next one to adhere to it. No.13 was the chosen parameters within the code for the final prints.

In Fig.43. number 15 was the only print that printed the full way, although it reached its full size there are large gaps between some of the layers.

NO.	FILE NAME	SPEED	TEMPERTURE	OFFSET	EXTRUDER SPEED	SCALE
1	TILE_V12_M4_7	2	0.5	0.8	6	70%
2	TILE_V12_M4_8	2	0.5	1.5	6	50%
3	TILE_V12_M4_9	2	0.5	1.5	6	70%
4	TILE_V12_M4_10	2	0.5	0.9	6	100%
5	TILE_V12_M4_11	2	0.5	1.2	5	100%
6	TILE_V12_M4_12	2	0.5	0.7	6	100%
7	TILE_V13_M4_1	3	0.5	0.8	6	50%
8	TILE_V13_M4_2	3	0	0.8	6	50%
9	TILE_V13_M4_3	6	0.5	0.6	9	50%
10	TILE_V13_M4_4	4	0.5	0.6	8	50%
11	TILE_V14_M4_1	4	0.5	0.6	8	50%
12	TILE_V14_M4_4	4	0.5	0.6	8	100%
13	TILE_V14_M4_5	4	0.5	0.6	8	100%

NOTE: Numbers here do not match those labeled in figure 43

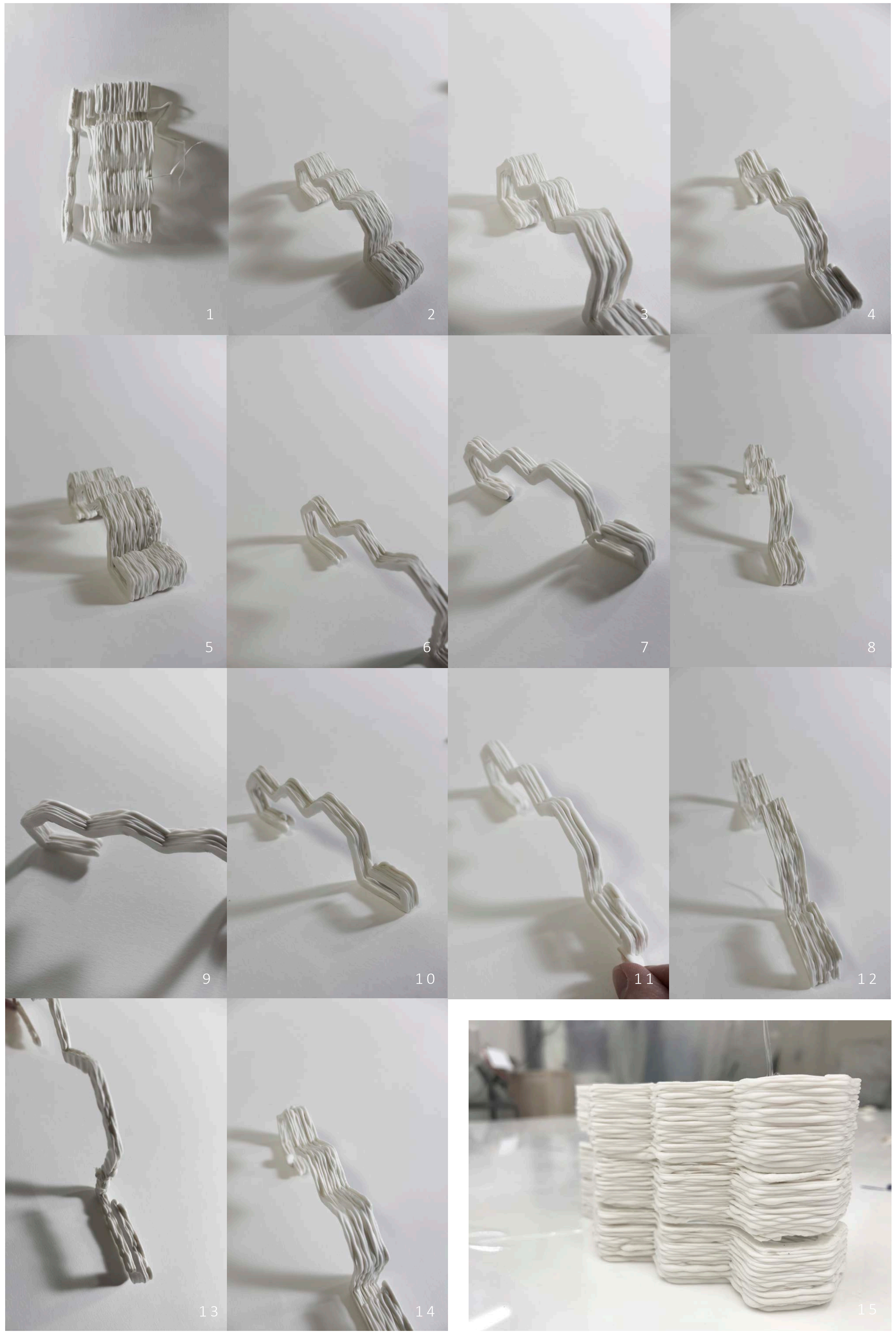


Figure 43: Testing PLA

Figure 44: Flattening the filament

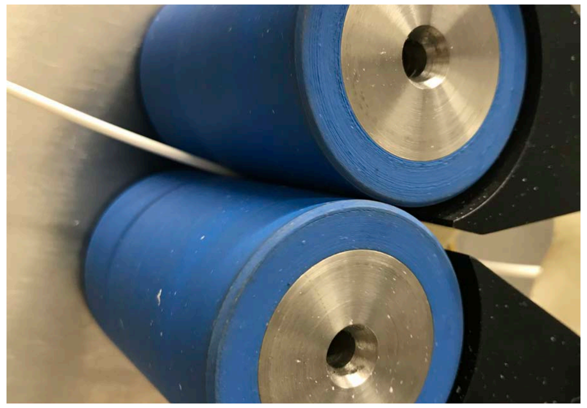


Figure 45: Protective wear

Figure 46: Filament extruding out

3.12. TESTING RECYCLED PLASTIC SUMMARY

A summary of the main findings when creating recycled plastic filament was that the most successful recipe for the recycled filament was PLA with a small amount (1mm) of HDPE added. This formula produced the most desirable printing qualities for the tiles. The HDPE was added for aesthetic qualities but it also helped to improve adhesion between layers.

PLA is not only a mechanical nutrient but it is also a biological nutrient (Braungart & McDonough, 2002), meaning that at the end of its life cycle if it is not reused it can either be composted or shredded and made into filament again. Bioplastics are a growing trend in helping to solve plastic waste, currently they account for only 0.5% of mass-produced plastics globally yet some controversy has arisen in how 'biodegradable' they are. This is something that will need to be taken into account when considering the circularity of the end product.

Making the filament:

When creating the filament the properties of the filament were dependent on how much shredded plastic was added into the twin-screw extruder, the temperature, the speed at which it extruded plastic and how it was spun onto the spool. If the filament came out a consistent thickness then it would provide a consistent print. If the filament was too thick it would not extrude and the same for if it was too thin. From when the shredded plastic was placed into the twin-screw extruder to when it reached the nozzle and started to extrude took approximately 5-6 minutes. The whole process took around 2 - 3 hours to produce the filament minus set up and cleaning the machine.

Optimal thickness of filament: between 2.5 to 2.8mm

Feeder Speed: 5 - 6

Torque: 20 - 40%

Speed RPM: 45

Temperature: 188

Chiller Temp: 5 - 10

(Note: it is hard to set exact desirable settings as other conditions can affect the results of these)

Printing with the filament:

The quality of the print was dependent on a few variables controlled by the Grasshopper code. The temperature had to be hot enough to melt the plastic but if it was too hot it caused the filament to bubble and cause an uneven texture.

The extrusion rate and print speed were also another factor which affected if the layers stuck together. If the print speed was too fast and the extrusion rate too slow then the filament would not be consistent.

An initial issue faced was that the print was not staying stuck to the print base. This was solved through slowing down the first layer, using double-sided tape and the formula of the filament. The airflow rate was another factor that affected the print. The issue with controlling this is that it has to be done manually. Having the air on slightly for the first layers helped keep the filament warm enough to stick to the base surface. The air was then turned up for the rest of the print as it allowed the filament to cool down resulting in a smoother texture while still giving the layers time to bond together.

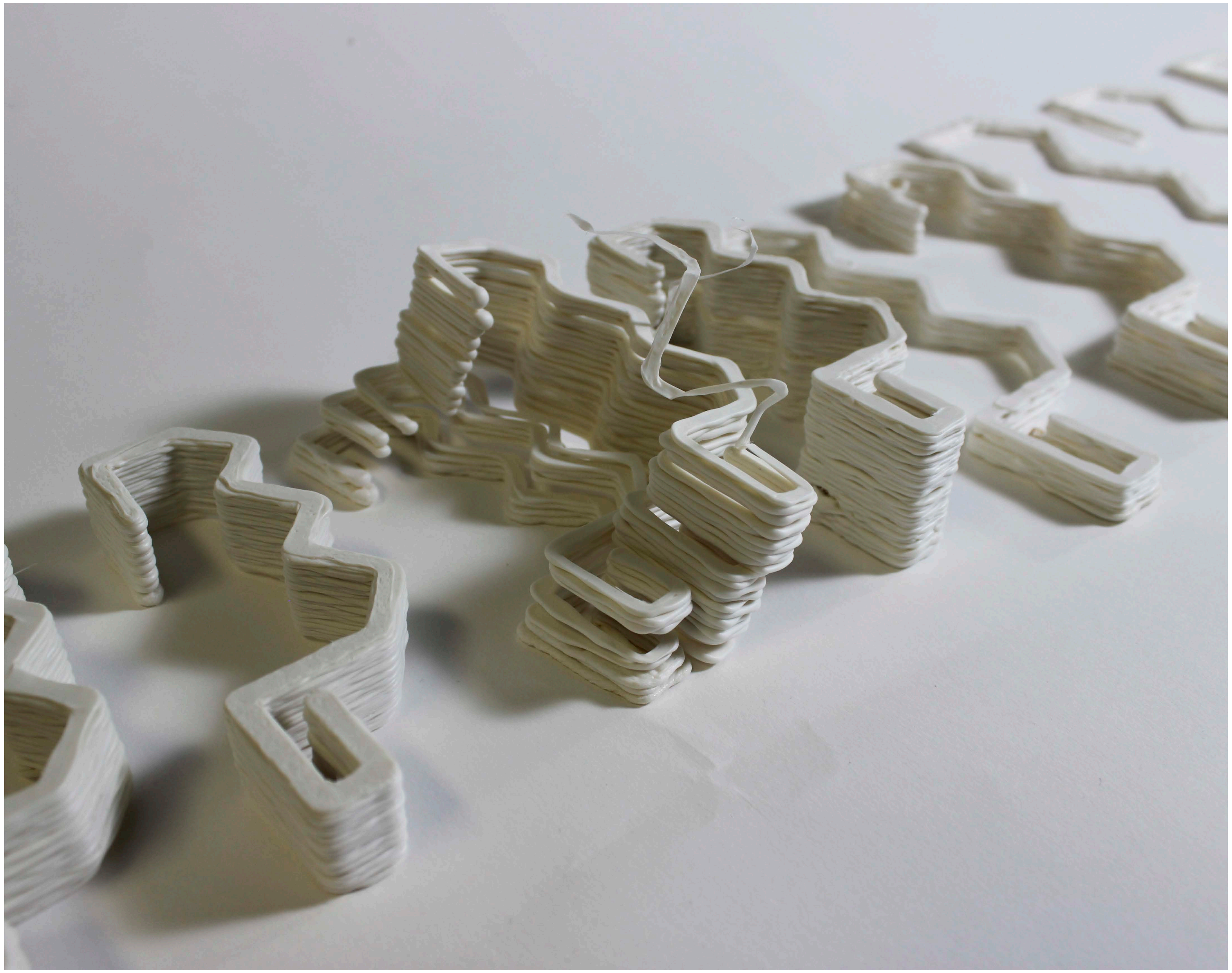
The offset between each layer of the print was another element to consider. If the layers were too close the print would not only take longer but it would bulge onto the lower layer as seen in Fig 41 .

