DISTRIBUTED PRINTING:

the use of a distributed 3D printing method as a new model of complex architectural project delivery

D I S T R I B U T E D P R I N T I N G :

the use of a distributed 3D printing method as a new model of complex architectural project delivery

By

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Throughout the writing of this thesis, I have received a great deal of support from those around me, for that I give thanks;

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Abstract

Distributed printing method is a process that allows complex architectural components to be fabricated by more than one production source at a global and local scale. While 3D printing (also known as additive manufacturing) is considered a revolutionary technology for many manufacturing industries, the application in the architectural industry lags in leveraging the potential of this innovative technology. Today, most architectural designers have to utilise large and expensive 3D printing equipment to create monolithic, singular buildings. Accordingly, there is a need for finding another workflow to deliver complex architectural structures, and the distributed printing method holds promise for this application.

The imminent question therefore is; ***how small-scale architecture can leverage the power of distributed 3D printing to deliver complex architectural structures.*** However, the current knowledge in distributed 3D printing for architecture has received little attention in the research literature.

To test the hypothesis that distributed printing methods could lead to faster and more affordable project delivery, a mixed methodology strategy, including literature review, case study, experiment, and simulation, was utilised in this thesis. Literature and some cases were researched to identify the potential workflow of distributed printing. Moreover, a series of small-scale models were fabricated to test the factors which may affect distributed fabrication. Furthermore, an experiment was conducted to simulate the entire process of delivering an architectural project using distributed printing methods.

The architecture proposed utilising digital design tools and the method of distributed printing to create an envelope formwork as a way of creating an outer shell or skin for the structure. It is not intended that the components form the final envelope skin.

In summary, the distributed printing methods positively impact complex architectural project delivery when utilised strategically. With the support of the distributed printing platform, architecture has the potential to utilise a larger number of printers beyond any single factory, therefore leveraging the full power of distributed printing methods to create time and cost benefits. At the same time, some negative factors, such as logistics delay, also show the risk of using distributed equipment worldwide. In the future, the ideal method will be more likely to provide distributed sites with closer geographical distance to users.

Key words: 3D printing, Distributed manufacturing, Distributed 3D printing, Digital fabrication, Digital architecture, 3D printing architecture, Complex geometric architecture

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Motivation

My motivation to conduct this thesis initially comes from my interest in digital fabrication using various innovative technologies. Moreover, I have always been intrigued with 3D printing, which allows users to create complex shapes from virtually any 3D model and geometry. Having seen a 3D printed sculpture with a complicated structure (Figure **1**), I was deeply attracted by its elegant form. I could not stop asking myself: can architecture leverage this power to construct complex architectural geometries?

However, the current state of 3D printing technologies for architecture makes me feel frustrated. I noticed that most existing 3D printed buildings using concrete 3D printing technologies typically have a simple orthogonal form, like any conventional suburban rectangular brick building. FDM printing is another common process that create a 3D printed object by depositing the melted material (such as PLA) layer by layer (Rael & San Fratello, 2018). While this technology has the capacity of creating a range of shapes, it has some significant drawbacks, such as an increasingly slow fabrication process, material limits (use plastics), making it challenging to be utilised for architecture. Architects have to compromise on their aesthetic and design ambition if they are interested in complex geometry due to these current approaches.

In the early stages of the 2020 Covid-19 Pandemic, I became aware of a large-scale exercise in 3D printing to address the shortage of PPE equipment. At this point, I realised that this might be a potential method for developing a similar platform for delivering architectural components. In this case, thousands of people worldwide utilised distributed FDM printers to produce numerous face shields in a short period (Perez-Mañanes et al., 2021). The digital files were supplied online and could be downloaded to print. This example demonstrated its potential by speeding up the fabrication process. If architecture could adopt this method, it would balance speed and flexible form. The idea was that people would then post the printing objects to where they were needed. As yet, there has been no systematic investigation of this method in architecture.

The method of distributed printing has demonstrated great promise, hence my interest in continuing this study and further developing a workflow for complex architectural project delivery.

Figure 1.Te Ahi Tupua in place at the Hemo Gorge roundabout. Photography By Warner (2020).

1 Introduction

Figure 1.1 Cover: The Pavilion.
By Author (2021).

1.1 Context & Background

3D printing, also known as additive manufacturing, creates a physical object by depositing materials layer-by-layer based on a digital model (Sakin & Kiroglu, 2017). It is increasingly recognised as a potential future technology for numerous industries, such as aerospace and biomedical uses. Today, 3D printing technologies deliver faster, cheaper, and larger outputs, making its followers believe that this technology can revolutionise the architectural industry. According to Grand View Research (2021), the global 3D printing construction market is expected to increase sharply at a compound annual growth rate of 91.5% from 2021 to 2028, as shown in Figure **1.2**. Many facts indicate that 3D printing has positive effects on the architectural industry; however, the development and application of real-life architecture are still in the early stages (Yin et al., 2018).

In terms of the current 3D printing technologies for architecture, it is mainly divided into two parts: concrete-based and FDM 3D printing, as shown in Figure **1.3**. Concrete-based 3D printing aims to construct affordable and time-effective large-scale buildings as a single stand-alone unit by developing larger printers and new materials with better mechanical properties, as shown in Figure **1.4**. Contrastively, the FDM process is more likely to be utilised for the small-scale architectural model or non-structural components.

Although researchers believe that concrete-based 3D printing is potential for the architectural industry, some significant limitations and issues need to be considered. The development of concrete-based 3D printing in the real-life construction market has not achieved the expectation of researchers and pioneers. For instance, in New Zealand, there is still no existing 3D printing of architecture (Loporcaro & Zhao, 2019). Figure **1.5** demonstrates that only a few regions have widely utilised this technology, such as Asian Pacific (Grand View Research, 2021). There are serval reasons of this situation. Firstly, the main feature of those 3D printers based on concrete is costly, making them only affordable by the largest firms (Rayna, 2021). In addition, the high capital investment regarding equipment is expected to hinder market growth (Grand View Research, 2021). Finally, 3D printed concrete buildings are lack

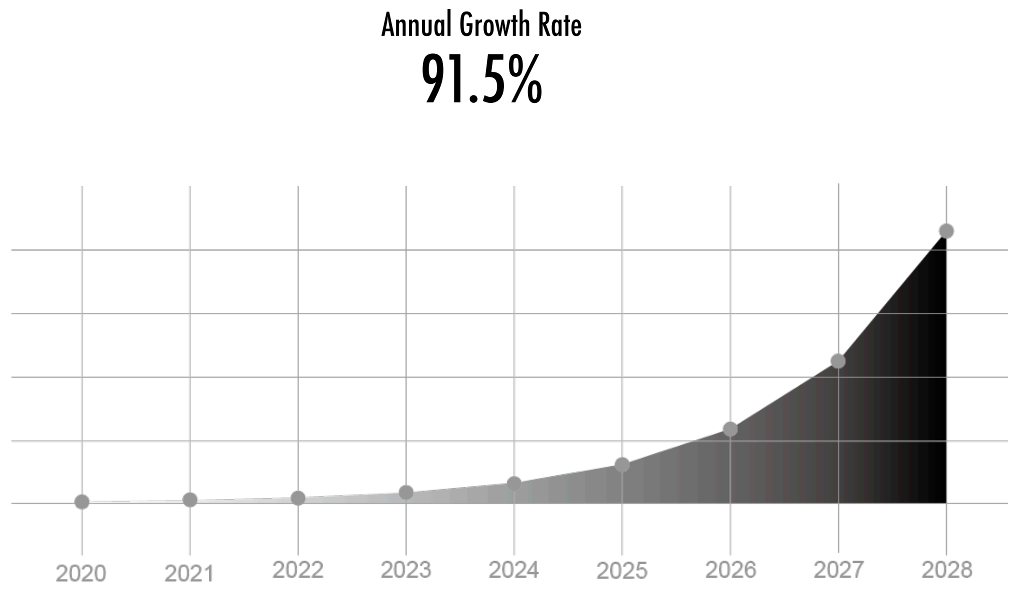


Figure 1.2 3D printing in construction market Annual Growth Rate. By Author (2021).

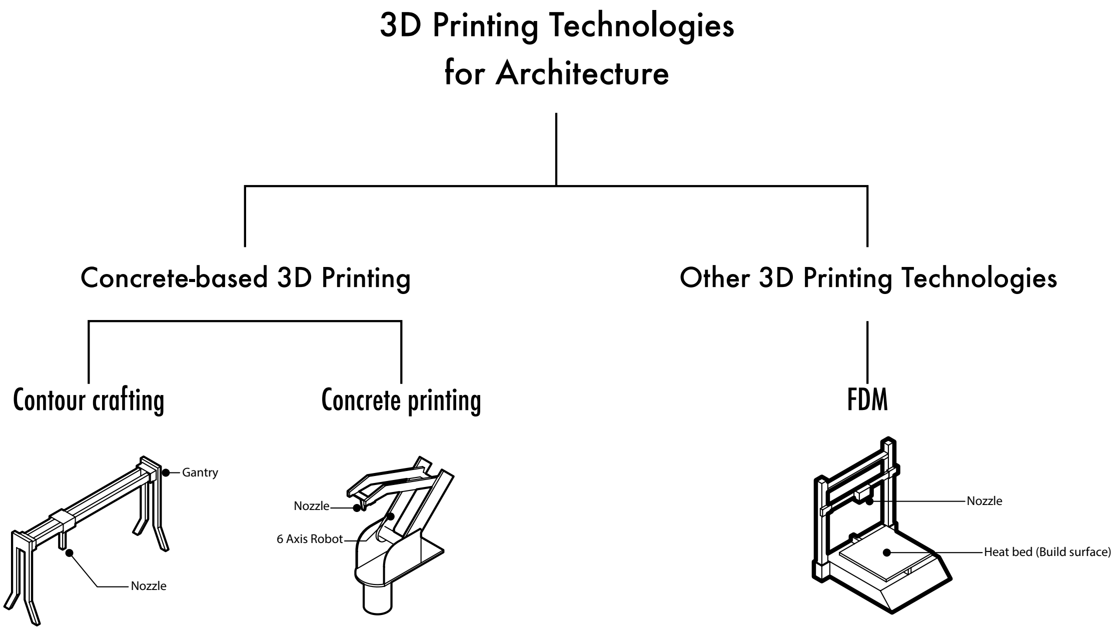


Figure 1.3 3D printing Technologies for Architecture. By Author (2021).

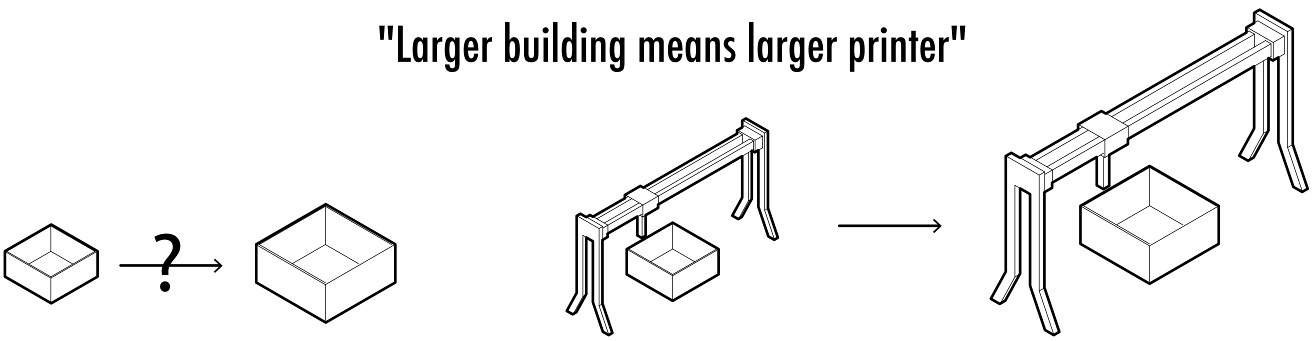


Figure 1.4 The relationship between build volume and manufacturing equipment. By Author (2021).

geometric freedom, which is considered one of the most significant features of 3D printing (BAÑÓN & RASPALL, 2021).

In contrast to concrete printers, FDM printers typically have cost-effective benefits. However, they cannot create large-scale objects due to their limitation of build volume and slow fabrication process. Materials also limit them as they generally use a range of plastics and nylons, which means they have limited suitability for durable construction materials. Consequently, FDM printers are more suitable for small-scale and non-structural components.

The successful application of 3D printing during the Covid-19 pandemic, as mentioned earlier, provides a remarkable opportunity for the architectural industry (Figure **1.6**). The application of distributed 3D printing enabled smaller manufacturers to be much closer to the end-user (Srai et al., 2016). Many FDM-based desktop 3D printers supported the 3D printer community to fabricate over 100,000 3D printed face shields for more than 200 medical sites within the United States in a short period (Manero et al., 2020). This result indicated that the main limitation of 3D printing, comparatively slow manufacturing speed (BAÑÓN & RASPALL, 2021), is more likely to be solved if there is adequate equipment for production. However, there has been little discussion about the feasibility of using a distributed 3D printing method for architecture.

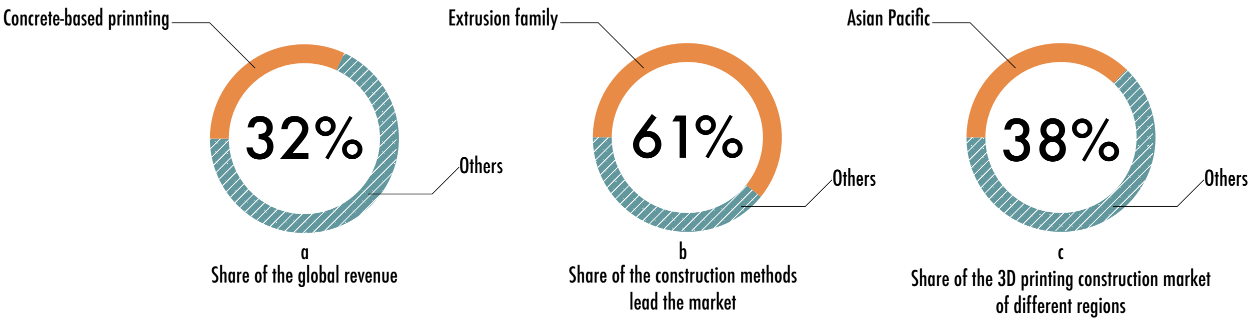


Figure 1.5 3D printing construction market Analysis. By Author (2021).

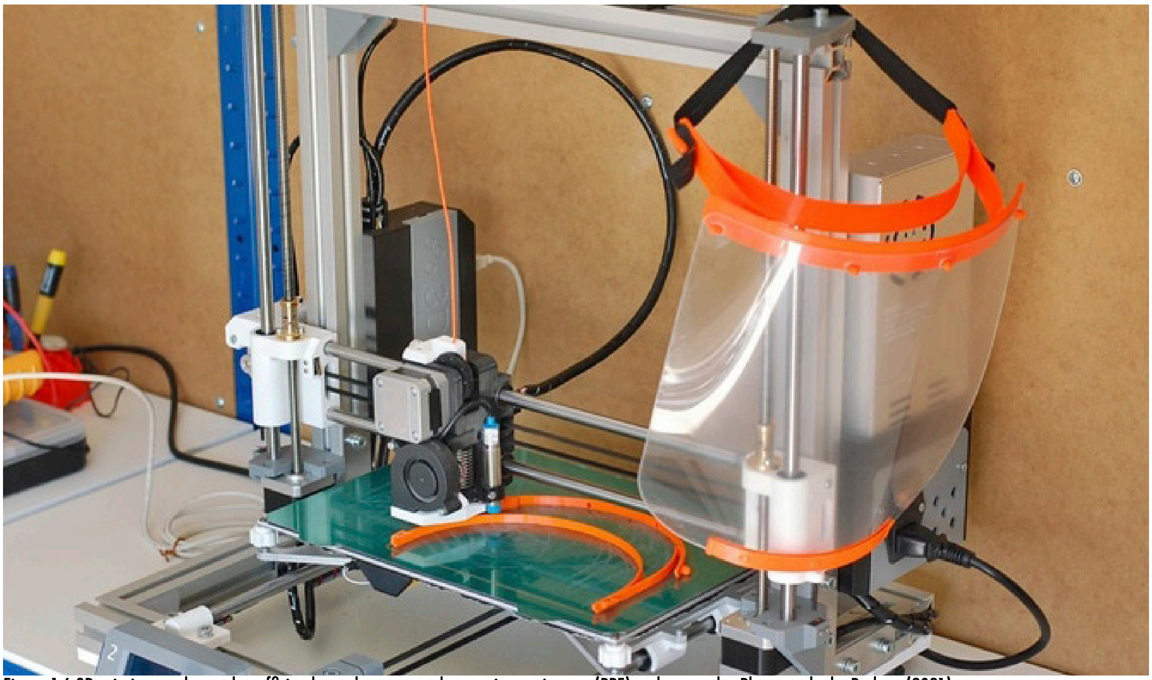


Figure 1.6 3D printing can be used to efficiently produce personal protective equipment (PPE) such as masks. Photography by Peclova (2021).

1.2 Previous Research

Much research on 3D printing for architecture in recent years has focused mainly on concrete-based 3D printing, including contour crafting and concrete printing that uses a concrete pump and boom or robotic arm on a flexible track (Gosselin et al., 2016). Many researchers believe they are promising methods for the future of the construction industry as the 3D printing construction market is dominated by concrete-based 3D printing (Grand View Research, 2021). Most studies in concrete 3D printing have only been carried out in a small number of areas, including sustainable and low-cost construction for domestic housing. Due to the material weight, mass constraints, the printing tasks are made on the final site. Although they will rapidly develop over time, they currently have limitations on shape complexity unless printed in component form.

Nevertheless, there has been less previous evidence for applying distributed 3D printing of concrete components to deliver architectural projects for obvious reasons (weight, mass structural reinforcing – shipping time and expense), especially with complex structures. Hence, further study is needed to fill this research gap.

1.3 Industrial Facts

While concrete-based 3D printing can deliver fast and large-scale architecture, this process has difficulty printing complex structures due to common factors facing all 3D printing. Some include scaffold requirements to support challenging overhangs and self-weight of materials as they are extruded. This places limitations on what can be feasibly designed in relation to material slumping and reinforcing. As a result, vertical variation is difficult to achieve. In terms of FDM 3D printing, its key benefit is delivering complex forms (Figure **1.7**). However, the build volume of this process is small, and the fabrication process is increasingly slow due to the size of the nozzle and the capacity of the hot end element to provide an adequate melting temperature range. FDM printing is not suitable for mass fabrication unless used at scale.

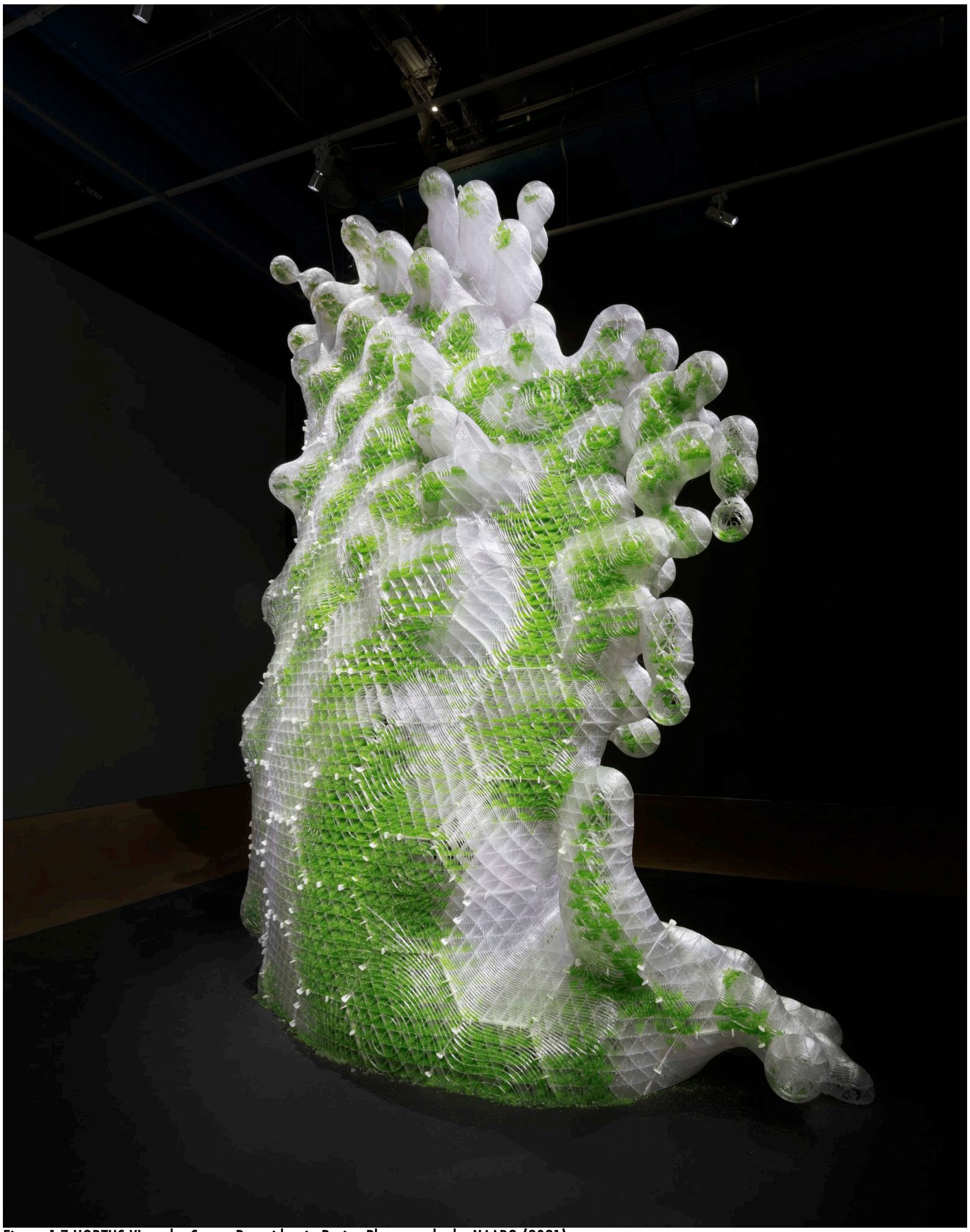


Figure 1.7 HORTUS XL at the Centre Pompidou in Paris . Photography by NAARO (2021).

1.4 Problem Statement

1.4.1 The limitations of different 3D printing technologies

Although many studies believe that 3D printing is a revolutionary technology for architecture, there are still numerous limitations that affect its application in the architectural industry, as shown in Figure **1.8**. The first limitation is between printing size and speed. Larger objects need much time for printing, which means that concrete printers are more suitable for large-scale products than FDM printers due to the larger size of the equipment. In addition, the problem between speed and geometric freedom is another limitation. Although the fabrication process of concrete-based 3D printing technologies is fast, the geometric form they create has to be simple and vertically consistent.

1.4.2 The accessibility of distributed 3D printing for architecture

Figure **1.9** demonstrates the limitations regarding the accessibility of distributed 3D printing for architecture. Firstly, the equipment limits the current application of 3D printing for architecture. For instance, neither concrete-based nor FDM printers can balance the build volume and printing speed. In addition, while there are some practices regarding distributed 3D printing in the other industries, there is still little knowledge of architecture. Furthermore, research indicates that the lack of management for distributed 3D printing is another limitation. For instance, IP protection is an essential issue when distributing digital files.

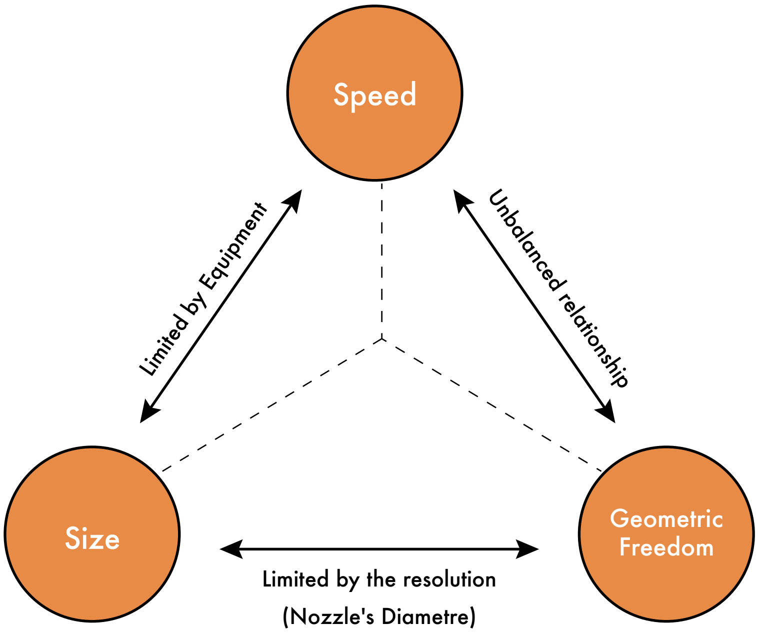


Figure 1.8 The limitations of different 3D printing technologies. By Author (2021).

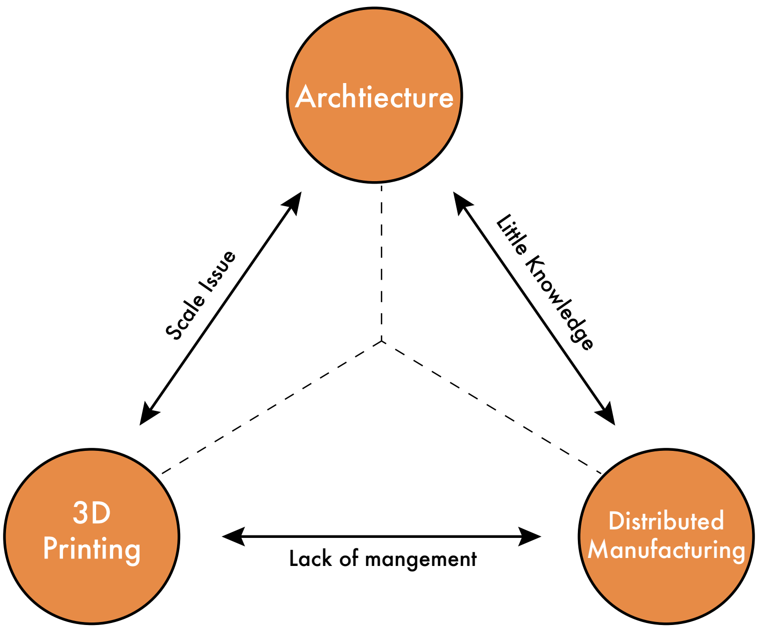


Figure 1.9 The accessibility of distributed 3D printing for architecture. By Author (2021).

1.5 Research Purpose and Question

1.5.1 Aim

The main aim of this project was to develop a new architectural delivery model which allows a complex architectural structure to be delivered by leveraging the full power of distributed 3D printing. The impact of a range of factors on distributed 3D printing was investigated to ascertain if distributed manufacturing based on the FDM process can contribute to the delivery of complex architectural structures.

1.5.2 Objectives

- Review literature and research cases to identify the potential workflow of distributed printing and the design approach.
- Develop a virtual distributed 3D printing platform to test the feasibility of this method for architecture.
- Fabricate a series of small-scale models to test the printing parameters which affect real-life fabrication.
- Simulate the entire process of delivering a complex architectural project to test distributed printing methods.

1.5.3 Research Question

How can small-scale architecture leverage the power of distributed 3D printing to deliver complex architectural structures?

1.6 Research Overview

STEP 01: Understanding the issue

Understanding the development and limitations of current 3D printing technologies and investigating ways in which complex architecture may benefit from the power of distributed printing.

STEP 02: Literature Review

Research into a suitable 3D printing technology for architecture and the application of an effective distributed 3D printing method for the delivery of complex architectural structures.

STEP 03: Case Studies

Learning from two ends of the spectrum, which are architectural design based on distributed printing method and the method utilising distributed printing to achieve complex architectural structures. Documenting the fabrication process of each case and analysing the benefits or drawbacks of them in order to develop the feasible method from these existing cases.

STEP 04: Design Development

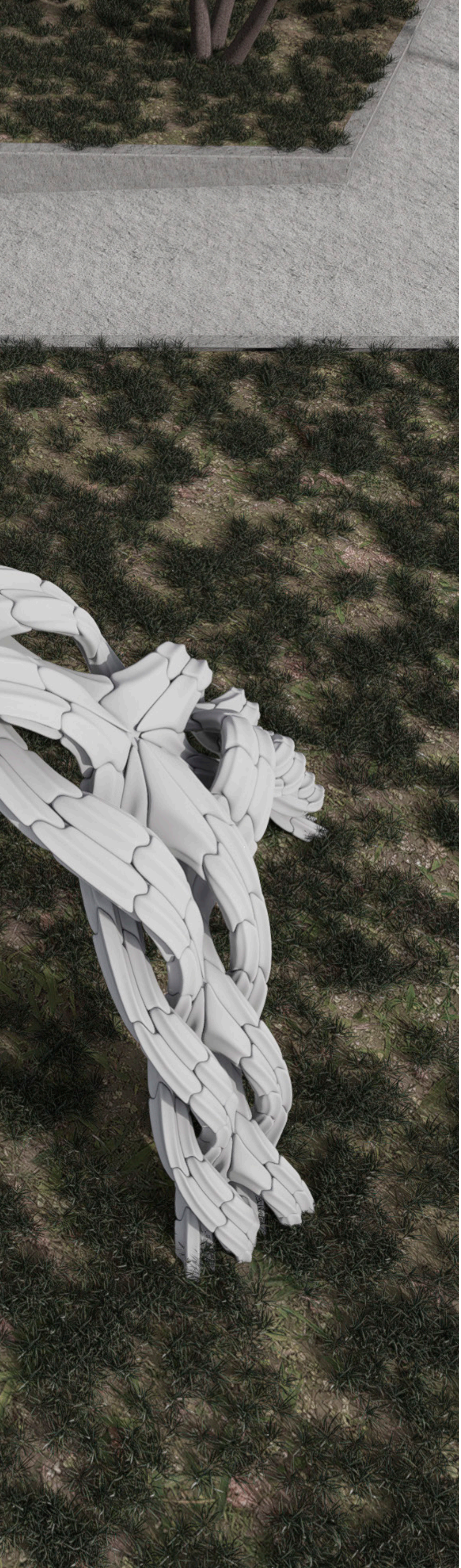
The design phase looks at how architectural design fits distributed 3D printing. In terms of detailed design, the suitable size of each component for distributed 3D printing and detailed design regarding manufacturing and assembly are critical factors of this chapter.

STEP 05: Experiment on small-scale models

Many factors affect the result of 3D printing, such as printing speed and layer height. These printing parameters should be considered before the real-life fabrication. Print some small-scale models to test how these printing parameters can affect the results to optimise the setting for real-life production.

STEP 06: Test the real-life production on a Distributed printing platform

Using three architectural components designed in the previous step to test the tolerance, task delivery time, and logistics time. Evaluating the results and testing the feasibility of this method.



2

Literature Review

Figure 2.1 Cover: Aerial View of the Pavilion.
By Author (2021).

2.1 Introduction

This chapter reviews the key literature concerned with the current 3D printing technologies for architecture and the distributed 3D printing method. Given that the current state of the architectural industry has not fully realised the power of distributed printing methods. Numerous scholars have conducted extensive research in an attempt to use and improve concrete-based 3D printing technologies for fast or sustainable project delivery. Although various studies have focused on applying the distributed 3D printing method in other industries, little research is concerned with its application in the architectural industry. Thus, this review critically summarises and evaluates theories and concepts in the available literature in a bid to address the gap.

This chapter begins with an overview of each 3D printing technology in the architectural industry through an evaluation and comparison to these technologies in order to identify the potential technology available for complex architectural projects. This is followed by a discussion on the definition of the distributed manufacturing method, the challenges users face in applying this method, and the suitable 3D printing technology for this method. Finally, this chapter evaluates existing evidence in the available literature to analyse the potential workflow for architecture and provide theoretical backup for hypothetical solutions.

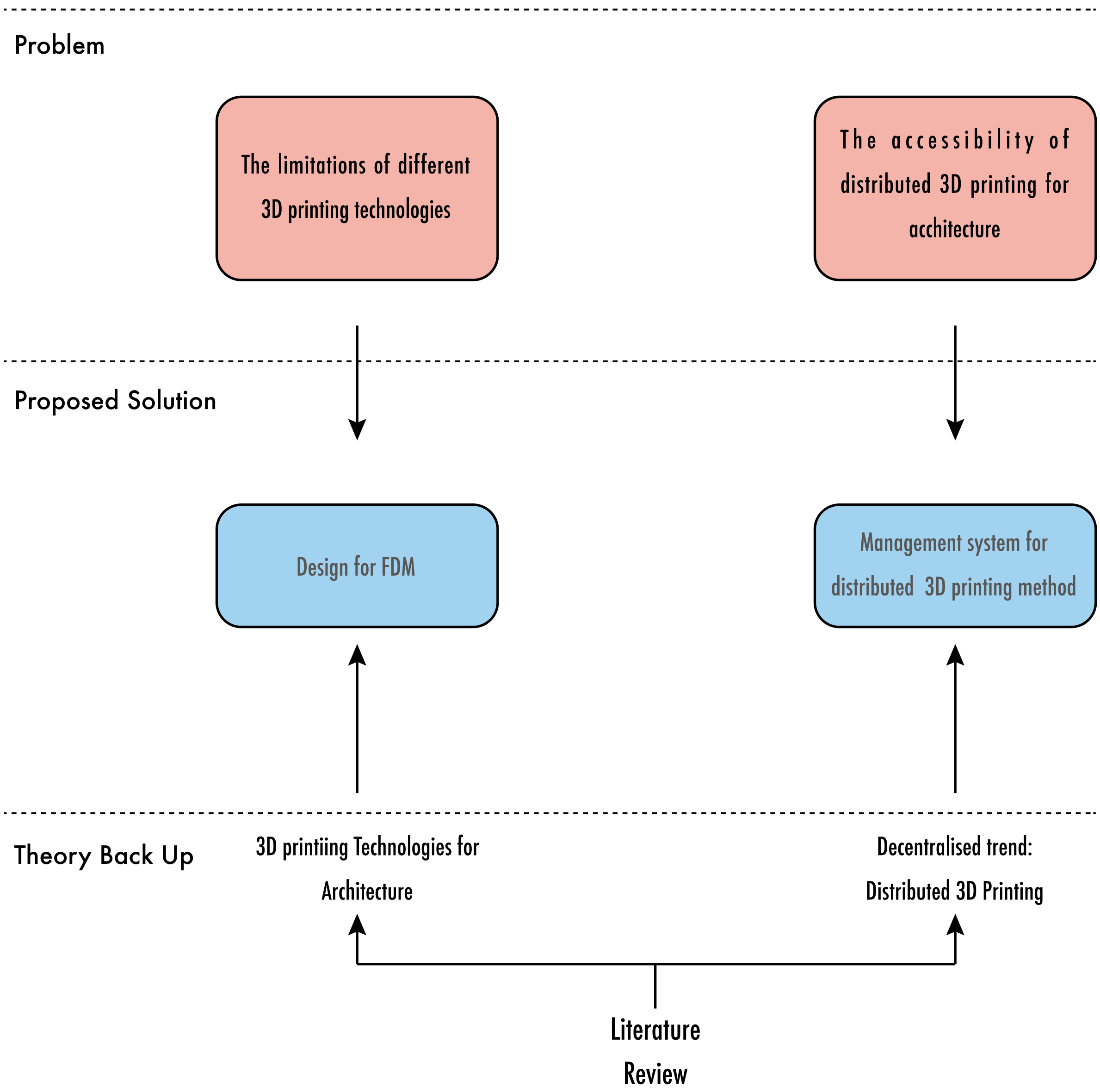


Figure 2.2 Literature Review Framework. By Author (2021).

