FINDING THE KEY:

DESIGNING TIMBER CONNECTIONS FOR CLT PANELS

GABRIELLA JOYCE

figure 01: robot milling

This research was presented at BuildNZ in June 2019 and a Prefab Cluster in August 2019.

The abstract of this research was accepted into the CAADRIA 2020 conference.

 word count: 19182

FINDING THE KEY: DESIGNING TIMBER CONNECTIONS FOR CLT PANELS

Gabriella Joyce

A thesis submitted to Victoria University of Wellington in partial fulfilment of the requirements for the degree of Master of Architecture (Professional)

Victoria University of Wellington

2019

ABSTRACT

In a climate where standard methods of construction are being challenged, developments in engineered timbers are allowing mass timber construction to be explored as a sustainable alternative to traditional building methods. Cross-laminated timber (CLT) is at the forefront of this evolution and, with the advancement in computational design and digital fabrication tools, there lies an opportunity to redefine standard construction. This project explores how digital modelling and advance digital fabrication can be combined to generate a connection system for CLT panels.

The advantages of CLT and mass timber construction are numerous and range from environmental and aesthetic benefits to site safety and cost reduction benefits. There are, however, issues that remain surrounding the connections between CLT panels. Steurer (2006, p.136) stated that, “Progress in engineered timber construction is directly related to developments in connector technology.” This thesis creates connections inspired by traditional Japanese joinery that have been adapted to be used for the panel construction of CLT structures. Using CLT offcuts as a primary connection material, the system not only reduces waste but also mitigates thermal bridging and lowers the number of connection points whilst increasing the ease of building and fabrication.

The connections are first considered at a detail scale. They use the literature review and case studies as a base for design before being tested using digitally fabricated prototypes. These prototypes are evaluated against a framework created in line with the aforementioned criteria. Within this framework, the connections are analysed against existing connection systems as well as previous designs to establish a successful system. The connections are then evaluated within the context of a building scale and considers large-scale fabrication and on-site assembly whilst continuing to focus on the reduction of waste. This research found that the simplicity of the connections is key to a successful system as this allows for faster and cheaper fabrication and installation. However, there is still further research needed surrounding large-scale fabrication and the structural capacity of timber connection systems.

CONTENTS

CHAPTER ONE

INTRODUCTION

1.0 INTRODUCTION

With the climate in a state of emergency, the construction industry needs to take responsibility and move towards a more sustainable built environment. It is one of the biggest contributors to New Zealand's landfill waste and the most commonly used construction materials, concrete and steel, make up 9-12% of global greenhouse gas emissions (Branz, n.d.; Green & Taggart, 2017). One way to reduce the effect of the construction industry on the planet is to increase the use of the most sustainable building material available, timber. It has long been known that timber provides numerous environmental advantages, however, construction and architecture has been limited by the material capacity of natural timbers. Advancements in engineered timber technology has seen the use of timber grow from small scale framed houses to multi-story mass timber construction. Thanks to the advent of panel construction and digital manufacturing and fabrication the industry is poised on the edge of a new standard.

The research focuses on the most commonly used engineered timber, cross-laminated timber (CLT). CLT is made up of layers of glued timber lamellas laid at 90 degrees to each other and compressed to form a structural panel. The cross laminations provide stability in both directions making CLT one of the strongest engineered timbers. The environmental benefits of CLT are evident from its fabrication through to building. It makes use of small, low-grade pieces of timber that would otherwise be waste and is faster, easier and safer to erect on site. It also uses far less CO_2 throughout production and construction than the more commonly used concrete and steel. Though the benefits are many, a key concern within the CLT construction industry is the panel connections.

Thanks to developments in digital and robotic fabrication, there are more opportunities than ever to create a new connection system. The industry is no longer restricted to the ability of hand tools, there are now a plethora of possibilities. This thesis uses computer-aided design (CAD) programs to design and simulate connection systems and a 6-axis robotic arm to prototype and test these designs. The connection design uses a combination of influences from existing systems and traditional Japanese joinery. This design approach allows for the commonly used metal fasteners to be replaced with adaptations of timber connections. Using timber as a primary connection material adds to the environmental benefits of CLT structures as it reduces the amount of metal required in such structures. It also creates a connection system that does not need to be concealed meaning that the CLT structure can remain exposed, creating a beautiful interior space as well as reducing material and cost through the elimination of interior linings.

As the connections are being designed for use in large scale construction, this research also investigates existing CLT factory processes and machinery in order to design a system that can be fabricated within existing environments. Designing with factory fabrication in mind creates a system that not only reduces waste but also looks to re-use it in the most efficient way. This research investigates how digital fabrication and waste reduction can be combined with traditional and existing connection systems to create a timber connection for CLT panels.

RESEARCH QUESTION:

HOW CAN ADVANCE DIGITAL FABRICATION BE USED TO DESIGN TIMBER CONNECTIONS FOR CLT PANELS WITH MINIMAL WASTE?

1.2 AIMS & OBJECTIVES

This research aims to use digital fabrication to create a timber connection system for CLT panels that reduces wastage.

1. Research existing connection systems and timber joinery and define assessment criteria based on this to evaluate design outcomes.

2. Use digital modelling to design and simulate the fabrication of connection system designs.

3. Robotically fabricate prototype designs to test the fabrication of the connections.

4. Explore factory fabrication and existing machinery processes to design for large scale fabrication.

1.3 SCOPE

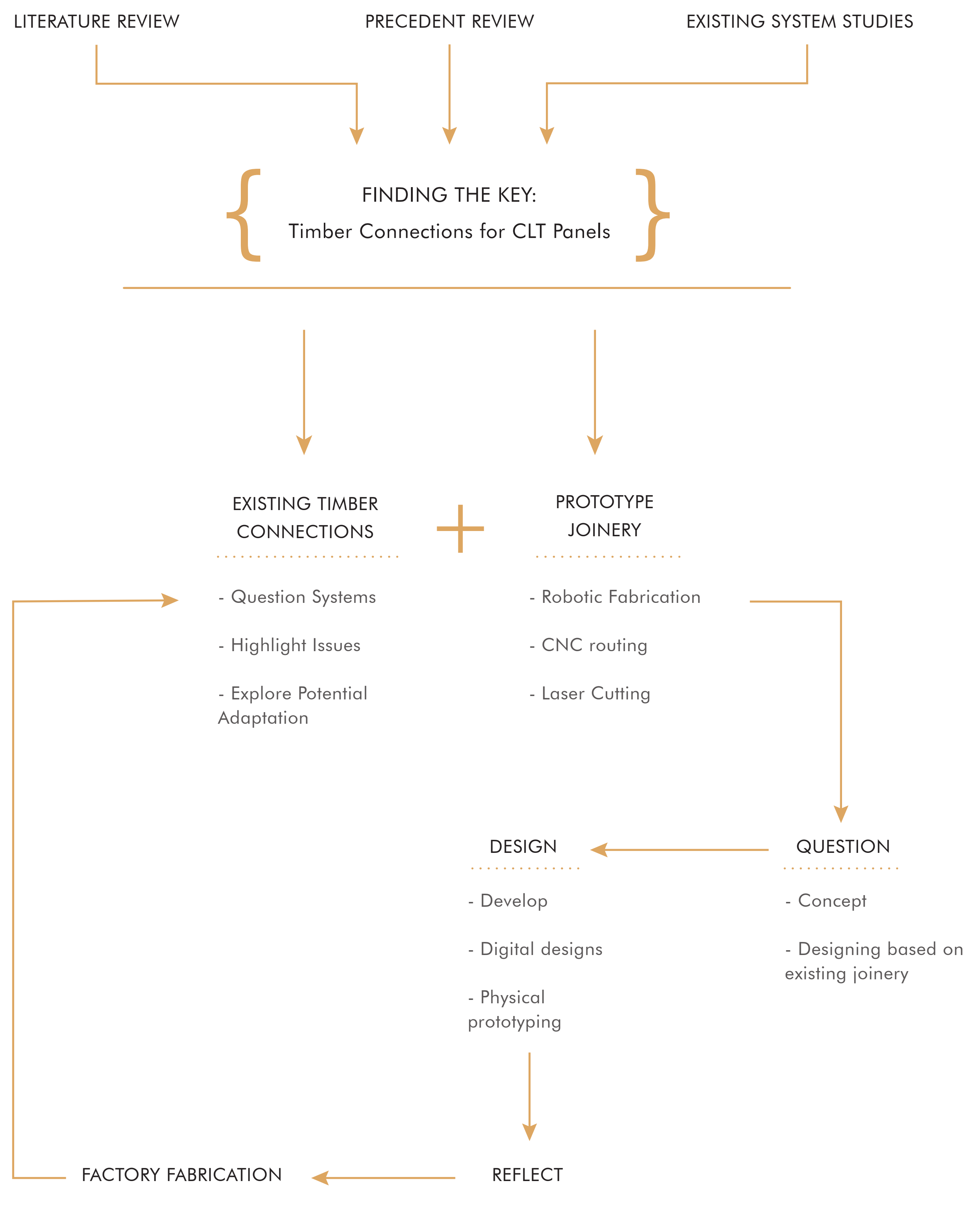
This research focuses on designing a connection system for cross-laminated timber that can be applied at a building scale. The research addressed a gap in the CLT construction process by exploring digital fabrication and waste minimisation. Using influence from existing systems and traditional joinery methods, the design process was explored using robotics to simulate production possibilities. The scope of this research requires the use of prototyping to simulate factory fabrication and serves as a base to show the potential to improve the CLT construction process. Structural testing of the connections lies outside the scope of this research, as does factory-fabricated prototyping due to access and time constraints.