Desirable temperature: 207.4 - 222.2 (0.5)

Print speed: 4

Extrusion speed: 8

Layer offset: 0.6



3.13. REFLECTION

The chapter has reviewed the process of turning the waste plastic into filament for additive manufacturing. Creating a circular economy for waste plastic by extending its lifecycle.

The initial comparison of plastics discovered that some are easier to recycle (PET and HDPE) than others through the current recycling systems. Turning waste plastic into filament makes it possible to recycle other plastics such as PLA, ABS, and PP. Upon further research, the toxicity of ABS meant that it was not a viable plastic to use for this system. PP is also easy to collect as it is an everyday waste material but it was hard to obtain in large enough amounts needed for the thesis. PLA was decided upon for the system due to its availability as to the waste material.

It has been determind that a system/process is now viable for turning plastic waste into filament. The results discovered when testing the scale of prints and the limitations are consistent with other research in this area (Cameron, 2018). It is also worth noting that the limited capability of the material. Plastic can be melted and made into new products but it is unclear how this affects the quality of the material. Due to the nature of the recycled plastic at some stages throughout the tests, there is a clear limitation of not being able to create a high-quality print, compared to other methods researched.

CHAPTER FOUR

4

DESIGN OUTPUT

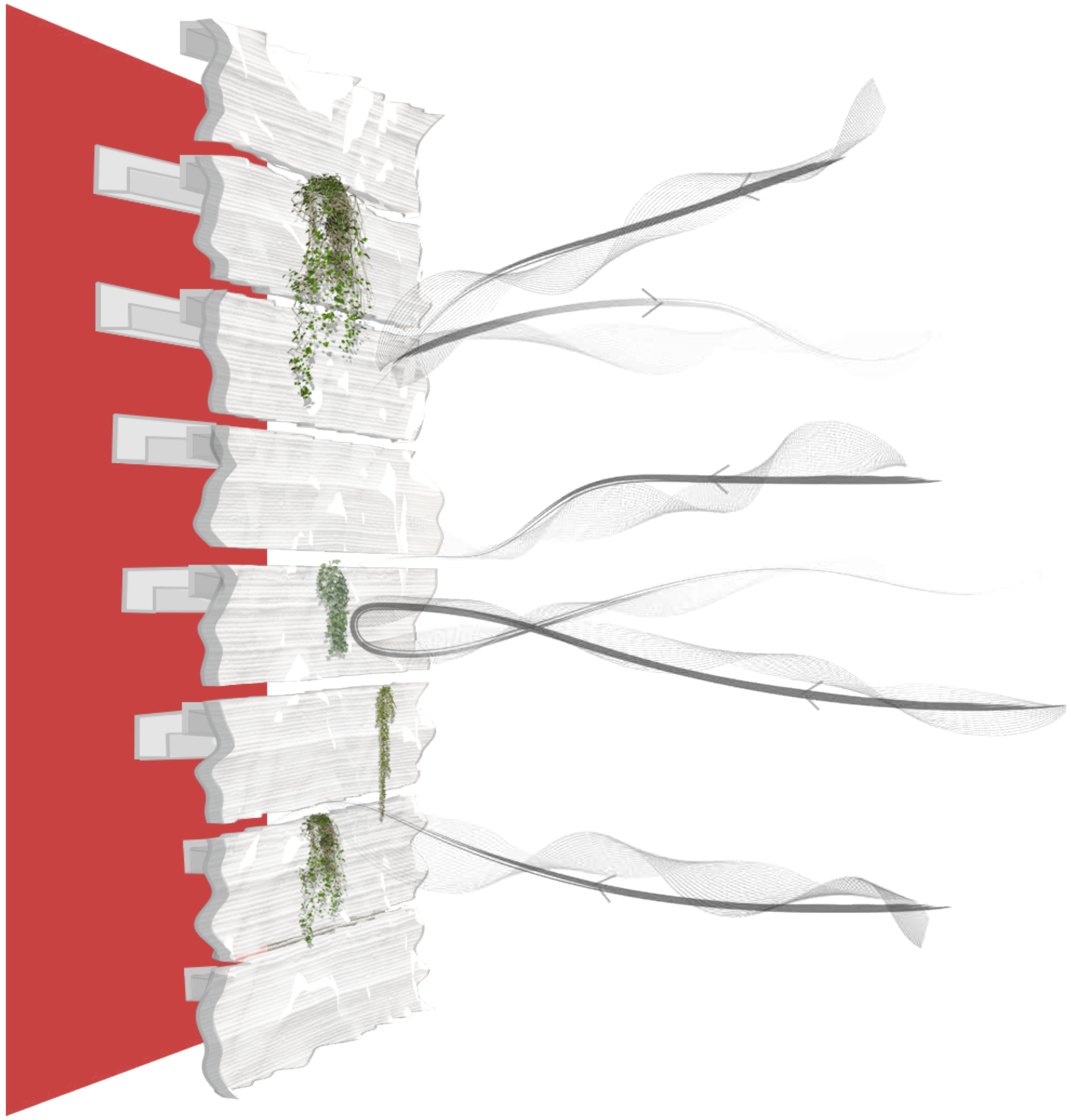


Figure 47: Initial Idea Example

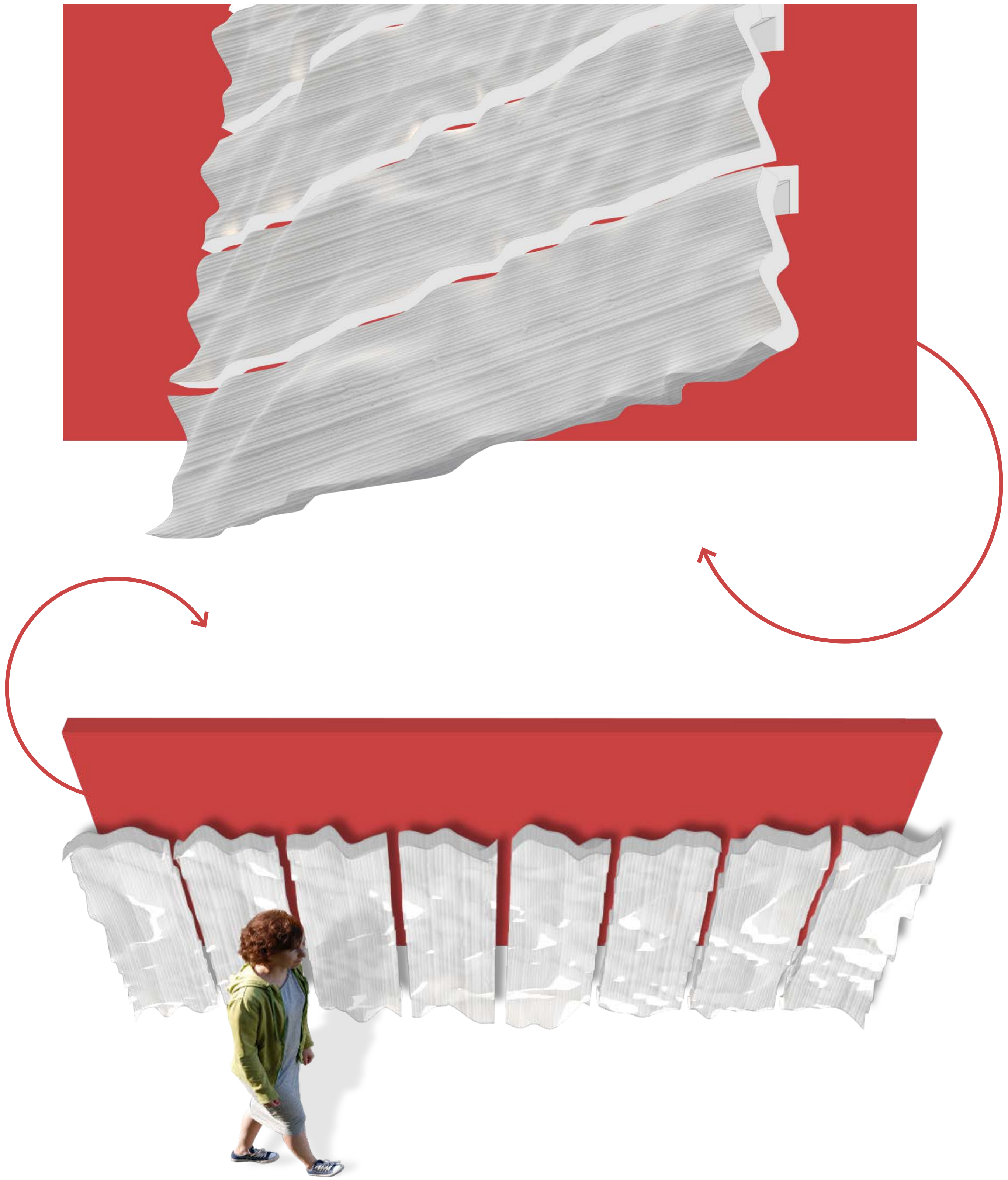
4.1. INTRODUCTION

Having determind the printability of the plastic, a design prototype was explored for further testing the performance of the plastic. This section of the thesis explores the design of the wall tiles. Each iteration is evaluated and reflected upon to lead to the next design and overall a final design output.

Chapter Overview:

- Iterations are explored and reflected upon
- Final design established
- The overall system
- The digital system
- Implementation of the system

INITIAL IDEAS



4.2. WALL TILES

To test the performance of the plastic recycling system, a building element was chosen to design and print. The chosen elements were wall tiles. These were chosen as they are something that is scalable, do not require fixtures to it, can be one material, and interior linings are a common waste material within construction. The tiles are made of recycled plastic and are part of a system that can be attached to an existing wall, then taken off at the end of its life-cycle and either reused or recycled into another plastic product.

The tiles are an example of a sustainable system that can be created using waste materials that can contribute to a circular economy by regenerating natural systems, they can provide nutrients when they degrade, although an industrial composting facility is needed. It can be placed in a household composting system but will take hundreds of years to degrade (Filabot, 2015). Being able to shred and reuse plastic waste filament/product keeps the product in use which eventually designs out waste and helps contribute to reducing pollution.

These factors were taken into consideration when designing the wall tiles and comparing them to current systems on the market. This system is not designed to replace any current systems at this stage as that is outside the scope of this thesis. It is merely an example of how waste material can be used to print a product to produce a more sustainable solution.

The first design focused on how the system could be attached to an existing wall. Fig. 48 shows how it can clip onto the wall.