2.2 3D Printing Technologies for Architecture

2.2.1 An Overview of 3D Printing Technologies for Architecture

3D printing (also known as additive manufacturing) creates objects from bottom to top, one layer at a time. Although 3D printing has been widely utilised in various industries, this technology is still emerging in architecture. This section will be exploring three types of 3D printing technologies for architecture, including concrete-base printing and FDM printing.

In terms of concrete-based 3D printing technologies, contour crafting and concrete printing are two critical examples. They have become the mainstream in the architectural industry (Gosselin et al., 2016), under broad research and utilisation. The main benefits are their capacities of fast fabrication and larger build volume. However, the costly manufacturing equipment and weak capabilities in creating complex geometric forms are the key drawbacks.

In comparison to concreted-based printing, FDM printing can build more complex forms. In addition, FDM printers are generally affordable (BAÑÓN & RASPALL, 2021), which is more suitable for distributed printing methods. Nevertheless, the slow fabrication process and small build volume limit its capabilities within the scale model and some non-structural components.

There is still debate among studies regarding which technology is more promising for the future architectural industry. Therefore, this review of analysing each process and evaluating them is significant.

2.2.2 Concrete-based 3D Printing

Contour Crafting

Extrusion-based contour crafting is a 'large-scale printing technique developed for the construction industry (BAÑÓN & RASPALL, 2021, p.19). It is the first additive fabrication process based on the material extrusion method developed for on-site construction (Davtalab et al., 2018). It uses a gantry system extruding material from a nozzle and a trowel to create a smooth printing surface, as shown in Figure **2.3**.

Contour crafting, considered a potential technology for the architectural industry, has various benefits, including rapid fabrication, automatic process, cost-reducing, and time-efficiency. Zareiyan & Khoshnevis (2017, p.112) claim that 'rapid fabrication and robotic application' are the main advantages of contour crafting. Moreover, Yin et al. (2018) reported that the fabrication process of contour crafting could be automated without human intervention, leading to reducing in cost and time. Similarly, Davtalab et al. (2018) believed that the construction cost could be fundamentally decreased by reducing the workforce required for the construction process. Conversely, Tay et al. (2017) argued that there is no evidence to prove that the application of 3D printing for the construction industry can reduce costs.

While contour crafting has many significant advantages, some drawbacks still limit its development. Firstly, its shaping capability is limited to 2.5D (Gosselin et al., 2016), unlike the geometric freedom feature of 3D printing. In addition, the direct printing of large building sizes is seriously limited due to the small dimension of 3D printers (Yin et al., 2018). Martens (2018) found that the printing equipment is expensive because the technique is in development, increasing construction costs.

Concrete Printing

Like contour crafting, Concrete Printing also belongs to the material extrusion family. The cement mortar is extruded and built in a layer-by-layer process to complete the object. This process mainly concentrated on construction-scale components and material performance rather than constructing complete buildings (Martens, 2018).

Compared to contour crafting, concrete printing has more benefits. Firstly, some new materials, such as high-performance concrete, are used in this process (Gosselin et al., 2016), which provide better mechanical properties. Moreover, Perkins & Skitmore (2015) found that concrete printing has greater geometric freedom than contour crafting, as the smaller nozzle allows a more detailed resolution.

While concrete printing has many advantages compared to contour crafting, the drawbacks cannot be ignored. Yin et al. (2018) claimed that the biggest drawback of this technology is the slower fabrication process than contour crafting due to the use of a single printing nozzle. Furthermore, Perkins & Skitmore (2015) found that the finishing and post-processing of concrete printing are more complex than contour crafting. If a smooth finish is required, it must be completed manually as the lack of trowel. Moreover, Perkins & Skitmore (2015) reported utilising high-performance concrete to compensate for the weaker structure of layered components due to the material and fabrication process. Finally, similar to contour crafting, printing large-scale buildings means that larger printers are required, often expensive.

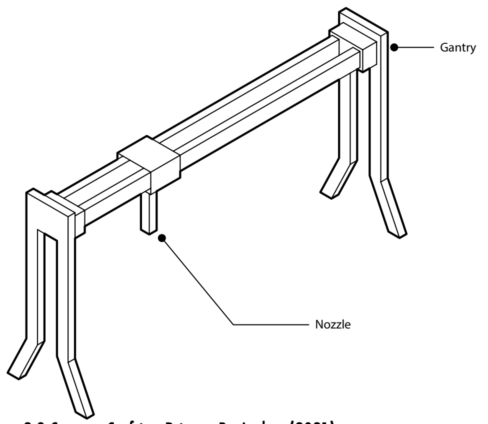


Figure 2.3 Contour Crafting Printer. By Author (2021).

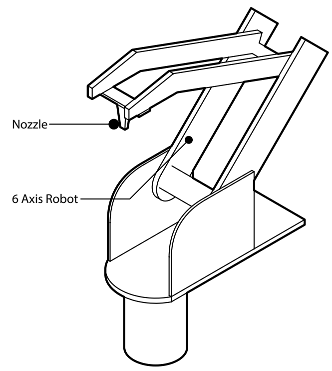


Figure 2.4 Concrete printing Printer. By Author (2021).

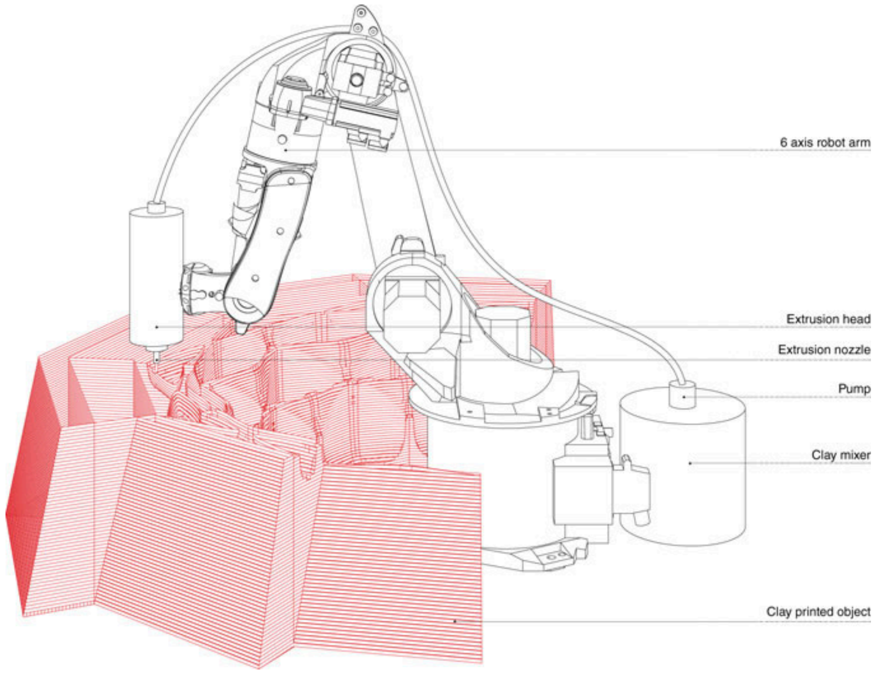


Figure 2.5 Concrete 3D Printing process. By BAÑÓN & RASPALL (2021).

2.2.3 FDM 3D Printing

FDM, or fused deposition modelling, was developed by S. Scott Crump during the 1980s (Rael & San Fratello, 2018). The advantages of using an FDM process are the least expensive cost and the most widespread equipment (BAÑÓN & RASPALL, 2021). FDM printers (Figure **2.6**) utilise a wide range of polymer materials in a filament form, such as PLA, ABS, and TPU (Bogers et al., 2016). It belongs to the extrusion family which polymer materials are heated and deposited on the bed layer-by-layer. The equipment and post-processing are demonstrated in Figure **2.7**.

FDM printers are widely used in different industries, but it is mainly utilised to create small-scale architectural models instead of the entire building for architecture. Some drawbacks of FDM printers limit their utilisation when used for architecture. Firstly, the limitation on size is the critical drawback of this process in that the typical build volume of an FDM printer is up to 500 x 500 x 500 mm (BAÑÓN & RASPALL, 2021). In contrast to the other products, architecture has a larger scale, making the FDM printer less suitable. Moreover, its printing speed is slow (BAÑÓN & RASPALL, 2021), making the manufacturing process lengthy, even if it fabricates small-scale objects.

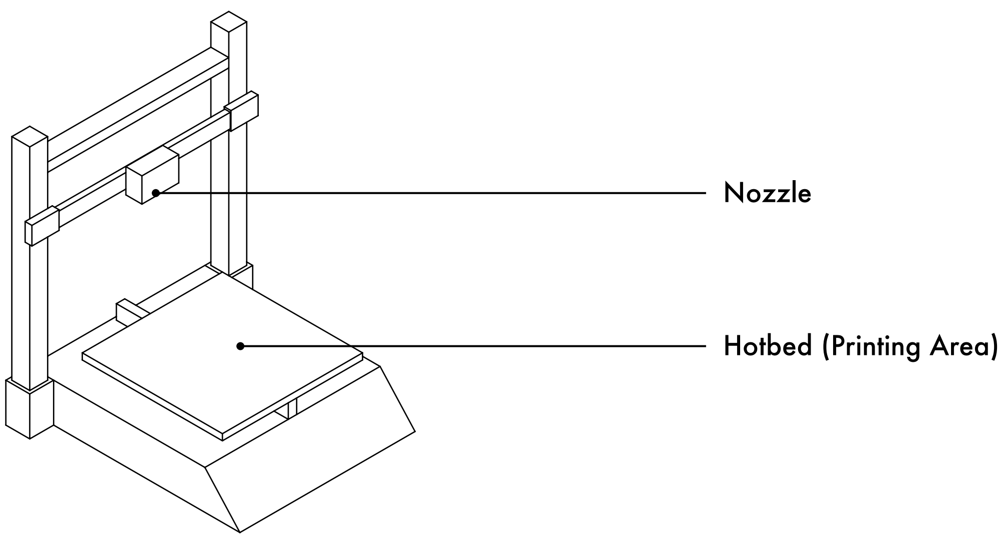


Figure 2.6 Typical FDM 3D printer. By Author (2021).

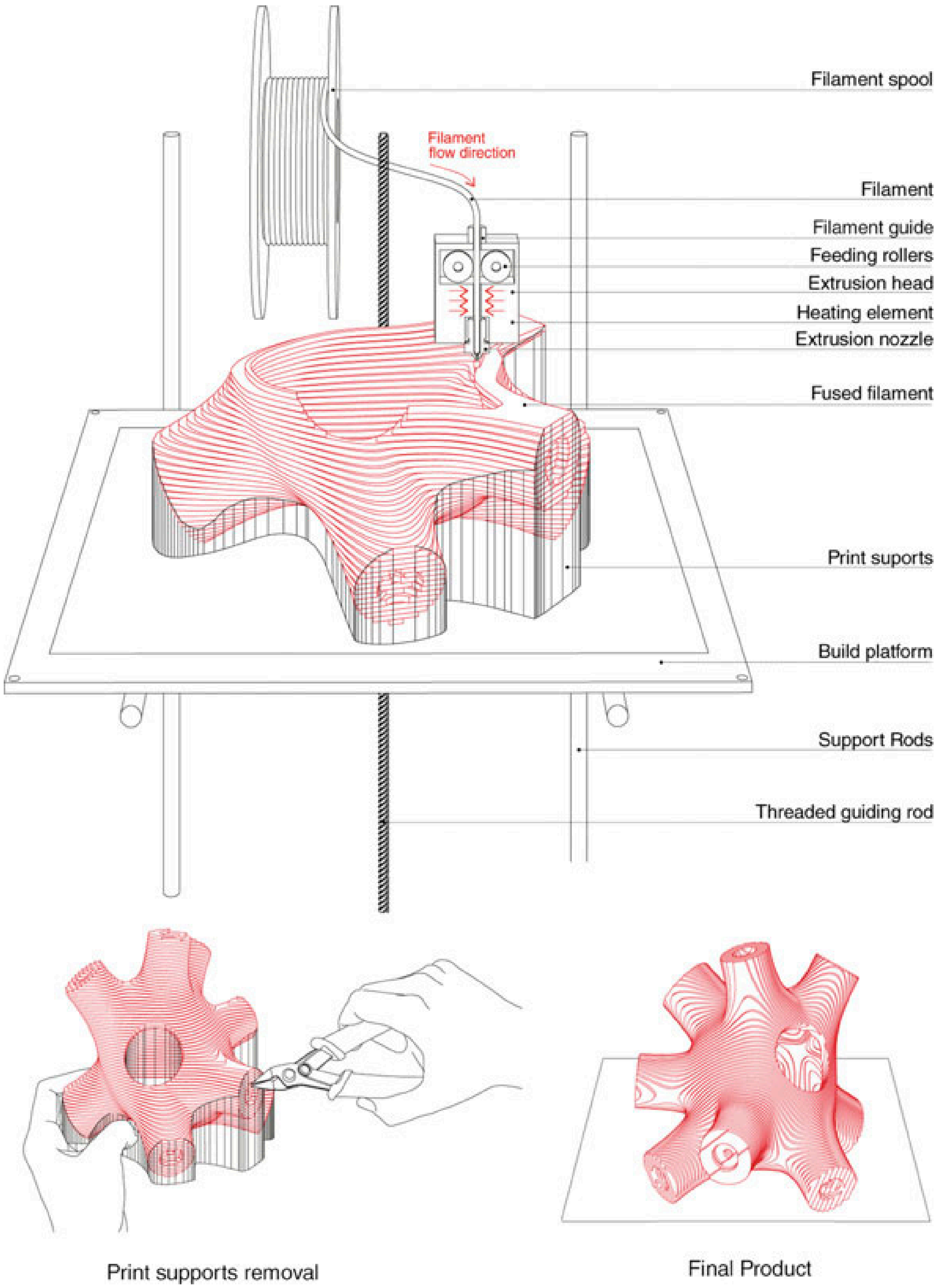


Figure 2.7 Top: Fused filament fabrication printing process. Bottom: Post-processing of main steps. By BAÑÓN & RASPALL (2021).

2.2.4 Assessment of different 3D Printing Technologies

Although those three technologies have been utilised in the architectural industry, it is still difficult to see many buildings using them because they are emerging technologies. Due to the physical features of 3D printing technology, the dimension of the printed object must be smaller than the dimension of the printer, which means that larger equipment is required to print full-size buildings.

Concrete-based 3D printing technologies have the benefits of fast fabrication, large build volume, and low construction cost. However, their devices are generally expensive (Attaran, 2017)) which make them challenging to develop. In addition, it is challenging for them to create complex geometric forms due to the limitation of the nozzle's resolution. Furthermore, concrete-based printing technologies need on-site construction that is seriously affected by factors such as bad weather. The main challenge of 3D printing is its implementation as on-site technology, and it can be less challenging where it is used as an off-site technology producing small-sized items (Sepasgozar et al., 2020).

Compared to concrete-based printing, FDM printing technology can create complex forms. However, its capacity of build volume is far smaller than concrete-based printing. Fabricating small components and assembling them is a potential solution. Without a large enough printer, a product's parts tend to be manufactured in segments (Attaran, 2017). It is, therefore, significant to consider how conventional small-scale 3D printers can be used in the architecture field. If using this FDM printing for the architectural project delivery, it is increasingly significant to consider a different design process that fits the features of this technology.

2.3 Decentralised Trend: Distributed Manufacturing

2.3.1 Background

Since the Industrial Revolution, the dominant manufacturing model tended to produce large scale goods in one place and ship them worldwide, defined as centralised manufacturing (Harrison et al., 2018). The main benefit of centralised manufacturing is that making it easier to control the manufacturing process or coordinate multiple tasks. Therefore, the product can be delivered fast with high quality.

During the twenty-first century, with the development of information technologies, an alternative model is starting to emerge due to the trend of digital manufacturing, defined as distributed manufacturing. Digital manufacturing allows customers to deliver their design in one location and send that design digitally to the manufacturing equipment worldwide, which can be produced with a digital copy (Lowe, 2018).

At the same time, the supply chain is affected by the trend of digital manufacturing. The main feature of 3D printing is customisation, which means that customers lead the manufacturing process. Therefore, this method promotes the transformation of the manufacturing model from centralisation to decentralisation (Bogers et al., 2016), as shown in Figure **2.8**.

20th Century - Mass Manufacturing

21st Century - Decentralised Manufacturing

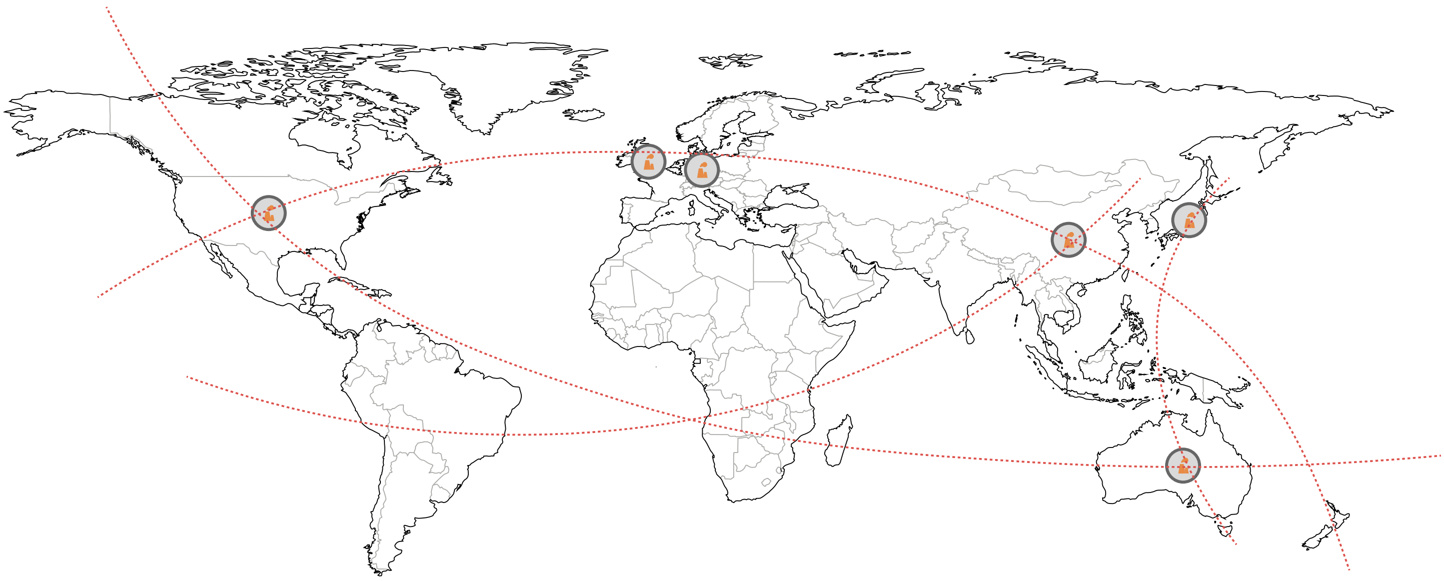


Figure 2.8 Centralised (top) versus Decentralised manufacturing (bottom). By Author (2021).

2.3.2 Definition of Distributed Manufacturing

Manufacturing is usually operated in large batches before the emerging concept of distributed manufacturing. Products are typically manufactured in one place and shipped worldwide because economies of scale motivate manufacturers to locate in low-cost locations (Lowe, 2018). Despite the mass production model providing factories with the ability to produce efficiently, it also affected the efficiency of the supply chain (Srai et al., 2016). Moreover, Bogers et al. (2016) claimed that full-scale small batch production had become a new manufacturing trend. Therefore, the manufacturing model can alter from centralised to distributed under this background.

The definition of distributed manufacturing is producing things on a smaller scale due to the global market being served by smaller fabrication sites across geographic regions (Lowe, 2018). At the same time, Srai et al. (2016) claimed that in defining distributed manufacturing, technological breakthroughs in engineering and computing play a significant role, bringing new capabilities to manufacturing in terms of automation, complexity, flexibility, and efficiency. Figure **2.9** demonstrates the workflow of distributed 3D printing.

3D printing, which represents a shift to on-demand, smaller-scale, localised manufacturing, is one of the key enabling technologies of distributed manufacturing. (Srai et al., 2016). Several significant features make 3D printing suitable for distributed manufacturing. Firstly, the digital fabrication process of 3D printing enables the digital design file to be sent anywhere, which have the capacity of a shift to smaller-scale manufacturing (Srai et al., 2016 & Lowe, 2018). Furthermore, the significant feature of 3D printing is high customisation (Mai et al., 2015); it enables the customer to produce and customise various parts for themselves and others, emphasising the change from centralised to decentralised manufacturing (Bogers et al., 2016).

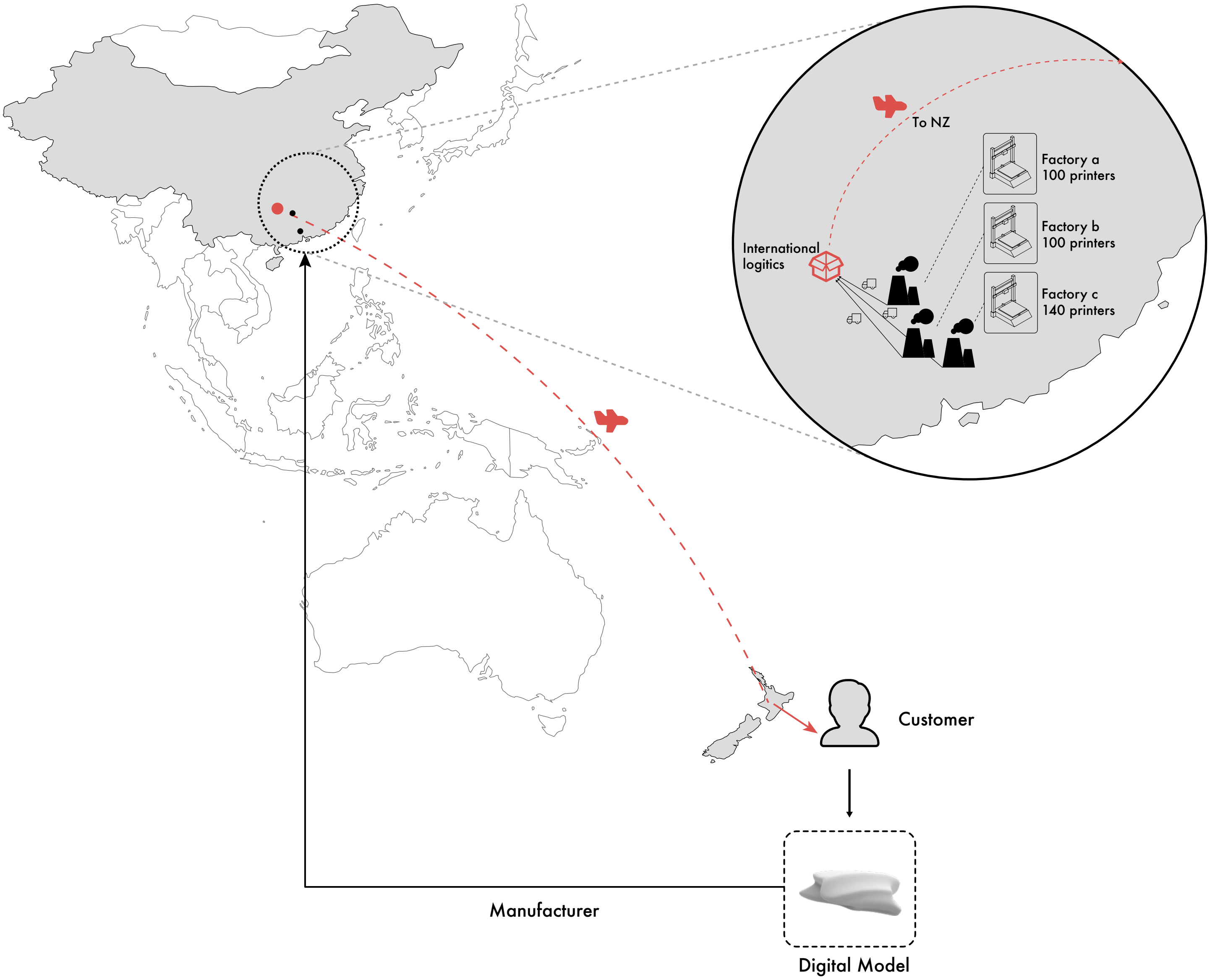


Figure 2.9 Workflow of Distributed Manufacturing. By Author (2021).

2.3.3 The Challenges of Distributed Manufacturing

Although distributed manufacturing can become a new trend with technological breakthroughs, some challenges still affect its development and application.

Firstly, the quality control of the product is a potential issue. Durão et al. (2016) believed that it is challenging to guarantee the highest quality and standards in distributed sites due to the nature of distributed manufacturing. In addition, in contrast to conventional technologies, the security of the digital design file using digital manufacturing (such as 3D printing) may be challenged. There are significant IP implications for ownership; it is, therefore, necessary to set a framework to prevent copyright infringement for design and development work (Srai et al., 2016). Moreover, the coordination of the entire process is also a significant challenge. While distributed manufacturing allows customisation of the products, manufacturers have difficulties controlling and managing the entire process (Bogers et al., 2016). Lowe (2018) explained that coordinating centralised control of different activities across geographical regions is difficult and complicated.

While the existing concept of distributed manufacturing provides opportunities for 3D printing, the challenges in IP protection, quality control, and coordination are still significant. Hence, a management system or platform based on distributed manufacturing needs to be considered.

2.3.4 3D printing technologies fit for Distributed Manufacturing

As discussed above, several different 3D printing technologies can be utilised for architecture. Nevertheless, not every process and technologies are equally suited to distributed manufacturing.

Some factors are affecting whether those technologies or processes fit distributed manufacturing. The dimension and investment of manufacturing equipment affect this method. Lowe (2018) found that large and expensive equipment involving manufacturing need highly specialist operators to control. This equipment tends to be harder to find in different locations due to the lack of highly specialist operators. That means that the achievement of distributed manufacturing is more likely to use low-cost and common equipment.

Bogers et al. (2016) claimed that FDM is the leading technology that can implement the concept of distributed printing. This technology is considered the most potential and accessible technology for distributed printing (Perez-Mañanes, 2021). As discussed above, the wide application of FDM printers during the Covid-19 pandemic proved that equipment with the features of low-cost and straightforward requirements for operating are more likely to be utilised in distributed manufacturing. Moreover, according to Perez-Mañanes (2021), the majority of the PPE products were manufactured by individuals (57.3%), manufacturing companies (28%), and universities (7.6%). This data demonstrates that individuals own most equipment in contrast to manufacturing companies, contributing much to the distributed manufacturing. Therefore, adequate and affordable equipment plays a crucial role in distributed printing methods.

Hence, in contrast to concrete-based printers, FDM printers are more likely to be used for distributed printing.

2.4 Conclusion

2.4.1 Findings Discussion

This literature review aims to explore how architecture can leverage the power of distributed 3D printing, and several findings have been found. Firstly, concrete-based 3D printing technologies are not suitable for complex architectural projects. In contrast, while FDM 3D printing has the benefit of creating flexible forms, the small build volume limits its application in architecture. In addition, compared to FDM, concrete-based 3D printing is not suitable for distributed manufacturing due to the limitations of the equipment. Furthermore, if using distributed 3D printing method for delivering architectural projects, a management system that can control the quality and allocate tasks efficiently is necessary.

2.4.2 Limitations of Existing Research

Research on the 3D printing technologies for the architecture and distributed manufacturing is compelling but has significant limitations. So far, there is little knowledge regarding using the distributed 3D printing method for architectural project delivery. Future research should address how can architectural design fit the build volume limitation of FDM printers. Future research should also examine the possibility of using the distributed 3D printing method for complex architectural project delivery. The majority of research on the use of distributed 3D printing has proposed the concept of this new method. However, there is little literature about applying distributed 3D printing in the architectural context.

3 Case Studies

Figure 3.1 Cover: Complex Structure.
By Author (2021).

3.1 Hemo Gorge Gateway Sculpture in Rotorua

3.1.1 Introduction

This project was initially designed by Stacy Gordine, of the New Zealand Maori Arts and Crafts Institute. Stacy is internationally acclaimed for his small-scale adornment works. He collaborated with Victoria University's digital design lecturer Derek Kawiti who has vast experience in digital design and advanced fabrication methods. The collaboration consisted of Kawiti's redevelopment and rationalisation of the concept to buildable geometry using a parametric delivery method. The concept of this project was derived from the use of a Maori geometry – Takarangi or double spiral and adapted to a three-dimensional helix form based upon a traditional narrative.

This sculpture is located in Rotorua, New Zealand. It has a height of 12 metres and a total weight of 3,300kg (Figure **3.4**). Initially, this project selected CNC mandrel pipe bending and 3D printing as potential fabrication methods due to their flexible shape. Although CNC using stainless steel was considered in the initial approach, it had to be replaced by an alternative method due to issues of self-weight and material tearing during curvature forming. This means that a lighter material was sought while maintaining geometric freedom. The density of stainless steel is 7.70-8.00g/cm^3, and PLA is 1.24g/cm^3; the mass of stainless steel, therefore, is approximately six times that of PLA for the same volume. As a result, if PLA was selected as the primary material with a carbon fibre sheathing, the issue of structural performance and self-weight could be effectively resolved. 3D printing using PLA was finally selected as the fabrication method in this context.

There is no doubt that this sculpture is an innovative project and was touted as the world's largest 3D printed sculpture at the time of completion. It effectively utilises advanced 3D printing technologies to create a flexible and complex design. One of the key challenges of the project was that the sculpture needed to be separated into smaller components to adopt an assembly approach, meaning that the manufacturer (Killwell Fibre Tube Ltd.) needed to fabricate a large number of components. As a result, they had to find a way to do this simultaneously within their factory in Rotorua. The unexpected delivery time of two years created huge risks due to only having eight printers. The capital investment for Killwell was a significant factor for the project as the eight printers cost over $90,000.00 and had constant breakages and technical problems.

Table 1. Project data of Hemo Gorge Gateway Sculpture

Dimension	12m in height
Year	2021
Printed parts	700 printed components
Material	PLA
Weight	3,300kg
Manufacturing equipement	8 3D printers
Delivery time	2 years

3.1.2 Connection System Design

The Male joint

The male joints (Figure **3.2**) of this project were separated into two parts, a large cylinder located in the centre of the cross-section, which can be steadily connected to the other segments, and a small cylinder that controls the angle of the curved shape. The large cylinder has its centre of the cross-section at the geometric centre of the whole segment so that it has the same shape and angle as the segment, only with a different diameter. The smaller cylinder is shorter than the larger one for more stable fixation and to increase the contact area of the adhesive.

The Female joint

The female joint (Figure **3.3**), an essential part of the segment, is a slot with the same shape as the male joint to which it is attached. Each component is based on an accurate digital model, and the connection process is simplified by inserting one male joint into the adjacent female joint.

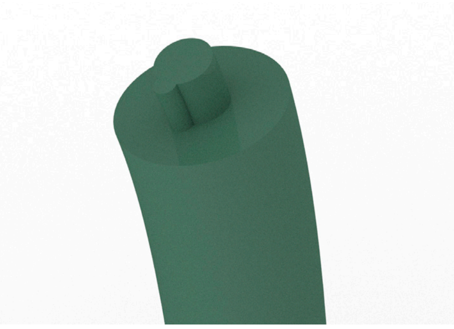


Figure 3.2 The Male joint. By Author (2021).

Figure 3.3 The Female joint. By Author (2021).

3.1.3 Manufacturing

Hemo sculpture was assembled from approximately 700 different segments, each approximately 750 grams. PLA was selected as the material for printing. The geometry of the base segments evolved from a tube connected by male and female joints. Each segment achieves the curved shape of the sculpture by shifting its shape and angle.

As each section weighs approximately 750g, it cost approximately NZ$25 for materials based on the New Zealand market. Moreover, the time required to print each segment was approximately 16 hours.

All components were manufactured at Kilwell Fibre Tube's factory, using eight 3D printers running 21 hours per day to print all parts seven days a week (Figure **3.5**). The printing work was estimated to complete within 79 days. Nevertheless, it took two years because of some unpredictable delay. The entire fabrication process approximately took 16,500 hours to print on-site.

3.1.4 Assembly

The sculpture has two parts: the inner helix and the outer helix. The inner helix was assembled at the beginning to avoid tolerance.

After those parts finished producing, they were sorted in order for connection. Each part was joined using adhesive and secured with a retaining ring, as shown in Figure **3.6**. Once the segments had been successfully connected, they were wrapped in carbon fibre fabric (Figure **3.7**).

Figure 3.4 Hemo Gorge Gateway Sculpture. Photography by Bathgate (2020).

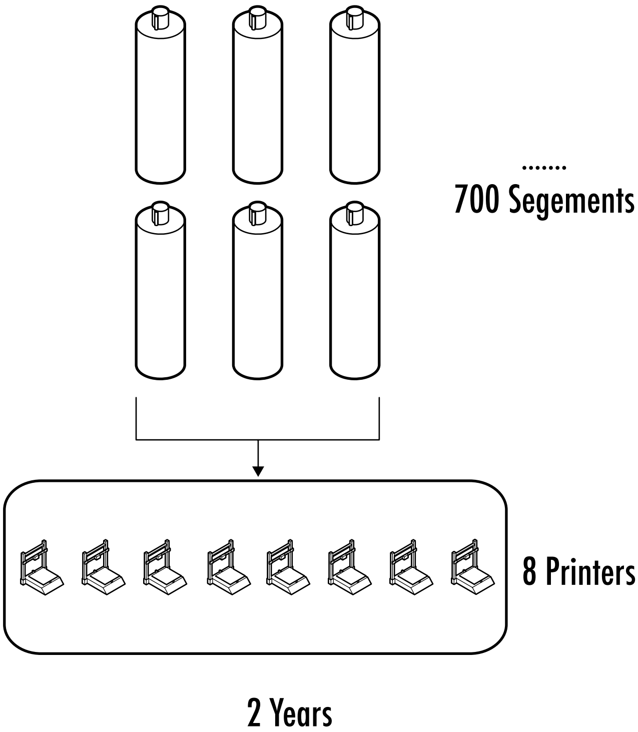


Figure 3.5. Manufacturing process. By Author (2021).

Figure 3.6 Assembly process. Source: Rotorua Lakes Council (2019).

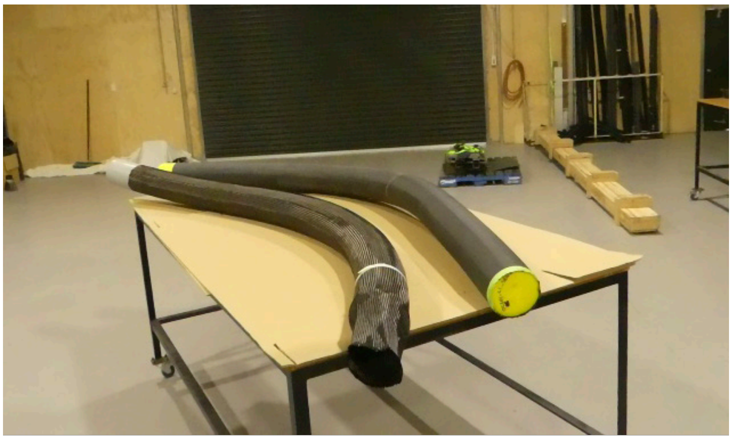


Figure 3.7 Assembly process. Source: Rotorua Lakes Council (2019).