1.4 METHODOLOGY

The primary research method for this thesis followed a research through design approach with a focus on iterative prototyping and evaluation. This approach allowed for continuous exploration of the question through the design process, using it as a tool to conduct research that lends itself to critical evaluation whilst engaging with multiple genres of information. The research process began with a literature review that concentrated on situating the research and identifying key issues with the current CLT construction process. This review led to the evaluation of existing CLT buildings and connection systems in order to create a base for designing an initial connection solution.

Following this, an exploration of initial design ideas and digital fabrication techniques was undertaken. During this time, first stage prototypes were made in order to assess the capabilities of the robot and CNC machine. This process allowed future designs to use these digital fabrication techniques in the most effective way. Throughout this, designs were critically reflected on against case studies, previous designs and defined assessment criteria in order to determine what was successful and what was not. This information was used to inform future designs and select systems to be prototyped and evaluated in detail. The use of prototyping at this stage allowed for an understanding of machine movement and limitations which influenced the subsequent designs.

These designs are further refined following an exploration into factory fabrication which investigates how the designs might be altered to work on a large scale within a real-world environment. By researching fabrication techniques within existing CLT factories the system can be designed to align with processes that are already in place. At each stage of the process, collaboration and communication with others in this area will be key in developing a system that is practical and applicable to the industry. This method situates the research back within the initial literature and highlights the potential to fill the gap that had been highlighted at the start of the thesis.



CHAPTER TWO

LITERATURE REVIEW

2.1.0 INTRODUCTION

The nature of this research means that it looks predominantly at a detail scale and uses a very specific set of tools to accomplish a design outcome. This chapter expands this scale to situate the research within a wider context whilst defining the key drivers of the thesis. Literature is used to explore the following categories:

- Timber Construction
- Mass Timber
- Cross-Laminated Timber
- CLT Connections
- Construction Waste
- Traditional Japanese Joinery
- Digital Fabrication
- Robotic Fabrication

Following this, this chapter returns to the detail and evaluates existing connection systems, both standard and bespoke. This allows for the identification and key issues across multiple connections in which the design section of this research can explore a solution.

2.1.1 TIMBER CONSTRUCTION

For millennia, wood was a fundamental material, the very substance of existence. It still is today, even if it sometimes remains hidden from view (Steurer, 2006, pg 136).

Timber has been used as a primary construction material all over the world for many years and is said to predate stone construction (Mayo, 2015). Before the industrial revolution, wood was used as much as stone and masonry and builders with knowledge of traditional craft were among the most respected craftsmen until the desire for taller buildings and structural innovation were sought after (Mayo, 2015). Concerns about the overuse of wood and the potential to deplete our forests coupled with minimal understanding of its structural capacities and properties have restricted the use of timber to small-scale buildings (Organschi, 2014). Though there is always cause for concern in regards to deforestation, in 2016, New Zealand had an estimated 1,704,747 ha of plantation forest and of this, 45,342 was harvested, or 2.65% (New Zealand Forest Owners Association Inc, 2017). This shows that so long as trees continue to be planted and allow wood to grow, it is a renewable source that will always be available.

The benefits of timber speak for themselves; it is locally available, has a low weight and low thermal conductivity, is a sustainable form of solar energy, is an energy source and is a universal construction material (Jeska & Pascha, 2015; Wegener, 2011). Additionally, the environmental effects, or lack of, when using timber provides more than enough motivation for expanding the use of timber in the construction industry. Wegener (2011, pg 13) writes,

Timber products save on energy and emissions, thereby helping to achieve a recycling-oriented and low-refuse economy. Today's society needs sustainable, natural and multi-purpose forest husbandry and an intelligent plan for the harvesting and use of timber that is efficient in terms of resource and energy – particularly in supplying timber to the construction industry.

The most widely used construction material, concrete, is responsible for 5-8% of global greenhouse emissions, closely followed by steel which accounts for around 4% (Green & Taggart, 2017). These figures include a variety of infrastructure applications (e.g. bridges) but given that in the United Kingdom around half of the carbon emissions come from the construction or use of buildings it is easy to see cause for concern (Waugh, 2014). Wood is the only commonly-used resource that does not use primary energy throughout its formative stages, meaning less CO2 emissions, whilst also requiring no interference as it is completely self-sufficient (Steurer, 2006). The environmental benefits of timber are furthered by the fact that the carbon storage becomes long-lasting when wood is transformed into building products whilst trees planted in their place soak up new carbon and release oxygen back into the environment (Green & Taggart, 2017; Waugh, 2014).

Over forestation remains an issue but the implementation of sustainable forest management (SFM) practices and principles into major wood-producing countries is looking to remedy this. SFM aims to ensure the quantity of wood harvested does not exceed what is grown annually, whilst also conserving and maintaining biodiversity and the productive capacity of forest ecosystems amongst many other focuses (Green & Taggart, 2017).

figure 02: forest cover

“The more timber we use, the better it is for the environment.”

- Waugh, 2014, pg 27

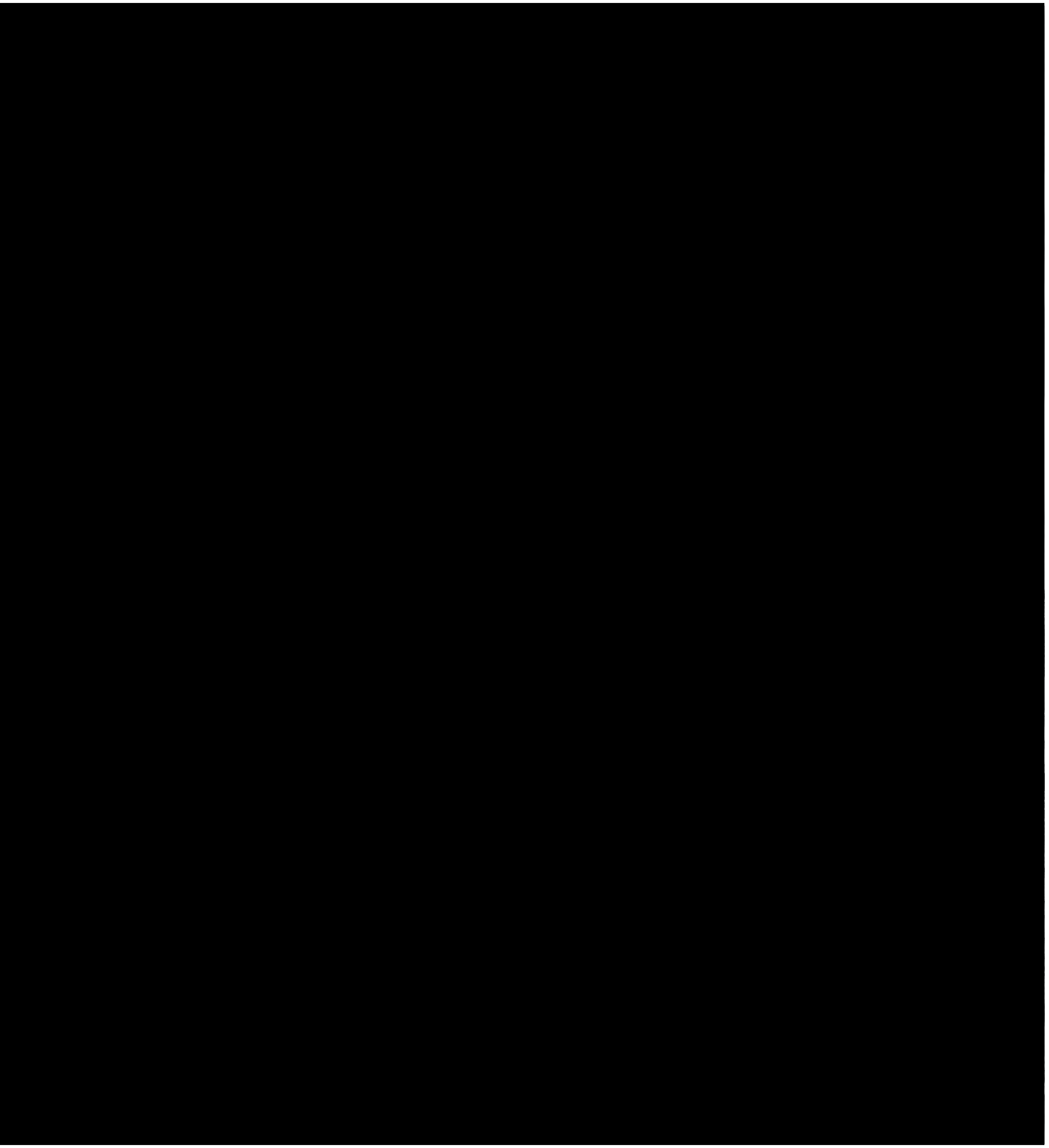


figure 03: Dalston Lane, London

2.1.2 MASS TIMBER

Expanding the use of materials with low embodied energy, such as timber, within the construction industry will help to reduce our impact on the environment that is already suffering the effects of climate change (Smith, Griffin, Rice, & Hagehofer-Daniell, 2018). This is where mass timber construction (MTC) comes in.