Performance Criteria

To examine the success rate of the wall tiles a performance criteria was created to test the properties of the tiles. These are seen in Fig.49.

Figure 49: Results Rating

0	5	10
poor results - pattern not clear - can not clip to panel - size incorrect	average results - pattern clear with flaws - can clip to panel - output within 10% of the virtual model	good results - pattern clear - can clip to next panel - appropriate size

Figure 48: Clipping System

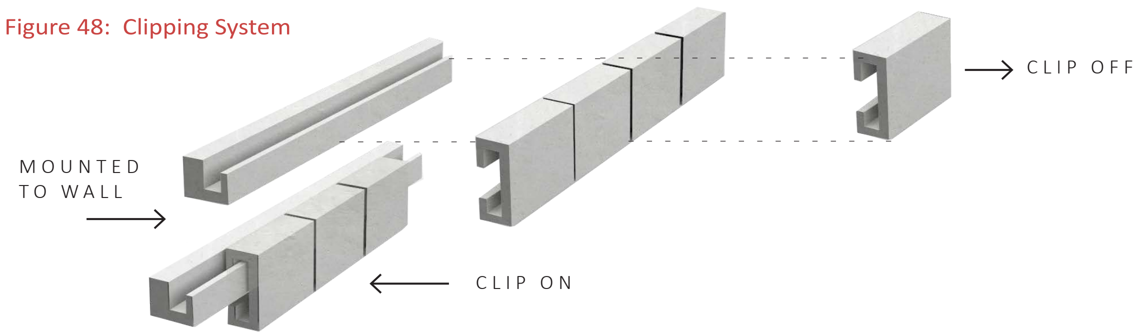


Figure 50: Iteration One

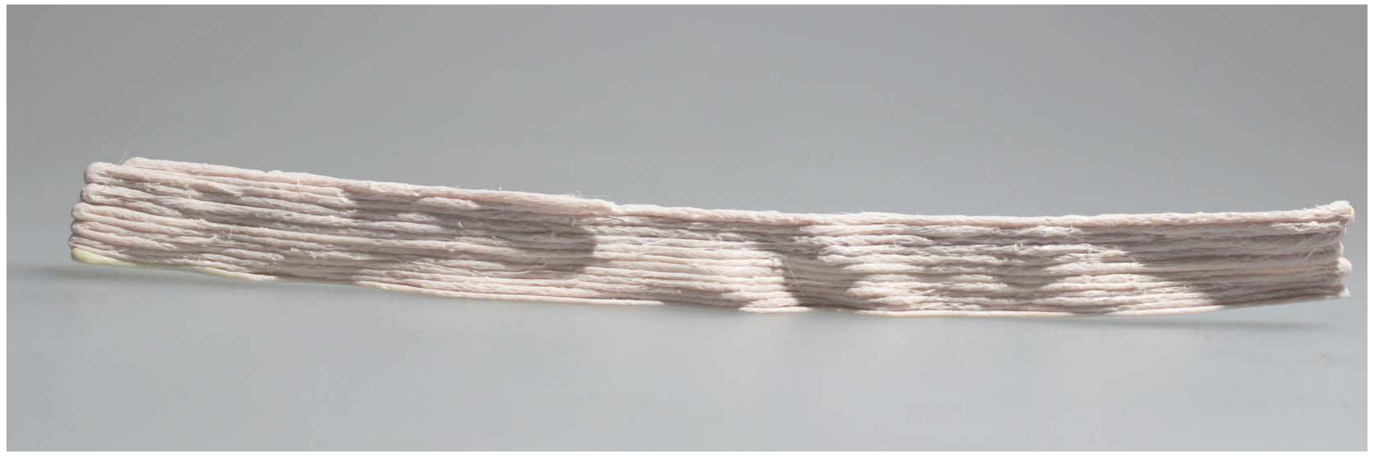


Figure 51: Iteration One

Figure 52: Iteration One

4.3. ITERATION ONE

Design:

This iteration was designed based on a formula in Grasshopper which uses a sine wave equation to create the smooth curves on a surface. (Fig 61 on page 84 has Grasshopper code for the wave)

Observation:

The wave pattern was clear to see when printed.

Limitations:

The layers between each line are offset too much which caused some gaps in the print. The print didn't stick well to the print surface causing the shape to deform (Fig.50-52)

The initial pattern was created on a large surface. Although this large surface would take a while to print, the surface was divided into smaller segments to print (Fig.53).

Performance:

This design gets a performance rating of 4. This is due to the pattern being clear but was not different to that of the digital model. The clip was also not introduced at this point so can not be assessed against the performance criteria.

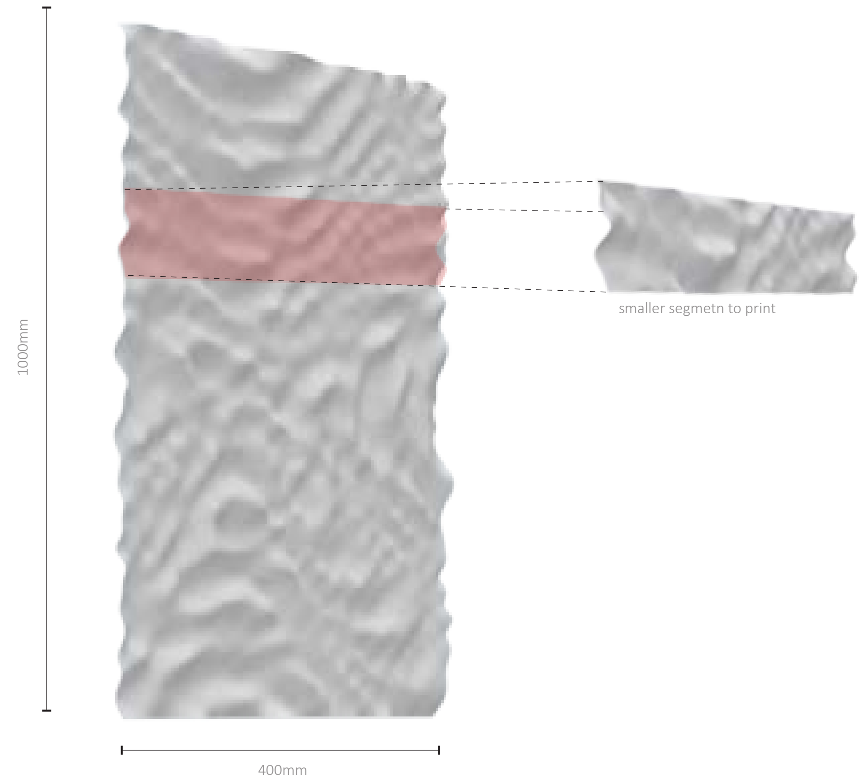
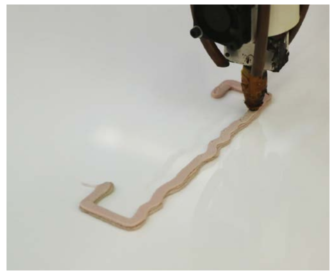


Figure 53: Digital model of print

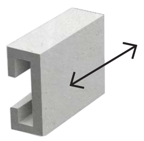


4.4. ITERATION TWO & THREE

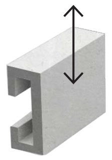
Dimensions: (measurements are the max distance)
- length: 14.5cm
- width: 1- 1.5cm
- depth: 3.5cm

Design:
This design built upon the findings from iteration one. The addition of the clip was a key solution to help solve the limitations from iteration one.

Observation:
The clip was added at one end to allow for it to attach onto a wall but the print kept coming off the print surface, so another clip was added (iteration three) to the other end helping to keep the print stuck down. This can be seen above, which shows how the one with only one clip curves.



PRINTING SIDE TO SIDE



PRINTING TOP TO BOTTOM

Figure 54: How the tile was printed

Limitations:
A limitation with some additive manufacturing this way is that it takes a while for the design to develop as it prints layer by layer. Therefore it is important to consider how the design is orientated for printing. The tiles had to be printed a certain way so it was possible for the clip to be apart of the design. If it was to be printed from bottom to top rather than side to side as shown in Fig.54. it would create a long but not very high print. Overall the addition of the 'clip' at either end of the print was a key aspect to the design in moving forward to further iterations.

Performance Rating:
Iteration two has a performance rating of 5.
Iteration three has a performance rating of 6.
(Refer to Fig. 49)

4.5. ITERATION FOUR

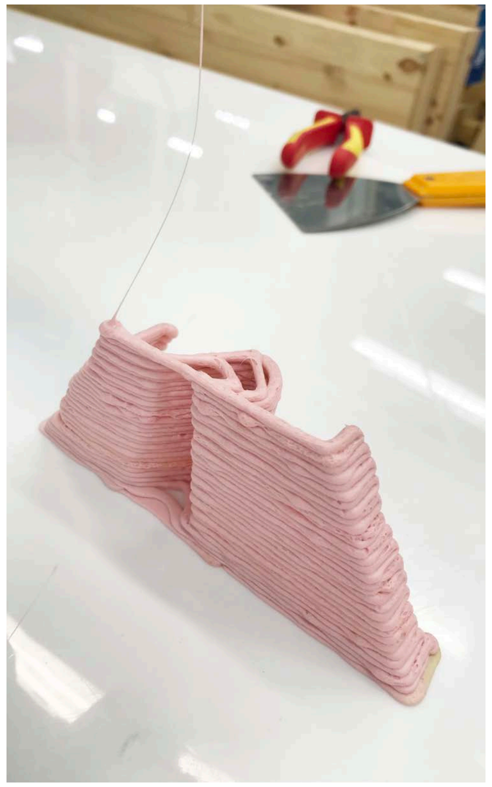
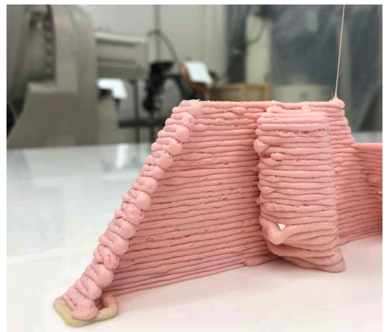
Dimensions: (measurements are the max distance)
- length: 14.5cm
- width: 1.5cm
- depth: 4cm

Design:
In previous iterations the wave pattern was subtle. This iteration works on emphasising these curves to make a more prominent pattern when used on a wall.

Observation:
The wave pattern is more evident compared to previous iterations. The complex form took longer to print than previous iterations.

Limitations:
At points along the print, the extruder would overheat causing it to pause and it would stop extruding. Then there were human errors, as these were printed in 'manual mode' which meant a trigger had to be held down or the robot would stop, also known as a 'dead-mans switch' for safety reasons. This happened a few times due to human error where the print would stop but the filament would keep extruding.

Performance Rating:
This iteration has a performance rating of 7. (Refer to Fig. 49)


4.6. ITERATION FIVE

Dimensions: (measurements are the max distance)
- length: 15.5cm
- width: 6.5cm
- depth: 4cm

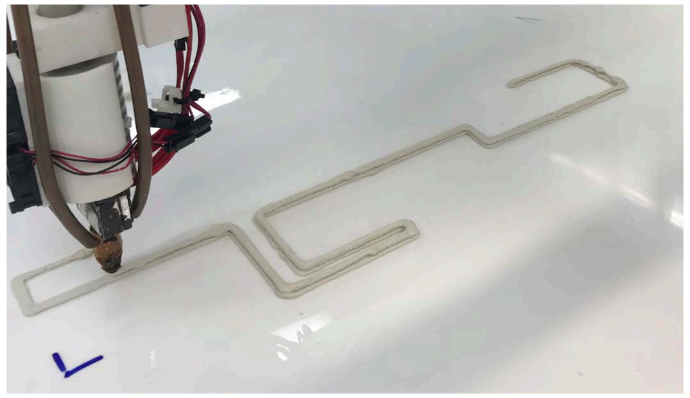
Design:
This design was for a tile that would double as a plant holder. The dip provides a space for a hanging plant to be planted to trail down the tile.