3.2 Adidas Flagship Store in Dubai

Design team : **Proto 21**
Location : **Dubai**
Category : **Modular Design**

3.2.1 Introduction

This project was designed by Proto21, one of the most prolific 3D printing service providers in the Middle East and the world. The project is a façade design consisting of 1008 components that form the 32-metre long modular facade of the new Adidas flagship Store in Dubai Mall (Figure **3.8**). It utilised a modular design approach, with each of the 1008 components that compose the facade measuring 200x200x180 mm (Figure **3.9)**.

Table 2. Project data of Adidas Flagship Store

Dimension	32m in leight
Year	2021
Printed parts	1008 printed components
Material	PLA
Manufacturing equipement	Multiple 3D printers
Delivery time	3 months

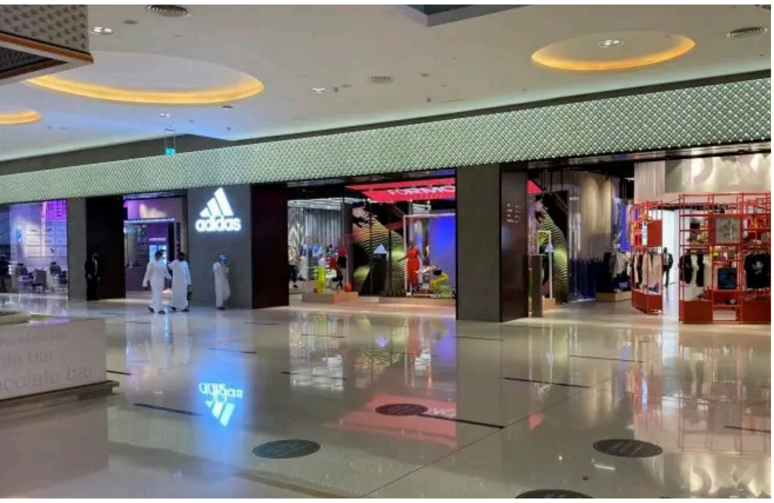


Figure 3.8 Facade design. Photography by Proto21 (2021).

Figure 3.9 Components. Photography by Proto21 (2021).

3.2.2 Manufacturing

The entire project requires over 20,160 hours of continuous printing, which means one 3D printer would have taken more than 28 months to complete. However, Proto21 used a multiple Prusa system to fabricate, allowing the entire project to take just three months. This system is a platform based on multiple 3D printers (Figure **3.10**) working simultaneously, meaning that each printer can produce different parts simultaneously.

3.2.3 Reflection

Although this project only concentrated on façade design, it also inspired that distributed printing would also be used for architecture if technical issues (such as structural strength) could be solved. This project has demonstrated that multiple 3D printers can accelerate the fabrication process (Figure **3.11**). Researching this precedent aims to recognise a different 3D printing fabrication method based on distributed manufacturing.

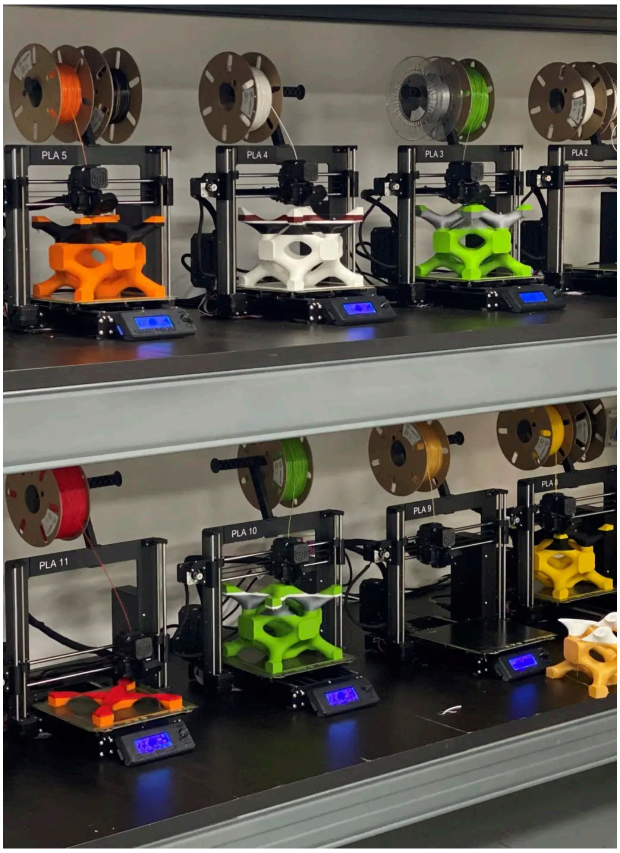


Figure 3.10 Multiple Prusa System. Photography by Proto21 (2021).

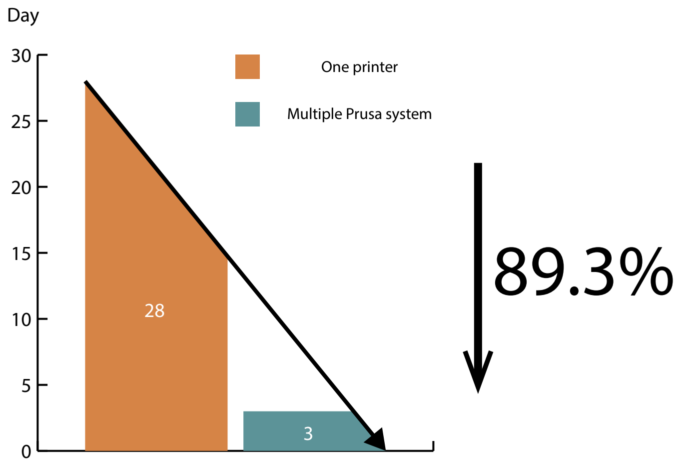


Figure 3.11 Comparison of delivery time. By Author (2021).

Figure 3.13 Modular component. Photography by ACTLAB (2018).

3.3 Trabeculae Pavilion in Italy

Design team : **ACTLAB**
Location : **ITALY**
Category : **COMPUTATIONAL DESIGN**

3.3.1 Introduction

Trabeculae Pavilion is a lightweight architecture that fuses advancements in Additive Manufacturing with bio-inspired computational design (Figure **3.12**). The project investigates 3D printing to answer the emerging shortage in material resources. The design is based on a computational process that finds inspiration in nature, specifically in the materialisation logics of the trabeculae, the internal cells that form the bone microstructure. From this investigation, custom algorithms have been developed to support the creation of a cellular load-responsive structure with continuous variations; the project investigates 3D printing for answers to the emerging problem of shortage in material resources. The design is based on a computational process that finds natural inspiration, specifically in the materialising, sizing, topology, orientation and section, to maximise material efficiency.

The built pavilion is a load-responsive shell composed of 352 components (Figure **3.13**) covering a total area of 36 square meters, additively formed by a 112 kilometres-long extrusion of a high-resistance biopolymer.

Table 3. Project data of Trabecilae

Dimension	7.5m x 6.0m x 3.6m
Year	2018
Printed parts	352 printed components
Material	High-resistance biopolymer
Manufacturing equipement	Multiple 3D printers
Delivery time	4352 hours

3.3.2 Manufacturing

The fabrication process of the building components was based on a Delta WASP printer farm ((Figure **3.14**), where multiple production processes allowed for continuous production for a total of 4350 hours.

3.3.3 Reflection

This pavilion is assembled by hundreds of components using Delta WASP printer farm to deliver the project. This printer farm can be considered as the initial concept of distributed manufacturing. While those components were not fabricated worldwide, the delivery time reduction can still prove the positive impact of the number of devices.

Figure 3.12 Trabeculae Pavilion Overview. Photography by ACTLAB (2018).

Figure 3.14 Delta WASP printer farm. Photography by ACTLAB (2018).

3.4 Timescapes in Singapore

Design team : **AIRLAB**
Location : **Singapore**
Category : **Computational Design**

3.4.1 Introduction

Timescapes is a pavilion designed for the Singapore University of Science and Technology's 10th anniversary. (Figure **3.15**). It serves as a time capsule with sculptural structure, preserving and displaying the most significant artefacts produced by the faculty and students during the university's first decade.

The concept of the design was conceptualised as a two-sided landscape. Inwardly, visitors are surrounded by a continuous surface provided by the pavilion to create an immersive experience. Outwardly, the outside surface creates a new space serving as a welcome bay.

Timescapes is a research-based project that aims to develop workflows for freeform ornamental architecture through parametric modelling and low-cost FDM 3D printing. This project completes the design, fabrication, and assembly stages, developing a unique ID system to manage many components.

Table 4. Project data of Timescapes

Dimension	12m x 12m x 4m
Year	2020
Printed parts	4037 units
Material	PLA
Weight	767.5 kg
Manufacturing equipement	50 printers
Delivery time	4 weeks

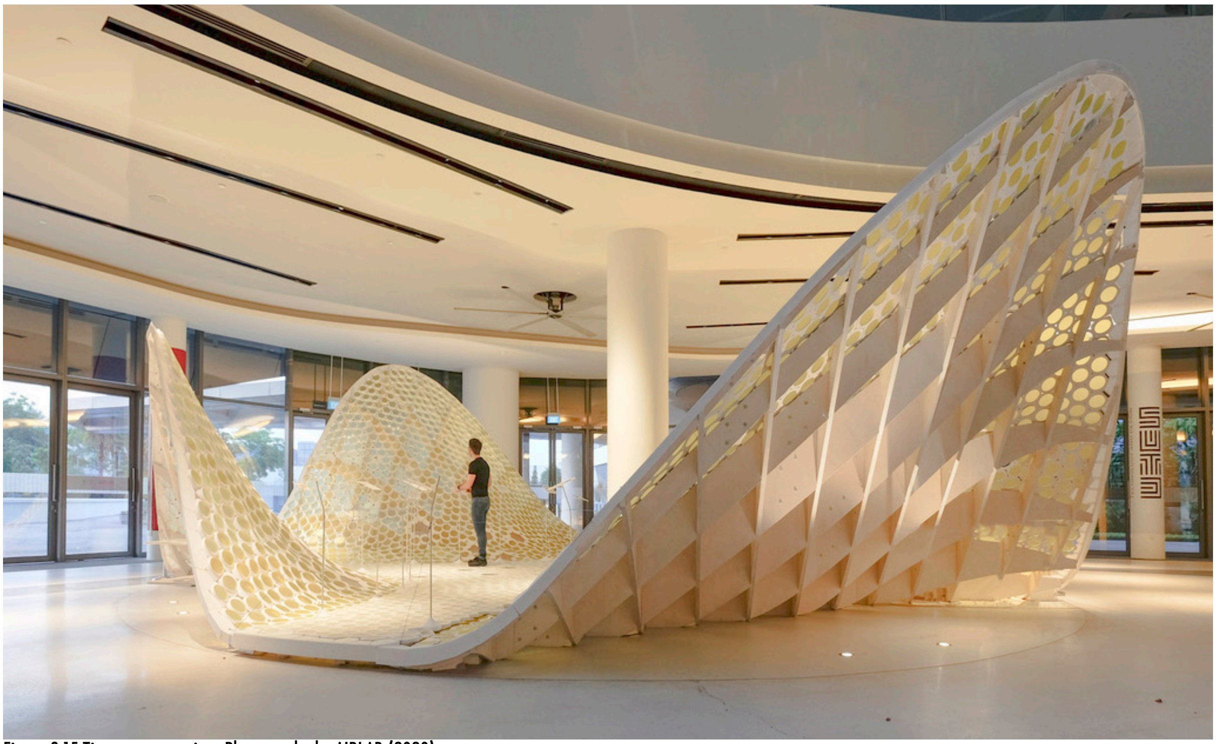


Figure 3.15 Timesacpe overview. Photography by AIRLAB (2020).

3.4.2 Manufacturing

The manufacturing process of Timescapes mainly has parts: the 3D-printed tiles, the flat plywood floor, and the rib structure. The 3D printed components are the most significant and most considerable parts of this project, involving more than 4000 unique components. Each component was designed to ensure that it could be printed in less than five hours. While the number of 3D printed parts was large, the project was finished within four weeks with 50 printers involved in the manufacturing process.

The reasons for selecting the FDM printer in this project instead of others are that it can meet the demanding budget and time constraints. FDM 3D printers can provide low-cost manufacturing. As a result, adequate devices can reduce the delivery time.

3.4.3 Assembly

Timescapes has more than 4000 printed components, which means that the assembly process is challenging to identify each part's correct position. A unique system was developed to support unskilled labourers to assemble them with minimal supervision. This system nested a unique ID for each component, indicating the component's position in the pavilion, as shown in Figure **3.16**. Moreover, 1:1 templates of the projection of each component were printed, decreasing the assembly time by identifying the position faster, as shown in Figure **3.17**.

3.4.4 Reflection

There is no doubt that Timescapes is an innovative project investigating the design and manufacturing workflows of 3D printing. Many details, such as the component design, can inspire the other projects. For instance, the dimension of each part was designed before manufacturing to meet the size requirement of the selected 3D printing process. In addition, the unique ID system is also significant for manufacturing with a large number of components. An efficient management system can sharply reduce the entire process.

Timescapes utilised the FDM printer as the manufacturing equipment for its low cost and time constraints. It is a fact that single or inadequate FDM 3D printers are not suitable for mass production due to their slow manufacturing process. Nevertheless, the delivery time could be reduced by increasing the amount of 3D printers. In contrast to the other equipment, the FDM printer is more affordable for mass manufacturing. Hence, the FDM process is more likely to be a potential tool for a project with many small-scale components.

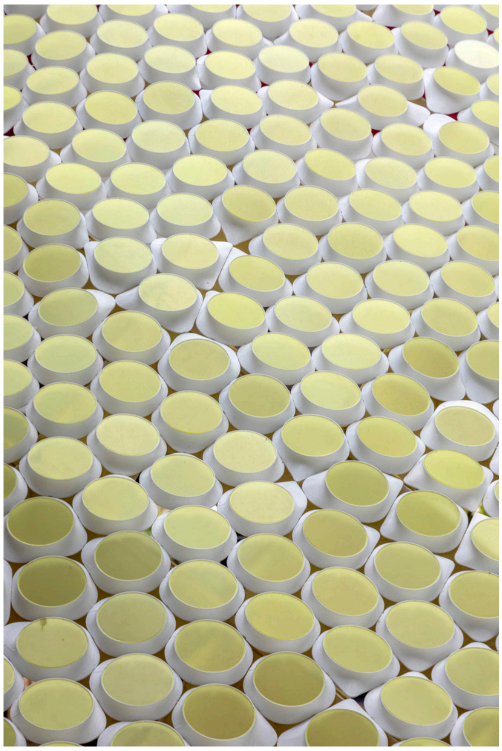


Figure 3.16 Unique ID of each part. Photography by AIRLAB (2020).

Figure 3.17 Template used to position all tiles in order. Photography by AIRLAB (2020).

3.5 Existing Distristured 3D Printing Platforms

3.5.1 Introduction

As discussed above, quality control, IP protection, and coordination are the main issues of distributed printing. In order to solve these issues, Guo & Qiu (2018) proposed the concept of cloud manufacturing to solve the drawbacks of distributed printing. Cloud manufacturing is a type of network-based manufacturing, which enables users to manage various manufacturing services online (Guo & Qiu, 2018). One of the key benefits of cloud manufacturing is that when 3D printing resources are distributed, it provides a convenient and accessible way to produce 3D printing products (Mai et al., 2015).

This section will explore three small-scale online 3D printing websites: Fiverr, Hubs, and Zelta 3D. They are online distribution platforms providing distributed printing services. Fiverr is the larger platform, offering various services, including 3D printing, while the other two are platforms focused on digital fabrication. Studying these existing platforms aims to investigate how they manage their distributed tasks and risks.

3.5.2 Fiverr

Fiverr is an online marketplace for freelancers. It enables them to offer their services to customers worldwide. Customers can also utilise this platform to search for the services (such as 3D printing services). While many manufacturers on this platform, not all of them fit the manufacturing requirements. For instance, only part of the manufacturers may have the 3D printers fit for the size limitation. That means that the customers have to search for the information themselves, and this process is not automatic. Moreover, the task management of this platform is also an issue. For instance, customers have to discuss with the service providers regarding the logistics, which may have the risk of increasing task delivery time.

3.5.3 Hubs

Hubs started its business as the world's largest peer-to-peer network of 3D printing services, and they offer a broader range of services, including CNC and metal fabrication.

In contrast to Fiverr, Hubs have several core features making it more accessible. Firstly, Hubs offers a convenient digital file management system, providing instant quotes and estimated delivery time. In addition, while Hubs arrange fabrication through hundreds of specialised manufacturing partners worldwide, it set a quality assurance standard for these distributed manufacturers to guarantee the quality. Moreover, according to Hubs, in terms of IP protection, it utilises production servers to store all digital models and drawings on them to protect the IP.

While Hubs no longer provides the 3D printing service, its concept of distributed 3D printing method and its management platform is still significant to be investigated.

3.5.4 Zelta 3D

Similarly, Zelta 3D is also an online manufacturing platform focusing on 3D printing. In contrast to Hubs, it provides a broader range of 3D printing technologies, including SLA, SLS, FDM, MJF, to fit different requirements of customers.

Compared to Hubs, the core advantage of Zelta 3D is its more professional online instant quote system. An online 3D printing platform allows customers to customise their settings (including materials, finishing, and dimension) before quoting. This means it can provide more accurate quotes to decrease the quote process.

Nevertheless, architectural components have different scales and tolerance than the other product. For instance, if the architectural components were large and had little tolerance limitations, it could reduce the manufacturing process by increasing the printing speed and layer height. Those settings are various for each part. As a result, a system focus on architecture is significant.

4

Proposed Solution

Figure 4.1 Cover: Complex Structure.
By Author (2021).

4.1 Introduction

This chapter will explore the potential solution that allows architecture to leverage the full power of distributed 3D printing. This chapter is mainly divided into the 3D printing process and system solutions. Investigating the potential solutions begins with the identified issues, as shown in Figure **4.2**.

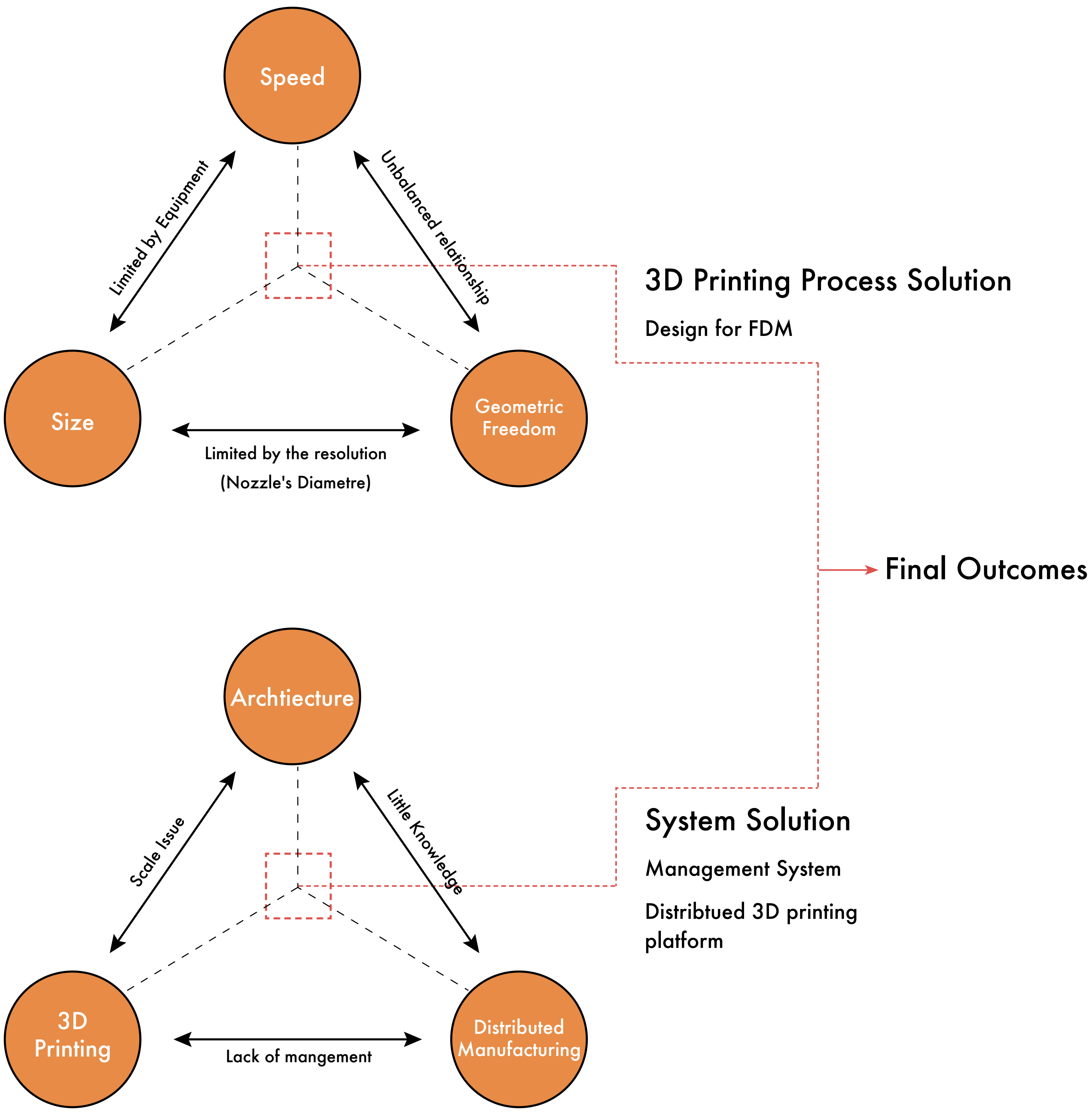


Figure 4.2 Solutions and Strategies. By Author (2021).

4.2 3D printing Process Solution - Design for FDM

There are various 3D printing processes used in different industries; however, concrete-based 3D printing and FDM 3D printing are critical processes for architecture.

Concrete-based 3D printing processes are more likely to provide rapid construction (Zareiyan & Khoshnevis, 2017) and low-cost building (Davtalab et al., 2018). While concrete-based 3D printing has various benefits, it is not suitable for architecture and distributed manufacturing. In terms of the architecture application, concrete-based 3D printing technologies do not have a strong capacity of freedom form (Gosselin et al., 2016). In addition, despite this method can construct large-scale building, the equipment involved in the construction process are generally large and expensive (Martens, 2018), which is considered not suitable for distributed manufacturing (Lowe, 2018).

In contrast to concrete-based 3D printing, FDM 3D printing is considered the most affordable and widespread technology (BAÑÓN & RASPALL, 2021). Those features of FDM 3D printing make it potentially be utilised for distributed manufacturing (Perez-Mañanes, 2021). Nevertheless, the application for architecture using this process still have a significant issue. Although FDM has the advantage of freedom form compared to concreted based 3D printing, its build volume and fabrication time are limited by the equipment (BAÑÓN & RASPALL, 2021).

However, for small-scale architecture with complex form or modular structure, FDM printing is the most suitable process to leverage the real power of distributed manufacturing. Therefore, it is necessary to consider the design approach that fits the FDM process's workflow.

4.3 System Solution - Management System

To date, various literature and researchers believe that the capacity of 3D printing technologies can be improved by distributed manufacturing. As discussed above, distributed 3D printing played a vital role during the Covid-19 pandemic; however, some concerns still need to be considered before utilizing it for architecture.

While integrating distributed manufacturing may benefit 3D printing, several issues have to be considered. Firstly, quality control is one of the significant issues due to the difficulty of controlling the quality and standards in distributed sites with different equipment (Durão et al., 2016). In addition, IP protection is another issue (Srai et al., 2016). As the digital feature of 3D printing, designers have to send their digital models to the manufacturer, which means that others can copy their work. Moreover, it is challenging to manage different tasks when manufacturing in distributed sites (Lowe, 2018).

Despite distributed 3D printing demonstrating its power in different industries, those issues may risk the project delivery for architecture. However, if those issues could be resolved, distributed 3D printing would become a powerful tool for architecture. Therefore, a management system that can control the quality, protect IP, and manage multiple tasks is necessary to achieve distributed 3D printing method for architecture.

4.4 Final Outcome - Distributed Printing Platform

4.4.1 Introduction

According to those two solutions discussed above, an online distributed server named 'Architecture Distributed' is designed for this project. Due to the limitation of budget and capacities, this server utilises Wix.com, an online platform for website design, to simulate it instead of running it in a real-life server, as shown in Figure **4.3**.

The research regarding 3D printing processes and the management system demonstrated that while FDM 3D printing is more suitable for distributed manufacturing, a management system is also necessary. Hence, an online server that can manage distributed 3D printers worldwide is significant for project delivery. The online server aims to provide distributed 3D printing manufacturing services for customers worldwide, mainly focusing on solving complex architectural projects.

With the help of this platform, complex architectural projects with many small-scale components can be achieved instead of being limited by the slow fabrication time of FDM printing. At the same time, in contrast to concrete-based printing, the freedom form which contributes to complex architectural structures can remain.

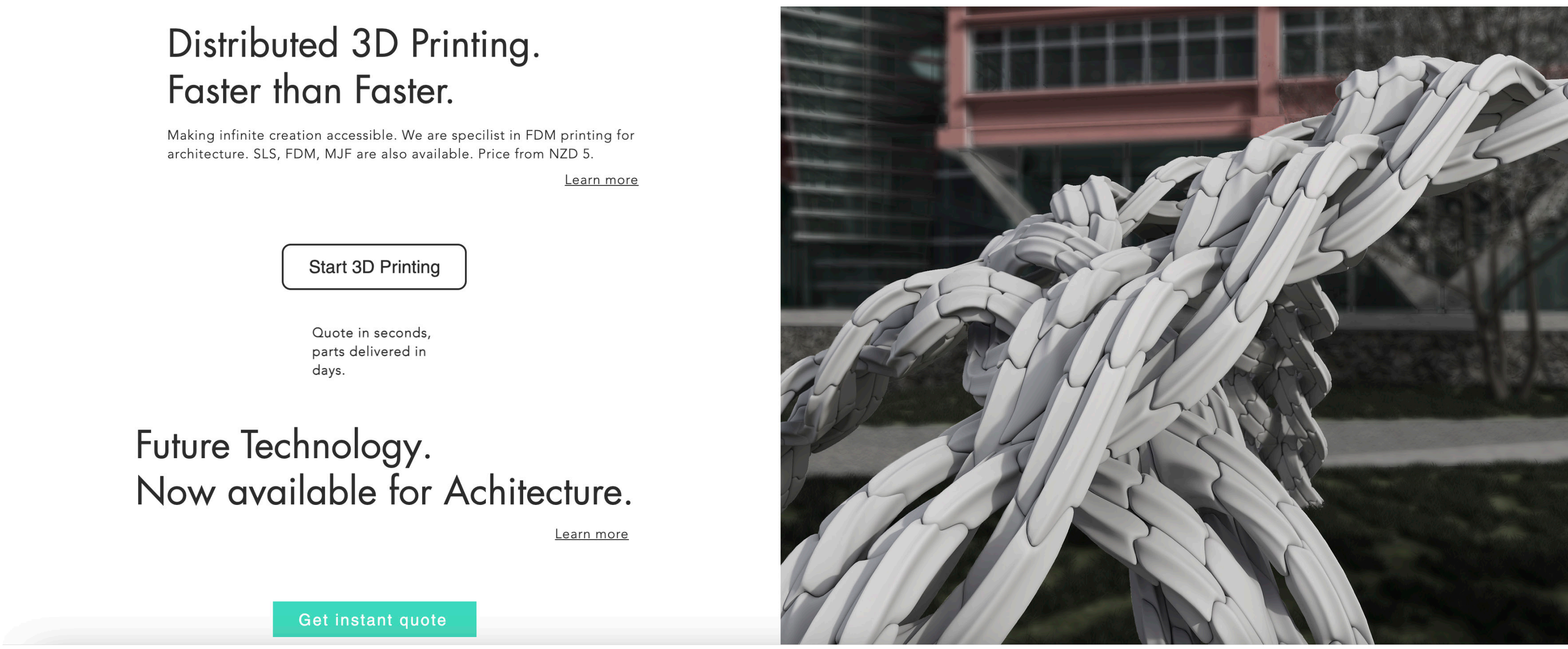


Figure 4.3 Online Distributed 3D printing Flatform Design. By Author (2021).

4.4.2 Platform Workflow

This online distributed 3D printing server consists of five core parts: a matching system, global manufacturer, remote monitoring system, quality control system, and logistics system, as shown in Figure **4.4**.

To utilise this platform, users need to upload their digital model file with their requirements to the server to get instant quotes (Figure **4.5**). The server will match the requirements and digital models with the capacity of global manufacturers and find the most suitable manufacturer (Figure **4.6**). When users satisfying with the product, it will be arranging the international logistics and be delivered to the users as soon as possible (Figure **4.7**).

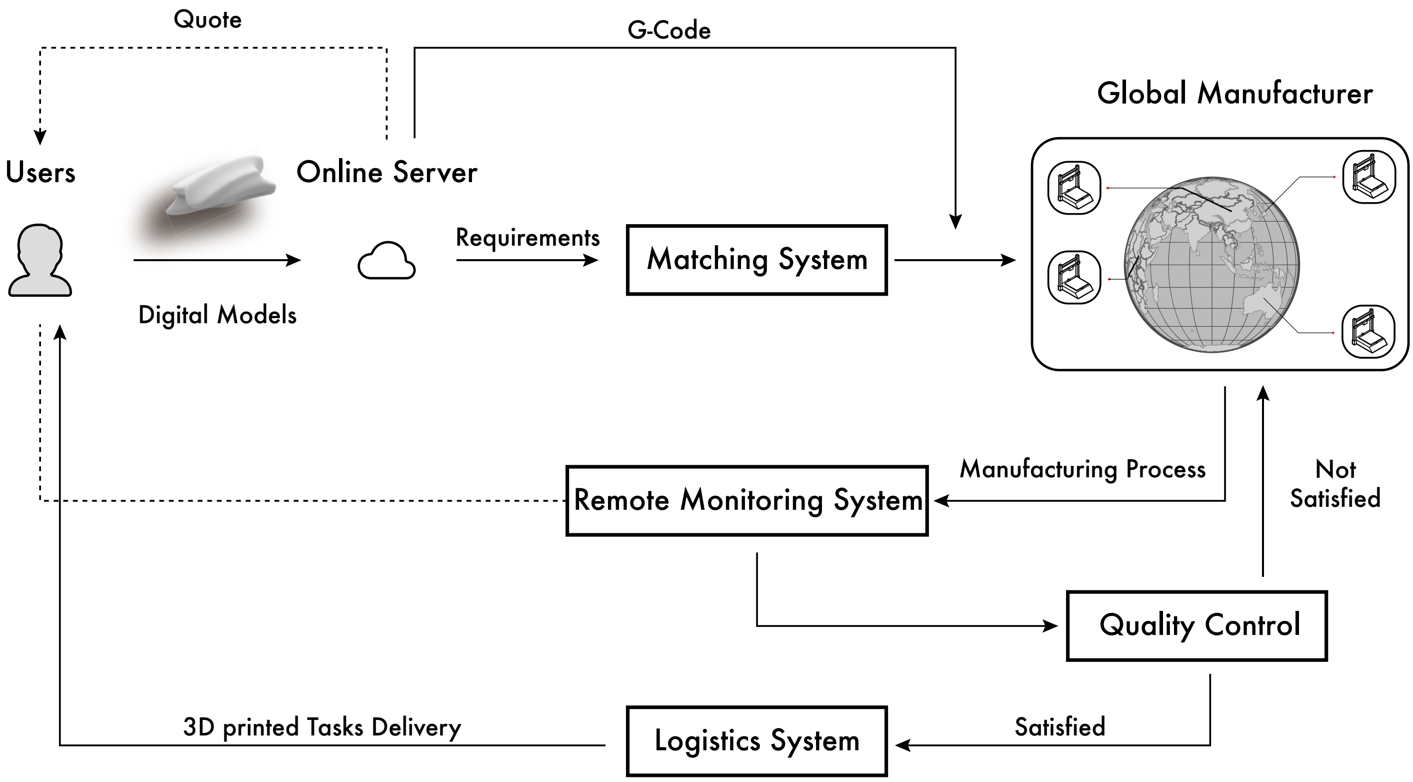


Figure 4.4 The workflow of Online Distributed 3D printing Server. By Author (2021).

STEP 1

Upload the digital model files

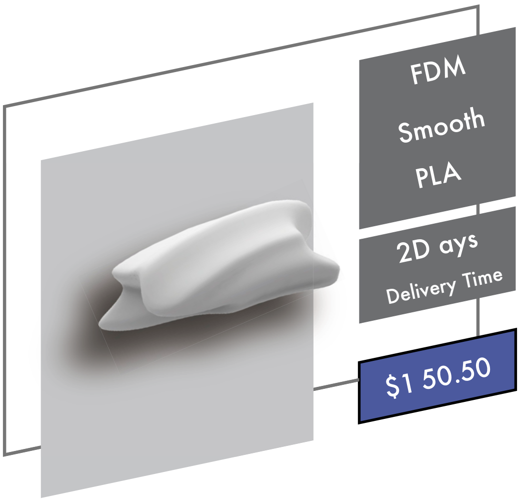


Figure 4.5 Step 1 - Digital model Upload and Quote. By Author (2021).

STEP 2

Global Manufacturers Arrangement

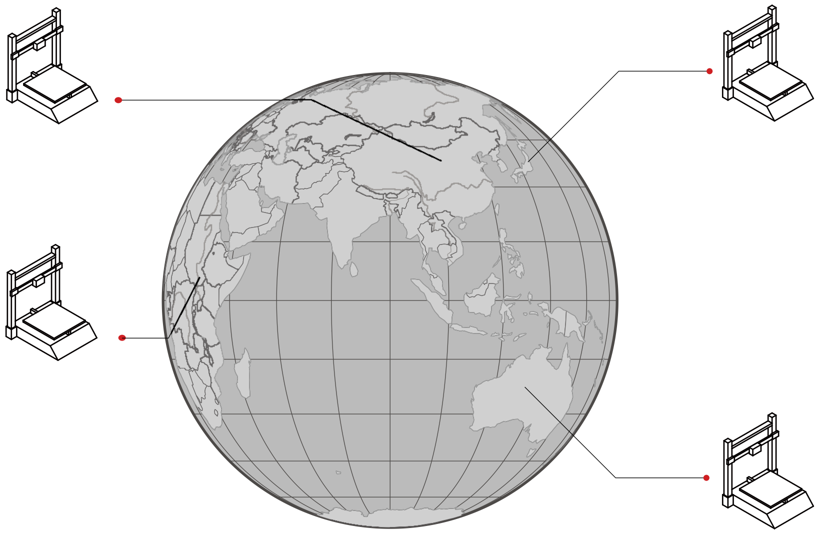


Figure 4.6 Step 2 - Match Global Manufacturer. By Author (2021).

STEP 3

International Logistics Solution

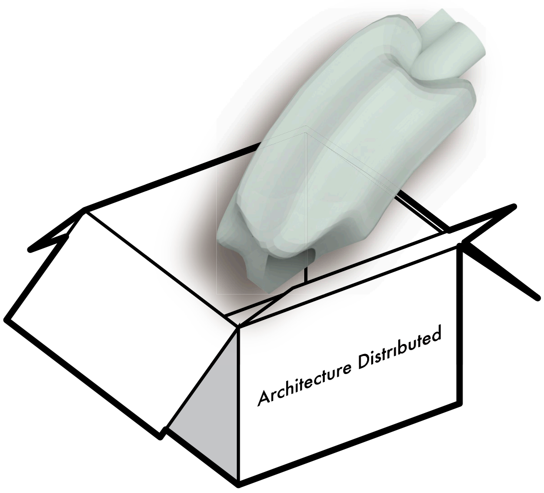


Figure 4.7 Step 3 - International Logistics Arrangement. By Author (2021).