MTC is a building method that uses engineered wood as the primary structural material as opposed to the more common concrete and steel (Kremer & Symmons, 2015). It consists of off-site fabricated elements that are manufactured and pre-assembled before being delivered to the construction site (Smith et al., 2018). The development of MTC has been possible thanks to innovation in timber products that are known as engineered timber. These include glue-laminated (glulam), laminated veneer (LVL), laminated strand (LSL), parallel strand (PSL), nail-laminated, dowel laminated and cross-laminated timber. Engineered timber products are produced by bonding wood strands, veneers and small sections of solid timber to form a larger composite that is stronger than each individual part (Green & Taggart, 2017). Because these products use wood fragments as opposed to solid lumber, it can recycle timber that has already been used and then can be recycled itself (Kremer & Symmons, 2015).

Now, thanks to the availability of digital tools, application of this material can be expanded significantly, new geometries can be created; and innovative construction materials and methods can be developed. In short, we can undertake an innovative exploration of structural engineering with regard to timber (Weinand, 2016, pg 7).

The benefits of MTC are numerous, studies have shown that on average it is 4.2% cheaper to build over traditional construction though, this is still variable due to ever-changing technologies. It is, however, easier to control costs thanks to the reduced number of changes in MTC projects (Smith et al., 2018). It has also been shown that MTC projects are on average 20% quicker than traditional builds and when on-site, have reduced noise and traffic levels thanks to off-site customisation (Kremer & Symmons, 2015; Smith et al., 2018). Site and material waste is also decreased as a result of precise manufacturing and adding value by using lower quality timber in higher-value applications (Smith et al., 2018).

There is always the fear of fire when building with timber, and MTC is no different, yet the properties of the engineered timbers meet and usually exceed standard fire requirements. This is due to the size of the engineered panels when faced with fire the timber forms a protective char layer on the surface leaving the core, and structural integrity, intact (Waugh, 2014). The structural performance of MTC projects is achieved through the strength of the large engineered timbers yet thanks to the strength to weight ratio of wood, they also perform well under seismic stress as there is less mass (Tomasi & Pasca, 2017). These benefits are particularly evident when using cross-laminated timber which is the focus material of this thesis.

2.1.3 Cross Laminated Timber

Cross-laminated timber (CLT) is at the forefront of developments in mass timber construction and has become the material of choice for many projects. CLT was first produced less than 25 years ago in central Europe and Scandinavia and uses a wide range of species and grades of timber to allow for high-performance applications and high strength (Waugh Thistleton Architects, 2018). Developed as a way to reduce waste in sawmills, CLT has the ability to use what would be a wasted resource as well as making use of smaller, lower-grade pieces of timber whilst ensuring the same strength as that of a higher grade panel (Mayo, 2015). CLT consists of layers, usually 3, 5 or 7, of timber bonded at 90 degrees to each other which creates a panel that can be used for walls, floors, and roofs. This panel form differs from the common timber frame as it allows the structure to take forces both in-plane a perpendicular to the plane (Silva, Branco, & Lourenço, 2013).

The crossing of the boards provides relatively high strength in both directions which produces a high axial load capacity and high shear strength along with good thermal, acoustic and fire performance thanks to the solid nature of the panels (Taylor, 2013). The crossing also allows for the interlocking of the plies which reduces the shrinking and swelling of the timber making it insignificant (Jeska & Pascha, 2015). This also provides stability that creates high tolerances for application in prefabricated construction (Mayo, 2015). The panels come in a variety of sizes but can have lengths of up to 16-20m and widths of up to 3m with thicknesses of up to 500mm (Kuilen, Ceccotti, Xia, & He, 2011).

“Prefabricated CLT building systems are easily erected in a low-dust, low-noise assembly with minimal site waste” (Harte, 2017, pg 121) CLT buildings offer advantages to developers, designers and builders for reasons including; reduced construction programme durations, lighter weight structures, customisation, waste minimisation and safer working environments on-site (Wood Solutions, 2012). Many of these advantages can be attributed to the fact that large amounts of the manufacturing and construction process is done off-site. These advantages are reinforced by Waugh Thistleton Architects (2018, pg 5) who wrote,

> The benefits are clear - building in timber is quick, clean, and easy. It can be achieved with a measured accuracy and lack of noise, waste, or need for material storage space. It has notable benefits in terms of warmth, acoustics, and structural efficiency. The only surprise to us is that the uptake in mass timber has not been faster.

Adding to this, developments in timber engineering have led to a composite system of post-tensioned timber or pres-lam. This is a system developed in New Zealand that is comprised of steel post-tensioned rods inserted within the panel which allows for long spans and high seismic resistance (Mayo, 2015). With ongoing research into this hybrid technology, it is clear that there is a movement to embrace mass timber construction.

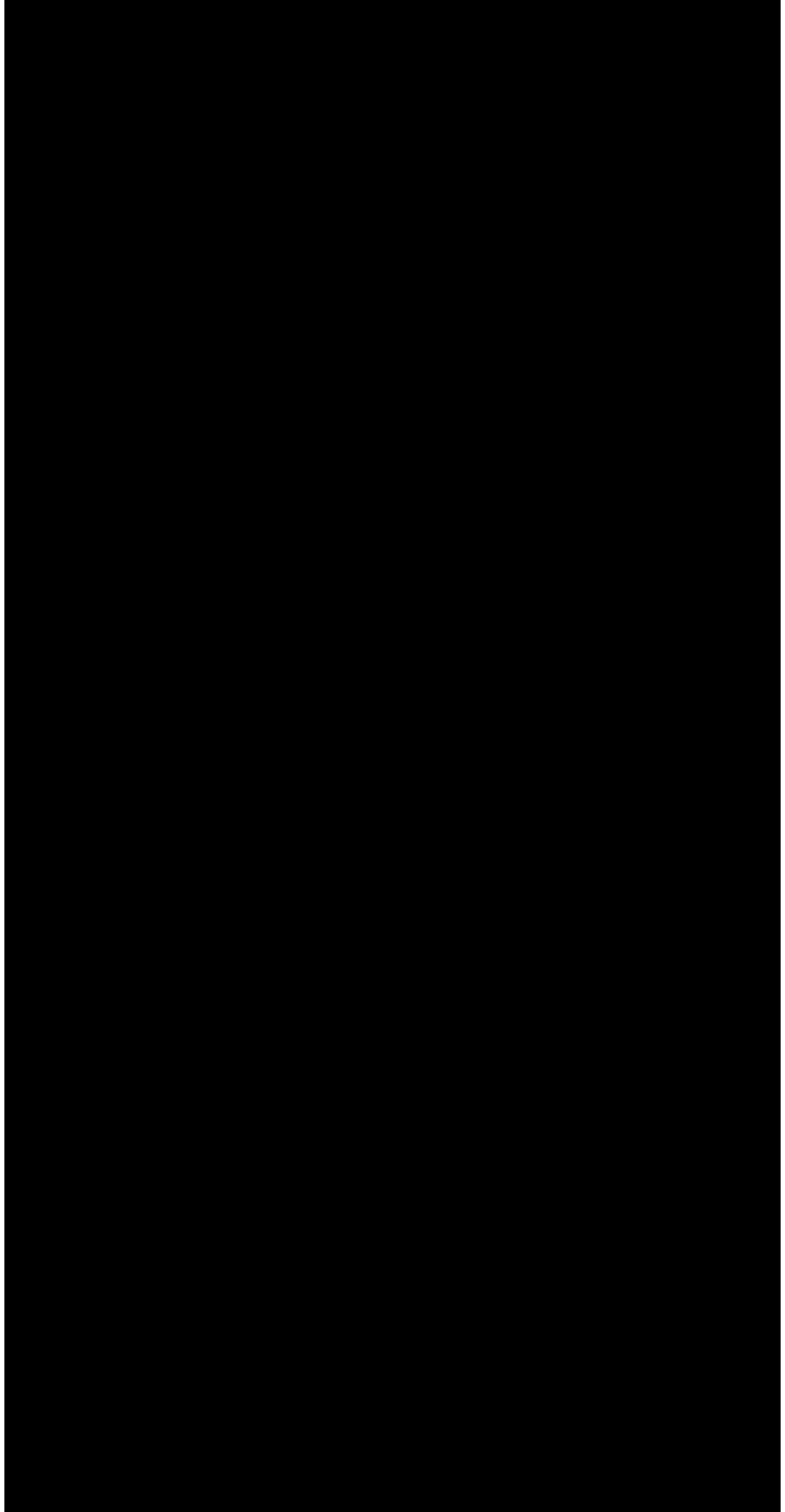


figure 04: Cross Laminated Timber

> PROGRESS IN ENGINEERED TIMBER CONSTRUCTION IS DIRECTLY RELATED TO DEVELOPMENTS IN CONNECTOR TECHNOLOGY.
>
> - STEURER, 2006, PG 136