Observation:
This was the first iteration when the whole tile was printed. The tile is dense resulting in a strong form. The surface is simple.

Limitations:
There are gaps between the layers where the plant would go therefore another layer would need to be added to stop water or soil leaking out. This would then create more waste if another element was added.
To help mitigate the gaps, layer heights needed to be reduced.

Performance Rating:
This iteration has a performance rating of 7. (Refer to Fig. 49)





4.7. ITERATION SIX

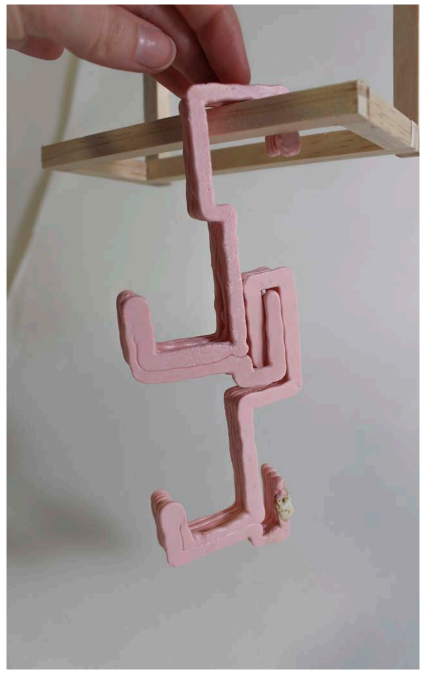
Dimensions: (measurements are the max distance)
- length: 38cm
- width: 8.5cm
- depth: 2cm

Design:
This design is another version of a plant holder but instead of providing a place for planting it provides a shelf for a pot to sit on.

Observation:
The quality of this print is poor compared to the smaller iterations. The design was simple and needed further improvements.

Limitations:
The scale of this design was larger than iteration five, this scale seemed to provide some difficulties to the design as well as the layer offset.

Performance Rating:
This iteration has a performance rating of 4. (Refer to Fig. 49)



4.8. ITERATION SEVEN

Dimensions: (measurements are the max distance)
- length: 10.5cm
- width: 6cm
- depth: 2cm

Design:
These iterations buildup iteration six. Initially the clip at the bottom was to help the print stay stuck to the print surface, but was later developed as a clipping system to reduce fixings to the wall.

Observation:
Iteration six at a smaller scale, printed effectively. The clipping system worked well but the design still needed some development.

Limitations:
When scaling this design it would also scale the clip, therefore it would no longer clip onto each other. This had to be taken into account before each print.

Performance Rating:
This iteration has a performance rating of 8. (Refer to Fig. 49)

4.9. ITERATION EIGHT

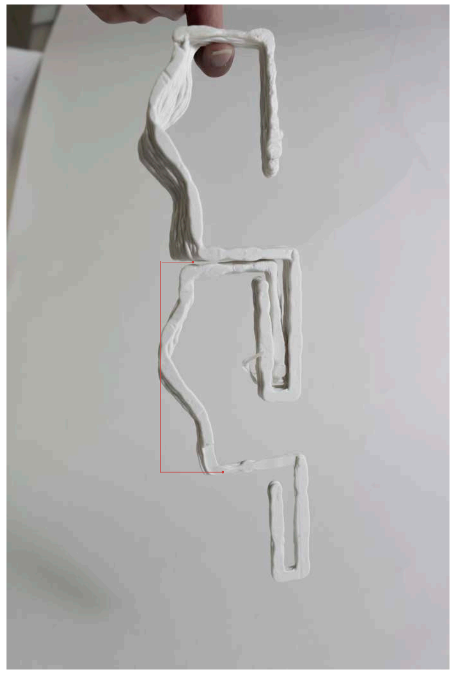
Dimensions: (measurements are the max distance)
- length: 11.5cm
- width: 4cm
- depth: 4cm

Design:
This iteration was designed to test the scale limitations of the prints. It also provided a useful form for testing as the geometry wasn't complex allowing for a full test print to run establishing an approximate time for the prints.

Observation:
This print took approximately 2 hours in automatic mode. It is 70% of the full size, therefore a full-size print is expected to take longer.

Limitations:
When designing these forms there are factors that need to be considered. The size and geometry are two parameters that affected the time and quality of the print. The more complex and larger scale it is, the longer it will take to print.

Performance Rating:
This iteration has a performance rating of 8. (Refer to Fig. 49)


4.10. ITERATION NINE

Dimensions: (measurements are the max distance)
- length: 17.5cm
- width: 7cm
- depth: 1cm

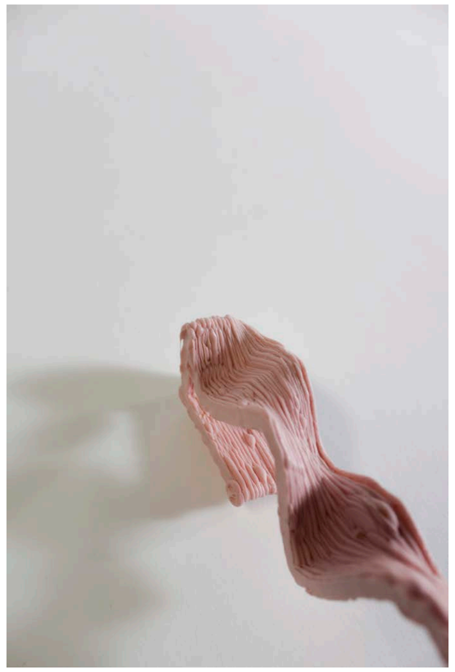
Design:
Once the scale limitations were established through iteration nine this design took forward iteration four and seven to develop further.

Observation:
As highlighted in the image above the front of the tile it was small and therefore would require more tiles printed to achieve an overall design.

Limitations:
Getting the clipping system to work took some time as the thickness of the tile had to be taken into account as this was not modelled digitally.

Performance Rating:
This iteration has a performance rating of 7. (Refer to Fig. 49)





4.11. ITERATION TEN

Dimensions: (measurements are the max distance)
- length: 20.5cm
- width: 7cm
- depth: 2cm

Design:
Building upon the observations of iteration nine, the size of the tile was increased. The wave pattern was also emphasised to make it more prominent.

Observation:
The wave pattern is clear and the tile size is viable for creating a wall system. The clipping system appears to need some work as the thickness of the filament was not taken into account.

Limitations:
Increasing the wave surface in the digital model was simple but some of the tiles were too complex and were not successful prints.

Performance Rating:
This iteration has a performance rating of 9. (Refer to Fig. 49)

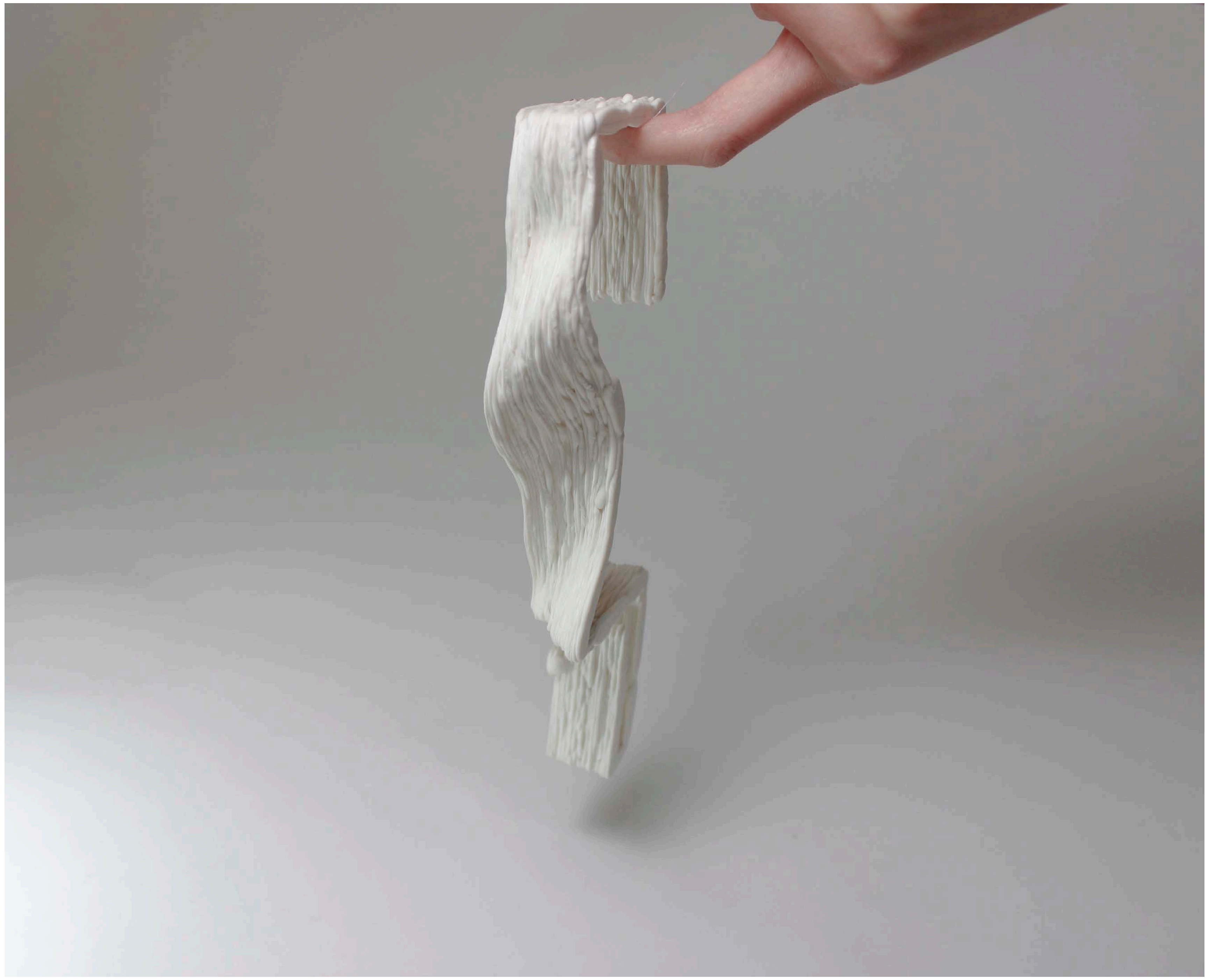


Figure 55: Digital model of print

4.12. FINAL DESIGN

Dimensions: (measurements are the max distance)
- length: 22 cm
- width: 7.5 cm
- depth: 2.5 cm

Design:

The final design takes into account all the observations and limitations from previous iterations to come to a final conclusive design. The design is similar to iteration ten but has a less complex wave pattern.

Observation:

The clipping system is successful meaning that the panels can be clipped together (Fig.56-57) and then unclipped and either reused or recycled at the end of their lifecycle. The wave pattern is evident to see.