Matching System

Matching System is one of the most significant functions of this platform. This platform focuses on 3D printing fabrication for architecture, especially FDM technology. Due to architectural parts typically having different requirements, such as tolerance, material mechanical performance, and quality. Therefore, a matching system that can allocate the tasks to a more suitable manufacturer is significant for users.

Figure **4.8** demonstrates all parameters that users can customise themselves before manufacturing. In contrast to the other 3D printing manufacturer, this system provides more customised parameters, especially quality control. For instance, if users tend to fabricate a complex architectural component with a smooth surface and tight tolerance, they need to select higher quality. At the same time, a simple form object with loose tolerance can select lower quality to decrease delivery time.

When users have determined their requirements, the server will search for the most suitable manufacturing partners worldwide. In order to protect the IP of the user's work, the digital model will be kept on the server. The manufacturer will be provided with the G-Code, which is not editable from the platform.

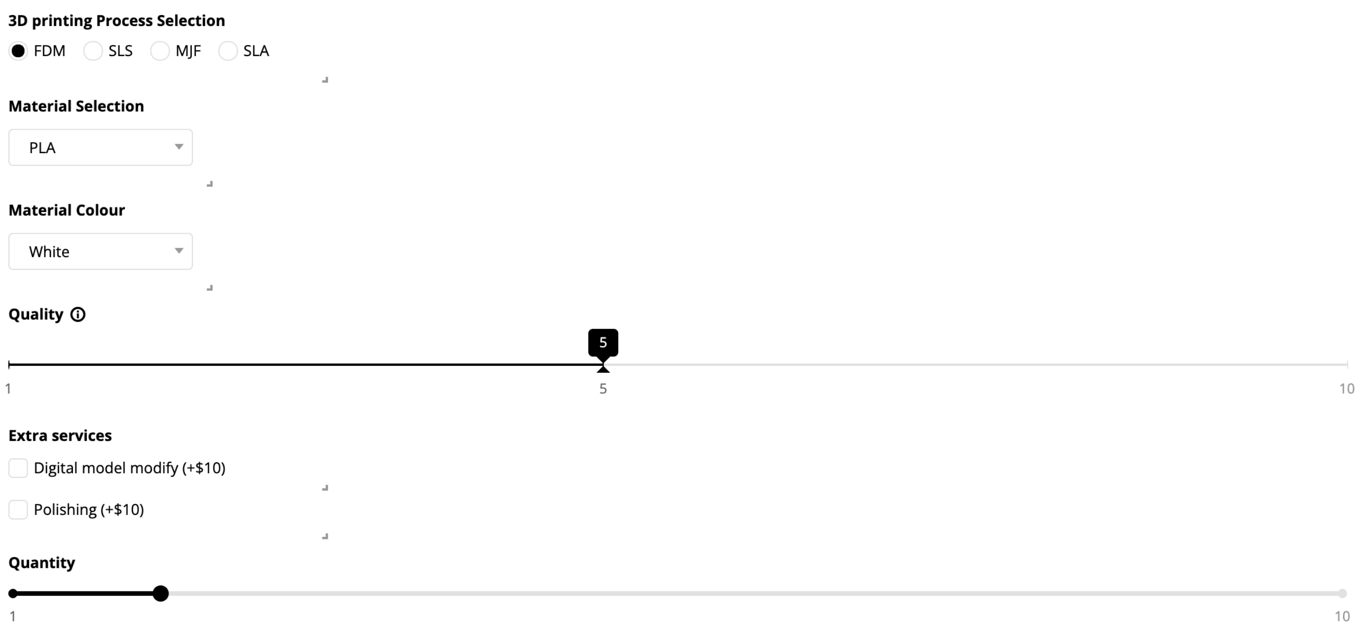


Figure 4.8 Matching System. By Author (2021).

Global Manufacturer

The essential advantage of this platform is that hundreds of manufacturers worldwide who are experienced in 3D printing can provide their services to fit different requirements.

This platform aims to cooperate with several sizeable 3D printing manufacturers, and each has more than 100 commercial 3D printers. Landu is one of the large 3D printing manufacturers, which can simultaneously fabricate more than 100 parts. Therefore, even users who utilise FDM 3D printers which typically provide slow delivery, can also achieve mass fabrication.

While distributed 3D printing can sharply decrease delivery time, quality control is critical. In order to maintain the fabrication quality of each part, manufacturers are provided default parameters of 3D printing which are suitable for architecture. In terms of IP protection, there are two strategies to keep its security. Firstly, if customers have similar parts, the platform will automatically disorder the part's code and arrange them to different manufacturers. In addition, only the G-Code, which cannot be edited is provided to the manufacturer to protect IP.

Remote Monitoring System

The remote monitoring system allows users to monitor every aspect of their 3D printing jobs from within the browser.

The remote monitoring system is used throughout the entire fabrication process, which can help users guarantee their works. For instance, constant feedback regarding the current progress of the print job can be sent to users by watching the webcam, as shown in Figure **4.9**. When the fabrication is finished, users can utilise this system to check the quality of the printing object. If the printing job fits their requirements, it will be delivered to the users. If the requirements are not fitted, the flatform will supervise the manufacturer to re-print it.

Logistics System

Logistics is more likely to become a potential issue when using the distributed manufacturing method, especially those distributed sites spread worldwide. For some distributed manufacturing platforms, such as Fiverr, this platform does not provide the logistics service, which means that the customers have to discuss the logistics solution with the manufacturer. In contrast to Fiverr, this platform automatically arranges suitable and fast logistics solutions for the users without any participation.

In terms of the logistics system, this platform tends to use big data to estimate the delivery time and cost from the websites of logistics companies, such as EMS, FedEx, and DHL. As a result, the 3D printing part can be allocated to a suitable logistics supplier and delivered to users as soon as possible.

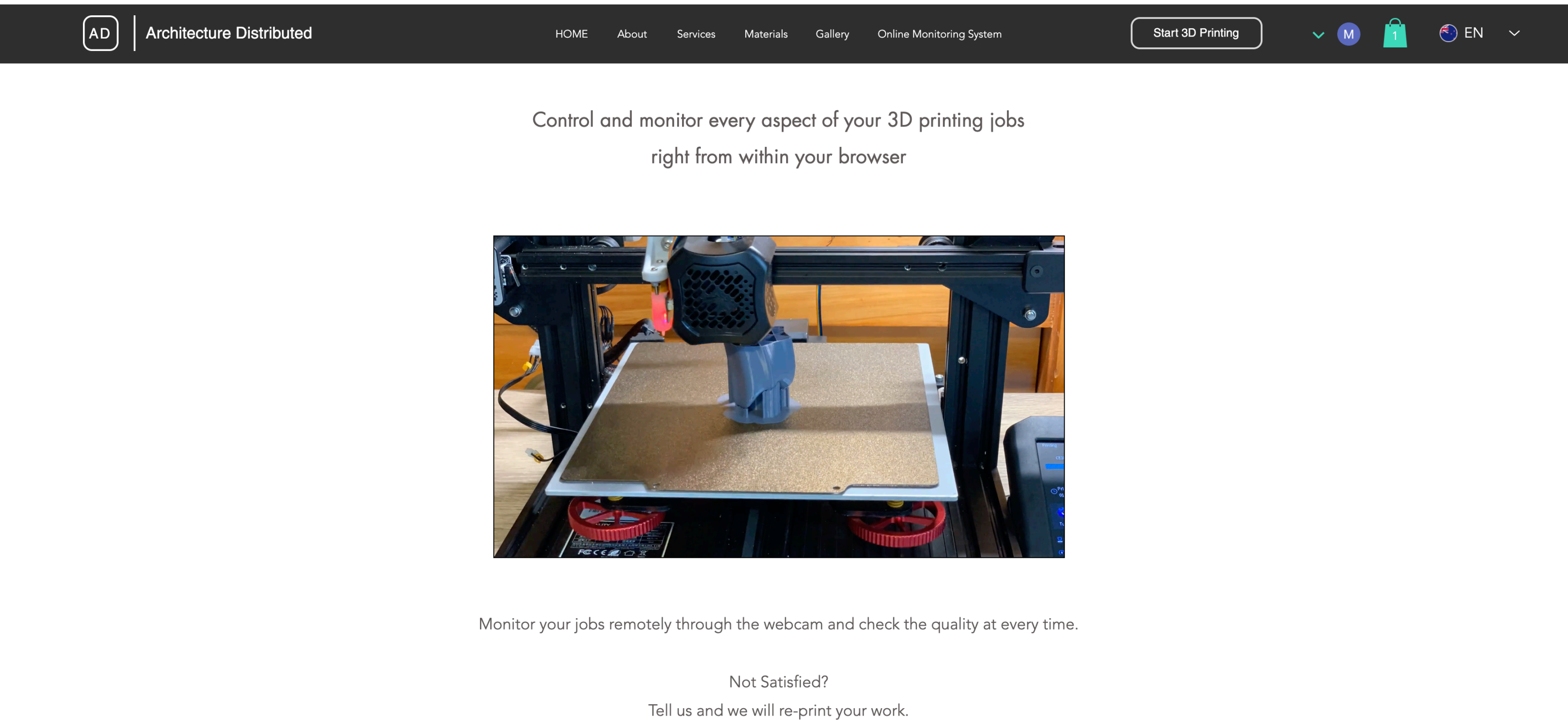


Figure 4.9 Remote Monitoring System. By Author (2021).

4.4.3 The Benefits of Distributed Printing Platform

Figure **4.10** shows the workflow of the conventional distributed 3D printing platform. In order to fabricate 3D printing parts with higher quality, users usually have to investigate the background and projects of various manufacturers, which make them spend more time before they determine the manufacturer. In addition, the STL file which can be edited needs to be provided to the manufacturer to slice and adjust the printing parameters. However, there is a potential risk regarding IP when sending the digital model to the manufacturer.

Figure **4.11** shows the differences between this platform and conventional distributed 3D printing platforms: IP protection, quality control, and fast task delivery. Due to this platform being designed for architecture and considering different factors that may affect architectural project delivery, it can provide safer and faster outcomes for customers.

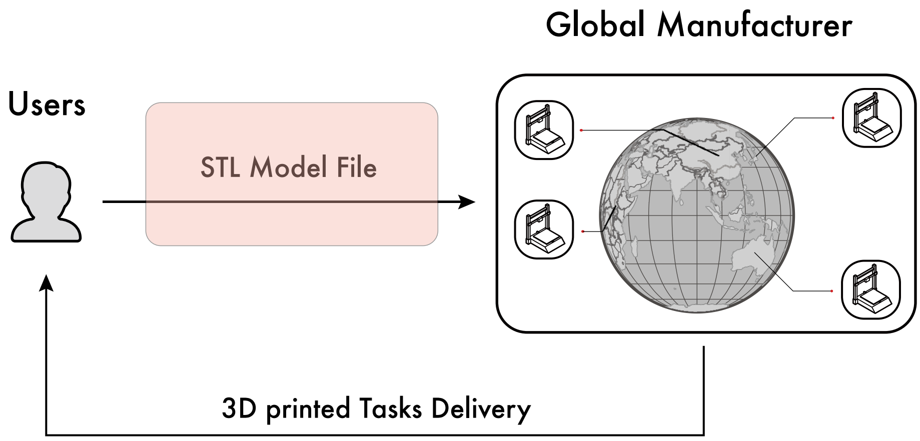


Figure 4.10 The Workflow of Conventional Distributed 3D printing Platform. By Author (2021).

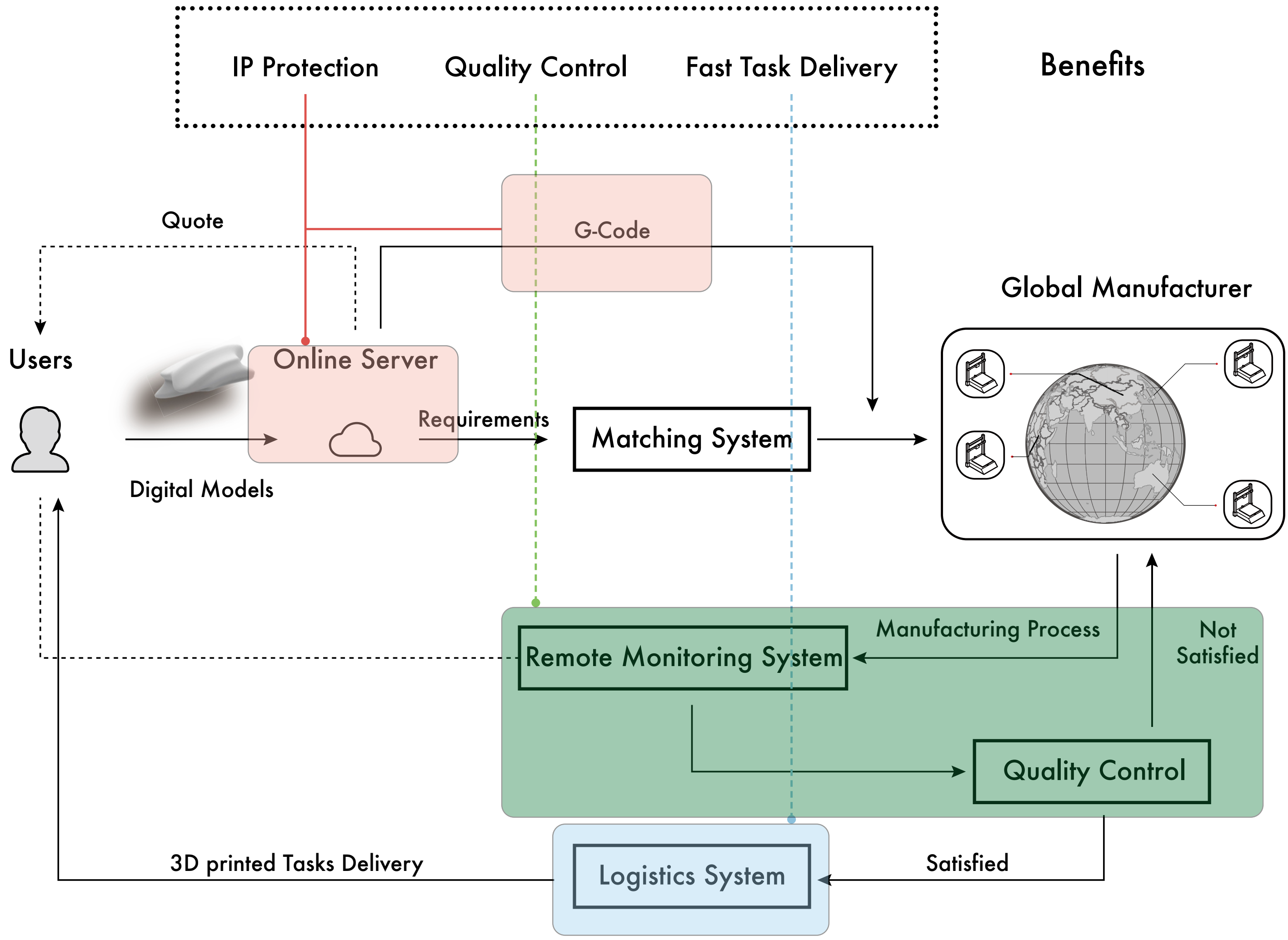


Figure 4.11 The Workflow of 'Architecture Distributed'. By Author (2021).

5

Methodology

Figure 5.1 Cover: Complex Structure.
By Author (2021).

5.1 Research Design

This exploratory research used a mixed research methodology to explore how small-scale architecture can leverage the power of distributed 3D printing to deliver complex architectural structures. The benefit of this approach is that it can leverage both quantitative and qualitative research benefits (George, 2021). The mixed methodology is usually used when the research question cannot be sufficiently answered independently by quantitative or qualitative data (George, 2021). Hence, this methodology is the most suitable approach for this research.

This research is an explanatory sequential design that aims to answer the research question and develop a hypothesis. There are four strategies used in this research: literature review, case study, simulation, and experiment.

This research was conducted in stages using the selected strategies to achieve this design research. The first stage employed the literature review and case study strategies to identify the main issues and develop a preliminary conclusion. Literature regarding the current 3D printing technologies for the architecture and distributed 3D printing was reviewed to develop an initial understanding of problem areas and the preliminary solution regarding the distributed printing model. The case study method was employed to explore the real-life strategies in which architecture can leverage the power of distributed 3D printing. Based on the data collected from literature and cases, two hypotheses were developed: FDM 3D printing is more suitable for distributed printing, and a distributed 3D printing management system can allow architecture to use the real power of this method.

The experimental method was employed in the second stage, aiming to test the hypothetical solutions developed above. The small-scale testing and real-life production experiment were conducted to collect and analyse the data.

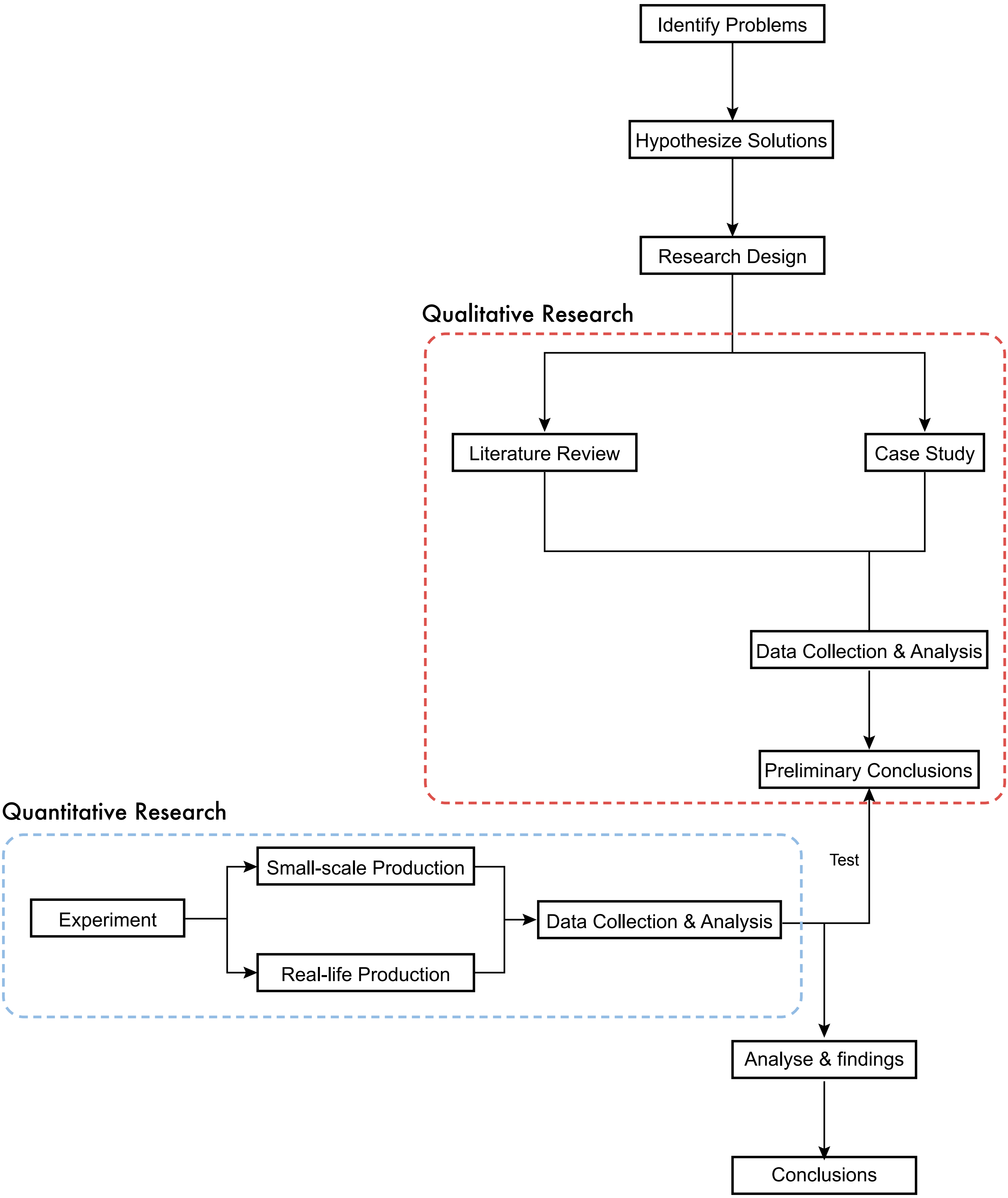


Figure 5.2 The Methodology Framework. By Author (2021).

5.2 Qualitative Research

5.2.1 Literature Review

The literature review method was used to provide an overview of the current situation of 3D printing technologies for the architecture and distributed manufacturing. Some adjustments need to suit this research because the scope and focus of previous studies differed in terms of research areas and context. This method is particularly significant in developing the primary solutions. Data were collected from relevant sources such as books, academic journals, internet websites, and reports for this process.

5.2.2 Case Study

The following research method is the case study where McCombes (2020) defines this method as a suitable approach to gain contextual and in-depth knowledge regarding a specific real-life experience. In other words, the design approach can be inspired by the strategies and methods used in those cases.

The Selection Criteria for Case Study

The main aim of this method is to gain significant knowledge and information which cannot be collected from the large-scale experiment due to the lack of resources and time. In order to collect enough information and comparison, the cases have been selected according to the following criteria, which were mentioned by McCombes (2020):

- Provide different or unexpected insights into the topic of this research
- Challenge or complicate existing hypotheses and theories.
- Propose practical methods to resolve research problems.
- Develop new directions for future research.

5.3 Quantitative Research

5.3.1 Experiment Design - Small-scale Model Production

Equipment

This experiment used a Creality Ender 3 v2 FDM 3D printer, with a build volume of 220mm x 220mm x 250mm, as shown in Figure **5.3**. As the build volume of this printer is small, it was only utilised for testing different printing parameters with some small-scale models.

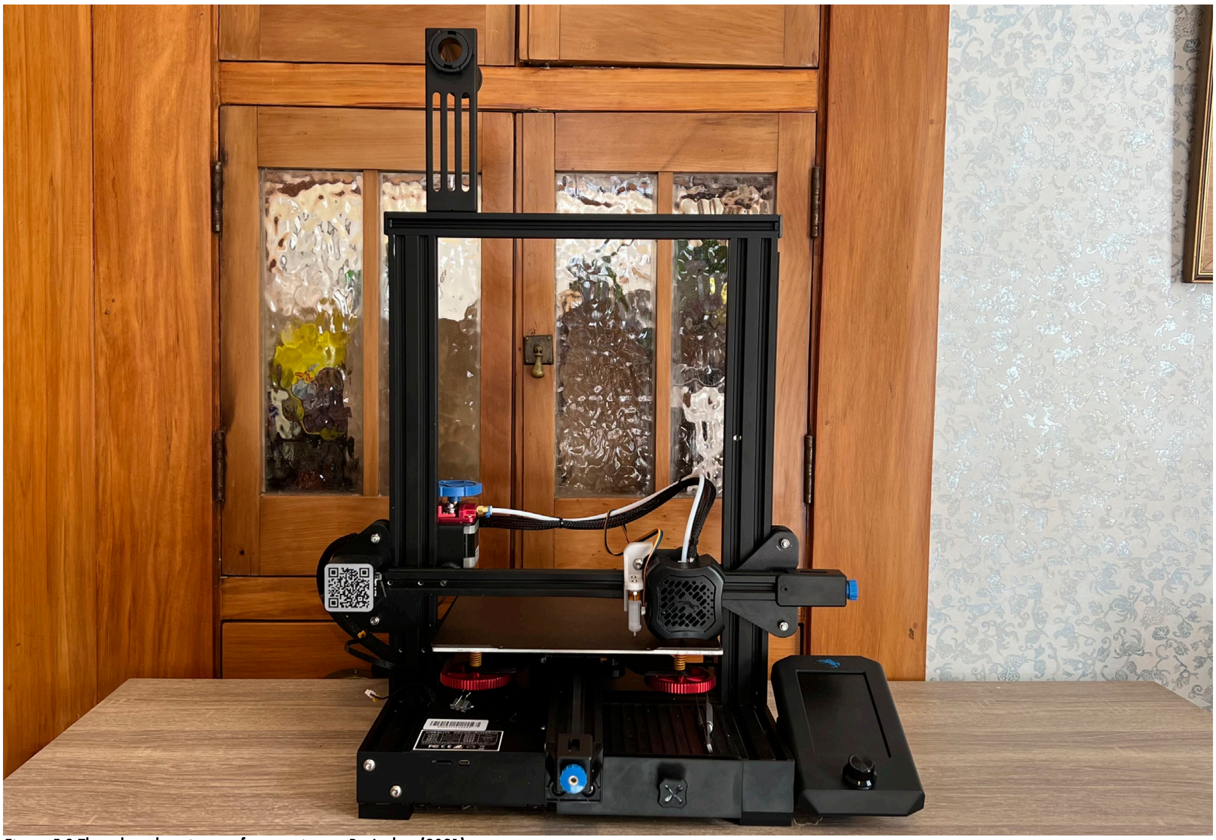


Figure 5.3 The selected equipment for experiment. By Author (2021).

Experimental Design

This experiment aims to find a balance between printing quality and speed before real-life production. As the print speed and layer height are two significant parameters that will affect these properties, this experiment set these parameters as the independent variables. Hence, surface quality and delivery time were set as the dependent variables. The nozzle's temperature and hotbed's temperature were set as the extraneous variables in this experiment. The nozzle's temperature was controlled at 200℃ and the temperature of the hotbed was controlled at 60 ℃ .

For the assessment and measurement purpose, a rating form regarding the surface quality was devised using the observation approach, as shown in Table **5**. Since measuring the surface smoothness is complex and requires professional equipment, this experiment only utilised the observation method.

There were two experimental groups set in this experiment. Group 1 set print speed as the independent variable and layer height as the control variable. I measured the dependent variables (surface quality and delivery time) by changing the print speed. Group 2 set layer height as the independent variable and print speed as the control variable. The dependent variables (surface quality and delivery time) were measured by setting different layer heights.

Table 5. Rating form of Surface Quality

5.3.2 Experiment Design - Real-life Production Simulation

Equipment

This experiment used several FDM 3D printers provided by global manufacturers. As it is difficult to ask the global manufacturers for providing 3D printers with the same brand, the process of all equipment are based on FDM.

Experimental Design

This experiment aims to test the feasibility of the primary solution (online distributed 3D printing server) as mentioned in Chapter 4. As the server is a simulative platform with the proposed functions instead of running on real-life internet, three printing objects were fabricated to simulate the entire process of this system in order to test its possibility. Due to cost and time limitations, all the global fabrication sites were selected in China.

As the selection of different manufacturers affects the experimental results, this experiment set this parameter as the independent variable. The printing parameters identified in the small-scale production experiment were set as the control variables. Task delivery time, logistics time, and total time are dependent variables, as shown in Table **6**.

There were three experimental groups set in this experiment. The capacity of each experimental group affected the result of three different dependent variables. The task delivery time and logistics time were analysed for calculating the total time by using this formula:

Total time = Task delivery time + Logistics time.

The results were simulated in the online distributed 3D printing server to estimate the entire delivery time of this project for testing the possibility of this method.

Table 6. The Fabrication Information

Component ID	
Fabrication Site	
Material	
Weight	
Manufacturing equipement	
Cost	
Task Delivery time	
Logistics time	
Total Time	

Risk Assessment and Analysis

This experiment tested the potential risks of using the primary solution (online distributed 3D printing server). This experiment developed an assessment criteria form to assess different manufacturers to achieve this goal. The score criteria are based upon delivery times and surface quality in terms of the assessment criteria. The total score is 10, and it was calculated by using these criteria, as shown in Table **7**:

Total score (10) = Delivery times (6) + Surface quality (4)

Note: 4 represents high (optimal) results, 0 represents low (critical) results.

Delivery times (6) = Task Delivery times (3) + Logistics times (3)

Note: 3 represents high (optimal) results, 1 represents low (critical) results.

Table 7. Assessment form.

					/10
					/10
					/10

5.4 Limitations

The methods employed in this research aim to avoid the result's influence. However, there are still some limitations regarding methodology.

Firstly, the sample size is one of the significant limitations of this research. Only three samples were used to conduct this experiment in the real-life production simulation. Despite the experimental results proving the proposed solution, the small size samples risk finding significant and accurate relationships from the data.

In addition, the performance of the equipment utilised in the small-scale model experiment is another limitation. Due to budget limitations, this experiment used an entry-level FDM printer to test the printing parameters. For instance, the mechanical performance of the motor may affect the accuracy of the relationship between print speed and delivery time. The resolution and tolerance of this equipment may also affect the result when assessing the surface quality.

Furthermore, as this research area is contemporary and evolving, the prior research studies on this topic are inadequate. Hence, it was challenging to find numerous scholarly papers addressing the research problem.

Figure 6.1 Cover: Complex Structure.
By Author (2021).

6

Design Proposal

6.1 Site Selection

Figure 6.2 Site Information.
Source: Google map (2021).

Figure 6.2 Site Information.
Source: Google map (2021).

School of Architecture and Design
Victoria University of Wellington,
Wellington,
New Zealand

6.1.1 Introduction

This project is located at the School of Architecture and Design by Victoria University of Wellington, New Zealand.

While the impacts of the site selection for this project is not essential, the selected site should have a strong connection with the architectural context. As discussed above, 3D printing is an innovative technology for architecture, and there are not adequate practical cases in New Zealand. As a result, the selected site should have the capabilities of attracting enough visitors to show off this advanced technology.

Due to the small build volume of each printed component, the pavilion's dimension is not large. Therefore, the area of the ideal site can be small but should be attractive. The lawns in front of the Vivian Building have the potential to be selected as the site. However, further analysis regarding pedestrian flow simulation is necessary to identify the result.

Figure 6.3 Victoria University of Wellington. By Author (2021).

6.1.2 Site Analysis

Figure **6.4** shows the site information, including a basketball playground, benches, the school of architecture and design building, and landscapes. While there are various open places within the site, only lawns without bushes or trees are potential sites.

In order to analyse which place is more attractive, a Grasshopper plug-in named 'PedSim' is utilised to calculate and simulate the pedestrian route and flow (See Appendix A). Figure **6.5** demonstrates some parts of the Grasshopper script. In PedSim, pedestrians' route is driven by the target of their interest, following the most optimised route, avoiding obstacles and other people. The targets of people's interest are defined by the different destinations, including basketball playground, benches, school, and lawns. The obstacles are defined by the places with bushes or trees, as shown in Figure **6.6**. After the simulation, the site that attracts the majority of visitors will be selected. As a result, architecture can utilise that attractive place to show off itself.

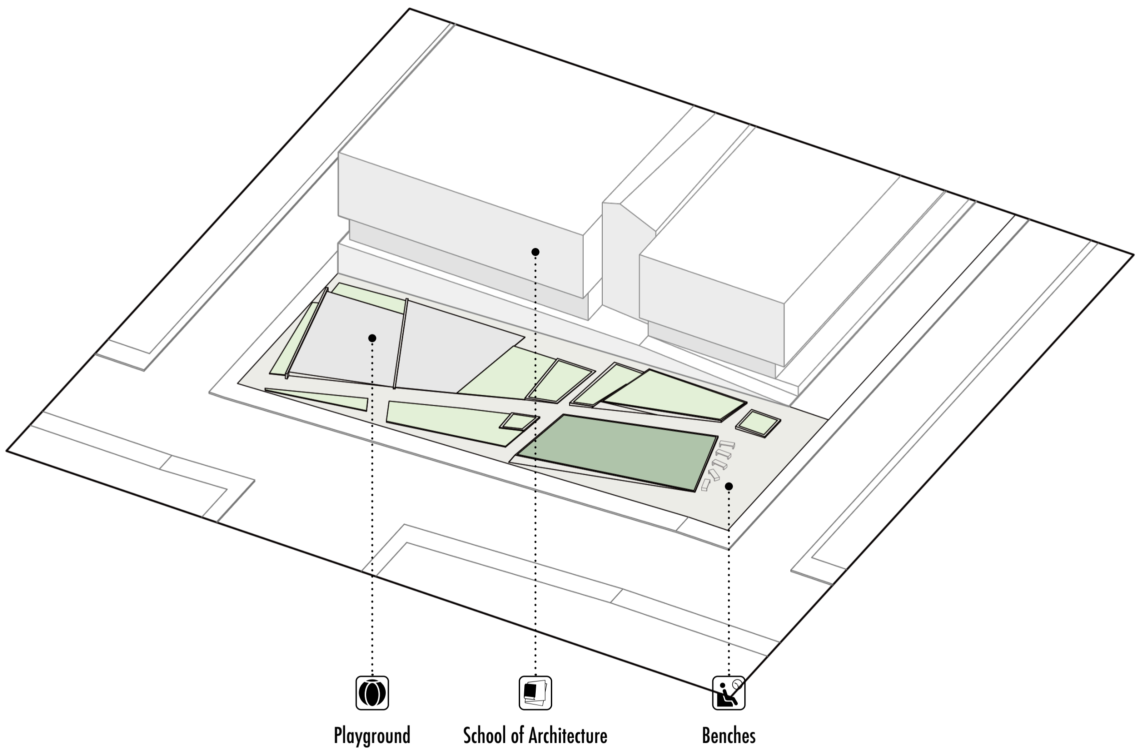


Figure 6.4 Site Basic Information. By Author (2021).

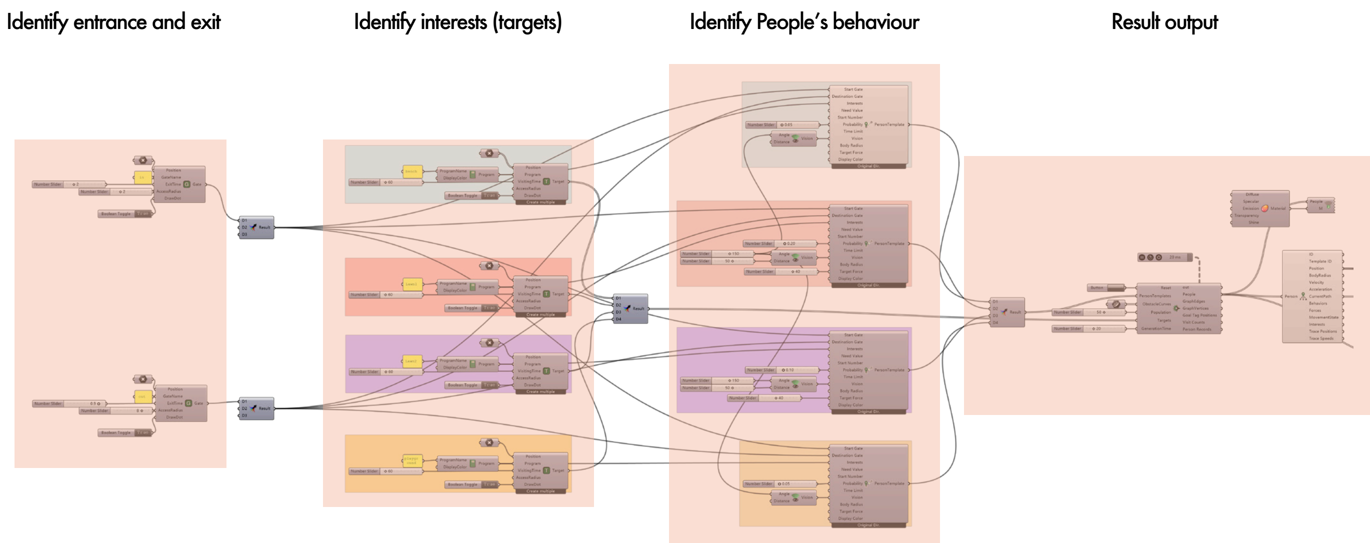


Figure 6.5 Workflow of PedSim in Grasshopper. By Author (2021).