figure 05: metal fastener

2.1.4 CLT CONNECTIONS

Though there are many benefits of CLT, it is a relatively new material and one that still has room for improvement. Ringhofer, Brandner, & Blaß (2018, pg 850) wrote, "CLT is in the process of catching up two very important steps: standardization and development of optimised connection type; the latter area still offers a lot of room for further developments and improvements." Through their research into dowel-type fasteners for CLT connections, they found that CLT panels have high stiffness and high resistance to shear, tension, and compression, meaning that the ductility and energy dissipation of the structure has to be provided by the connections.

It is important to also understand the qualities of wood as a raw material in order to understand its engineered counterpart. When put under seismic stress, timber buildings provide high levels of safety due to their light weight, as the forces acting on any building are proportional to its weight, less weight means less force (Tomasi & Pasca, 2017). Given this high strength and low mass, timber does not perform as well under tensile stresses reinforcing the conclusion that the ductility of the structure has to be in the connections. The key is in ensuring that the plasticizing of the joints, or ductile element, takes place before the brittle element, the timber, fails (Bruhl & Kuhlmann, 2017).

The jointing systems for CLT are currently made up of common fasteners that have been adopted from use in light-weight timber construction, they use both angle brackets and hold downs to resist both shear and uplift forces within the building (Ringhofer et al., 2018).

When investigating the behaviour of angle bracket connections in CLT structures, Pozza, Saetta, Savoia, & Talledo (2018) found that for mid and high-intensity actions (such as earthquakes) the energy dissipation within the structure is largely concentrated in the connections. It is important to consider the geometry of the connections, how they fasten and how they are anchored within the structure (Izzi & Fragiacomo, 2018). Weinand (2016) wrote, "when designing a timber building, it is imperative to consider the junctions, which are integral to the structure, and to specify the entire structure, including its joints."

Research undertaken by Jockwer, Fink, & Kohler (2017, pg 17) that looks into the failure modes of existing connection systems reinforces the previous statements by stating, "The structural performance of a timber structure is considerably influenced by the performance of the connections between the individual structural members. These connections are often the cause of failure of timber structure" adding that, "For a reliable design of connections the entire system of the individual members of the connection has to be assessed."

Additionally, Brunauer (2017, pg 6) wrote, "connections determine the cost of a structure. Their related influence increases disproportionally with the number of joints in the single structural member," Based on these factors, it is clear that the connections play a key part in ensuring the safety of the building system as well as having an effect on the cost of the building. "An attempt should be made to create made-to-measure prefabricated systems incorporating connection technologies and precise prefabricated elements" (Weinand, 2016, pg 10).

figure 06: construction wastage

2.1.5 CONSTRUCTION WASTE

Waste related to the construction industry is commonly thought to be one of the largest contributors to landfills internationally. It is often stated that construction and demolition waste makes up 17% of total landfill in New Zealand (Storey, Gjerde, Charleson, & Pedersen Zari, 2005). However, this figure does not account for clean fill dumps which are recognised as the most common receptor of construction and demolition waste (Storey et al., 2005). In reality, construction and demolition waste could account for up to 50 % of all waste in New Zealand, with 20% of this is landfill and 80% in clean fill (Branz, n.d.).

"Construction waste is defined as the by-product generated and removed from construction, renovation and demolition workplaces or site of building and civil engineering structure" (Tam, Tam, Zeng, & Ng, 2007, pg 3642). Construction and demolition waste is predominantly comprised of offcuts, packaging, surplus material, formwork, protection materials and damaged materials (Branz, n.d.). These waste items come from many material sources such as wood, concrete, steel, brick, plasterboard, glass, plastics and more, however, it is estimated that concrete, plasterboard, and timber make up 81% of all construction and demolition waste (Inglis, 2007).

There are many factors that contribute to the wastage of materials. A study conducted by John & Itodo (2013) identified that the dominant factors that contribute to on-site waste are; poor supervision, re-work and poor material handling, closely followed by design errors and inadequate worker skill. This study also showed that material wastage contributes an average of 21-30% to the cost overrun on a project and therefore any effort to minimise waste would be beneficial (John & Itodo, 2013). Efforts are being made to reduce waste, namely, the Ministry for the Environment has developed the Resource Efficiency in Building and Related Industries (REBRI) as a set of guidelines to reduce waste from construction and demolition (Inglis, 2007).

There are many environmental issues related to the wastage of construction materials, the space required to house landfills is just one. If the construction industry continues to proceed as it is now, (Mah, Fujiwara, & Ho, 2018, pg 347) states that "the environmental impacts caused by landfilling of construction and demolition waste is estimated to increase 20.2% by 2025." Waste items in landfill are not being recovered and, as they break down, are leaching chemicals into the soil and waterways as well as releasing methane into the atmosphere (Branz, n.d.). It is possible to re-use a large amount of this waste through designs that support adaptation, disassembly, and reuse of materials, or, where this is not possible, through recycling, which is possible with the use of the right technology (Mah et al., 2018).

Using the three main contributors as examples it is evident that, although each is different, the combined effect of sending these to landfill is extremely hazardous to the environment. Plasterboard is biodegradable but releases leachate and gas whilst breaking down (Level, n.db). Concrete is inert but large volumes can fill up a landfill very quickly, requiring more and more space to send waste (Level, n.da). If untreated, timber it is biodegradable but releases CO_2 into the atmosphere when degrading, CCA-treated timber has to be disposed of in hazardous material areas to isolate the waste and contain leachates so as not have as big of an effect on the environment (Level, n.dc).

It is clear that waste within the construction industry is an issue, and though there are systems of waste management and minimisation in place, it important to consider the lifecycle of not only the material but the building too. If wastage is addressed in the design phase it is possible to reduce the amount of material that is required and wasted.

2.1.6 Traditional Japanese joinery

Many parts of the Japanese way of life rely on their strong connection to nature and the belief that humankind cannot be separated from nature (Locher, Simmons, & Kuma, 2010). Construction in Japan is no different. "They integrate relations between man, nature, material and the creative will to form a harmonious whole (Blaser, 1963). With an abundance of wood in Japan, this naturally became the primary construction material, coupled with its ability to withstand natural forces such as typhoons and earthquakes it is easy to see how it became so widely used (Seike, 1977). Sadler (2009) wrote, "The character of the land with its abundance of timber and the natural taste of the inhabitants for this medium have combined to present us with the most advanced wooden architecture in the world."

The Japanese are famous for their attention to detail, quality of craftsmanship and woodworking techniques, something that is unsurprising given that the construction is rarely hidden and surface materials are left plain (Sadler, 2009). Having spent hundreds of years perfecting the art of wood construction in a fairly volatile climate, the Japanese have also become renowned for their earthquake-resisting construction. A lot of the strength in the Japanese construction methods comes from the beautifully refined joints and connection techniques, it is these that the Japanese are most famous for.

Traditional Japanese buildings are renowned for the fine craftsmanship of the timber structure and wood details, especially the complex joinery (Locher et al., 2010, pg 65)

The intricacies seen in these connections are only found when the construction has been carefully planned and executed to the highest standard (Blaser, 1963). It also relies on extensive knowledge of the material and the way in which it reacts in various situations. The Japanese understand that due to wood being natural, it will always respond to changes in nature, expanding and contracting as the humidity fluctuates (Seike, 1977).