Limitations:

There are still minor design faults in the print such as gaps in the print and bubbles but these may be attributed to the filament or additive manufacturing technique used.

Performance Rating:

This iteration has a performance rating of 9.5. (Refer to Fig. 49)

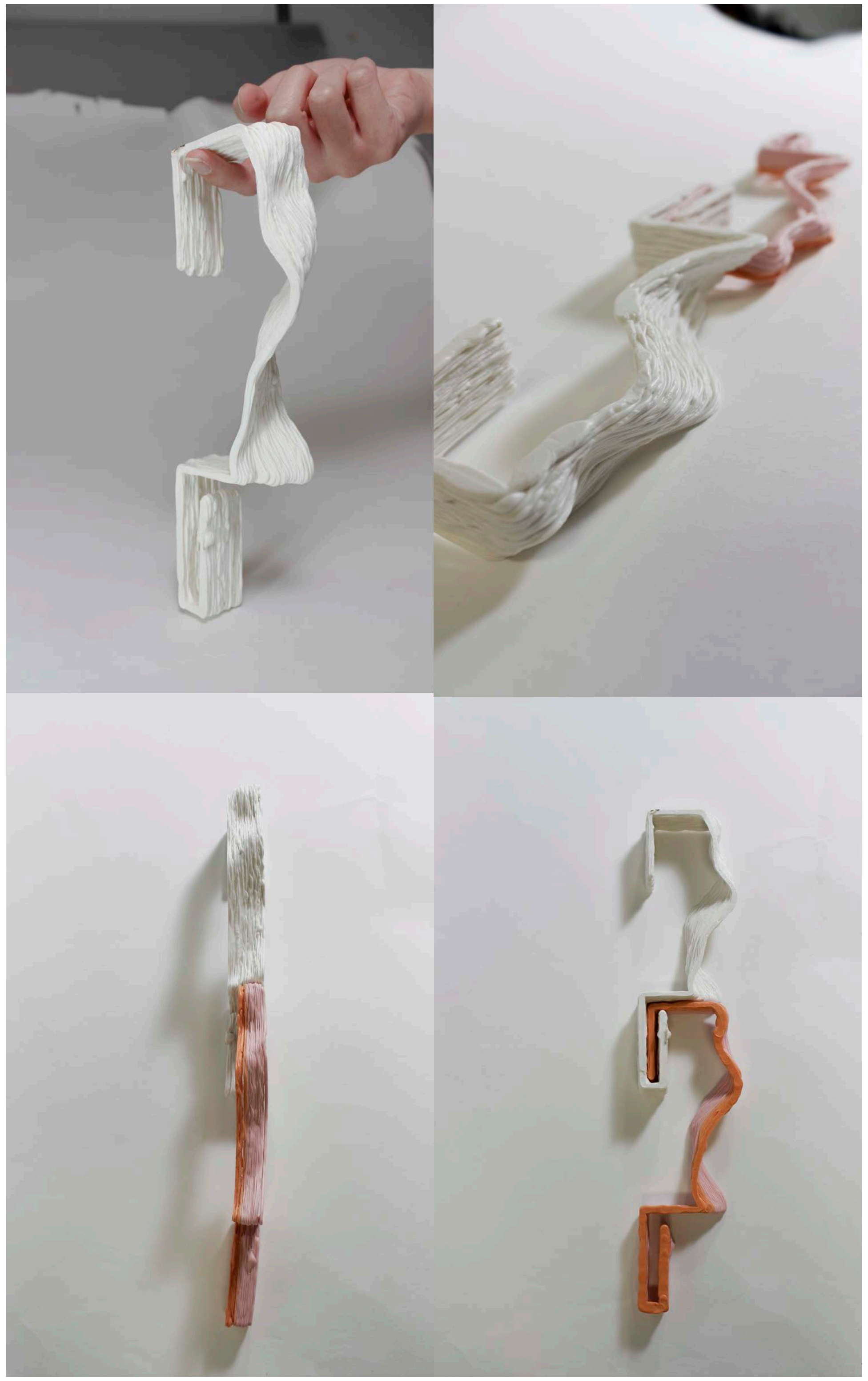


Figure 56: Digital model of print

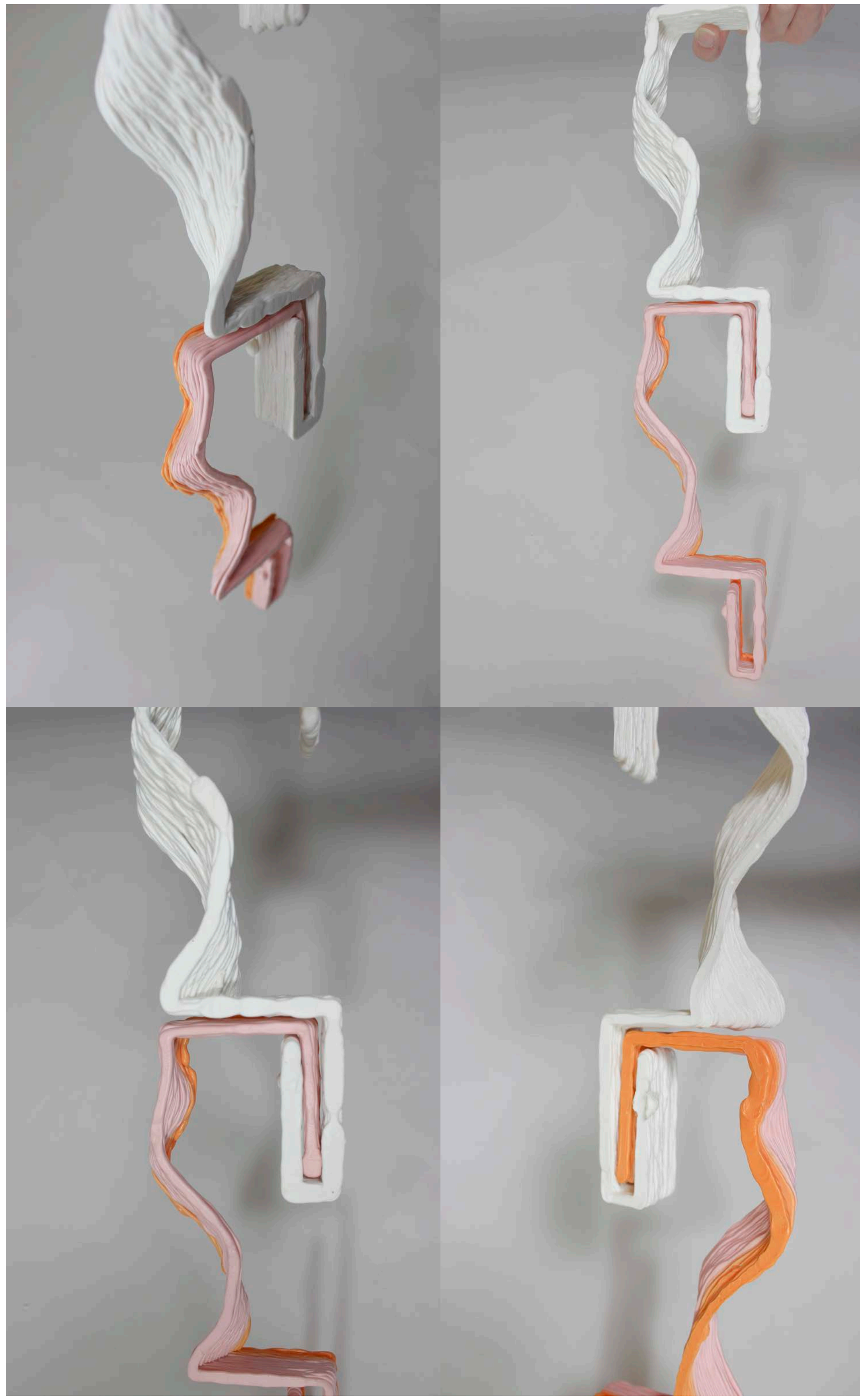


Figure 57: Digital model of print

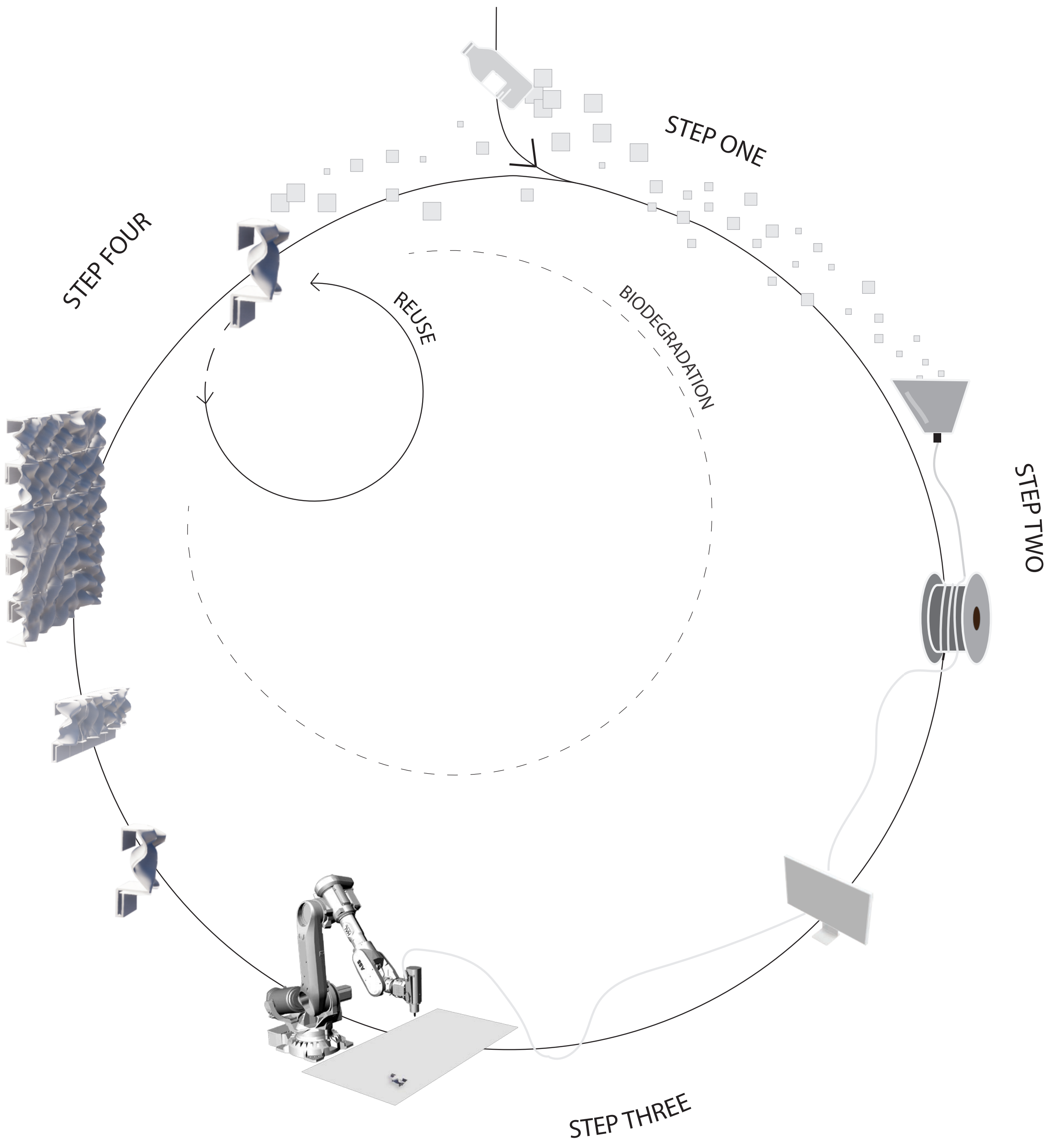


Figure 58:

A CLOSED LOOP SYSTEM FOR WASTE PLASTIC

4.13. THE OVERALL SYSTEM

A recycling plastic waste process through additive manufacturing is now possible and adapts a circular economy.