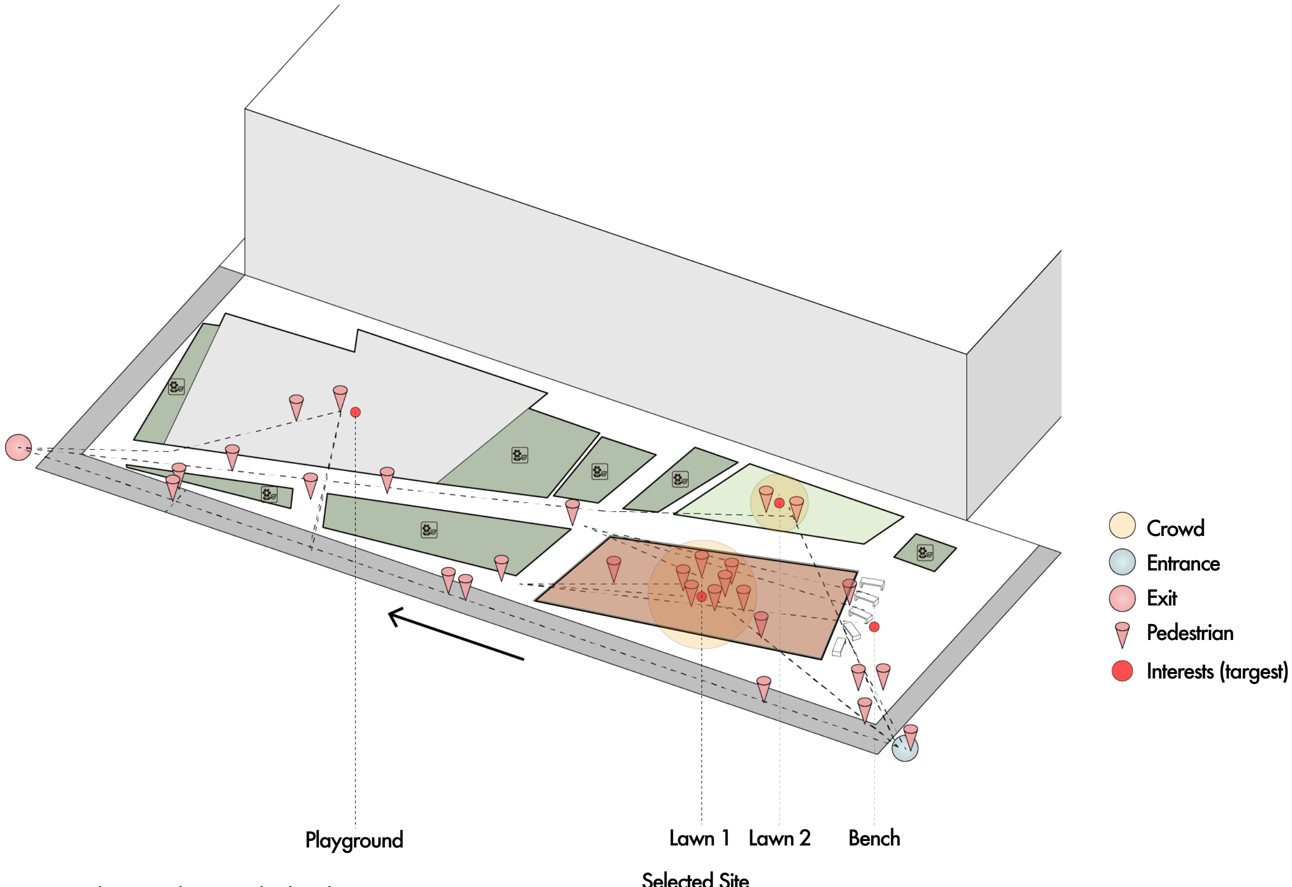


Figure 6.6 Site Pedestrian Analysis. By Author (2021).

6.2 Design Concept

Figure **6.7** shows the design concept framework of this project. This unique design aims to develop a complex structure that fits for distributed printing methods. The research behind the structure and form of this pavilion has its fundamental objective: to develop and demonstrate a seamless digital design delivery workflow from design to fabrication, focusing on distributed 3D printing.

The initial idea of the design is derived from the features of FDM printers that are more suitable for small but complex objects. In order to fit the build volume limitation, this project tends to use a large number of small-scale modular components based on parametric workflow to assemble the pavilion. In order to show the capabilities of 3D printing in creating complex geometries, the envelop formwork is developed from a simple shell structure into a complex hybrid structure.

As discussed above, quality control and management of multiple tasks are significant challenges of distributed 3D printing methods. Therefore, this project will be considering these factors during the design phase, intending to develop suitable outputs for distributed printing methods.

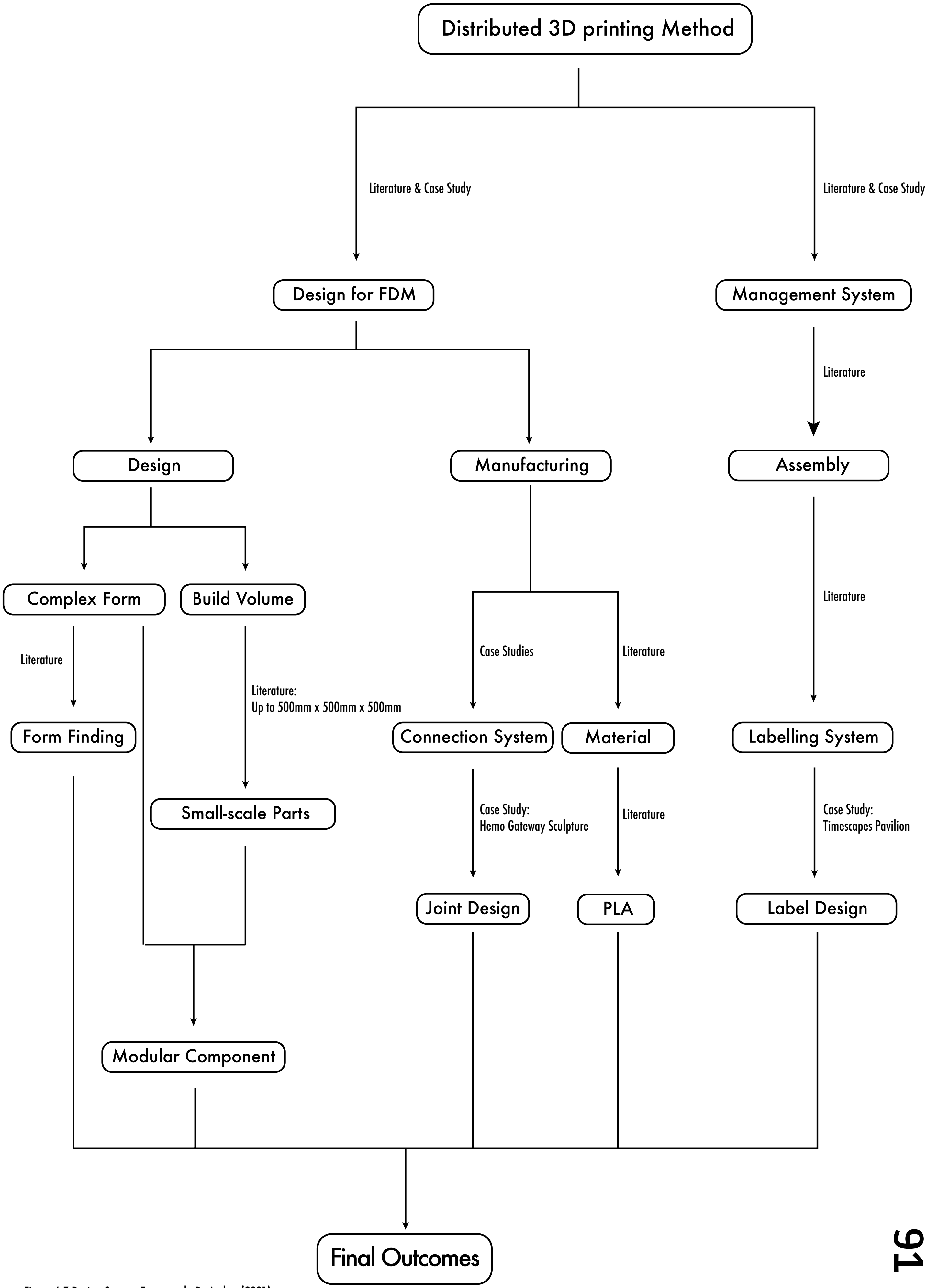


Figure 6.7 Design Concept Framework. By Author (2021).

6.3 Form Finding

6.3.1 Background

This pavilion design tends to utilise shell structure; therefore, it is significant to investigate how this type of form be developed. The shape of a structurally efficient shell should depend on the flow of forces and vice versa, and its design requires a form-finding process (Li et al., 2017). Some cases regarding shell structure are reviewed to explore the historical precedents of representative architects. This section mainly refers to the cases of Frei Otto and Heinz Isler and the methods they used in form-finding.

The benefit of form-finding is that it can calculate the natural form with the highest structural efficiency. In the pre-computer age, architects and engineers widely used physical models, such as hanging and tension models, to construct shells (Li et al., 2017). The form of a hanging model is self-forming with the capacity of transferring its weight and loading entirely through tension, resulting in a pure compression model when inverted. Heinz Isler developed many handing models to determine the shape of the concrete shell. Figures **6.8** show his hanging models. Tension models, which Frei Otto frequently applied, are usually made of soap film or gauze to find a surface's balanced shape with fixed boundaries. For instance, Frei Otto used this model when designing the Stuttgart train station, as shown in Figure **6.9**.

With the professional computer and digital design development, several computational methods make form-finding more accessible for designers. For instance, the Kangaroo, a grasshopper plug-in, can simulate the physical shape by setting some parameters, such as gravity. While it can obtain form-finding using a similarly physical way like hanging models or tension models to simulate, some structural issues due to the incorrect parameters setting might affect the result of the shape. Therefore, this project uses Rhinovault 2 and Karamba 3D to obtain a structurally efficient shell shape in the form-finding process.

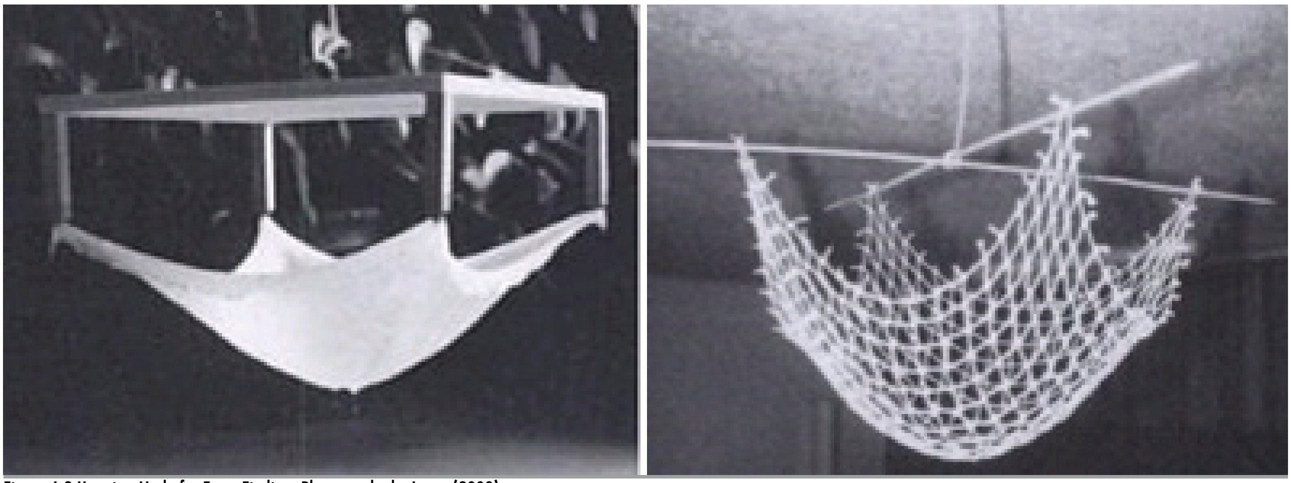


Figure 6.8 Hanging Mode for Form Finding. Photography by Isono (2009).


Figure 6.9 Form Finding Model of Stuttgart Train Station. Photography by Knauf (2021).

6.3.2 RhinoVault 2

This project selected RhinoVault 2 as an essential form-finding tool using in the early design phase. This project attempted to utilise other approaches before using this method, such as a Grasshopper plug-in – Kangaroo. Kangaroo can create and simulate a shell structure based on parameters like gravity. However, the form-finding result could not quickly achieve the structural requirement. Consequently, it is significant to find an alternative approach for form-finding.

RhinoVault 2 is a computational form-finding tool based on Thrust Network Analysis (TNA), an 'extension of graphic statics providing a graphical approach to three-dimensional funicular form finding' (Rippmann, 2016, p.103). The entire workflow of Rhinovault 2 is shown in Figure **6.10**, solving horizontal and vertical equilibrium are the essential sections of the whole workflow.

As shown in Figure **6.10**, the form diagram is defined as the horizontal projection of the thrust network, and the in-plane equilibrium also represents the horizontal equilibrium (Rippmann, 2016). Rippmann (2016) also reported that because of the equilibrium of the horizontal force components, the thrust network is in equilibrium with the given loading, which is then found for the given support vertices.

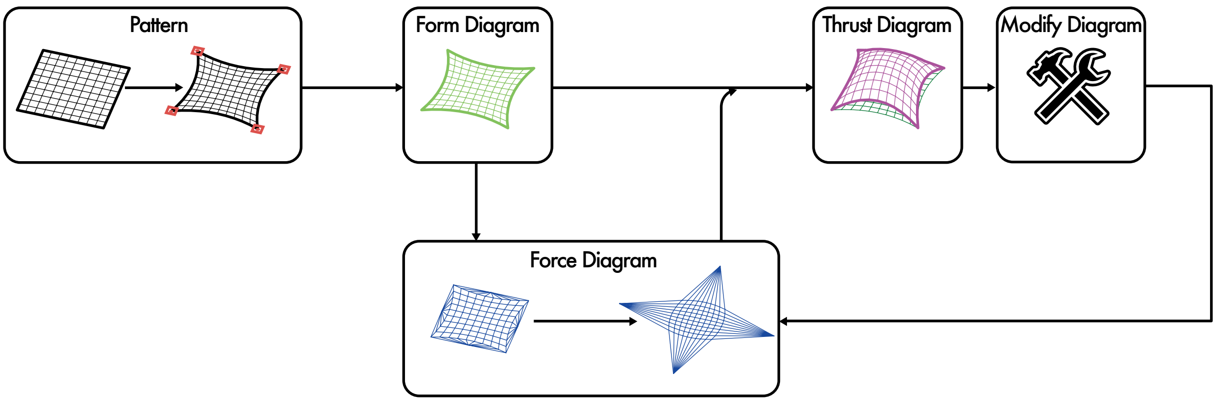


Figure 6.10 Workflow of RhinoVault 2. By Author (2021).

6.3.3 Form Evolution

Figure **6.11** shows the form evolution process, based on a principle from simple to complex. The first test begins with a simple triangle-like skeleton line to develop a stable shell structure. With the successful result of the first test, increase the complexity of the skeleton line to calculate more complex shell structures. This project tends to design an overlapping structure. In order to achieve this, adjustment developed from previous tests is utilised in this process.

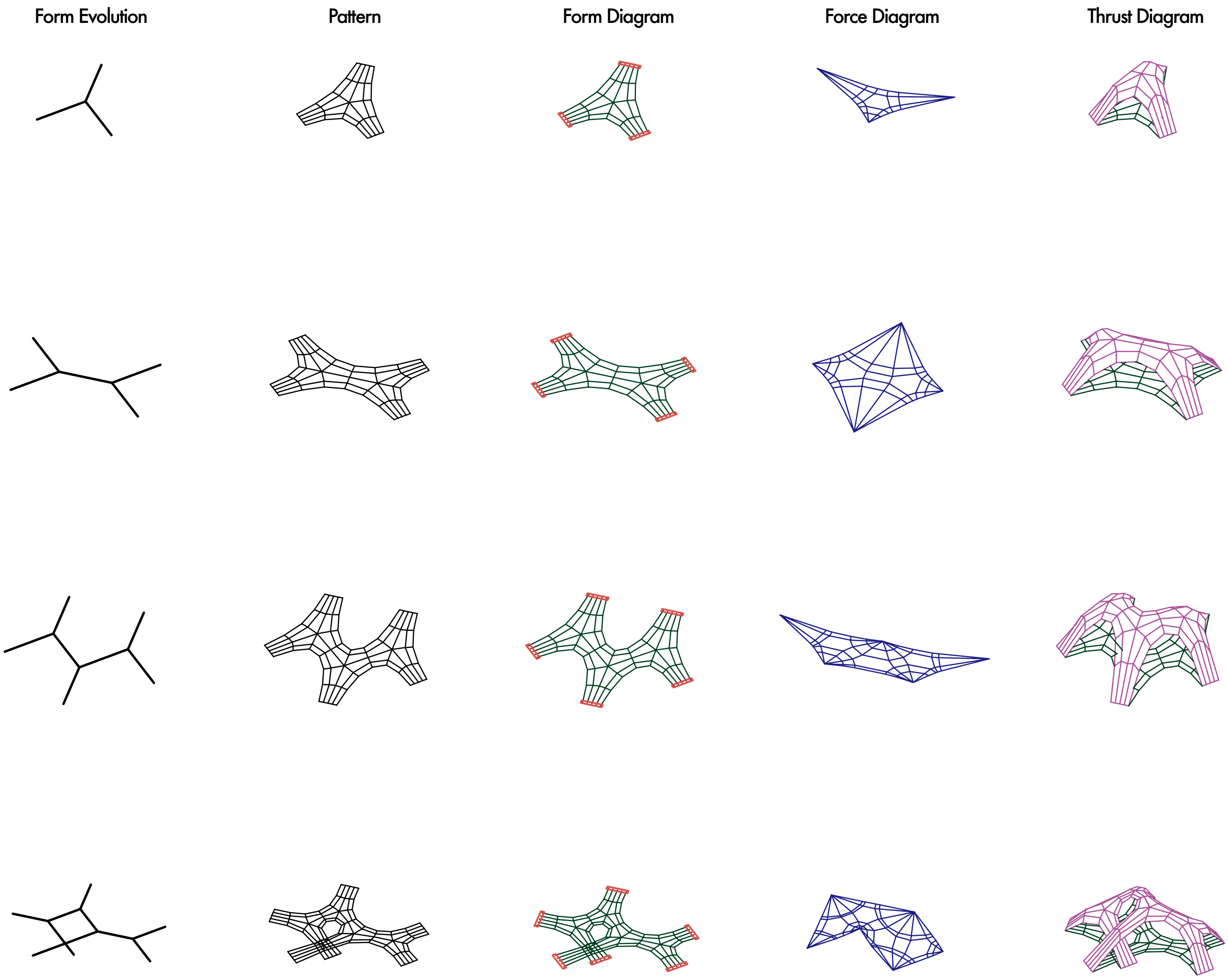


Figure 6.11 Form Evolution. By Author (2021).

6.3.4 Loading Analysis

For this section, this project will be investigating two structural optimisation tools for loading analysis, which are achieved through Rhinovault 2 and Karamba 3D. Karamba 3D is a Finite Element Analysis (FEA) plug-in in Grasshopper for accurate structure calculation and simulation.

In the beginning, the shell structure is simulated in Rhinovault 2 to calculate a load-balanced form. The initial load analysis will be using Rhinovault 2, as shown in Figure **6.12**. However, the analysis result in Rhinovault 2 is not accurate, and only the gravity load can be analysed with a diagram. Therefore, it is necessary to export the shell into Karamba 3D to conduct more accurate testing (See Appendix B). Figures **6.13** & **6.14** demonstrate the vertical and lateral load analysis diagrams. The data of each diagram prove that this shell structure is feasible and stable in the vertical and horizontal directions. Figure **6.15** provides further evidence about the feasibility of this structure.

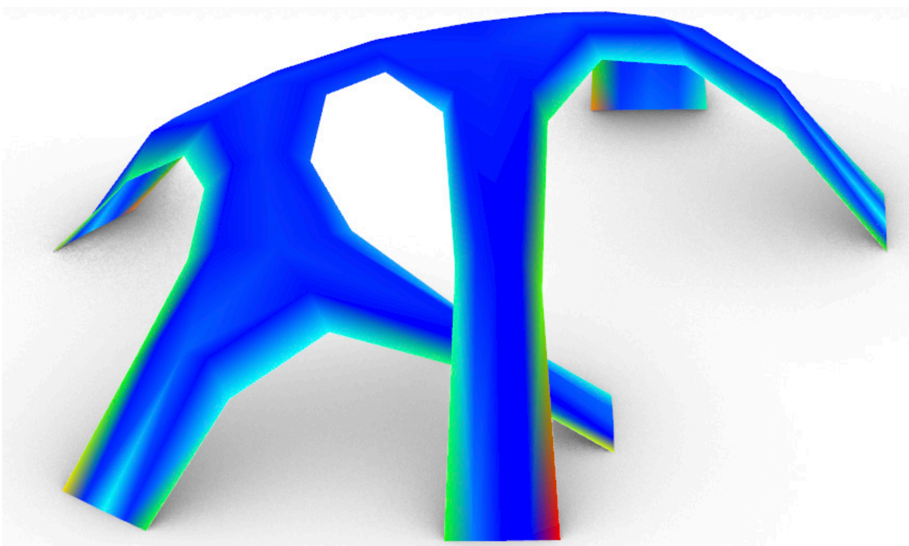
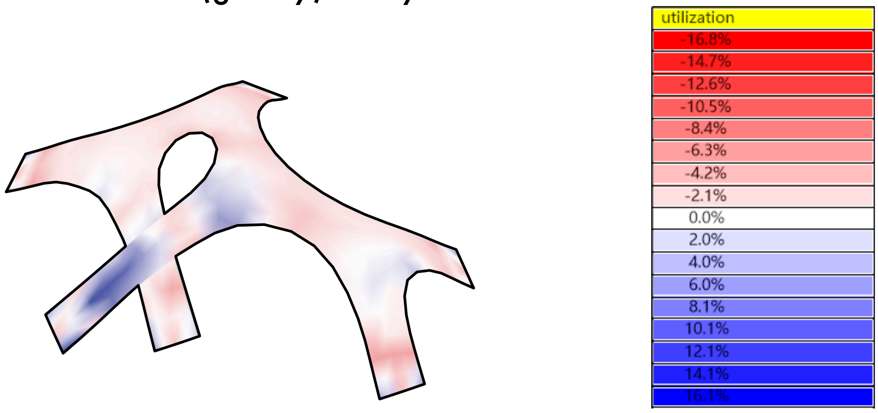


Figure 6.12 Gravity Loading Diagram in Rhinovault 2. By Author (2021).

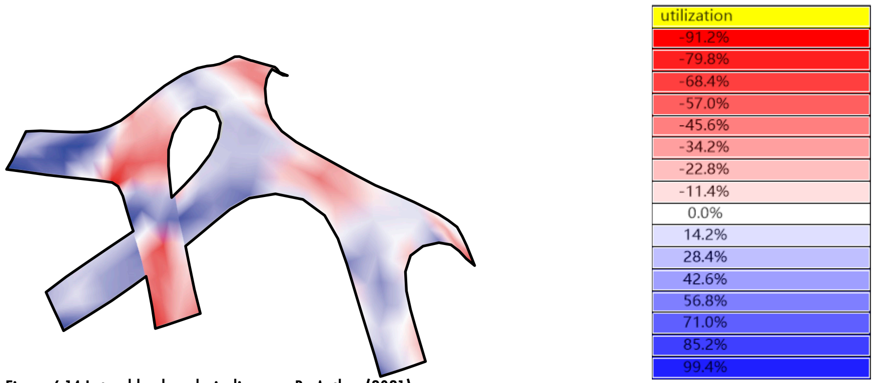
Vertical load (gravity) Analysis



Gravity load result in Karamba 3D

Figure 6.13Vertical load (gravity) analysis diagram. By Author (2021).

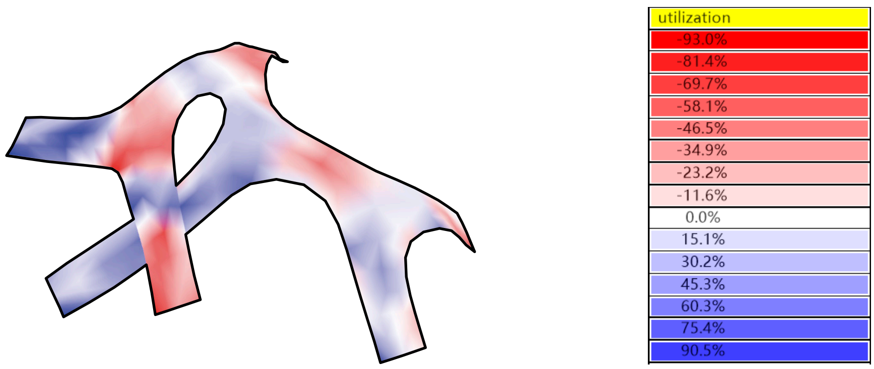
Lateral load Analysis



Horizontal load result in Karamba 3D

Figure 6.14 Lateral load analysis diagram. By Author (2021).

Verical and Lateral load Analysis



Horizontal and Vertical load result in Karamba 3D

Figure 6.15 Vertical and Lateral load analysis diagram. By Author (2021).

6.4 Design Development

6.4.1 Modular Component Design

As discussed above, the build volume of typical 3D printers is 500mm x 500mm x 500mm. The dimension of the modular component will be limited to that size. In other words, the pavilion consists of a large number of small-scale components connecting each other.

The design and concept of the modular component are based on a computational process that finds inspiration in nature, specifically in the connection structure of bone, as shown in Figure **6.16**. The nature of bones allows them to connect and orientate each other. The way modular components connect each other is similar to the skeleton system that is naturally connected by bones.

This modular component is modelled in Blender, which is modelling software with a solid capacity to create a digital model with a high degree of geometric freedom. Figure **6.17** shows a unique form of this component created by Blender, allowing components to orientate and connect from front to back (Figure **6.18a**) and side to side (Figure **6.18b**).

Figure 6.16 Inspiration from bone. Photography by Zahren (2019).

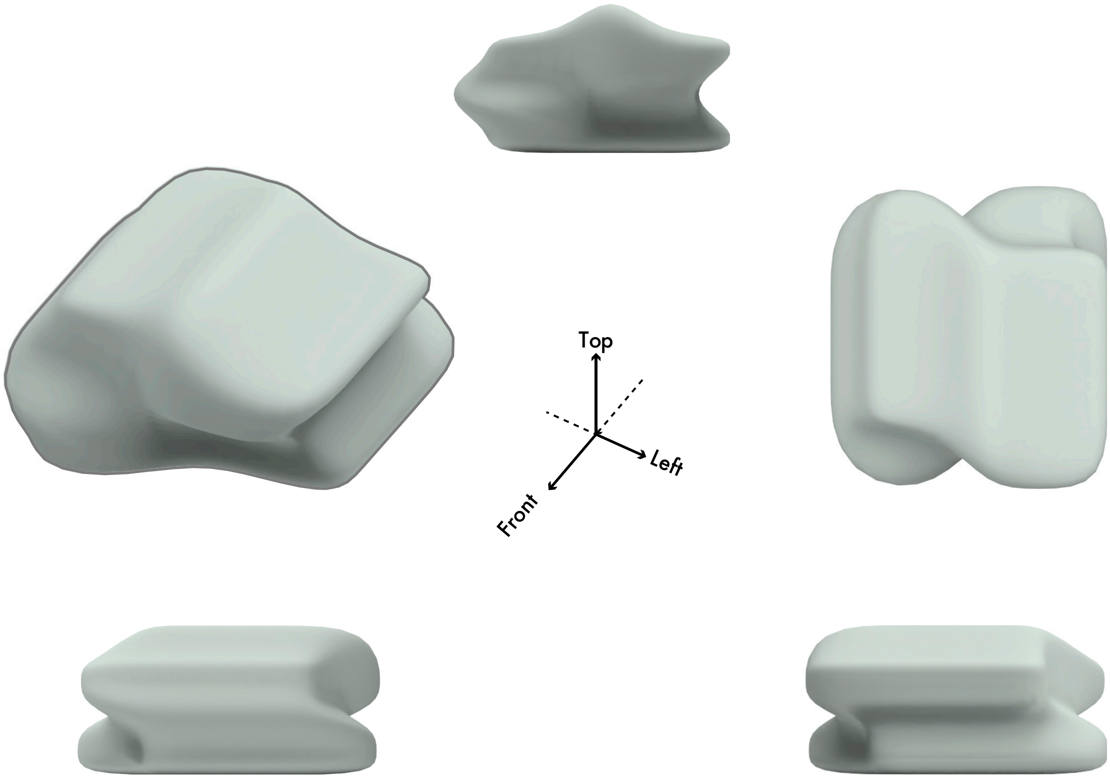


Figure 6.17 The unique form of the component. By Author (2021).

6.18 a From front to back connection

6.18 b Side to side connection

Figure 6.18 Connection method consideration. By Author (2021).

6.4.2 Modular Component Form Deformation

One of the key benefits of 3D printing is the capacity of geometric freedom; therefore, the modular component is more likely to be designed with an organic shape to utilise the full power of this technology.

The deformation of the initial modular component utilises the 'Tissue' plug-in in Blender to develop the shape from simple to complex and organic, as shown in Figure **6.19**. Tissue plug-in uses surface morph to create and develop the different forms of the modular component, and the subdivision of the initial component defines its complexity. The Tissue plug-in controls the dimension of the modular component by shifting parameters to fit the build volume limitation of FDM printers. Figure **6.20** demonstrates the deformation result of a typical component.

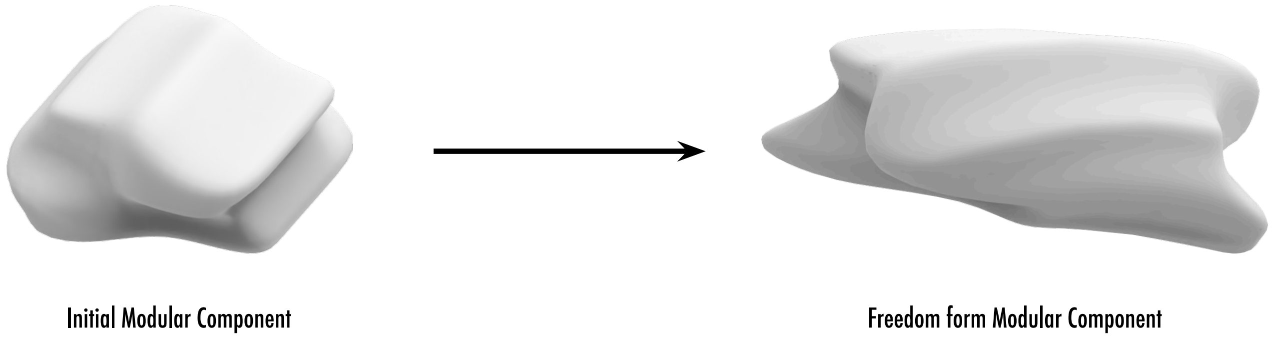


Figure 6.19 The Deformation process of the modular component. By Author (2021).

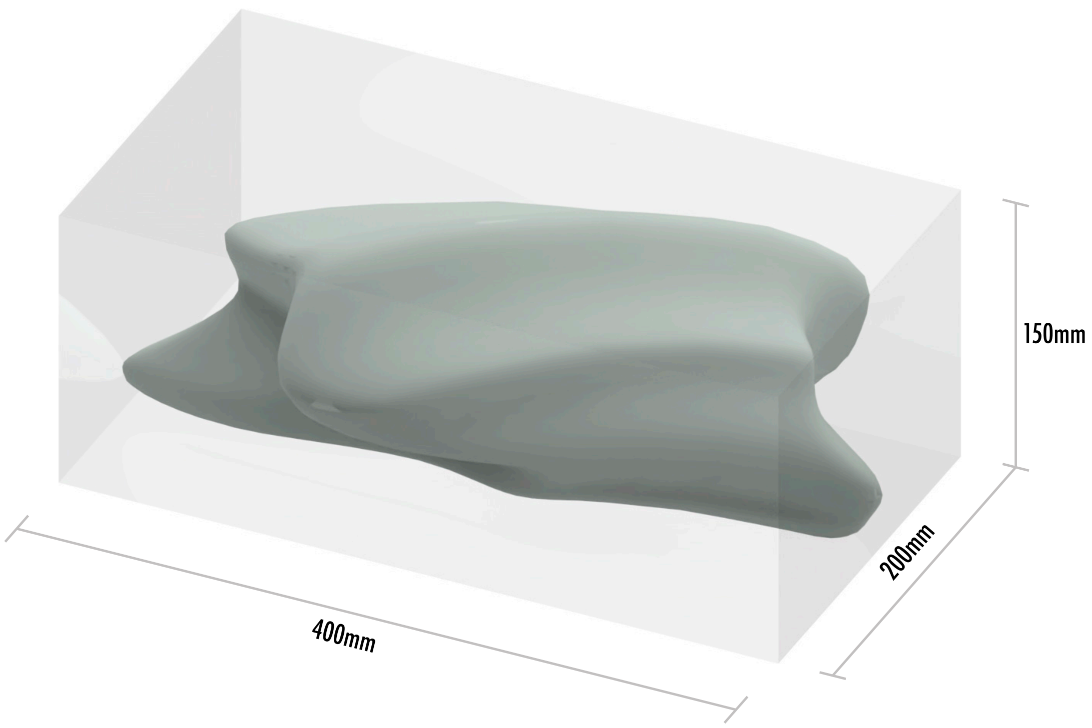


Figure 6.20 The size consideration about the typical modular component. By Author (2021).

6.4.3 Structure Deformation- from Simple to Complex

While the initial shell structure created from Rhinovault 2 can meet structural feasibility, Blender cannot directly be utilised due to the different modelling methods between Rhino and Blender. Blender uses the subdivision surfaces to control the number of components when using Tissue plug-in based on the surface morph. Therefore, it is necessary to increase the subdivision of the initial surface in Blender. At the same time, the form of the shell structure needs to remain at the initial shape to meet the structural requirements. Figure **6.21** shows the increase of the subdivision process, in which the size limitation of 3D printers controls the number of subdivision surfaces.

In order to meet the fundamental feature of 3D printing in creating complex geometric forms, the subdivision surface hybridises with a crossing structure component to create a helix structure using Tissue Plug-in, as shown in Figure **6.22**.