There are many different connection types that have been developed, each with a different purpose and construction method. The connections are split into two categories, splicing joints or tsugite, and connecting joints or shiguchi (Seike, 1977). Splicing joints are used to join shorter lengths of timber to create long posts and beams meaning it is not necessary to find a single long piece of timber (Seike, 1977). Splice joints can come in many forms however commonly employ tenons, such as dovetails, laps, and pins or keys to lock the joint together (Sumiyoshi & Matsui, 1991). Connecting joints are used to join timbers at an angle with the most common being the mortise and tenon (Seike, 1977). Connecting joints often employ wedges and housed dovetails tenons to secure the joints and can be designed to be hidden or exposed (Sumiyoshi & Matsui, 1991).

Though there are differences between the joint types, there are similarities between them, primarily, the fact that both connection types require a snug fit to ensure the strength of the joint (Sumiyoshi & Matsui, 1991). This is where thorough knowledge of the material is critical, as the moisture content in the joints increases it causes the members to increase in size which tightens the joint allowing it to become one (Seike, 1977). When external forces are applied to these joints, the energy is reduced thanks to the friction within them meaning a large amount of the energy is absorbed here avoiding the rest of the structure (Seike, 1977).

The Japanese have clearly mastered woodworking and have proven the success of their connection systems though there are few people with the excellent craftsmanship required to produce such joints. With advancements in technology allowing access to previously unseen tools, it may be time to redefine what it means to be the expert craftsman.

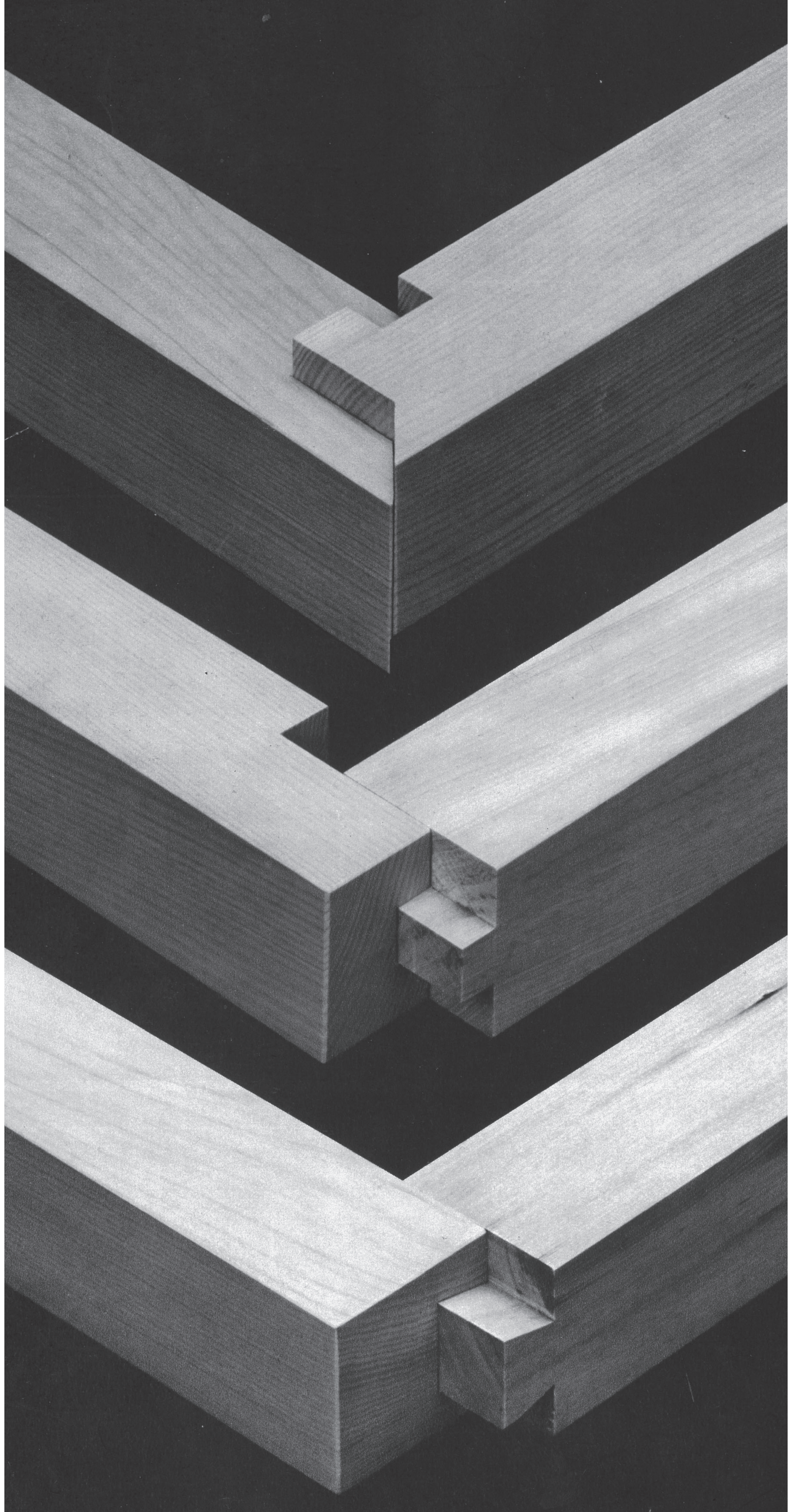


figure 07: dovetail lap joint, scarf joint w/ tenons, stun tenon joints, cross stub tenon

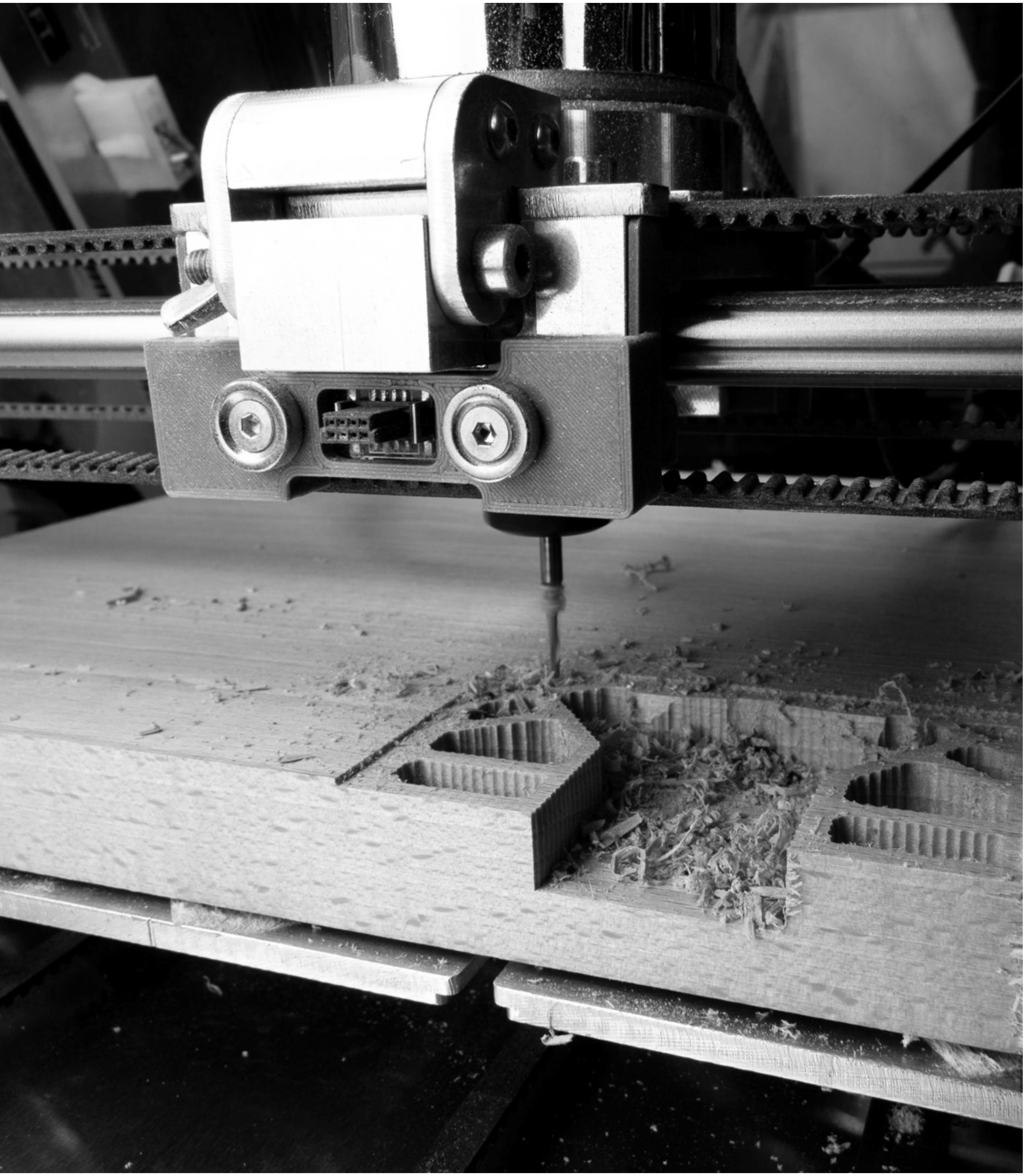


figure 08: CNC machining

2.1.7 Digital Fabrication

The digital age has radically reconfigured the relationship between conception and production, creating a direct link between what can be conceived and what can be constructed. (Kolarevic, 2003, pg 31).