Following were the steps taken throughout the process:

- STEP ONE

Waste plastic is collected, cleaned, sorted, shredded and dried.

- STEP TWO

The waste plastic shreds are put into a twin-screw extruder which is used to make the recycled plastic filament.

- STEP THREE

A design is developed digitally, then printed using additive manufacturing.

- STEP FOUR

The new product/ material output is used, then at the end of its lifecycle, it is either reused, sent to a composting facility, or shredded to create a new product and begin a new lifecycle.

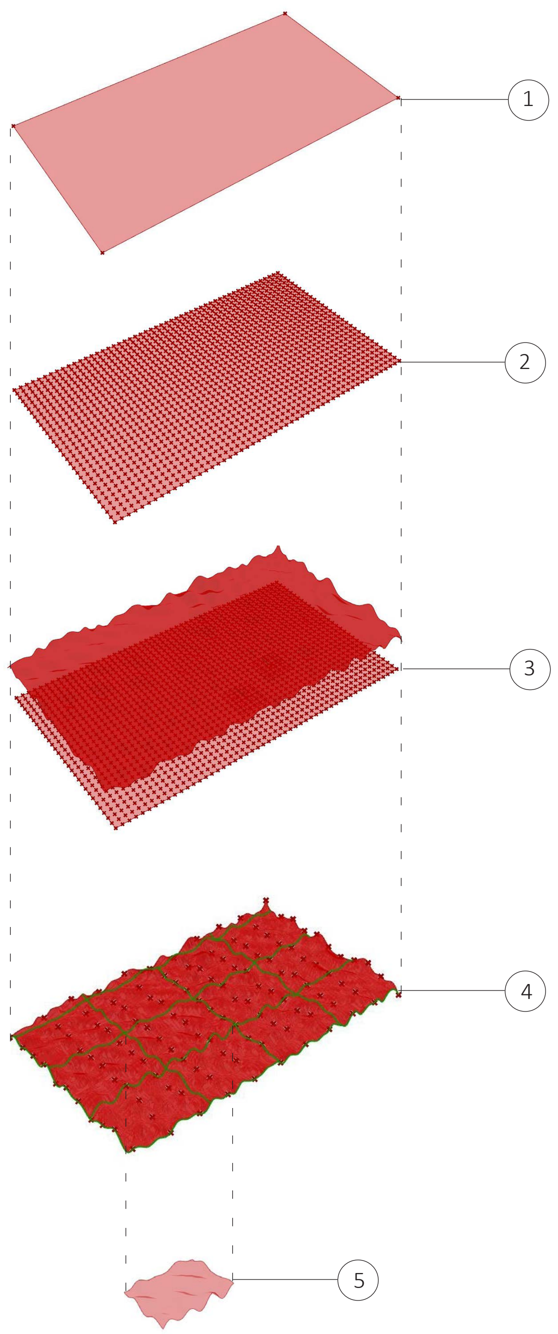


Figure 59: The Digital Process

4.14. THE DIGITAL SYSTEM

The digital workflow to produce a design output starts by creating a parametric system. The tiles need a wall to be placed on. The grasshopper code allows for the wall size to be input. This then established how big the surface area of panels will be.

- STEP ONE

A surface area for the tiles is established based on the wall area

- STEP TWO

The surface is divided into points

- STEP THREE

The code in Fig. 61 creates a wave pattern over the surface using a sine wave equation in Grasshopper.

- STEP FOUR

The surface is then divided up so each panel can be selected and printed

- STEP FIVE

A panel is selected and added into another part of the code where the clip is added. Then the tile is ready to be printed. The tile is then attached to a new code which allows it to be printed. The code can manipulate the layer heights, scale, temperature and speed.

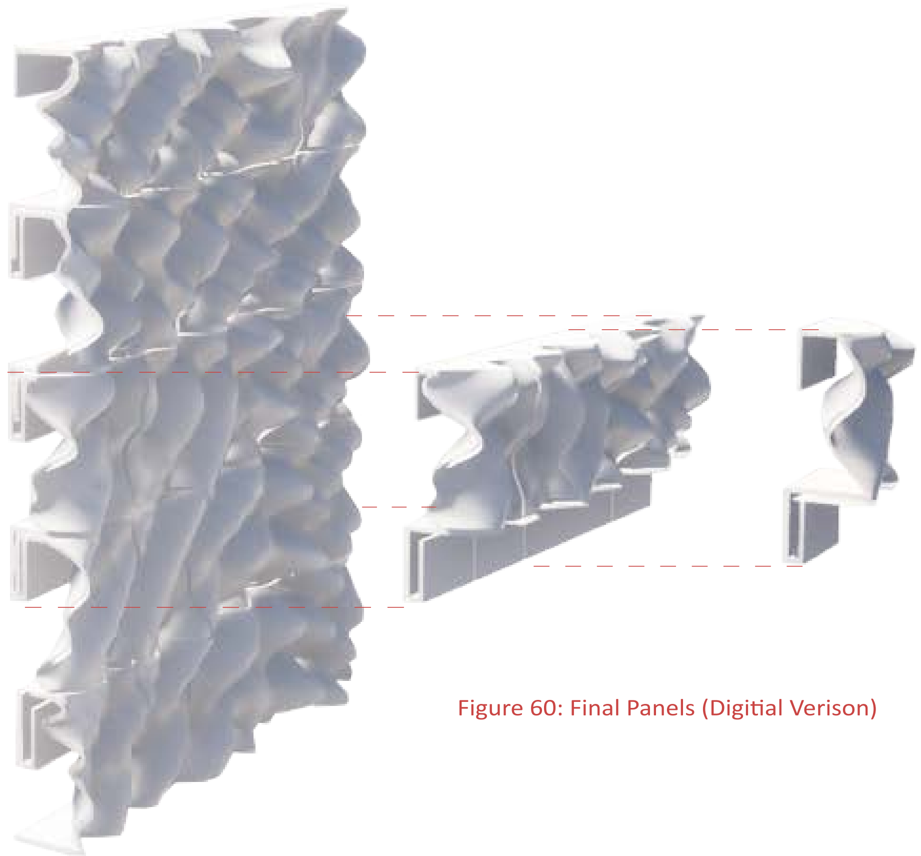


Figure 60: Final Panels (Digitial Verison)