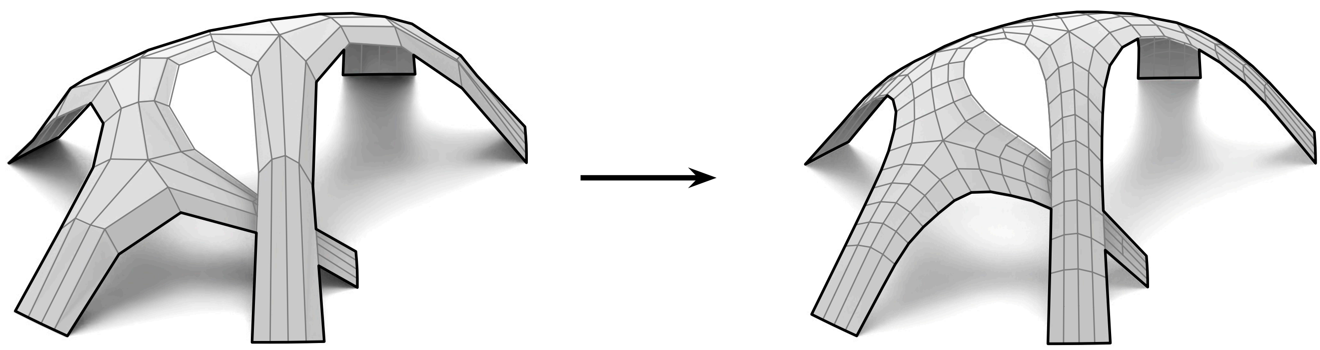


Figure 6.21 Increase the subdivision of the initial surface. By Author (2021).

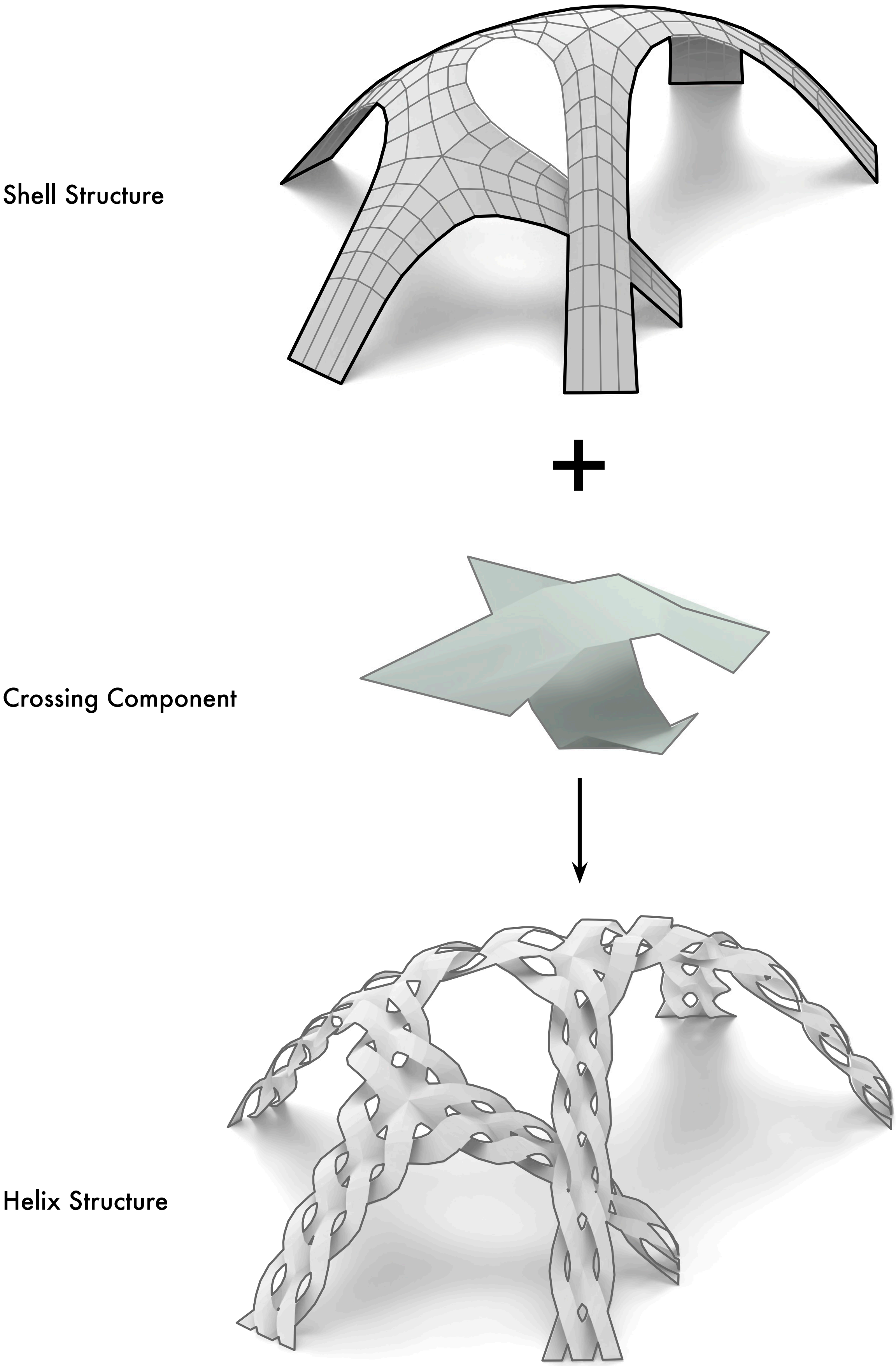


Figure 6.22 Develop a helix structure using using Tissue plug-in in Blender. By Author (2021).

6.4.4 Final Structure

After developing the helix structure from the initial shell structure, development is necessary to integrate it with the modular component described in the above section.

The final structure of this pavilion is still using the Tissue plug-in workflow to achieve this unique and organic structure. Figure **6.23** demonstrates the deformation process of this workflow. The first stage is to control the surface morph with the modular component. The result will be printable as the dimension of the modular component and the helix structure has been considered and designed to meet the size requirements. The next stage is to adjust the parameters that can control the size and form of the pavilion components in the Tissue plug-in. The final stage is to inspect the digital model, as the Tissue plug-in sometimes would cause unexpected results which cannot be used for 3D printing.

With the contribution of the Tissue plug-in, the design concept of this project can be achieved. The final structure of this pavilion consists of over 700 components with similar shapes and dimensions, which means that each component is printable.

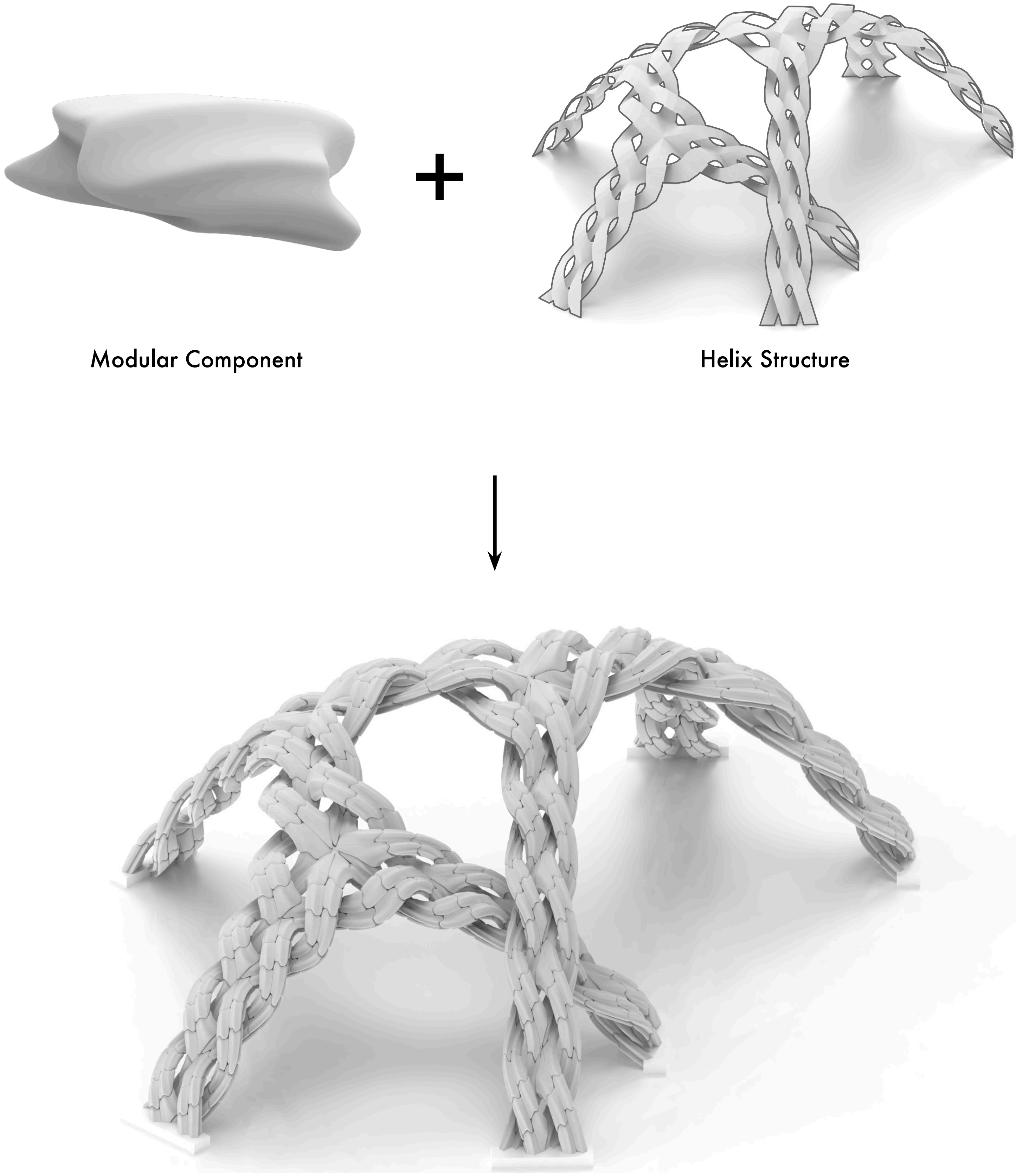


Figure 6.23 The development of the final structure using Tissue plug-in in Blender. By Author (2021).

6.4.5 Final Pavilion Scheme

Master PLan

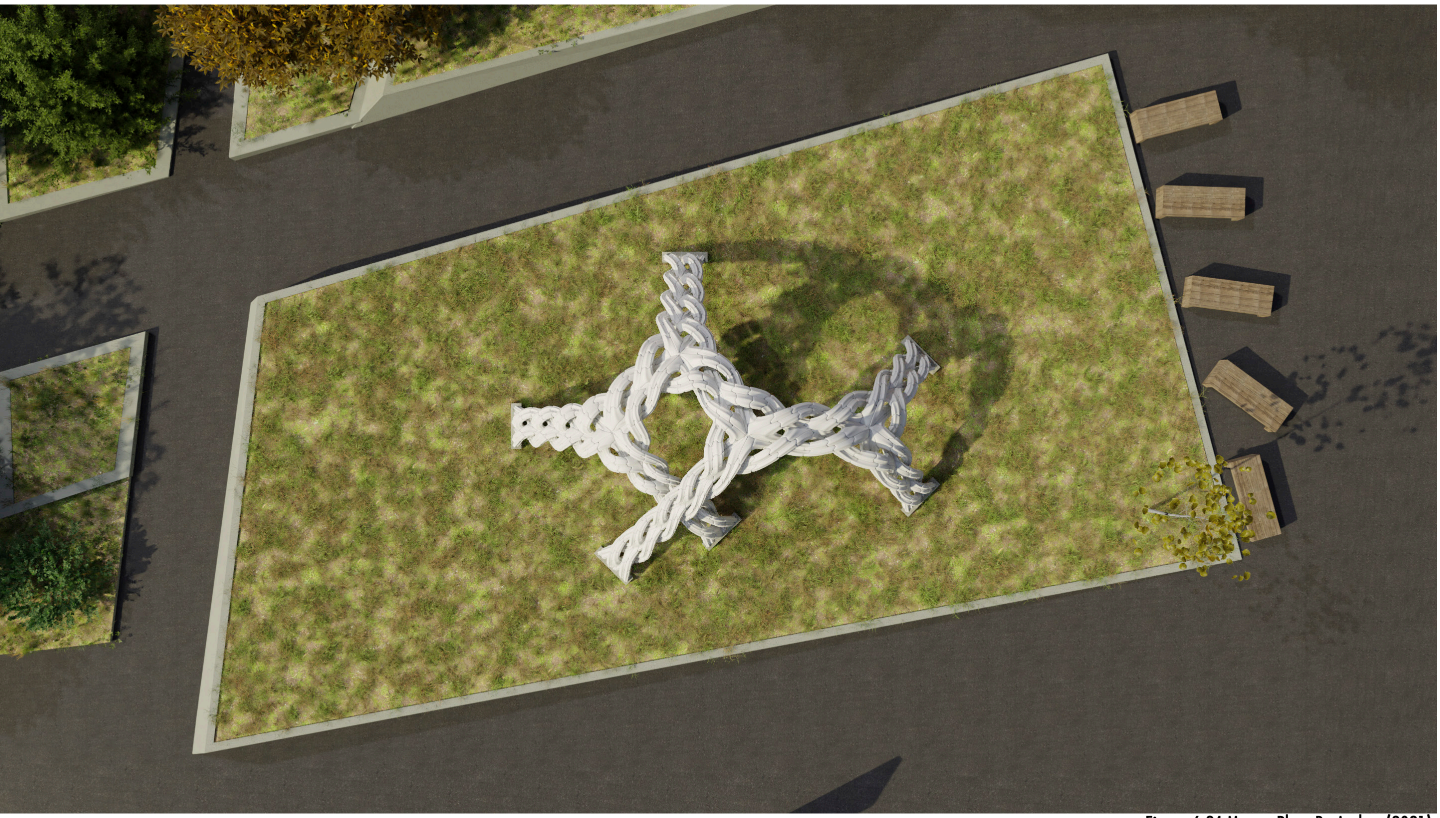
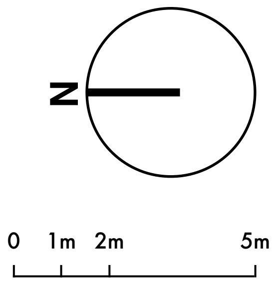


Figure 6.24 Master Plan. By Author (2021).



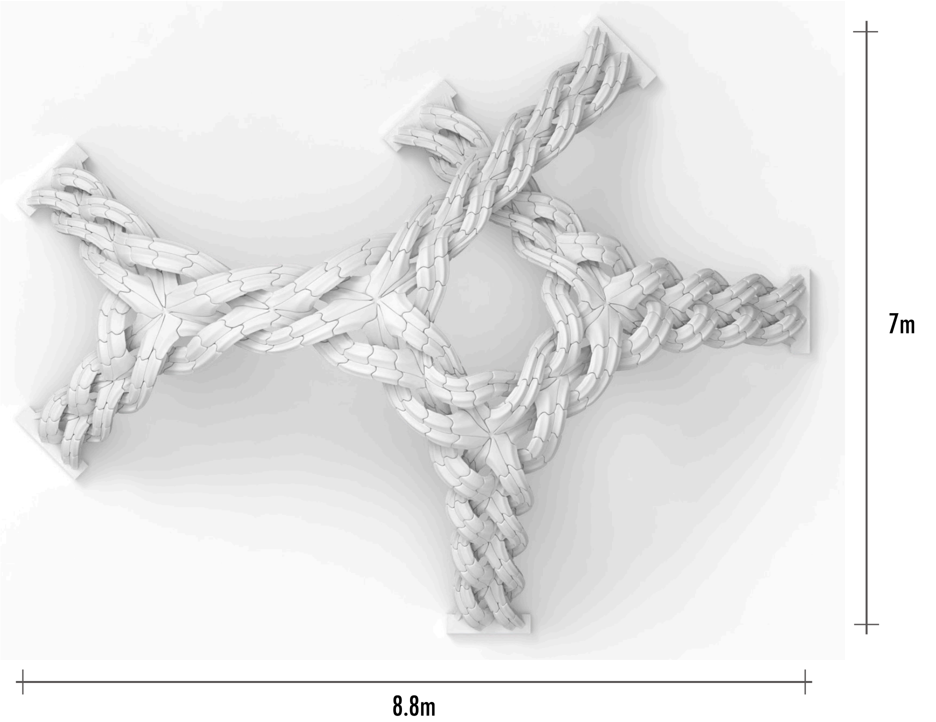


Figure 6.25 Floor Plan. By Author (2021).

Figure 6.26 Elevation. By Author (2021).

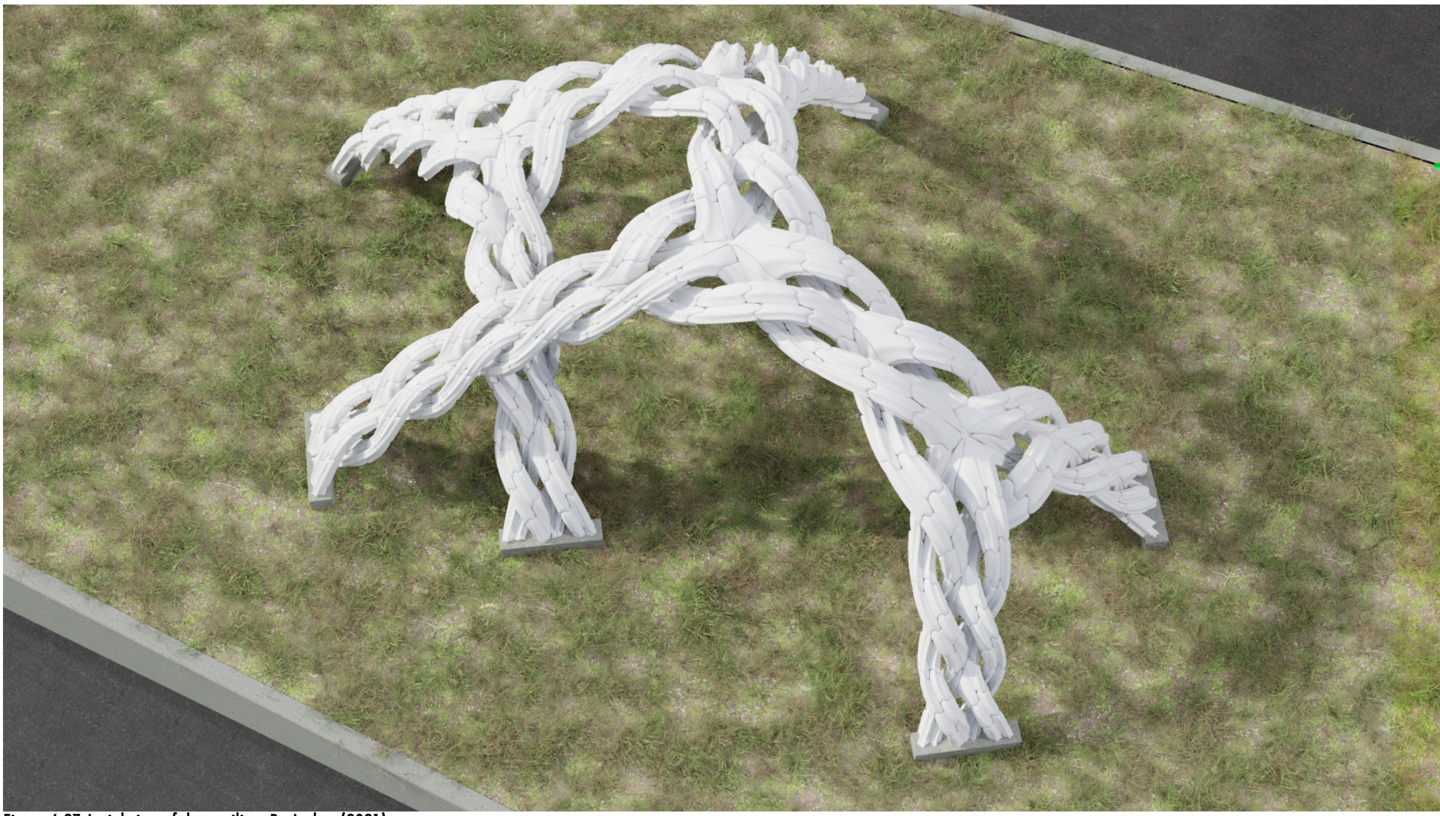


Figure 6.27 Aerial view of the pavilion. By Author (2021).

Figure 6.28 The pavilion at the School of Architecture. By Author (2021).


Figure 6.29 Detail of the pavilion's structure. By Author (2021).

Figure 6.30 Inside the pavilion. By Author (2021).

Figure 6.31 Detail of the pavilion's structure. By Author (2021).


Figure 6.32 Detail of the pavilion's structure. By Author (2021).


Figure 6.33 Detail of the pavilion's structure. By Author (2021).

6.5 Manufacturing

6.5.1 The Joint Connection System

The connection system design is a crucial aspect of the system. The design of this system is inspired by the joint system design of 'Hemo Gorge Gateway Sculpture', which uses male joint and female joint to connect each component.

The components of this project have a more complex and organic form; therefore, the shape and design of the joint need to adjust to fit the requirements of this project. This project utilises Grasshopper in designing the parametric connection system due to many components. The joint is mainly divided into two parts, a large cylinder to retain the connection strength between the male joint and female joint and a cube to define the specific connection angle of each component. Figure **6.34** demonstrates the typical connection system of this project.

Although industrial 3D printers can print accurately, the error between the two components cannot be avoided. Hence, a suitable tolerance of each joint needs to be considered and tested before real-life production. This part will be described in detail later.

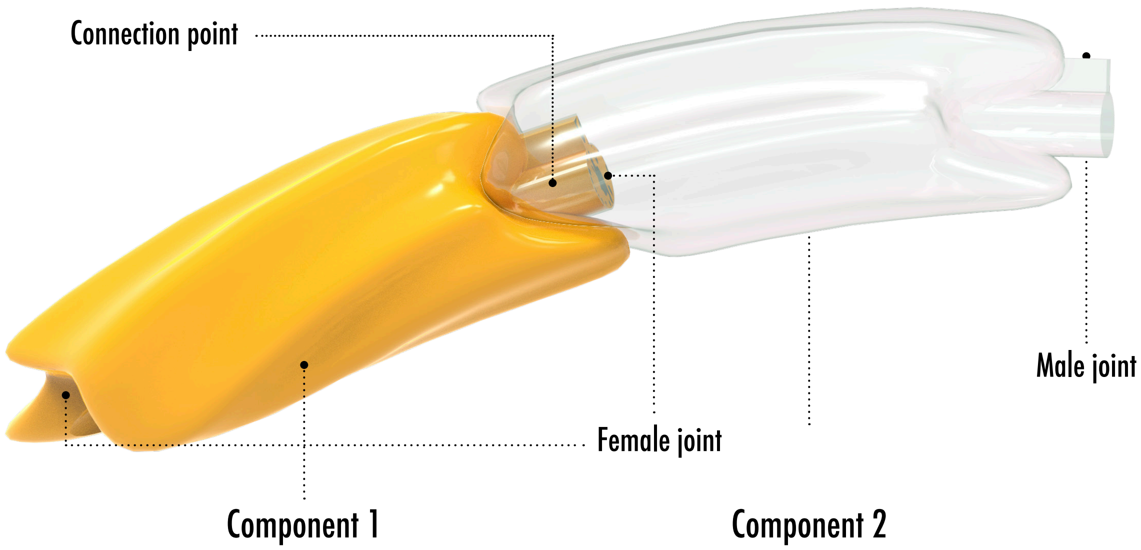


Figure 6.34 The Joint Connection System. By Author (2021).

6.5.2 Design Process

Structural Lines

When designing the connection system, the first stage is to extract the structural lines from the basic surfaces, as shown in Figure **6.35**. The structural lines define the specific angle and direction between two components, and the male joint and female joint are also based on these lines.

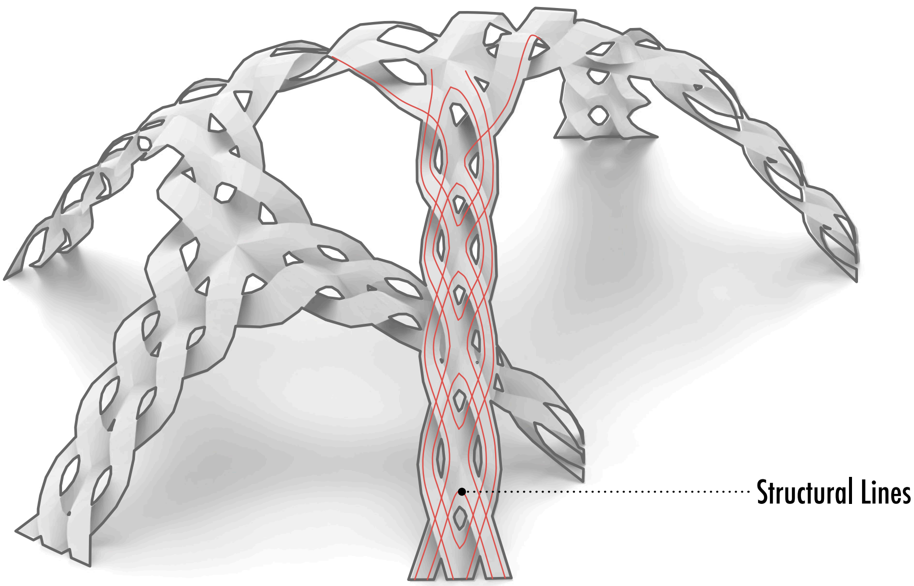


Figure 6.35 Structural lines of the surface. By Author (2021).

Parametric Design Workflow

It is challenging to manually design the joint for each component because this pavilion is assembled from over 700 components. Therefore, a parametric workflow that can set different parameters to control the outputs is necessary for the project. Grasshopper as a parametric design tool providing the entire parametric workflow for the connection system design.

Parametric Joint Design

The entire process of designing the parametric joint used the grasshopper (See Appendix C). There are three steps involved in designing the joint system. The first step is to calculate the centric line of the joint, which develops from the intersection between the structural lines of the basic surfaces and the components, as shown in Figure **6.36a**. Figure **6.36b** shows the process of adjusting the centric line of the joint. As the initial centric lines are developed from the curved structural lines, the joint's shape will have an issue when extruding the section alone the centric lines. Therefore, extract the beginning point and endpoint from the centric lines and connect them to create a new line (Figure **6.37**). As demonstrated in Figure **6.36c**, the third step is to create the joint section. A rectangle and circle are created and use the Boolean tool to integrate them into an entire section. The section can improve the connection strength and identify the connection angle (Figure **6.38**), making it convenient for the assembly phase. Figure **6.39** illustrates the details of the joint system.

Step 1

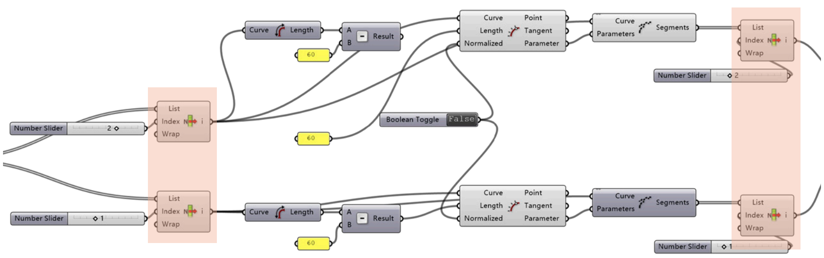


Figure 6.36a Step 1 of the parametric joint design.

Step 2

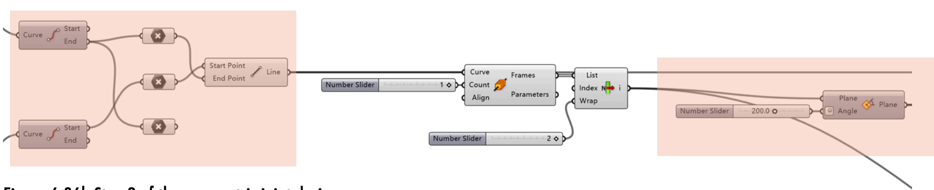


Figure 6.36b Step 2 of the parametric joint design.

Step 3

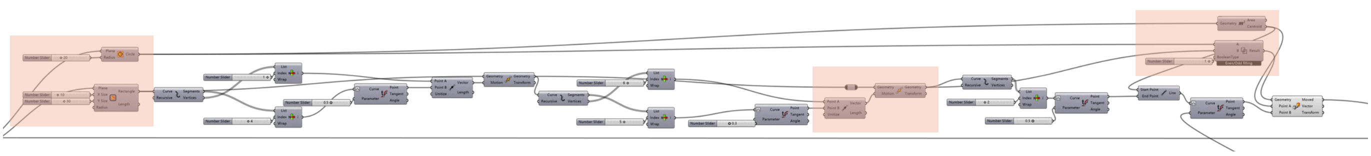


Figure 6.36c Step 3 of the parametric joint design.

Figure 6.36 The parametric joint design. By Author (2021).

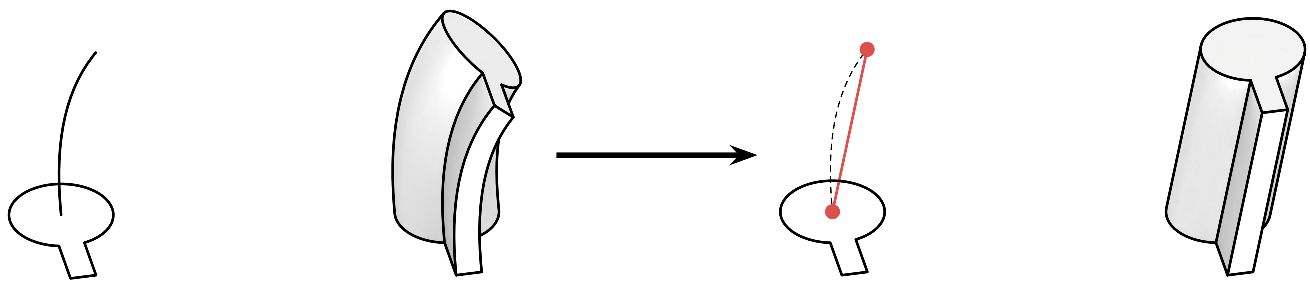


Figure 6.37 Extrusion line adjustment. By Author (2021).

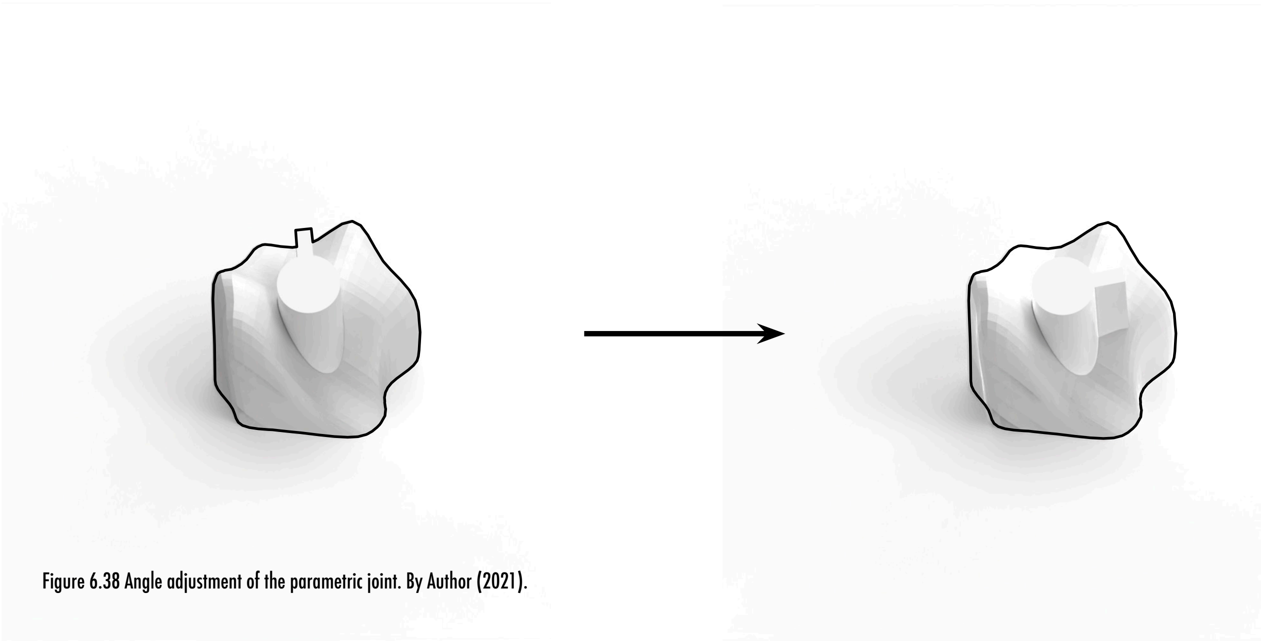


Figure 6.38 Angle adjustment of the parametric joint. By Author (2021).

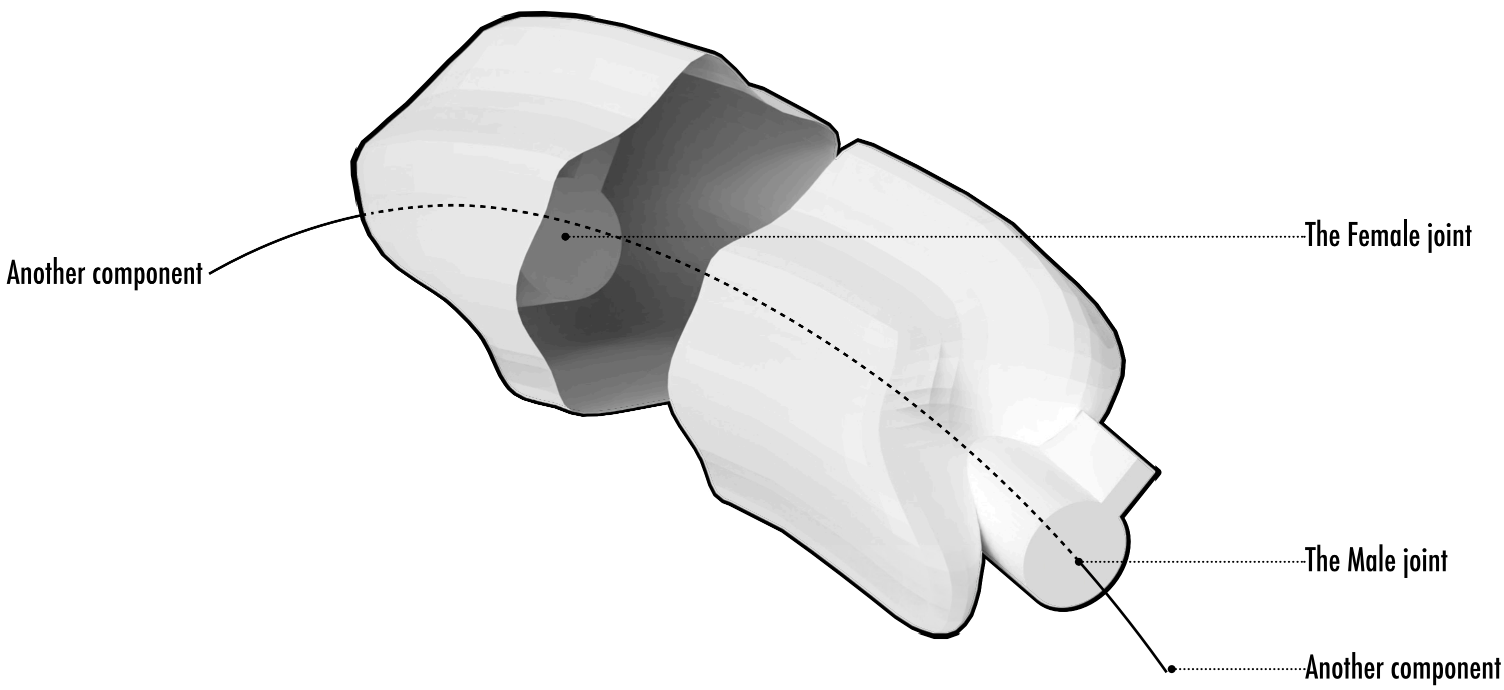


Figure 6.39 The section of a typical joint. By Author (2021).