The beginning of the 20th century saw a change in construction that adopted industrial manufacturing processes which allowed for the prefabrication of building elements and standardised housing. The beginning of the 21st century is seeing another change in the way we build – one that is led by digital fabrication and robotics (Bock & Langenberg, 2014). Exploration into digital fabrication began in 1962 when MIT researchers paired an early computer with a milling machine, creating the first machine controlled by a computer instead of man (Gershenfeld, 2012). Since then, advances in technology have seen the use of machines such as laser, plasma arc, and water jet cutters along with CNC milling machines become commonplace with computer-aided design (CAD) taking hold of the industry (Kolarevic, 2003).

"Each time the architectural production technology changes; then architecture changes as well" (Agkathidis, 2010, pg 118). The common use of digital tools, such as CAD, in architectural practices is allowing for new forms of architecture to be designed and manufactured (Hudert, 2010).

The tools we use today are digital - their impact on our time is undeniable. It is always the case with whatever we create - the tools are somehow and undeniable part of the product. These new tools give us new ways of seeing, new eyes - possibly a new future - almost to the point where one can think digitally. (Macfarlane, 2003, pg 183)

Architects have always drawn what could be built or built what could be drawn but with the advent of CAD and digital fabrication, architects can design for the machines and push the capabilities of construction (Kolarevic, 2003). This new 'digital workflow' means that designing and building are no longer separate, they can be seen as one process that allows architects to break old boundaries of form and geometry (Agkathidis, 2010; Kloft, 2010).

Digital fabrication methods can be separated into cutting, subtractive fabrication, additive fabrication, and formulative fabrication, with each offering different opportunities for the exploration of new geometries (Kolarevic, 2003). Although each type of fabrication is different, they all have the ability to do whatever they are instructed to do. "A computer-controlled (CNC) fabrication machine does not care whether it is producing a thousand similar or a thousand different work-places" (Scheurer, 2012). This digital manufacturing, the pairing of CAD and computer-aided manufacturing (CAM), is establishing a seamless relationship between design and production (Hudert, 2010).

Variety no longer comprises the efficiency and economy of production
(Kolarevic, 2003, pg 52).

2.1.8 Robotic fabrication

Despite digital fabrication, as we know it now, being a fairly recent development (within the last 15 years) it has already seen many changes (Dunn, 2012). "Over the past decade, robotic fabrication in architecture has succeeded where early digital architecture failed: in the synthesis of the immaterial logic of computers and the material reality of architecture" (Gramazio, Kohler, & Willmann, 2014, pg 14). The change means that architects can conceive designs both digitally and physically and allows different questions to be asked. Instead of asking whether something can be built, the question is now, what instrument is needed to build it (Kolarevic, 2003).

Although industrial robots have been widely used in mass manufacturing since the 1970s, the field of architecture has only been exploring their potential for the last twelve or so years, but they have already transformed practices and the scope of designers (McGee, Velikov, Thün, & Tish, 2018). Robotic production is not focused on one machine but takes a more holistic approach allowing design, material, manufacture, and assembly to be a single process that can be manipulated and re-defined at any stage (Daas & Wit, 2018). New industrial robots are versatile, they can accomplish a wide range of tasks and be freely designed and programmed, with the ability to work with any tool there is a new level of flexibility when it comes to fabrication and assembly (Daas & Wit, 2018; Gramazio et al., 2014).

Robotic arms have the ability to work in many axes to accomplish a range of tasks and can work alone, with other robots and even with humans (Daas, 2018). Robots have an almost unlimited number of applications, from material handling and milling to spot welding and printing (Dunn, 2012). This is both positive and negative, it requires the user to have a clear idea of what is needed. "Knowing where to focus the complexities and where to keep things simple is about astute design decision-making" (Rabagliati, Huber, & Linke, 2014, pg 49).

For the last 20 years, the timber sector has been at the forefront of digital fabrication in the building industry, commonly using 3 to 5 axis CNC machines so it provides an ideal market for further development (Stehling, Scheurer, & Roulier, 2014).

Specifically in timber construction, industrial robots can provide higher degrees of kinematic freedom and fabricational flexibility in comparison to established and process-specific CNC wood working machines, and therefore offer the opportunity for new design and fabrication strategies or else the reinterpretation and re-appropriation of existing techniques - both of which offer the potential for novel architectural systems. (Schwinn, Krieg, & Menges, 2012, pg 49).

Robotic fabrication provides an opportunity to combine computer-controlled systems with traditional woodworking machines such as rotary blades and milling cutters to reimagine the way in which we use wood (Menges, 2011). Thanks to the efficiency and precision providing by digital manufacturing systems, there is the opportunity to reuse traditional timber connections such as dovetails, pegs and lap joints which have since been replaced by fixing plates and other metal and engineered solutions (Stehling et al., 2014).

The employment of robotics in architecture is opening up the prospect of entirely new aesthetic and functional potentials that could fundamentally alter architectural design and the building culture at large (Gramazio et al., 2014, pg 14).

figure 09: ABB Robot at Victoria University

2.2.0

PRECEDENT REVIEW

2.2.1 TAMEDIA OFFICE BUILDING

GENERAL INFO

Zurich, Switzerland
Shigeru Ban Architects
2013
(Green & Taggart, 2017)

INTEREST AREA

The connection between the beams and columns demonstrates the ability to create Japanese inspired joints through digital fabrication as well as showcasing the structural capacity of timber.

(Cohn, 2014)

figure 10: Tamedia Office Building structure

figure 11: Japanese inspired connection

2.2.2 WOOD INNOVATION & DESIGN CENTRE

GENERAL INFO

Prince George, Canada
Michael Green Architecture
2014
(Green & Taggart, 2017)

INTEREST AREA

The CLT floor panels are staggered in a corrugated arrangement to allow for the transportation of services removing the need to cover the natural wood.

(Bernheimer, 2014)

figure 12: Column to beam connection

figure 13: Corrugated CLT floor

2.2.3 BJERGSTED FINANCIAL PARK

GENERAL INFO

Stavanger, Norway
Helen & Hard
2019
(Helen & Hard, n.d.)

INTEREST AREA

The CLT floor structure is supported by a frame of double LVL beams and columns that is achieved with all connections made using beech timber dowels as the jointing method.

(Helen & Hard, n.d.)

figure 14: Bjergsted Financial park render

figure 15: Timber dowel connection

2.2.3 MT PLEASANT COMMUNITY CENTRE

GENERAL INFO

Christchurch, New Zealand
Chris Moller Architecture+urbanism
2013
(CMA+U, n.d.)

INTEREST AREA

The use of exposed timber panels and the way in which they show off the metal screws and bracket connections that make up the structure as part of the aesthetics of the building.

(CMA+U, n.d.)