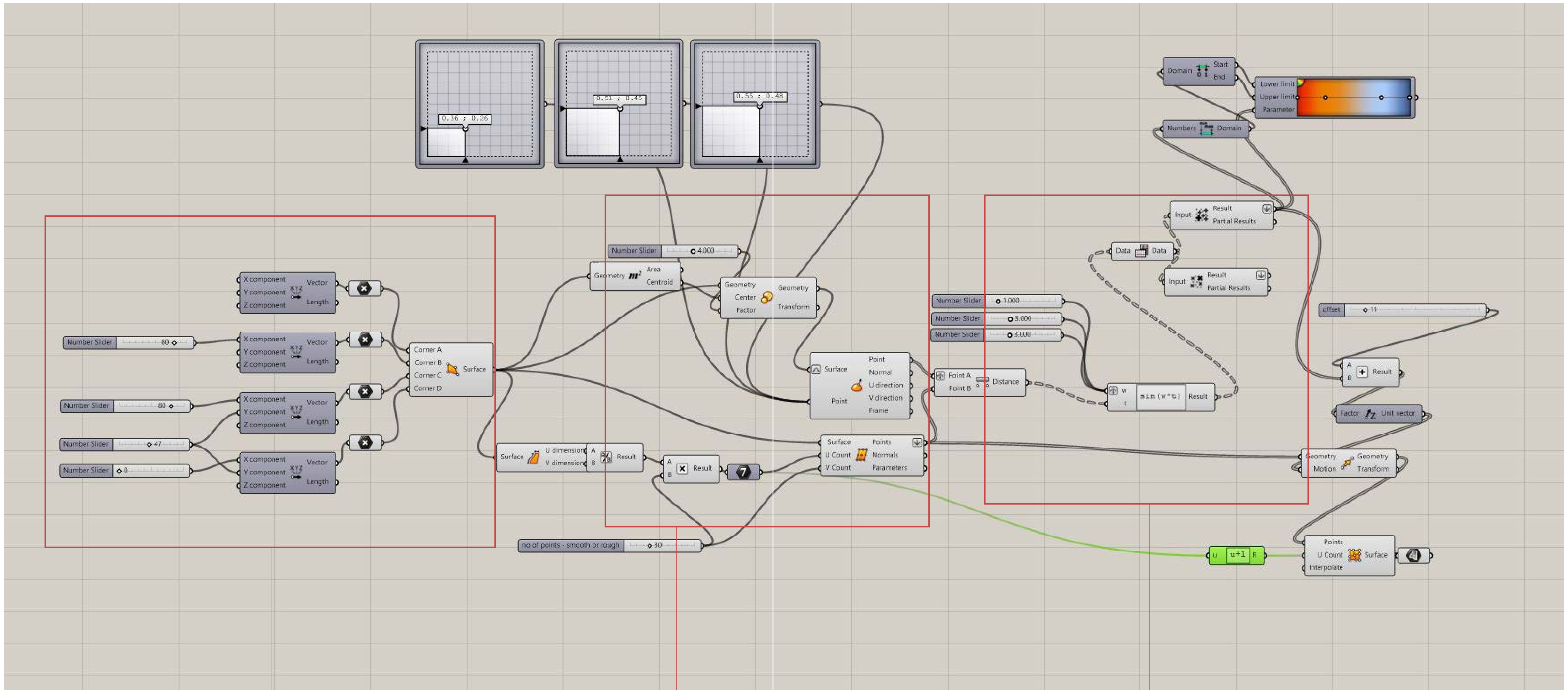


Figure 61: The Code

surface area for tiles

dividing the surface into points

adding the sine wave equation to generate the wave pattern

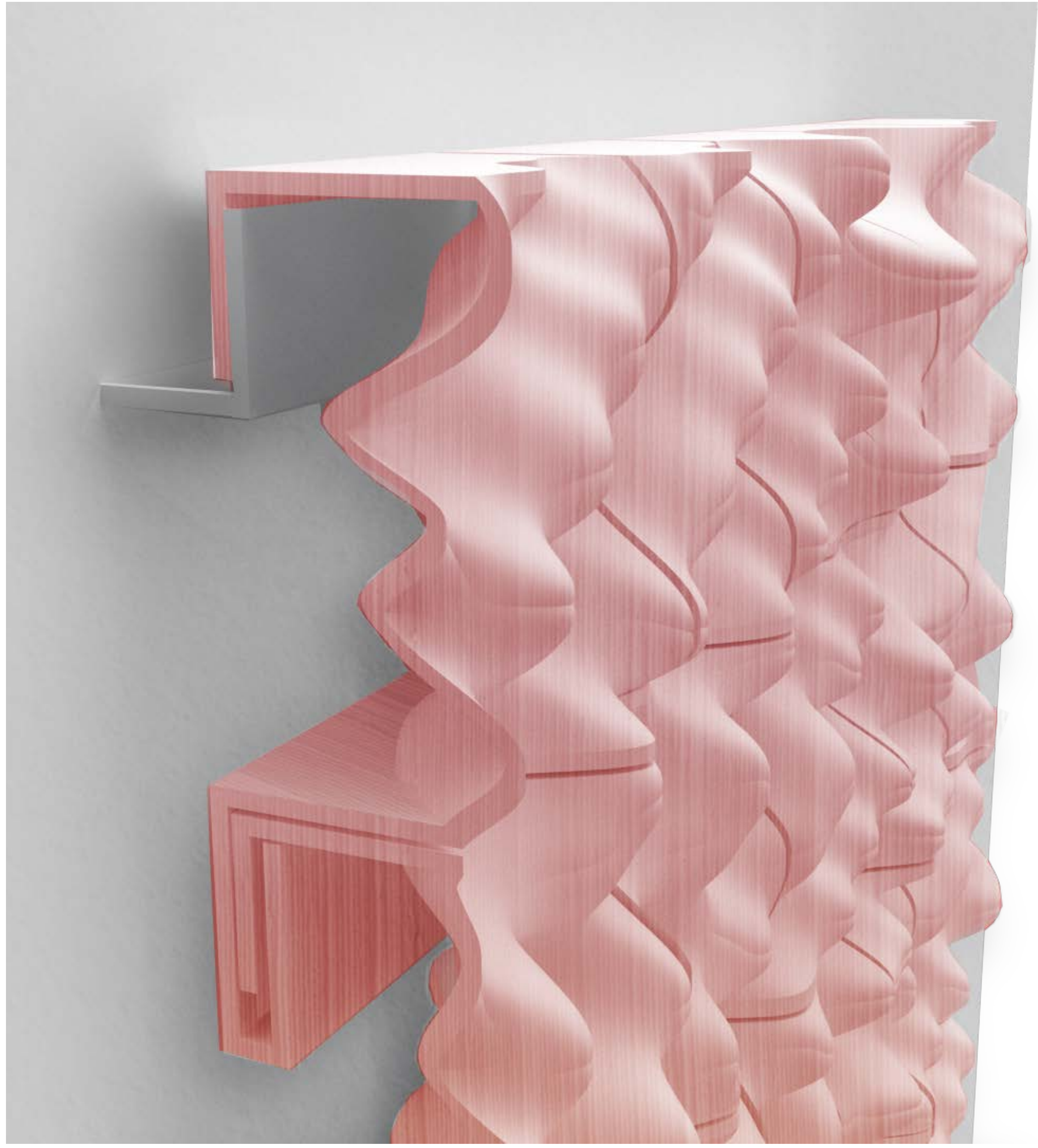


Figure 62: Tiles clipped to wall

*the texture and thickness of these renders is different to that of the printed examples