6.5.3 Tolerance Consideration and Testing

Tolerance is a significant factor that needs to be considered before real-life fabrication. Even industrial 3D printers with higher accuracy cannot avoid error; therefore, a specific tolerance parameter is essential when distributing components to the 3D printers worldwide. Figure **6.40** shows the alteration process of the size adjustment in terms of the joint section in Grasshopper. The section of the female joint slightly scales up to meet the tolerance requirement with the male joint, as shown in Figure **6.41**. Figure **6.42** demonstrate the connection approach between two components with the digital section. The scale-up female joint allows the male joint to insert successfully. Before real-life production, two 1:3 small-scale models were fabricated to test the feasibility of tolerance design. The result demonstrates that those parameters suit the joint system, as shown in Figure **6.43**.

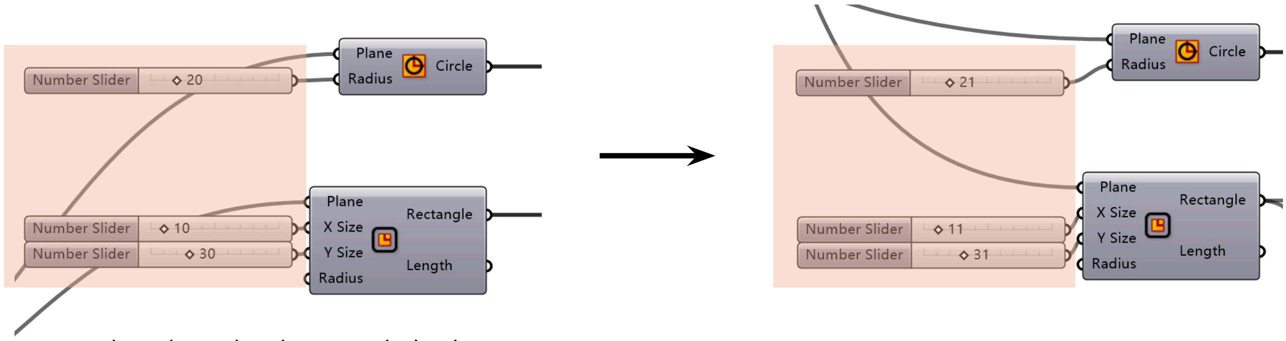


Figure 6.40 Tolerance design and consideration. By Author (2021).

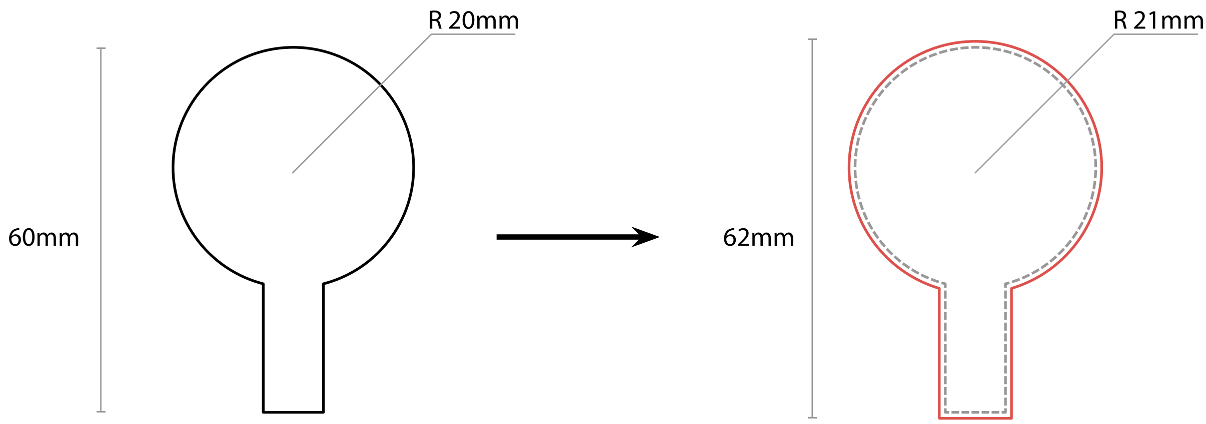


Figure 6.41 Section of the Male joint and Female joint. By Author (2021).

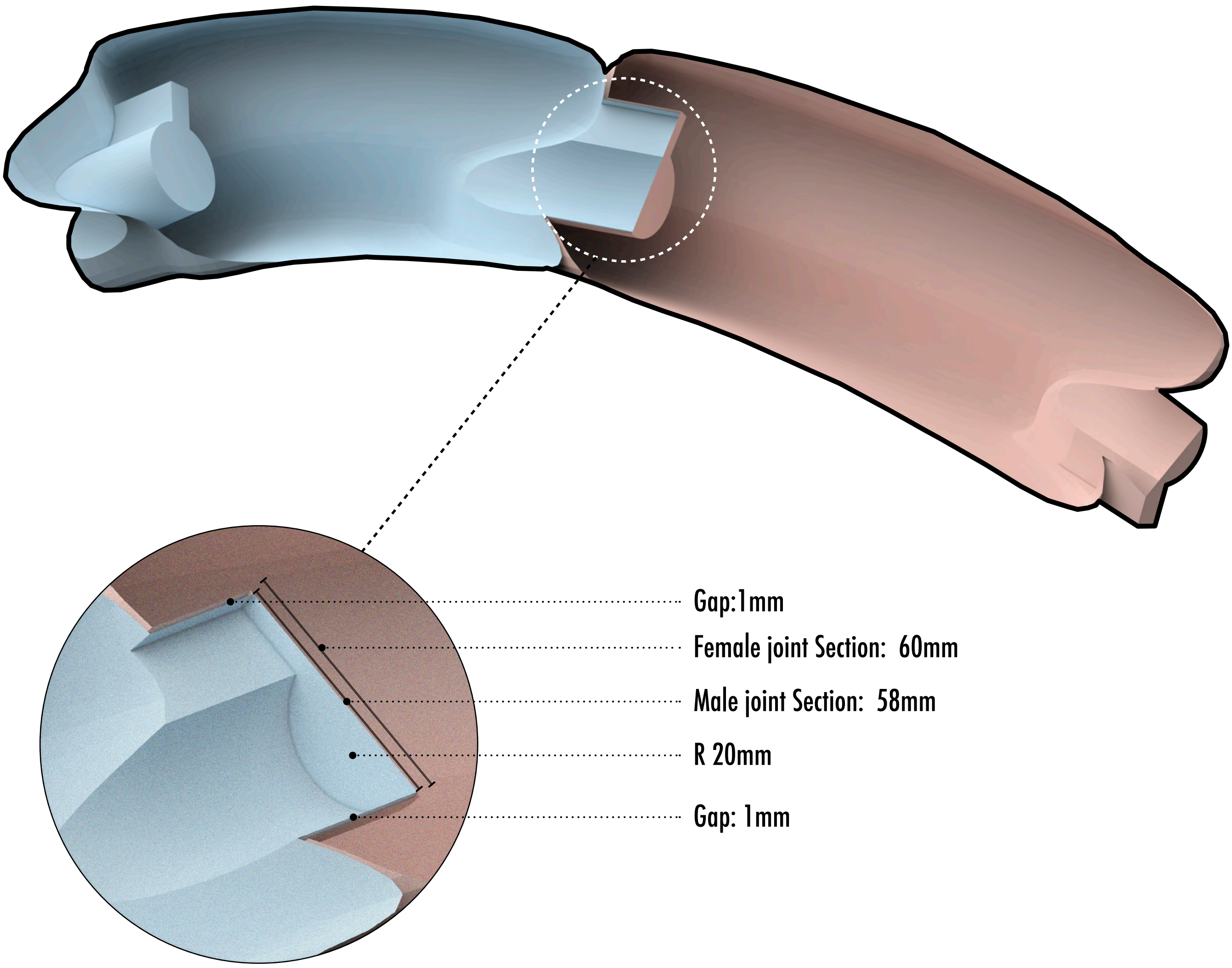


Figure 6.42 Tolerance design and consideration. By Author (2021).

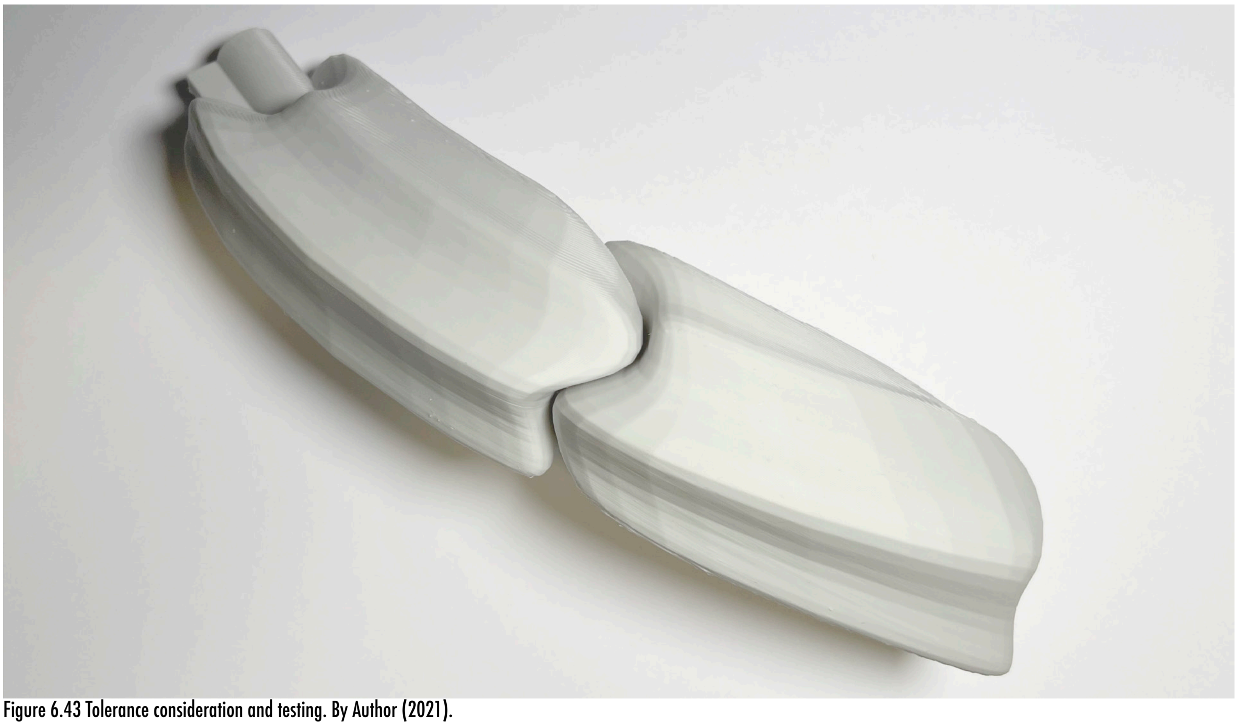


Figure 6.43 Tolerance consideration and testing. By Author (2021).

6.5.4 Material Selection

PLA

PLA is a bio-based and sustainable material made from starch or sugar cane. It is incredibly convenient to use, making it one of the most common 3D printing materials.

There are some benefits of this material. Firstly, it is easily pigmented and can be utilised in various colours and tones. In addition, it has decent strong and hard mechanical properties available for most industrial parts (Carolo, 2021). Furthermore, in contrast to the other 3D printing materials, such as ABS, PLA is a non-toxic material that does not release any toxic odour when printing (Übel, 2021). Moreover, PLA is an affordable material that costs between $15 and $20 per kg on average (Carolo, 2021).

The significant drawbacks of PLA are its lower melting point, which means that PLA printed parts have the risk of deforming when the environment's temperature is high, and its brittle feature (Carolo, 2021) may cause the break of the printing part.

ABS

ABS is one of the most common plastics worldwide, frequently utilised in the injection moulding process.

The key benefit of ABS for 3D printing is its remarkable mechanical properties, which can fabricate durable, heat resistant, and stable, functional parts (Carolo, 2021). There are also some drawbacks to this material. Firstly, the thermal shrinking during cooling is a significant issue when using ABS in 3D printing, making it challenging to fabricate parts with tight tolerance. In addition, ABS is considered a toxic material that will release toxic fumes when used for 3D printing. In contrast to PLA, the price of ABS is higher, which is between $20 and $35 (Carolo, 2021).

Reflection

As this project consists of more than 700 components, a more accessible material for fabrication is necessary. Despite ABS can provide better mechanical properties, its feature of thermal shrinking makes it challenging to control the quality and tolerance when using distributed 3D printing method. In addition, in contrast to ABS, PLA is a more affordable material when used in mass fabrication. At the same time, it can also fit the mechanical properties for most situations. Therefore, this project selects PLA as the fabrication material.

6.6 Assembly

6.6.1 Labelling System

Introduction

Initially, the assembly sequence was simulated with 1:5 physical models to understand the behaviour of the structure and the connection system during the assembly process. The aim was to work as accurate as possible to simulate the feasibility of the structure and connection system.

Nevertheless, the small-scale joint connection system was not entirely successful in connecting and orientating each component due to tolerance accumulation. Therefore, a digital simulation regarding the assembly process is required. The 1:1 assembly process was simulated in Rhinoceros, which can accurately show the assembly details of each component, such as the way the male joint and the female joint connect each other, and the orientation of each component.

As this pavilion consists of more than 700 components, it is challenging to identify the correct parts when connecting them. Hence, a custom-made labelling system is developed using Autodesk Netfabb to identify the correct part rapidly. The main factors of the labelling system are to arrange a unique object ID for each component. And then, create a label with those IDs on the bottom of each component in Autodesk Netfabb using the labelling tool. The 1:3 component with the label was printed to check the feasibility of this system, as shown in Figure **6.44**.

The final phase is to simulate the on-site assembly process. Two 1:3 components were fabricated to demonstrate how this system works. The on-site operators can connect different parts according to the sequence shown on the component, as shown in Figure **6.45**. With the contribution of this system, the issue regarding assembly could be resolved.

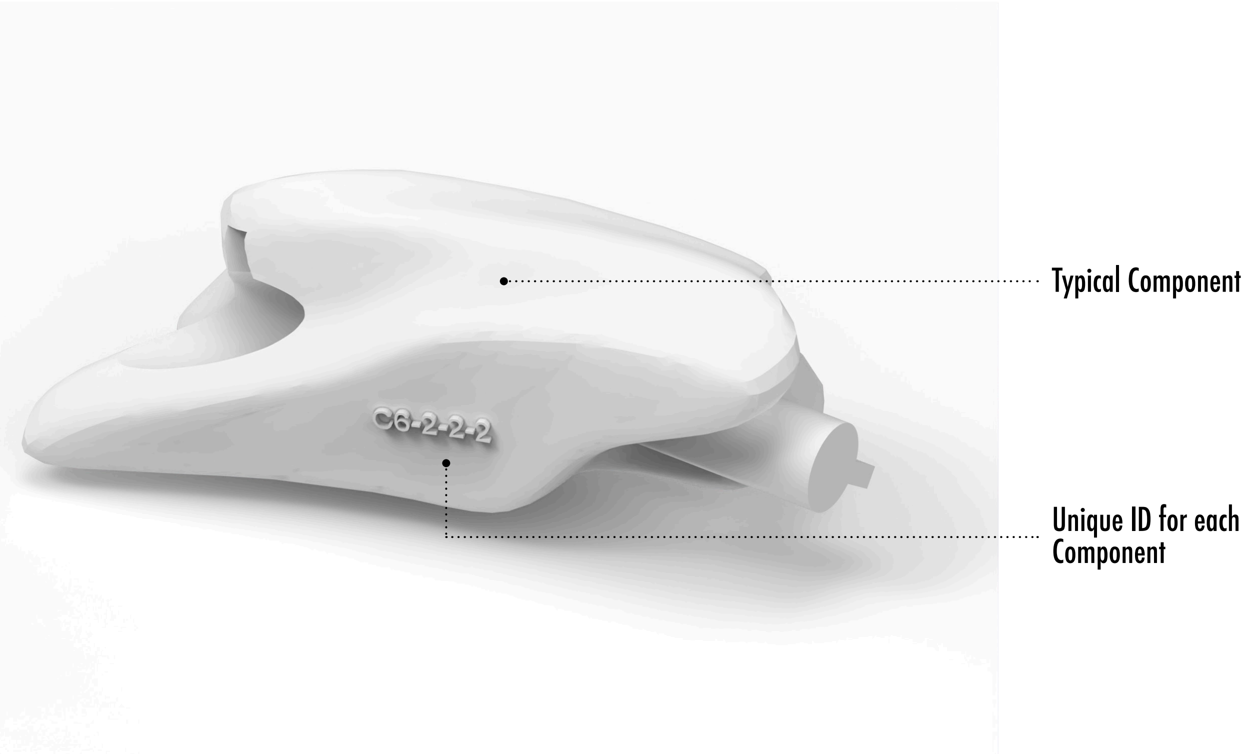


Figure 6.44 Rendering of the Labelling System. By Author (2021).

Figure 6.45 Assembly testing. By Author (2021).

6.6.2 Coding Principle

As each component has to allocate a unique ID, a systematic coding principle is increasingly necessary. As shown in Figure **6.46**, the first part of the component ID is determined by the sequence of the pavilion's column. The following part follows the position of different helixes, as shown in Figure **6.47**. The sequence of the third part is determined by the adjacent branches (Figure **6.47**). The last part is the sequence of each segment. Figure **6.48** demonstrates the final result of the coding principle.

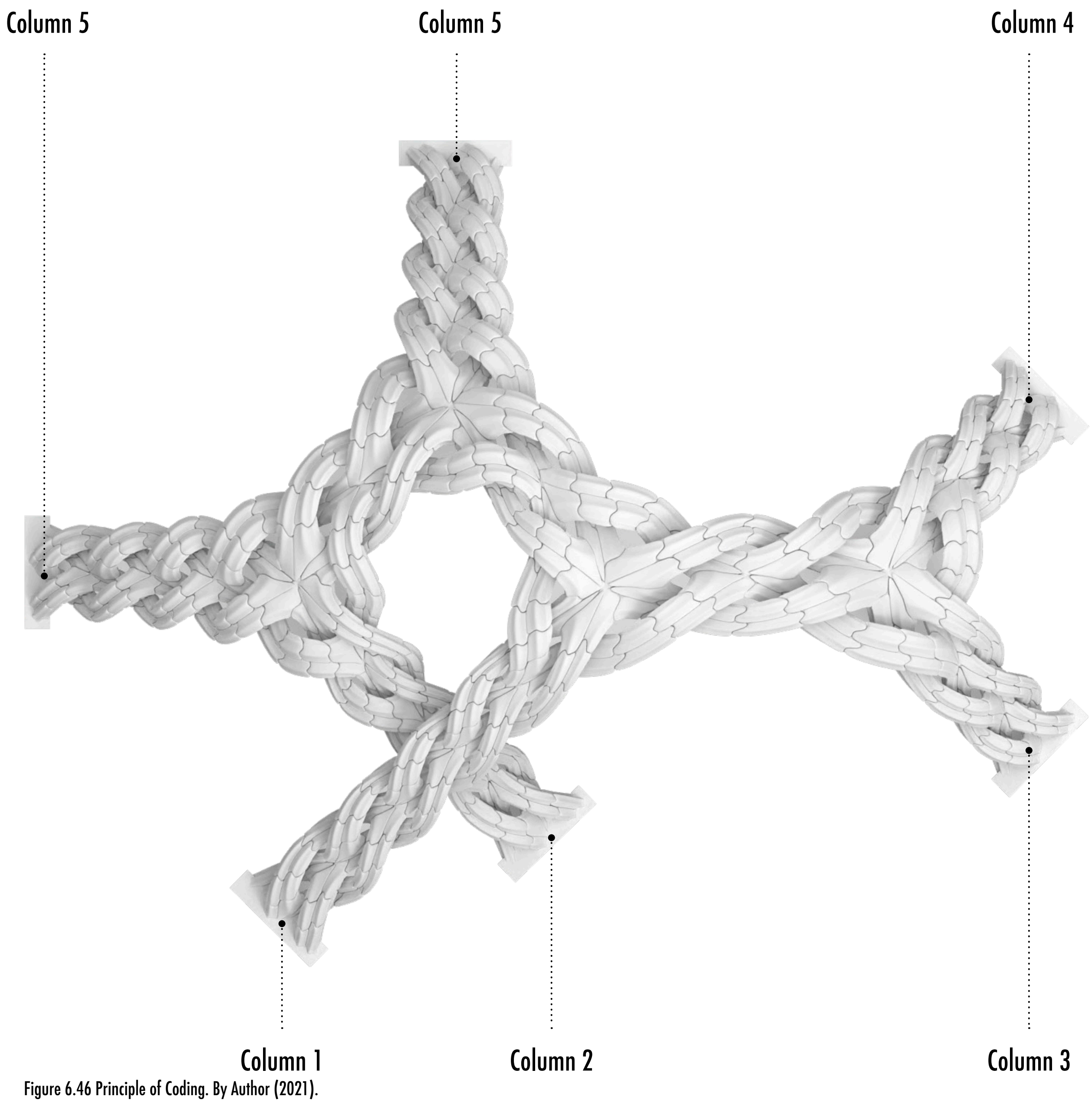


Figure 6.46 Principle of Coding. By Author (2021).

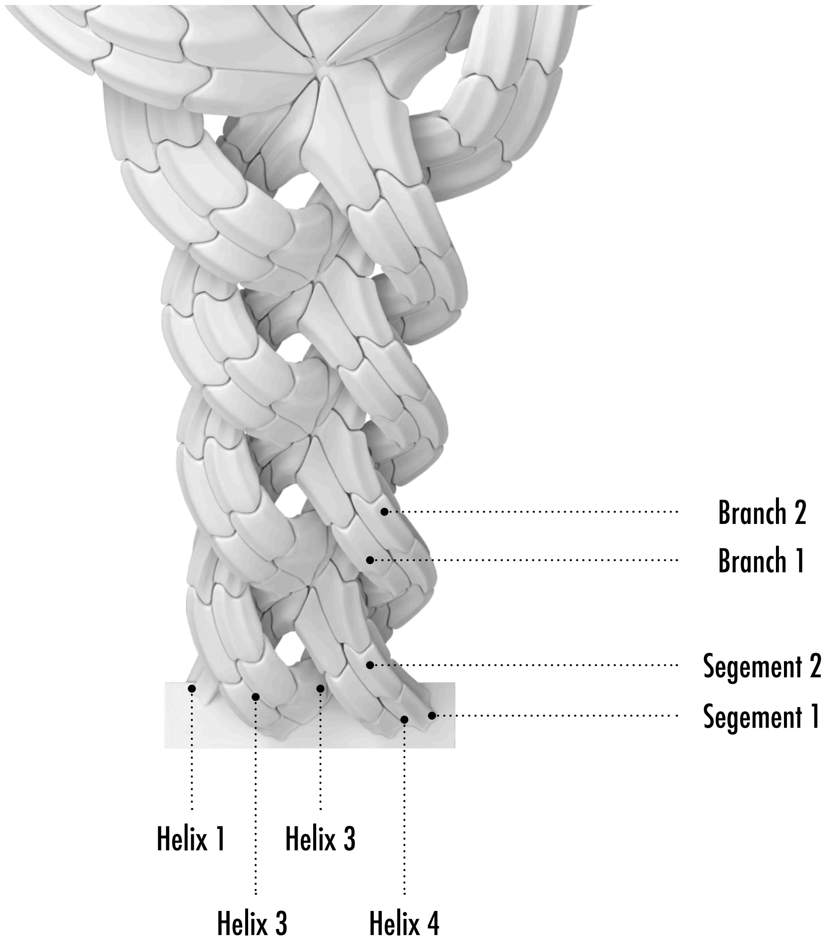


Figure 6.47 Principle of Coding. By Author (2021).

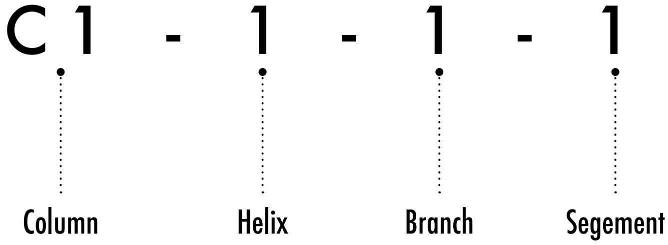


Figure 6.48 Principle of Coding. By Author (2021).

7

Experiment & Testing

Figure 7.1 Cover: Pavilion.
By Author (2021).

7.1 Small-scale Experiment

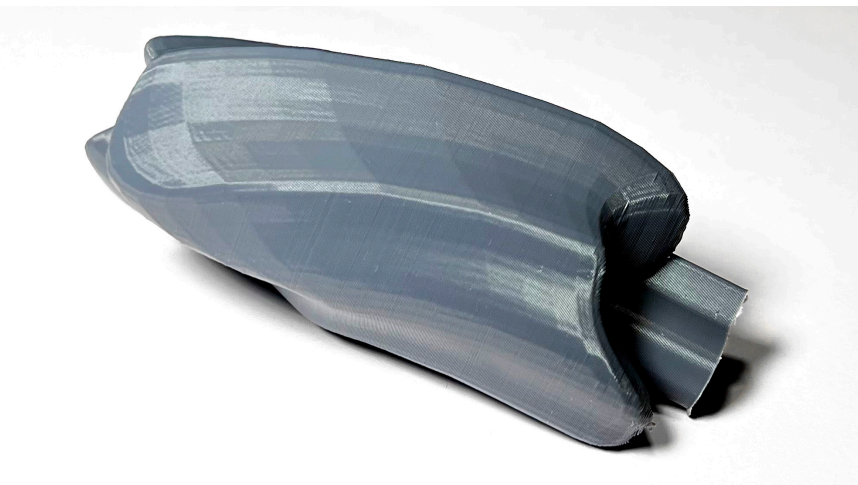
7.1.1 Small-scale Model Fabrication

1	2	3	4
Print Speed	Layer Height	Surface Quality	Delivery Time
mm/s	mm	Rate: 1-5	Hour

Table 8. Printing Parameters Testing

1	60mm/s
	—
2	0.2mm
	—
3	5
	—
4	206mins

1	80mm/s
2	0.2mm
	↓ 20.0%
3	4
	↑ 13.1%
4	179mins

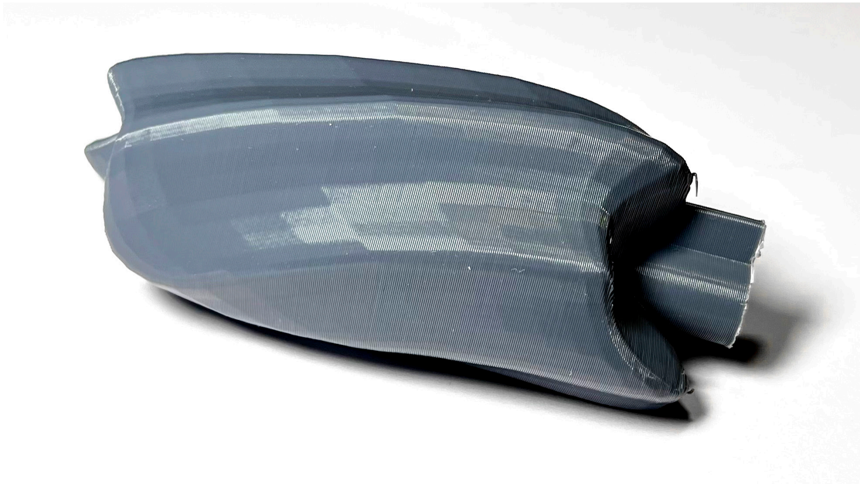


1	100mm/s
2	0.2mm
	↓ 20.0%
3	4
	↑ 16.5%
4	172mins

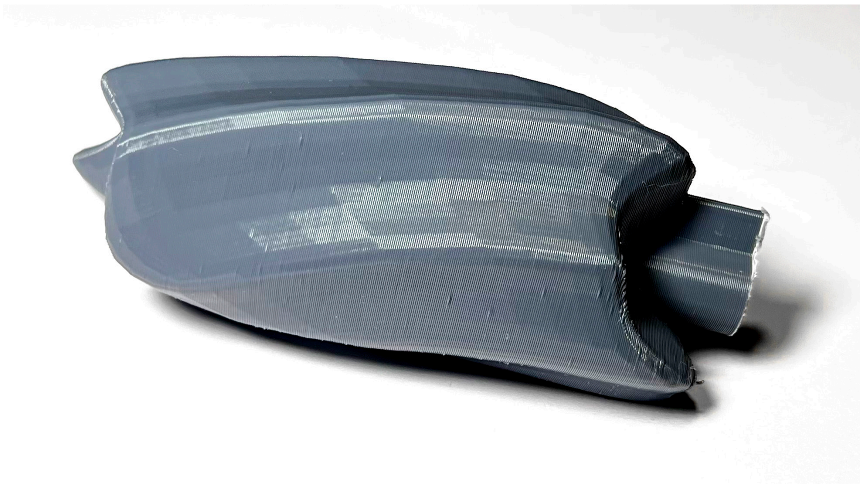
Figure 7.2 Printing Parameters testing. By Author (2021).

1	2	3	4
Print Speed mm/s	Layer Height mm	Surface Quality Rate: 1-10	Delivery Time Hour

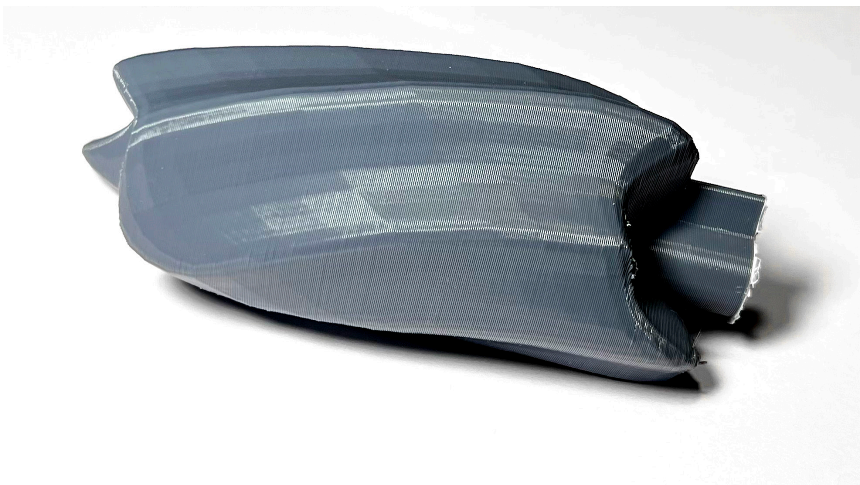
60mm/s	1
0.28mm	2
↓ 40.0%	
3	3
↑ 25.2%	
154mins	4



80mm/s	1
0.28mm	2
↓ 60.0%	
2	3
↑ 33.5%	
137mins	4



100mm/s	1
0.28mm	2
1	3
↑ 36.9%	
130mins	4



7.1.2 Problem & Analysis

This section utilises a 1:3 model to test several parameters that can affect the 3D printing result to determine the most suitable parameter for real-life manufacturing for this project.

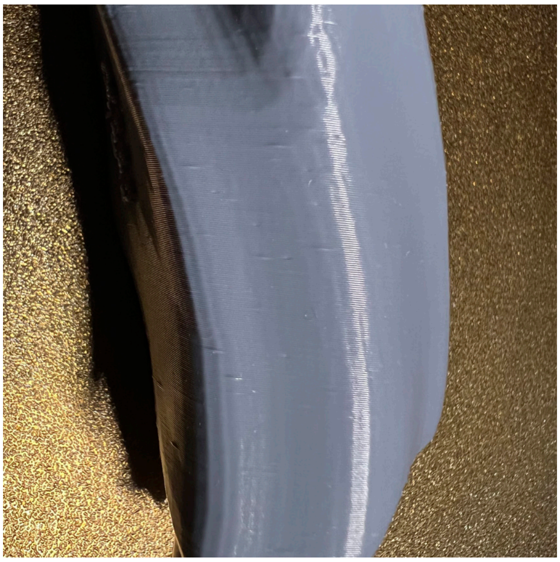
Analyse the data from Table **7**, and the printing speed has a strong relationship with quality and delivery time. When the printing speed increases from 60mm/s to 80mm/s, the delivery time sharply decrease. However, the delivery time decreased slightly when the printing speed increased from 80mm/s to 100mm/s. At the same time, with the increase of the printing speed, the quality of the printing parts become worse, significantly when increasing the printing speed to 100mm/s, as shown in Figure **7.2**. In terms of layer height, increasing layer height contribute much to the decrease of task delivery time (Table **7**). Nevertheless, a higher layer height creates a rough surface of the printing parts, as shown in Figure **7.3**.

Hence, the lower printing speed and layer height are more suitable for 3D printing parts with complex forms and smooth surfaces. The higher printing speed and layer height are suitable for printing parts with a simple shape and rough surface.

7.1.3 Final Printing Parameters

The form of the modular component is complex and organic; therefore, a smoother surface is necessary to demonstrate the complexity of the structure. Hence, 2.8mm layer height is unsuitable for this structure due to its worse surface quality. Due to the 1:1 component having a larger dimension that needs more time for fabrication, balancing the quality and delivery speed is necessary.

Hence, the final printing parameters regarding printing speed and layer height are determined at 80mm/s and 2mm to balance the surface quality and task delivery time.



Layer Height: 2mm

Printing Speed: 80mm/s

Figure 7.3a Printing Problem Analysis.

Layer Height: 2mm

Printing Speed: 100mm/s

Figure 7.3b Printing Problem Analysis.

Layer Height: 2.8mm

Printing Speed: 80mm/s

Figure 7.3c Printing Problem Analysis.

Layer Height: 2.8mm

Printing Speed: 100mm/s

Figure 7.3d Printing Problem Analysis.

Figure 7.3 Printing Problem Analysis. By Author (2021).

7.2 Real-life Production Experiment

7.2.1 Fabrication Simulation in the online distributed server

This section will be utilising a part of components to simulate the workflow of 'Architecture Distributed'. As shown in Figure **7.4**, each component will be arranged by a suitable manufacturer for fabrication after the user uploads their digital models and the requirements to the server. The fabrication sites are determined by the printing requirements and the IP protection, which confirm that each manufacturer will not fabricate parts in sequence.

Component number: C1-1-1-1
Fabrication Location: China

Component number: C1-1-1-2
Fabrication Location: China

Component number: C1-1-1-3
Fabrication Location: Japan

Component number: C1-1-1-4
Fabrication Location: The US

Component number: C1-1-1-5
Fabrication Location: China

Component number: C1-1-1-6
Fabrication Location: Germany

Component number: C1-1-1-7
Fabrication Location: The US

Component number: C1-1-1-8
Fabrication Location: China

Component number: C1-1-1-9
Fabrication Location: Japan

Component number: C1-1-1-10
Fabrication Location: China

Component number: C1-1-1-11
Fabrication Location: Germany

Component number: C1-1-1-12
Fabrication Location: China

Component number: C1-1-1-13
Fabrication Location: Japan

Component number: C1-1-1-14
Fabrication Location: China

Component number: C1-1–15
Fabrication Location: The U.S

Component number: C1-1-2-1
Fabrication Location: Australia

Component number: C1-1-2-2
Fabrication Location: China

Component number: C1-1-2-3
Fabrication Location: Australia

Component number: C1-1-2-4
Fabrication Location: New Zealand

Component number: C1-1-2-5
Fabrication Location: China

Component number: C1-1-2-6
Fabrication Location: The UK

Component number: C1-1-2-7
Fabrication Location: China

Component number: C1-1-2-8
Fabrication Location: Australia

Component number: C1-1-2-9
Fabrication Location: The US

Component number: C1-1-2-10
Fabrication Location: China

Component number: C1-1-2-11
Fabrication Location: Singapore

Component number: C1-1-2-12
Fabrication Location: Japan

Component number: C1-1-2-13
Fabrication Location: New Zealand

Component number: C1-1-2-14
Fabrication Location: Australia

Component number: C1-1-2-15
Fabrication Location: Chinaw

Figure 7.4 Fabrication simulation in online distributed printing server. By Author (2021).