figure 16: Exposed brackets on timber wave

figure 17: Screw fixings joining panels

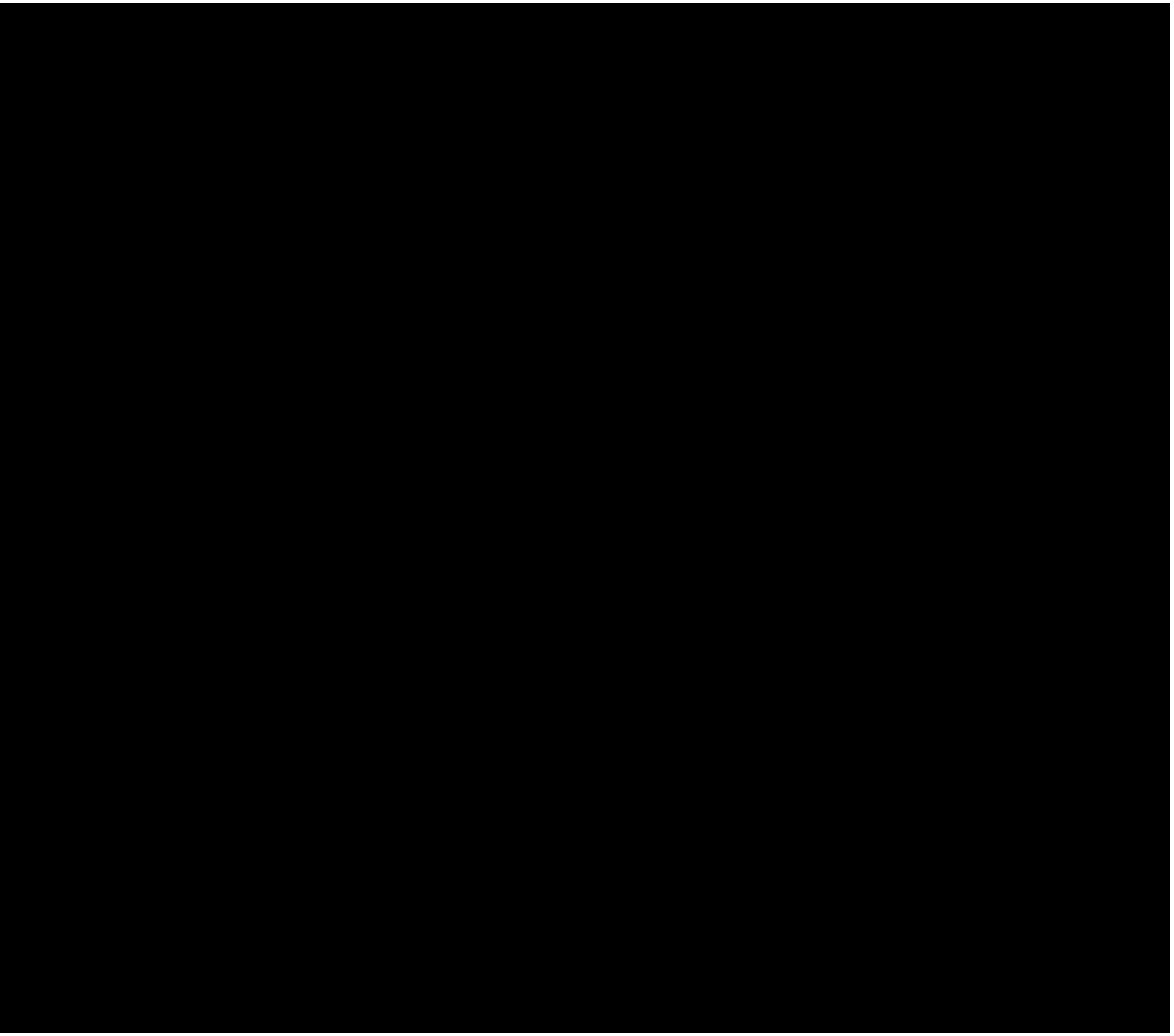


figure 18: Murray Grove, Waugh Thistleton

2.3.0

EXISTING SYSTEMS STUDIES

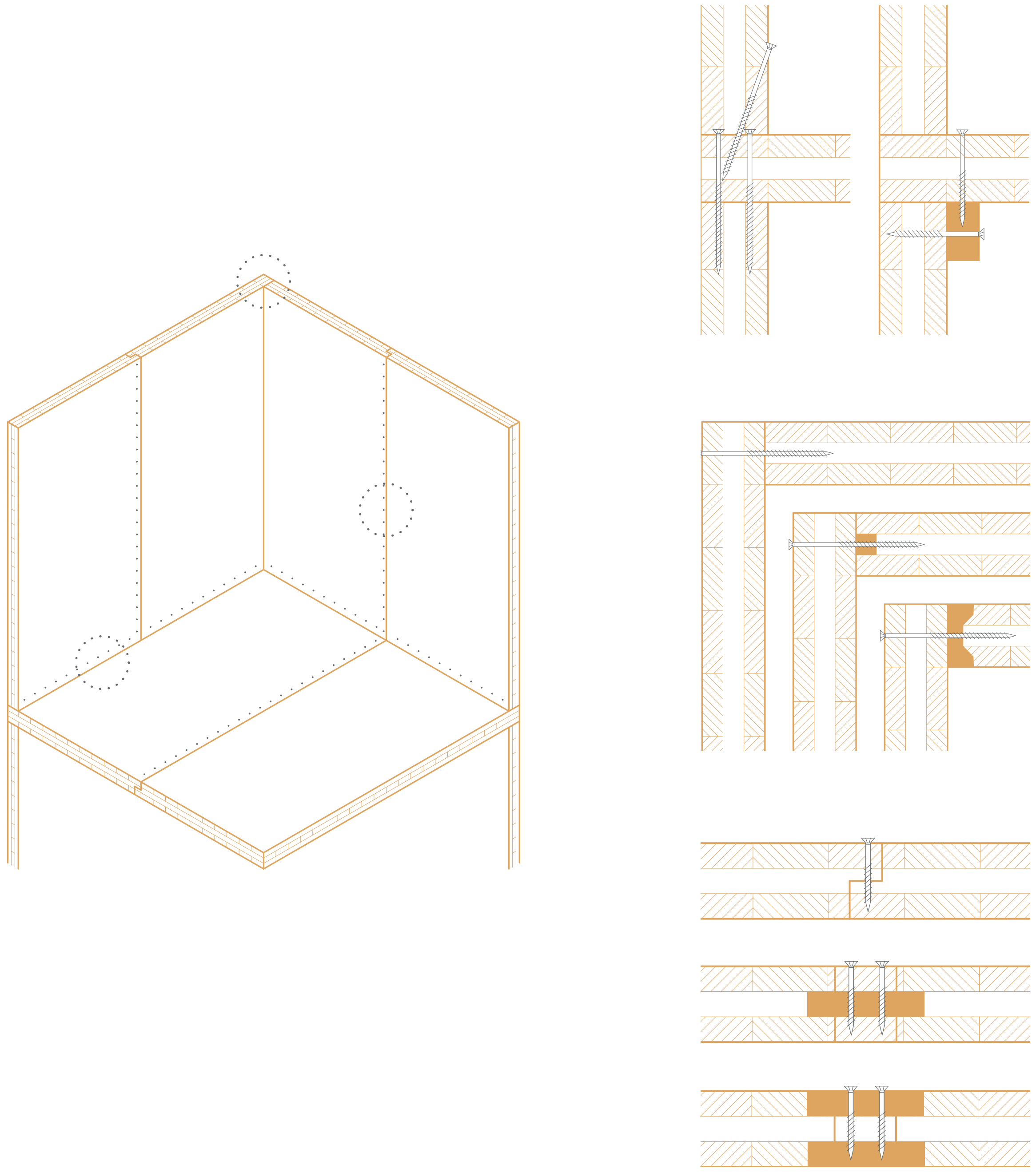


figure 19: (left) dowel-type connection system, (top) wall to floor, (middle) wall to wall, (bottom) panel to panel

2.3.1 DOWEL TYPE FASTENERS

Dowel type fasteners are the most common form of connection at the moment, paired with bracket connections, they make up the majority of connections for CLT buildings. They have been adapted from traditional timber buildings and employ the use of self-tapping screws, dowels or nails at regular intervals to join panels (Ringhofer et al., 2018). Lots of research has been conducted into how effective these connection systems are within CLT structures. This has revealed that differentiating between the side and narrow faces is mandatory and that although huge efforts have been made to adapt current connection systems to CLT there is still no adequate solution (R. Brandner, Flatscher, Ringhofer, Schickhofer, & Thiel, 2016).

The most commonly used dowel type fastener is self-tapping screws. These are usually combined with plywood or LVL splines or lapping of the CLT for increased stability (Mohammad, 2011). This system is popular as it is easy to install and is simple, structurally efficient and cost-competitive however, there are still issues (Mohammad, 2011). The simplicity of the system means there is no need for special training yet special consideration has to be given to the potential for splitting, brittle failure modes and the angles in which screws are inserted. Though the system is successful it is by no means the most effective way to build as it requires a large amount of labour as well as assistance from other connection methods such as brackets.

2.3.2 BRACKET CONNECTIONS

As previously mentioned, bracket connections make up a large number of connection systems used in CLT construction. Mostly used in conjunction with dowel type fasteners, they provide the stability that screws and dowels cannot. Whilst self-tapping screws are successful in panel to panel connections, they need additional support when used in wall to floor or wall to wall connections (Mohammad, 2011). Again, there has been extensive research in this area, specifically using experimental tests to explore the lateral and axial displacements when using angle bracket connections (Pozza et al., 2018). The angle brackets prevent horizontal sliding and uplift of the structure which is critical during events such as earthquakes and high winds (Tomasi Roberto & Smith Ian, 2015). The energy dissipation of CLT structures is focused in the connections which causes three main failure modes; pull-out failure, block failure and, bracket fracture (Shen, Schneider, Tesfamariam, Stiemer, & Mu, 2013).

Being one of the most commonly used systems, angle brackets are well known and easy to install resulting in ease of construction. However, like dowel type fasteners, the construction process is labour intensive and requires many anchor bolts and self-tapping screws to be manually put into place. Another key drawback is the aesthetics. The metal brackets have to be installed at regular intervals and quickly become an eyesore that needs to be covered, requiring extra labour and cost to do so. The metal systems also do nothing for the thermal qualities of the space, adding countless thermal bridges that, although small, contribute to the diminishing thermal comfort of the space. These two factors create a large gap in the overall success of this connection method despite its structural ability.