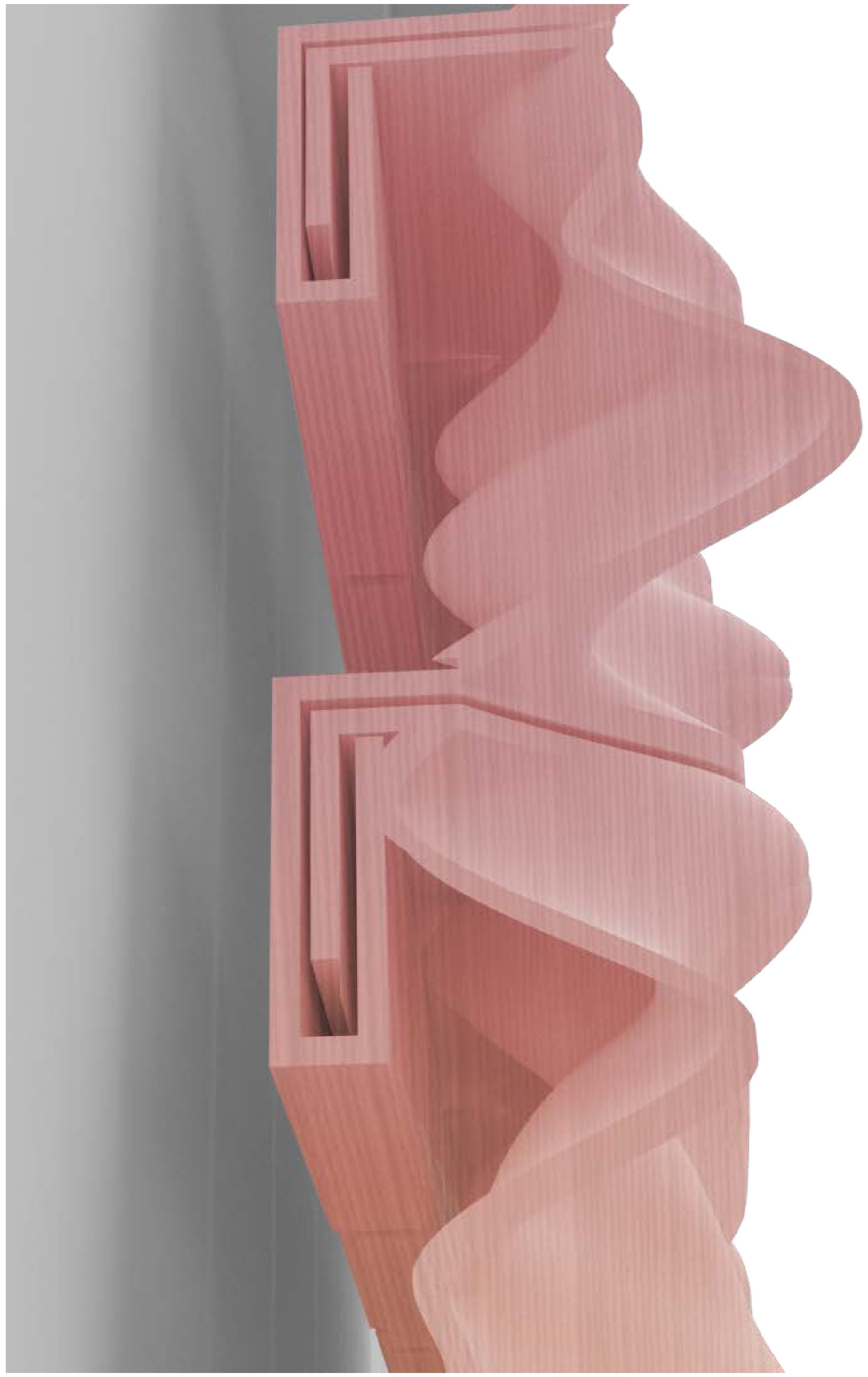


Figure 63: Clipping system

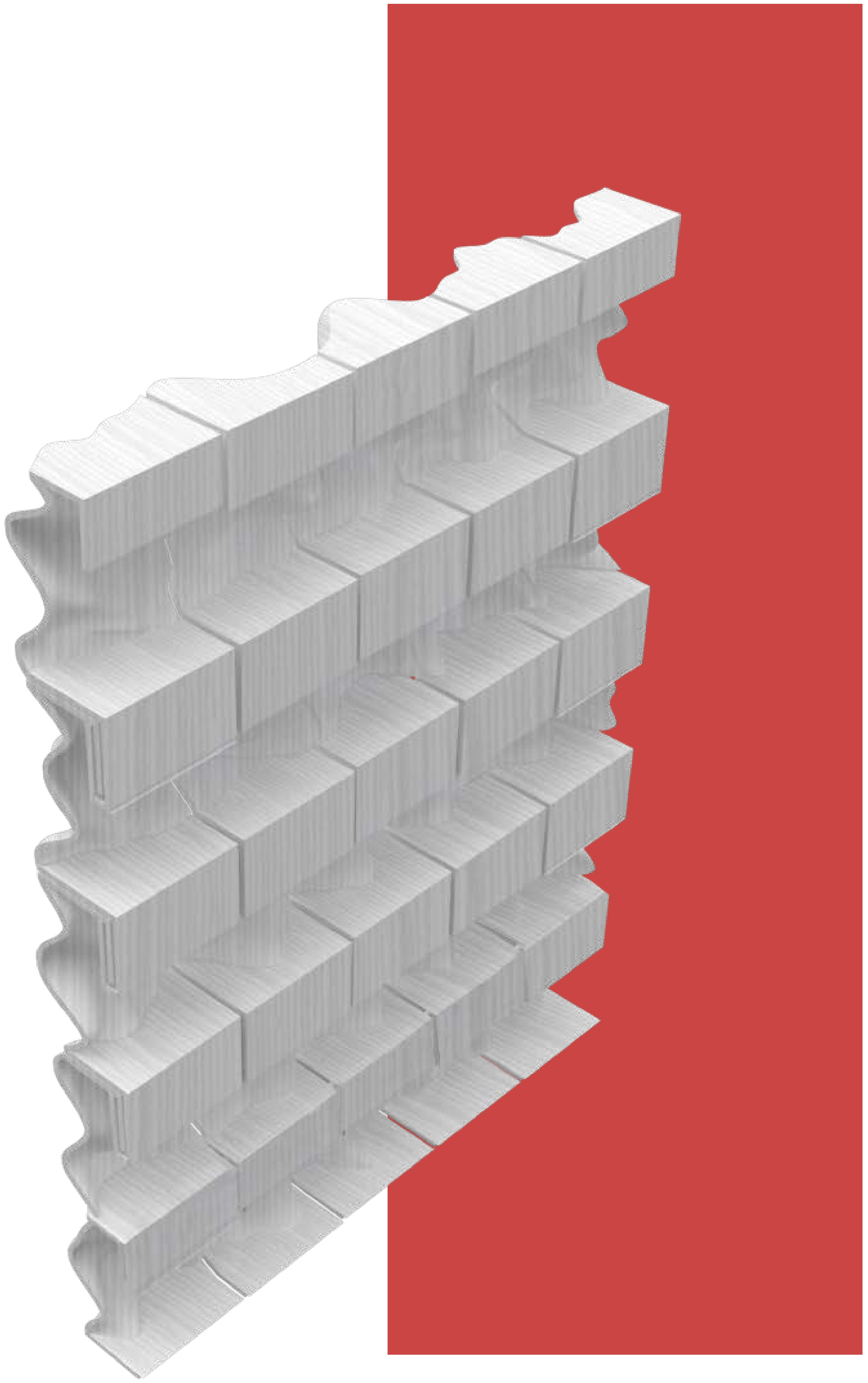


Figure 64: Exterior View

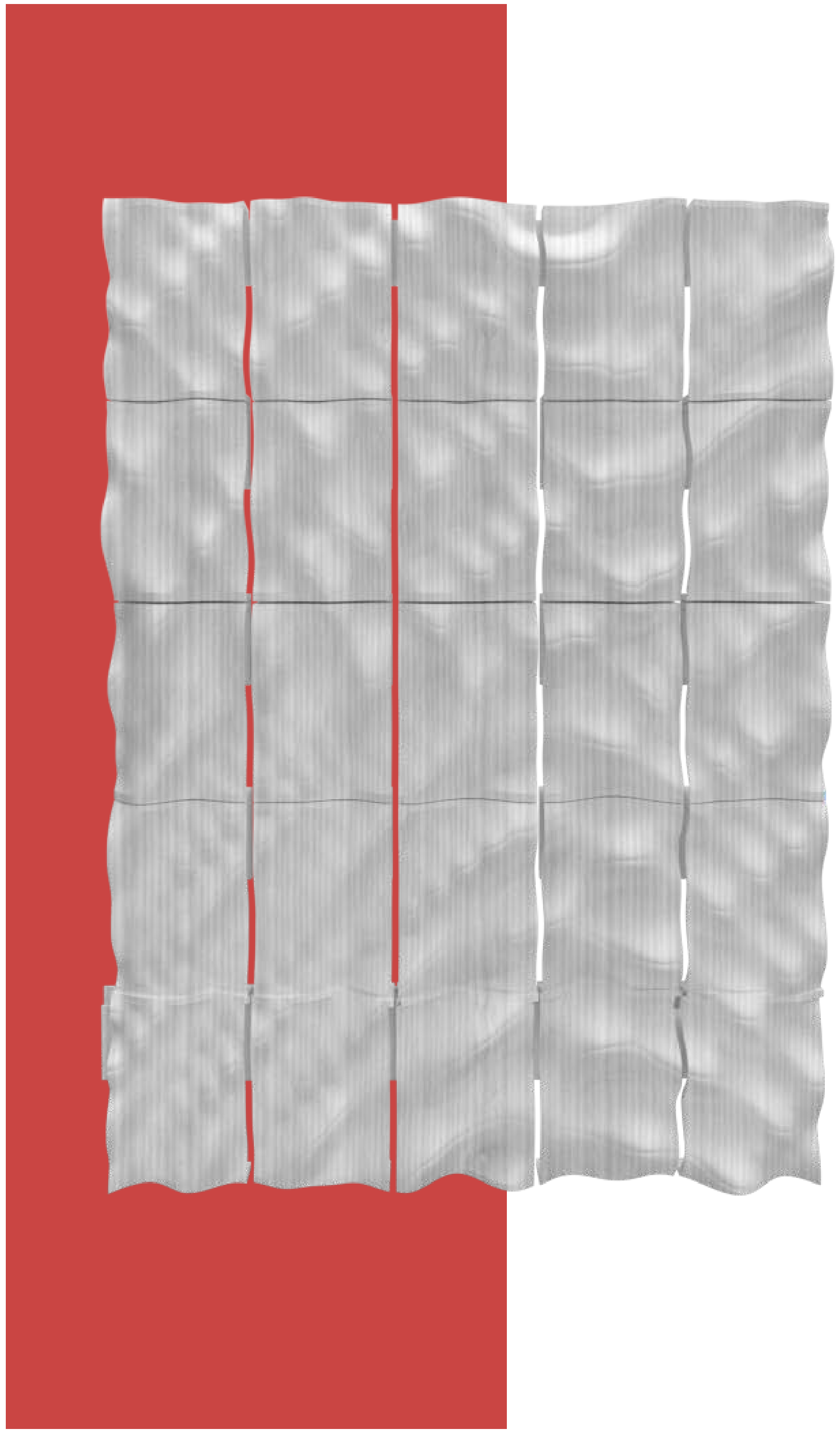


Figure 65: Front Elevation

4.16. IMPLEMENTATION

When introducing a new system/process to any industry it can be a challenge. It has taken the construction industry alone many years to adapt to new health and safety regulations. As this system requires new technologies, there is a learning curve involved with its introduction. Industry may not agree with the ideas proposed.

A purpose built facility would have to be designed and built for this system to be applied. A source of plastic waste will have to be established. Finding a source that can provide enough valuable plastic waste to drive the production is important for the production of the process. Current recycling processes for recycling waste dont include an additive manufacturing phase, as they produce pellets for companies to use instead (eg. Snell, 2019).

WALL TILES

The design output of the wall tiles for testing the recycled material has some advantages and limitations to the system:

Advantages

- Easy to assemble
- Parametric design to suit multiple spaces
- Can be designed for any wall
- Only one fixing point needed
- Can be any colour

Limitations

- The size of the panels is limited
- Not fully secure
- Textutre

Disclaimer

The aim for the design output was to print out a 1m2 area example of the tiles. Due to the closure of the workshop for earthquake strengthening this was no longer possible.

CHAPTER FIVE

5

CONCLUSION

5.1. SUMMARY / REFLECTION

The research concludes that additive manufacturing can be used to recycle waste plastic. Suitable waste plastics were able to be collected, shredded, dried and turned into filament. A design system was generated to create unique parametric designs to print. The filament was then used to additive manufacture wall tiles.

The identified system has the possibility to be used as an alternative recycling system to contribute to the circular economy of plastic. By closing the loop on waste plastic and creating a material that can be used to produce new building elements. Products made from recycled plastic now can be ground up and used again in the built environment instead of entering the waste stream and polluting the planet, further reducing our reliance on raw materials. It requires 76% less energy to recycle plastic than it does to make it from raw materials (Hutchinson, 2008). Not only does this study find a way to change the future of plastic waste by redesigning, reusing and recycling waste plastic, but it also helps to create awareness of the issue.

The research has provided deeper insight into additive manufacturing. 3D printing now has the possibility to shape our future through the use of alternative materials, adding value to a once valueless waste product. The research provides a deeper insight into a different method of recycling plastic waste and to reproduce it into a usable product, extending and contributing to our knowledge in this area.

The collecting of waste plastic and the creation of the filament demonstrated that there were multiple parameters to consider when dealing with the waste plastic. A significant finding is that similar plastics had to be used together as different plastics have different melting points therefore affecting the quality of the overall material produced. Indicating that the condition of the end product made from the mixed plastic will be poor quality.

A strength of this study is the development of a workflow to produce a viable method of recycling waste plastic.

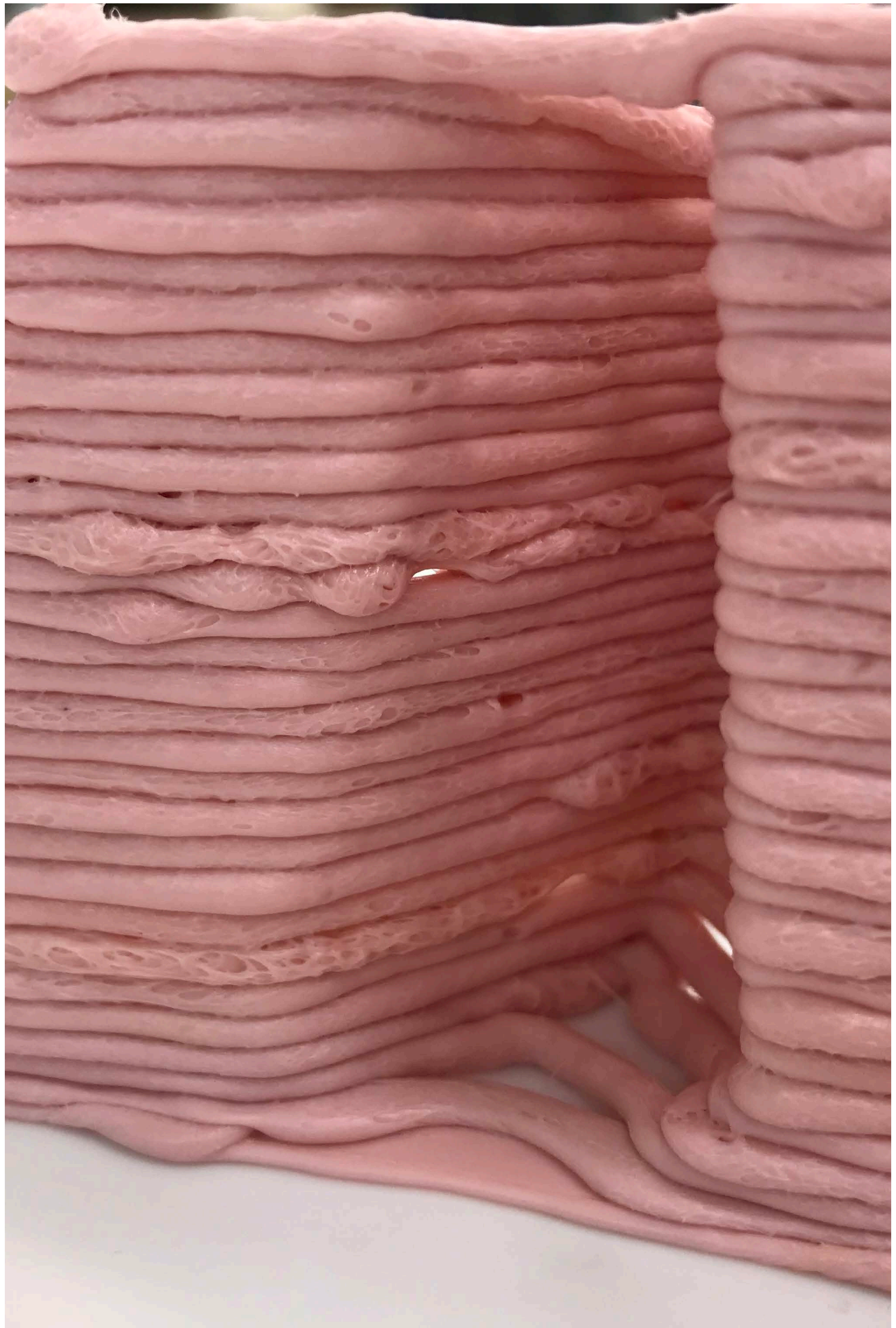
5.2. LIMITATIONS AND FUTURE RESEARCH

The creation of the plastic filament was problematic for the research. The overall process of collecting, shredding, making the filament and printing with it is a highly volatile process. Observation, care and patience must be practised at each stage to achieve a desirable outcome. The plastic must be collected and sorted appropriately. Failure to do so will result in unpredictable formulas for the filament. Care must be taken during the extrusion process to ensure that the filament is consistent. If the filament is inaccurate, it creates problems for the extruder that delivers the plastic to the surface. If the filament is too thick or thin then it will not extrude at a consistent rate. The research was limited by an inconsistent output of recycled filament that made repetition in experiments difficult. There are new filament extruders that can help to solve these issues, giving more time to focus on experimenting with materiality.

Finally, although this research is based on a small-scale building element, the findings suggest that there is a possibly for it to be up-scaled. This has also been demonstrated by previous work, although the work did not use recycled materials. The quality of the filament produced would be the biggest limitation of creating full-scale building components as the quality of the material affects the final quality of the product printed.

This research has thrown up many questions in need of further investigation. Limitations provide evidence that more research is needed in terms of additive manufacturing with waste plastic to gain knowledge in this area. A key area that needs development is the quality of the extruded material. Due to the constraints of the twin-screw extruder getting a consistent diameter thickness of filament was hard to maintain. As technologies develop improvements in this area can help to resolve this issue and provide better quality filament resulting in higher quality printed products.

Resolution of this issue also means that there is potential for exploration in the use of additives to plastic or the use of other materials. There is then also the opportunity to explore the additive manufacturing tool of freeform 3D printing to its full potential, looking into the structural strength of the material.



Prints from other students work can be shredded and turned into fialment

Prints from other students work can be shredded and turned into fialment

Presenting the research for final thesis review

CHAPTER SIX

6

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5.3. REFERENCES

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