7.2.2 Real-life product Testing

This experiment will be testing three components that different manufacturers fabricated. This project only selects three smaller typical components. In addition, manufacturers who can provide cheaper fabrication costs from China are selected to test the feasibility of this online distributed platform.

Component 1

Figure **7.5** shows component 1 (C6-2-2-3). This component was fabricated by LanDu 3D printing Technology, a 3D printing manufacturer with more than 100 commercial FDM 3D printers. The fabrication process of this component (Figure **7.6**) was four days exceeding the estimated delivery time due to the issue with the 3D printer. In terms of international logistics, this component was delivered by Ship2U, taking seven days to arrive in New Zealand. As shown in Table 8, the entire delivery time of this component was 14 days.

Table 9. Fabrication information of Component 1

Component ID	Component 1 (C6-2-2-3)
Fabrication Site	Shanxi, China (LanDu 3D printing Technology)
Material	PLA
Weight	512g
Manufacturing equipement	Commercial FDM Printer
Cost	NZ $46.8
Task Delivery time	4 Days
Logistics time	10 Days
Total Time	14 Days

Figure 7.5 1:1 fabrication experiment of Component 1. By Author (2021).

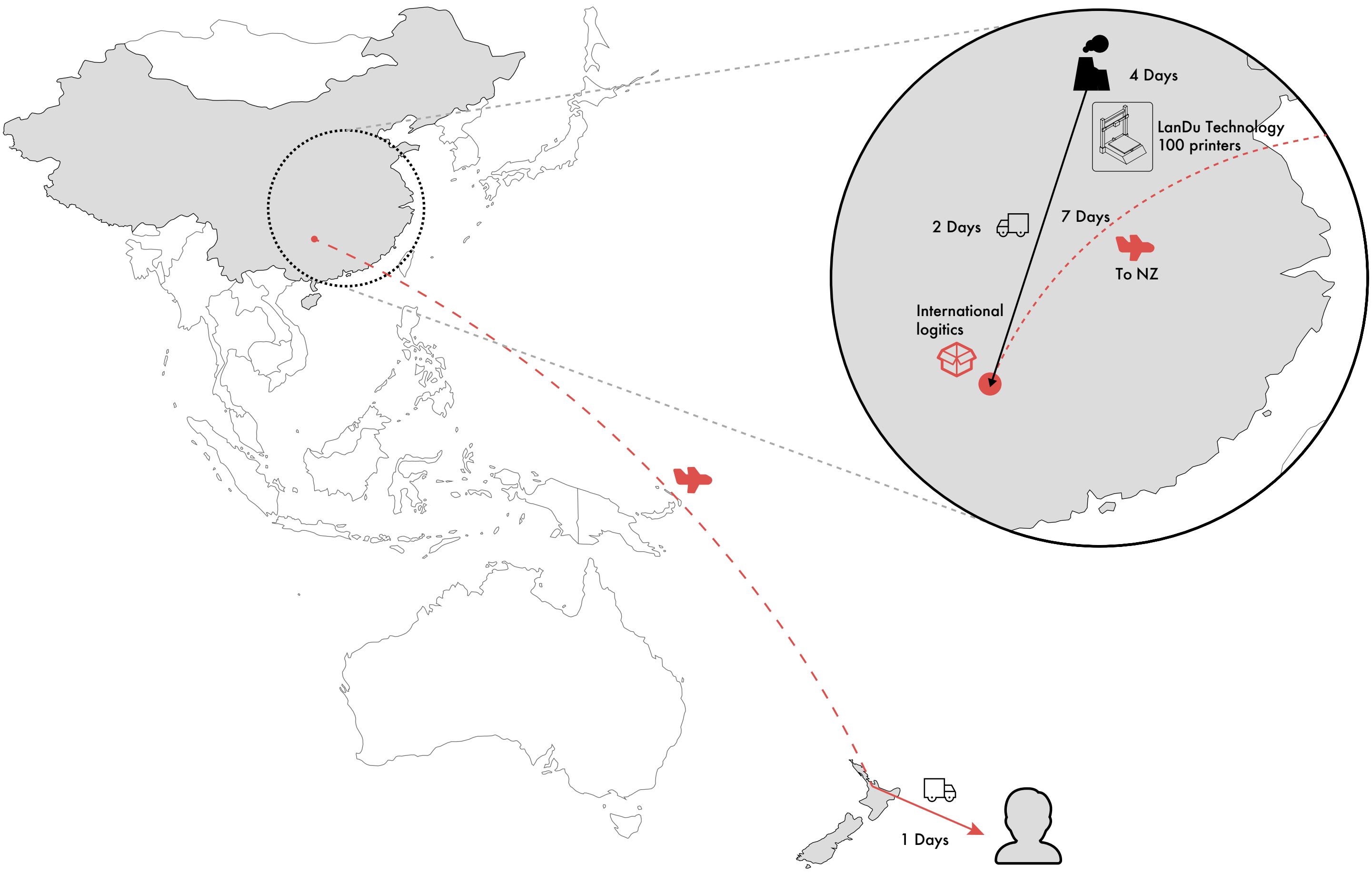


Figure 7.6 1:1 The entire task delivery process of Component 1. By Author (2021).

Component 2

Figure **7.7** shows component 2 (C6-2-2-4). Wei Feng Technology fabricated this component, a 3D printing manufacturer having more than 100 commercial FDM 3D printers in Shanxi, China. The fabrication process of this component (Figure **7.8**) was two days, meeting the estimated delivery date. In terms of international logistics, this component was delivered by NZ Post, taking seven days to arrive in New Zealand. As shown in Table **10**, the entire delivery time of this component was 11 days.

Table 10. Fabrication information of Component 2

Component ID	Component 2 (C6-2-2-4)
Fabrication Site	Shanxi, China (WeiFeng 3D printing Technology)
Material	PLA
Weight	584g
Manufacturing equipement	Commercial FDM Printer
Cost	NZ $45
Task Delivery time	2 Days
Logistics time	9 Days
Total Time	11 Days

Figure 7.7 1:1 fabrication experiment of Component 2. By Author (2021).

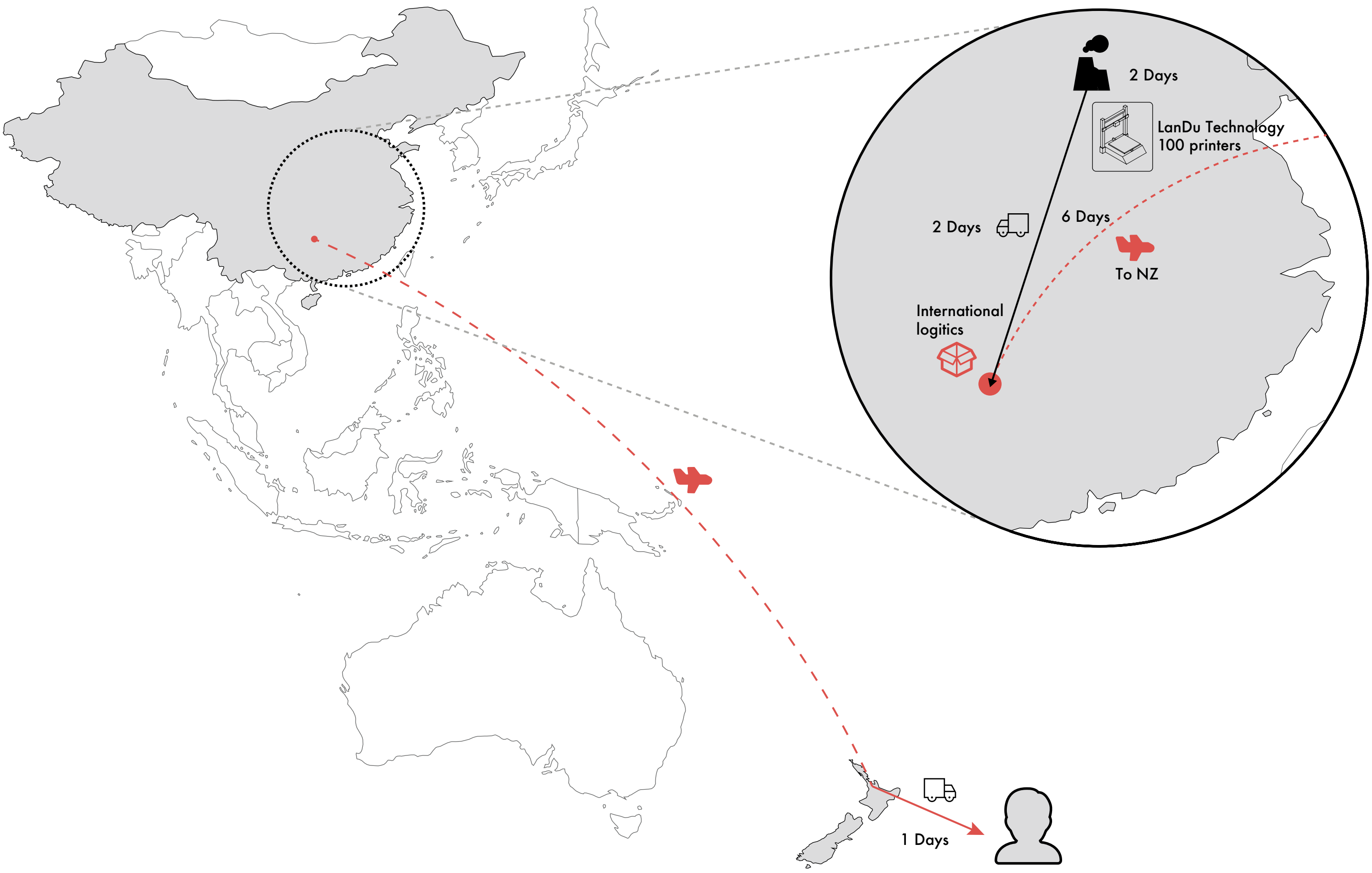


Figure 7.8 The entire task delivery process of Component 2. By Author (2021).

Component 3

Figure **7.9** shows component 2 (C6-2-2-4). This component was fabricated by Zhen Rui Technology, a 3D printing manufacturer with more than 140 commercial FDM 3D printers in Guangdong, China. The fabrication process of this component (Figure **7.10**) was two days, meeting the estimated delivery date. However, there was a significant issue regarding this in terms of international logistics. Due to the lockdown in China due to the Covid-19, the number of international flights from China was sharply reduced. As a result, this component spent over 30 days delivering it by China Post to New Zealand. As shown in Table **11**, the entire delivery time of this component was 32 days.

Table 11. Fabrication information of Component 3

Component ID	Component 3 (C6-2-2-2)
Fabrication Site	Guangdong, China (Zhenrui 3D printing Technology)
Material	PLA
Weight	592g
Manufacturing equipement	Commercial FDM Printer
Cost	NZ $46.2
Task Delivery time	2 Days
Logistics time	30 Days
Total Time	32 Days

Figure 7.9 1:1 fabrication experiment of Component 3. By Author (2021).

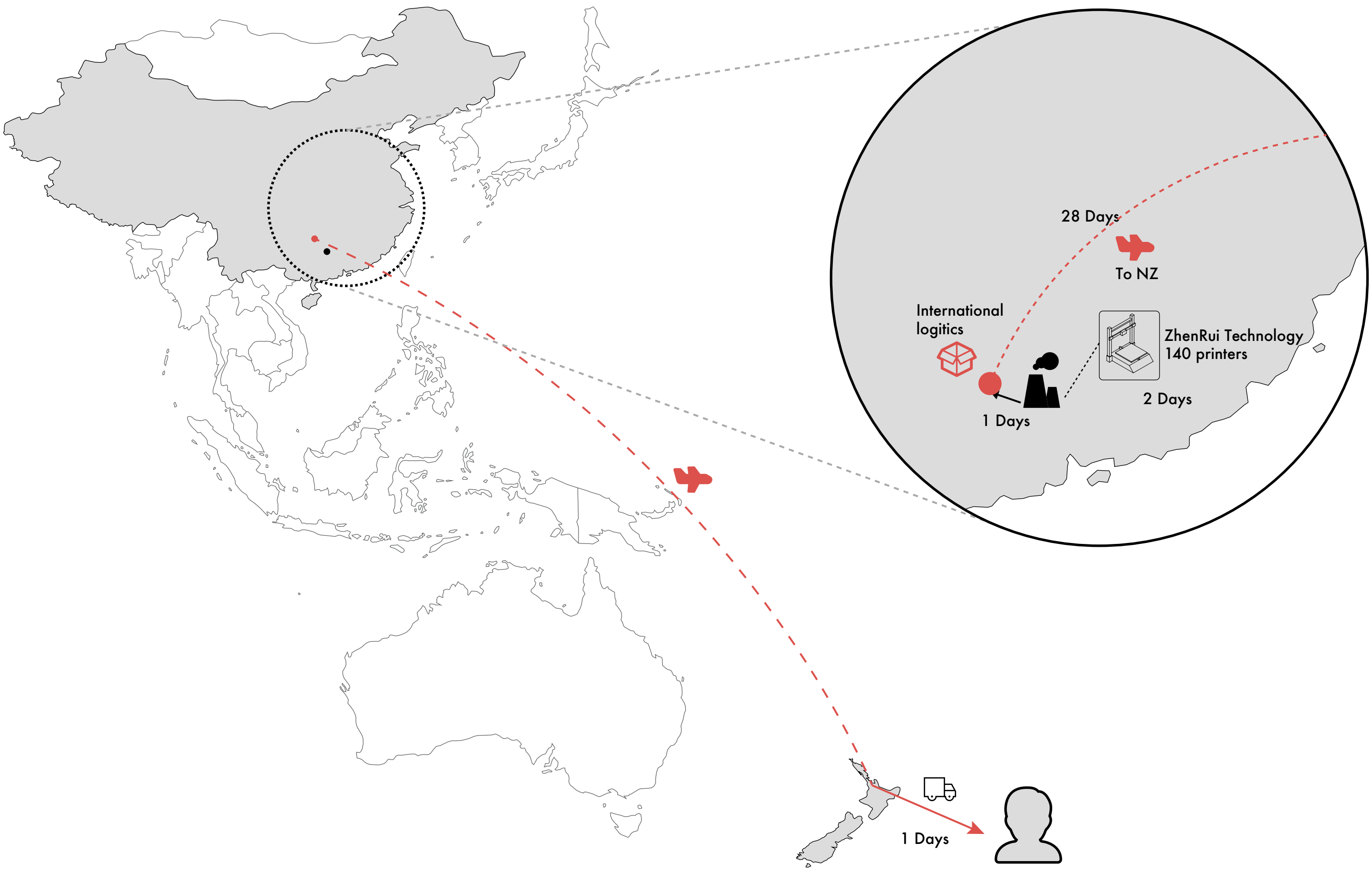


Figure 7.10 The entire task delivery process of Component 3. By Author (2021).

7.2.3 Data Analysis

As shown in Table **12**, this pavilion has more than 700 unique components. Due to each component having a complex geometric, each part could be printed for up to 55 hours. If those components were fabricated by one 3D printer, it would take more than four years to deliver the task. As a result, it is approximately impossible to complete such a project with many complex form components only with a single or inadequate manufacturing equipment.

Nevertheless, with the support of distributed printers, the challenge of delivering this project could be credible. As shown in Figure **7.11**, most components were finished fabricating within two days instead of component 1. While component 1 met unexpected delays during the fabrication process due to the issue of the 3D printer, those issues which may cause delay are not expected. Therefore, this project still can leverage the power of distributed printing to achieve rapid fabrication.

As shown in Figure **7.11**, there is a significant issue regarding logistics. While most time, the international logistics is fast and stable, the delay of component 3 also demonstrates the potential risk of distributed manufacturing. Hence, to reduce the possibility of logistics delay when utilising the method of distributed printing, the online distributed platform (Architecture Distributed) needs to undertake much responsibility to select a more suitable logistics solution.

Despite the fabrication testing result showing that there are still some risks and issues when manufacturing at distributed sites worldwide, it still has a positive effect on delivering the project. For instance, if those issues could be reduced with the help of the quality control system and logistics system provided by the online distributed platform, the entire project could be delivered within two weeks on the most optimistic situation instead of more than four years.

Table 12. Project Data

Dimension	8.8m x 7m x 3.2m
Printed parts	732 Components
Material	PLA
Manufacturing equipement	Commercial FDM Printers
Component Dimension	350mm x 200mmx 150mm
Task Delivery time	3 Days
Each Component Fabrication Time	50 ~ 55 hours
Total Delivery time	36,600 ~ 40260 hours (4.2 ~ 4.6 years)

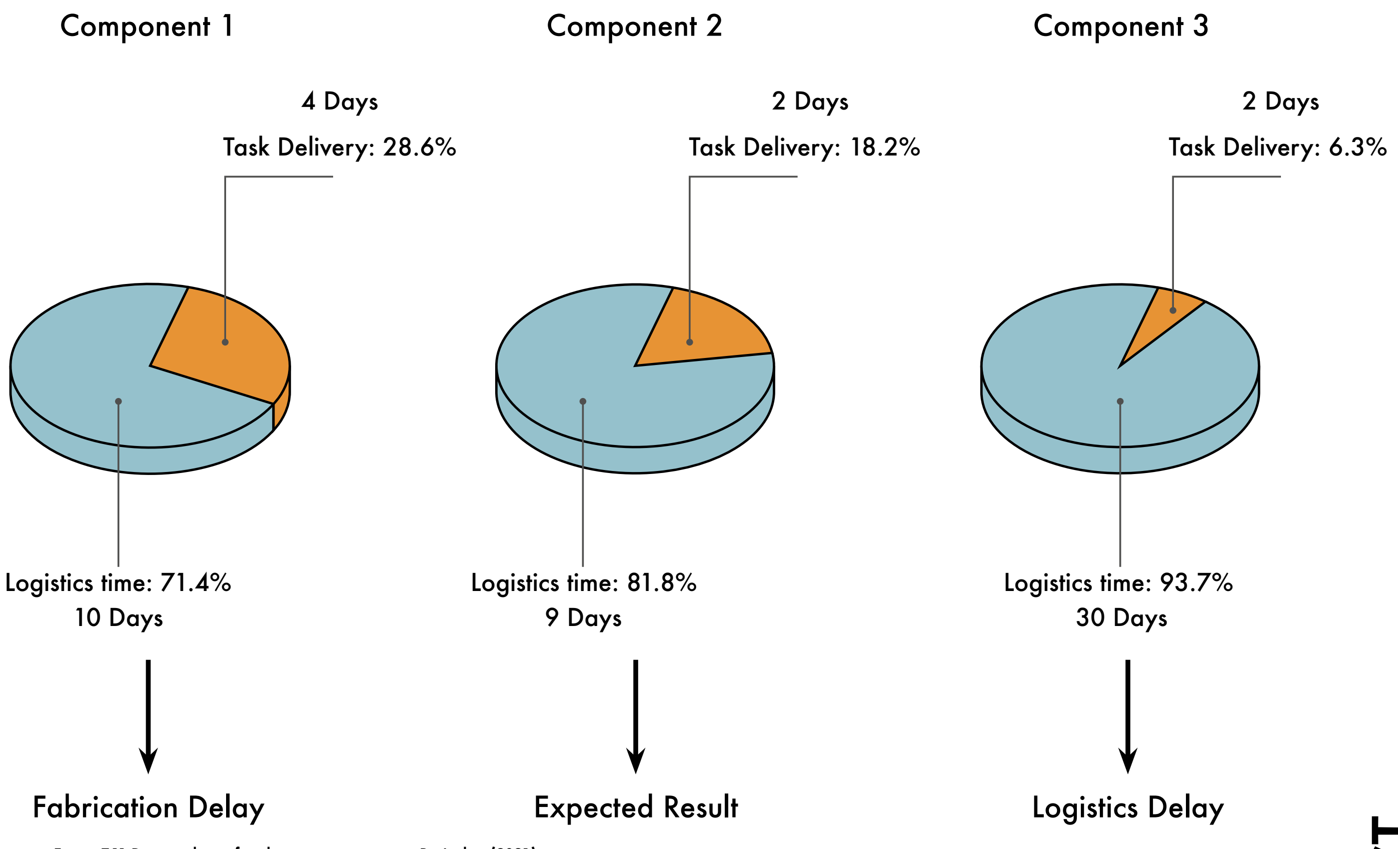


Figure 7.11 Data analysis of each printing component. By Author (2021).

7.2.4 Risk Assessment

This section aims to analyse and assess the potential risks if using the method of distributed 3D printing to deliver the architectural project. While the data of three components demonstrates that distributed 3D printing method reduced the delivery time, there are still some risks that might affect the project delivery.

The international logistics delay demonstrates a risk that might delay the project using distributed 3D printing in a real-life project. The potential solution is to select a closer manufacturer or leave more than one month before the deadline.

Quality control is another issue that might lead to increasingly slow product delivery or poor quality. Hence, giving manufacturers the default printing parameters that the designer has tested before fabrication.

Regarding selecting a global manufacturer, the language barrier might become a significant issue that is more likely to cause miscommunication or incorrect outputs. The potential solution is to have a contact person who can help communicate.

Table 13. Assessment of the Experiment

Item ID	Manufacturer	Advantages	Issue	Risk	Score
C6-2-2-2	Zhenrui 3D printing Technology	Fast task delivery & Good quality	International Logistics Delay	Unexpected delay of the entire project.	8/10
C6-2-2-3	LanDu 3D printing Technology	Good Communication	Unsatisfying quality control	Very slow delivery of product/ poor quality.	7/10
C6-2-2-4	WeiFeng 3D printing Technology	Good quality	Language barrier	Miscommunication. Mistake/ incorrect outputs.	9/10

Table 13. Assessment of the Experiment

Item ID	Solution
C6-2-2-2	Select close manufacturer or leave more than one month before deadline.
C6-2-2-3	Give them default printing parameters to fabricate.
C6-2-2-4	Communicate clearly and graphically or have a contact that can help.

7.2.5 Findings & Reflection

The experimental results demonstrate the opportunities of using distributed 3D printing as a new method to deliver the architectural project. In most situations, the delivery time of the entire process can be increasingly reduced. However, the situation regarding the logistics delay also shows the risk of using globally distributed manufacturers. Hence, the trend of distributed 3D printing is more likely to close to the users if there are enough affordable equipment.

This experiment selected FDM printers as the manufacturing equipment, more likely to fit small-scale architectural projects. While the FDM process can create complex geometric forms, the build volume limitation also affects design freedom. Therefore, 3D printing is still a new technology, and its efficiency is expected to be increased drastically in the near future.

Furthermore, the language barrier is a significant issue in global manufacturing. Although an online distributed 3D printing platform was proposed to resolve this issue, this method was not tested because the server is not run in real life. Therefore, future research regarding this issue is still necessary.

8

Conclusion & Reflection

Figure 8.1 Cover: Pavilion.
By Author (2021).

At a broader level, this thesis was motivated by the interest in digital fabrication and observation that 3D printing can create complex structures. It explored how this method may become a new model for the architectural industry—all with the aim to answer the question of ***how small-scale architecture can leverage the power of distributed 3D printing to deliver complex architectural structures***. The current state of knowledge in the field of distributed 3D printing for architecture has received little attention in the research literature. Hence, an in-depth analysis of literature and existing precedents has been conducted to discover similar methodologies throughout this research and why this area needs to explore alternatives. This study also developed a significant distributed printing model and has tested its feasibility in a real-life context.

This chapter starts with summarising the contribution of this research and then moves on to the discussion of the main findings; the limitations and future research work direction will also be explained.

8.2 Findings Discussion

8.2.1 Suitable 3D printing technologies for Distributed Manufacturing Method

In this research, three leading 3D printing technologies for architecture were analysed based on the technologies' capabilities and processes, including contour crafting, concrete printing, and FDM 3D printing. These three technologies were analysed along with several relevant parameters to assess their potential (focusing on the capabilities of fitting distributed manufacturing and achieving complex architectural projects). In the assessment based on the literature and existing 3D printed building, **FDM is the leading technology considering its features fit for distributed manufacturing methods** - mainly due to its capacity of creating complex forms and its fewer requirements about equipment.

Although FDM 3D printing is suitable for distributed manufacturing and complex forms, its limitations might affect the design approach, such as small build volume. Hence, if use this technology, consideration about potential design issues is necessary. Nevertheless, advances in other technologies, for instance, more innovative 3D printers, could potentially change this position and make any of them the preferred technology over time.

In this research, literature regarding distributed manufacturing was examined and found that while the distributed 3D printing method has the potential to be leveraged by architecture, some limitations might affect its power. For instance, the challenges of IP protection, quality control, and task coordination might affect its feasibility when using this method. Hence, if using distributed 3D printing method for delivering architectural projects, **a management system that can control the quality and allocate tasks efficiently is necessary.**

8.2.3 Distributed 3D printing Methods for Architecture

An online distributed 3D printing platform was designed as a model for complex architectural project delivery, aiming to resolve the issues of distributed 3D printing. This model was simulated in a real-life project to test its workflow and feasibility in a real-life context. **The experimental results illustrate that distributed 3D printing can be a potential model for architecture to deliver complex projects.** However, some potential risks, including logistics delay, quality control, and language barrier, need to be considered if using this model. Therefore, as the number of 3D printers increases in the future, **the ideal distributed printing model is more likely to bring manufacturers closer to users, thereby reducing logistics risks**.

8.3 Limitations

There is value in this research, but nonetheless recognised limitations. Firstly, the inadequate sampling size is the limitation of this research. This research only tested three components. In addition, while this research developed a new model of distributed 3D printing, this model was not tested in a real-life context. Simulation of this model only tested parts of its features and functions; therefore, the findings might be affected. To overcome this limitation, I selected the most significant factors of the distributed 3D printing model, including delivery time and quality, to conduct the experiment.

8.4 Future Research Agenda

Distributed printing methods can lead to faster and more affordable architectural project delivery in the future, however only if more research is done and some aspects of the optimisation are improved.

- One aspect that could be done in future research is to increase the smaple size by fabricating more components, enhancing the reliability and generalisability of this research. Although this research tested three components and found that most time distributed methods positively impact task delivery and cost, various factors might affect these results, such as manufacturers' location and global disease. Hence, increasing the sample size is necessary to collect more accurate data for analysis.

- Future study should select 3D printing service suppliers in New Zealand or closer to New Zealand. Although this research concluded that the ideal distributed sites are more likely to be close to the users, the camparison to different distances was not conducted.

- The distributed printing platform should be run in real-life to test more features instead of simulating them in future research. Although this project proposed the concept of this platform based on literature and developed its framework, some functions could not be tested in a real-life context. Thus, designers and researchers could build a real-life server to test whether this platform can reduce the risk of distributed printing methods

- Further research should be done to investigate whether the better 3D printing technology can replace FDM 3D printing to overcome its limitations of build volume and fabrication speed. Researchers can expect that more advanced 3D printers would be used for distributed printing as the development of 3D printing technologies is increasingly fast.

In summary, with the collation of literature and cases, this study proposed a distributed printing platform capable of utilising a larger number of printers beyond the geographical barrier. The outcomes and findings confirmed the feasibility of using distributed printing methods as a new model for complex architectural project delivery. While this method has various limitations and risks, it is still promising for the future architectural industry. It is important for architects and designers to have an awareness and understanding of distributed printing methods to explore the further possibilities of digital fabrication and achieve their aesthetic and design ambition.

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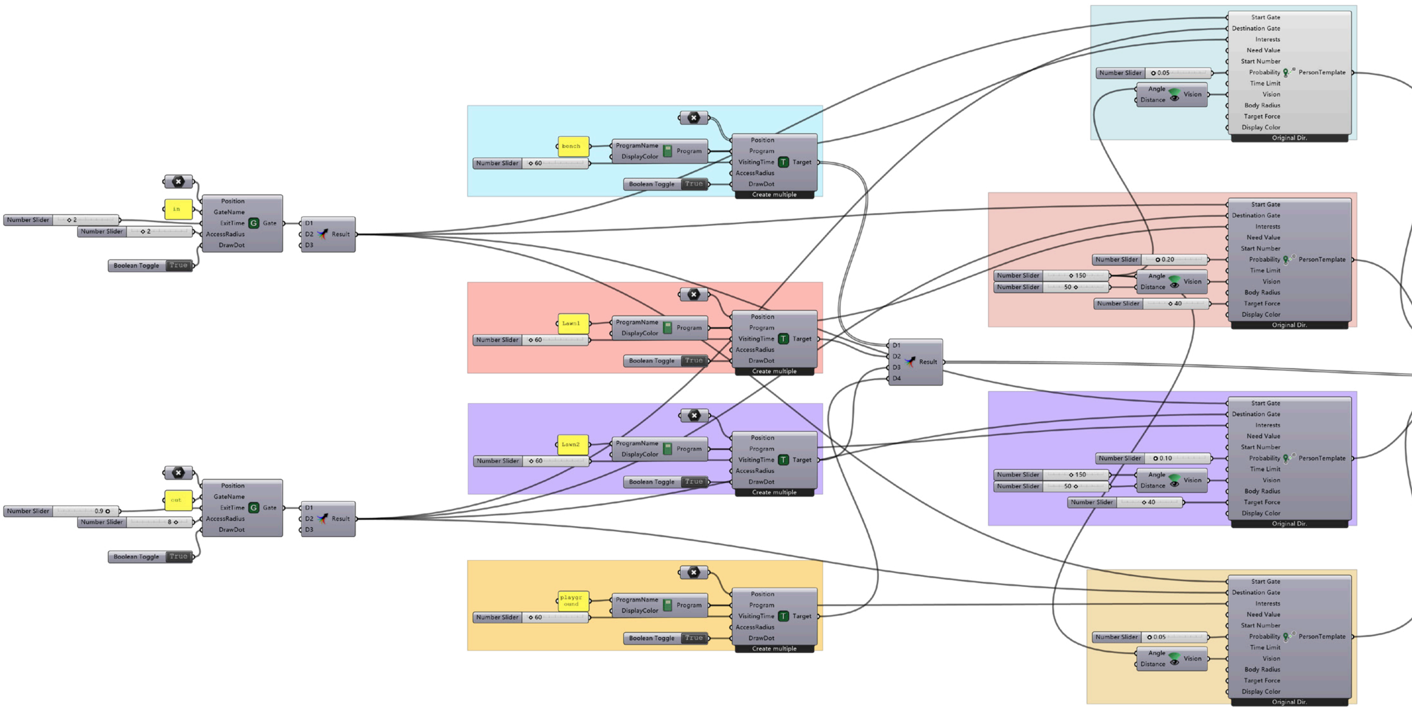
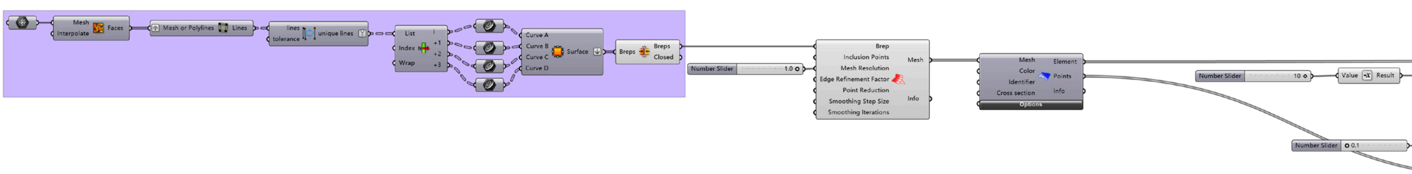
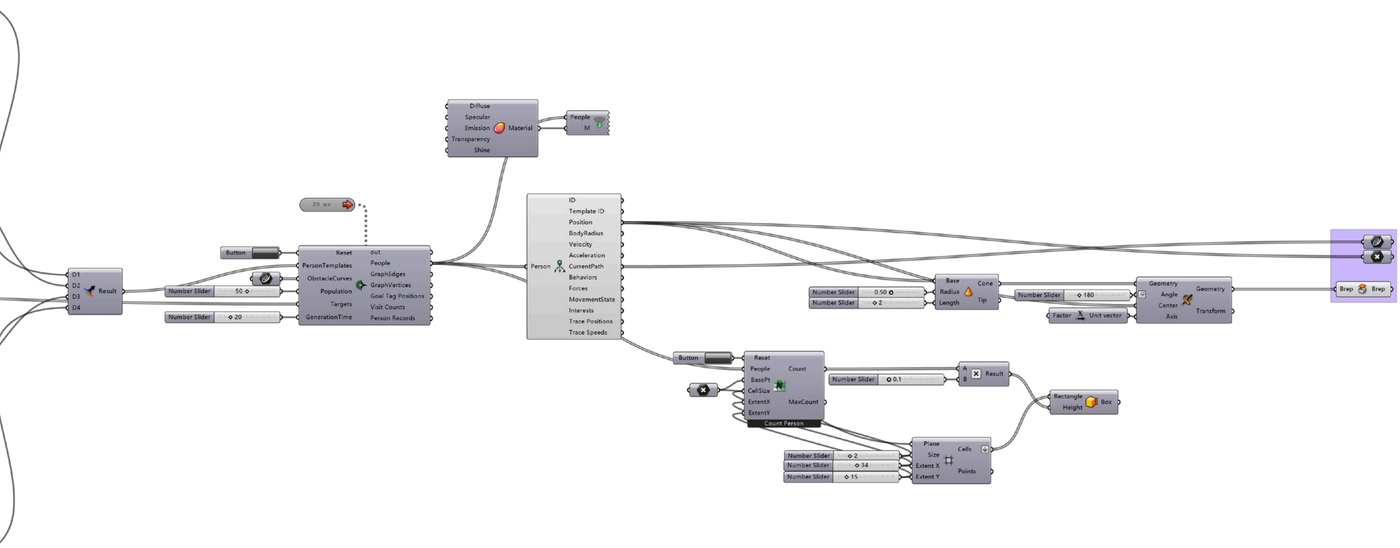
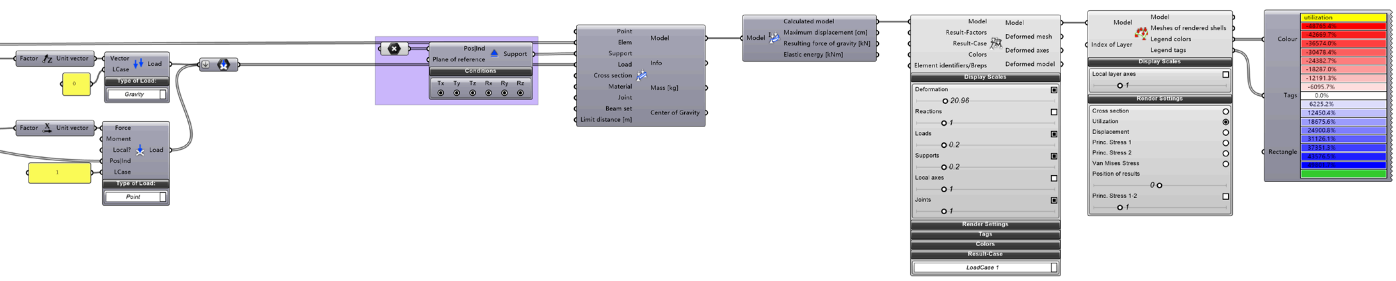
Appendix A The Grasshopper script of the pedestrian simulation



Appendix B The Grasshopper script of loading analysis







Appendix C The Grasshopper script of the parametric joint