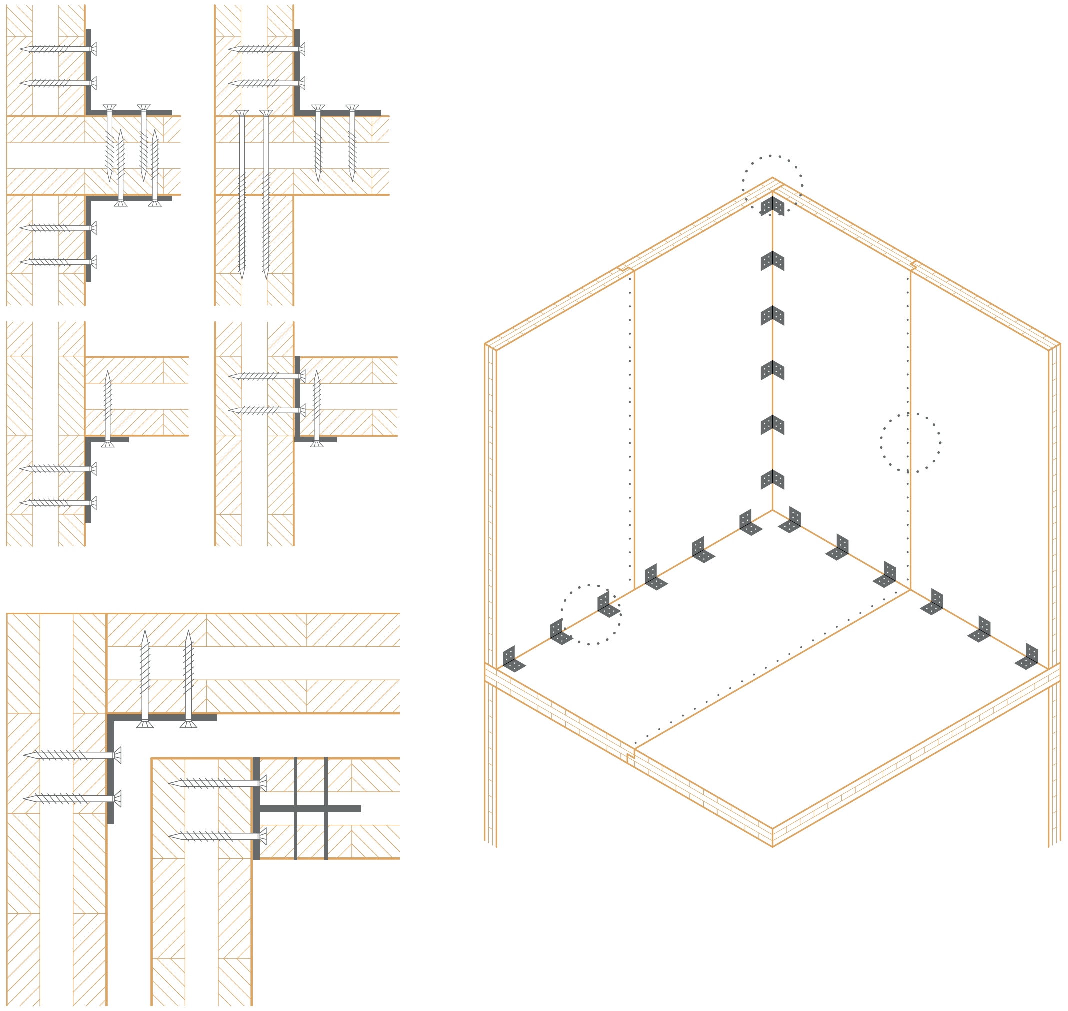


figure 20: (top) wall to floor, (left) wall to wall, (right) bracket connection system

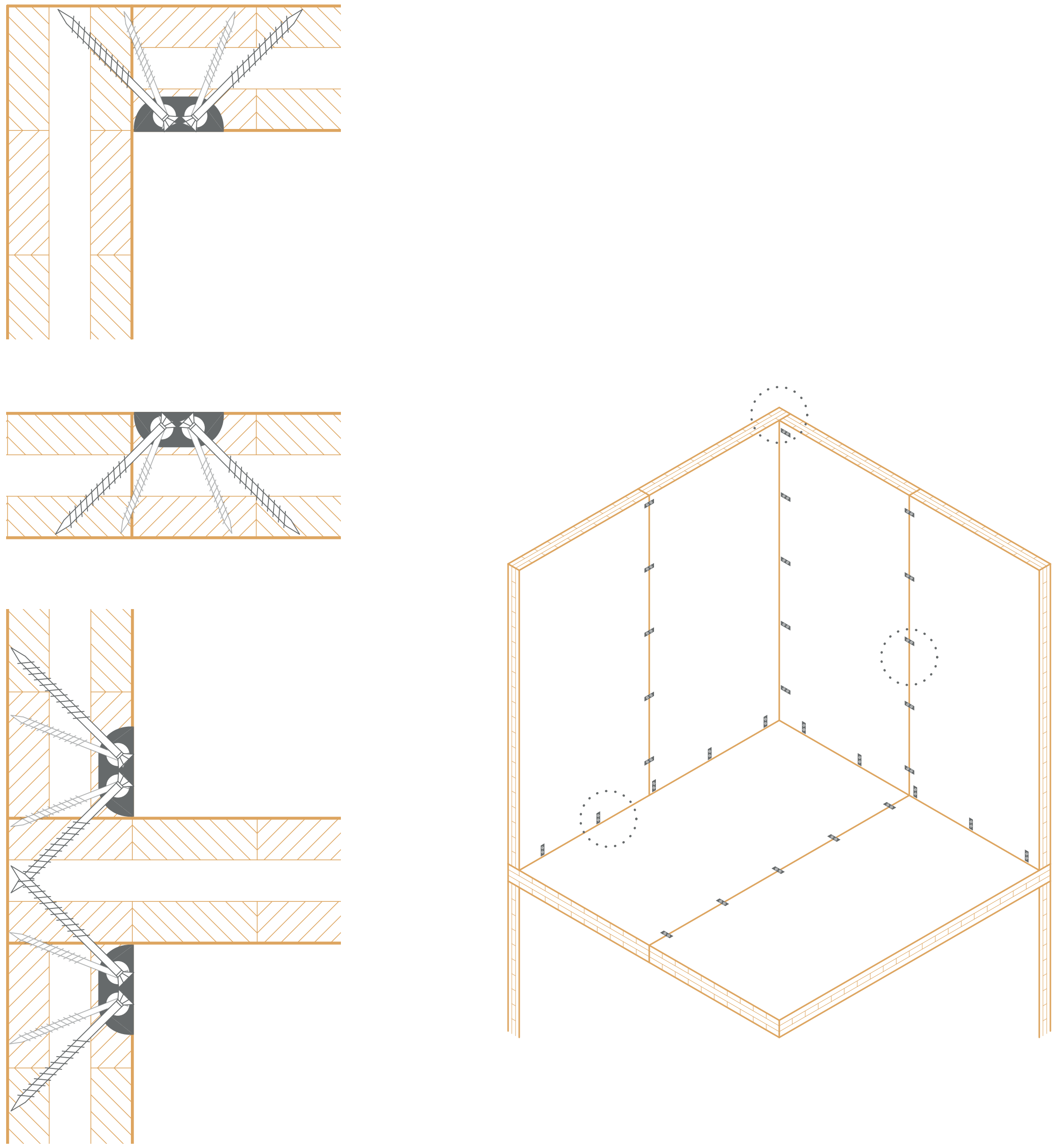


figure 21: (top) wall to wall, (middle) panel to panel, (bottom) wall to floor, (right) Sherpa connection system

2.3.3 Sherpa system

figure 22: Sherpa CLT Connector

The SHERPA CLT-connector is a newly developed system that can be used for angle joints, T-joints and parallel joints (Sherpa, 2013). The connector is small, 18mm x 40mm x 110mm, and has been optimized for three and five-layer CLT elements and can be pre-assembled and mounted flush in the panel allowing for ready-for-installation delivery to site (SHERPA, n.d.). The system can be combined with soundproofing and has proven long-term behaviour and durability however there are issues with the system.

Despite the fact that the connectors can be added off-site, the on-site process is not a simple one. With an average of 2 connector pieces per running meter (lfm) and 10 screws per connector, the labour and time required to fix all of these parts make up a large part of the construction time (Sherpa, 2013). Additionally, like the bracket connections, the system needs sealing and covering thanks to the metallic nature of the connectors. Though the small pieces of the system are more successful in being discreet and the ability to pre-assemble has the potential to be more efficient, the need for so many metallic elements coupled with the need to cover them up leaves much to be desired.

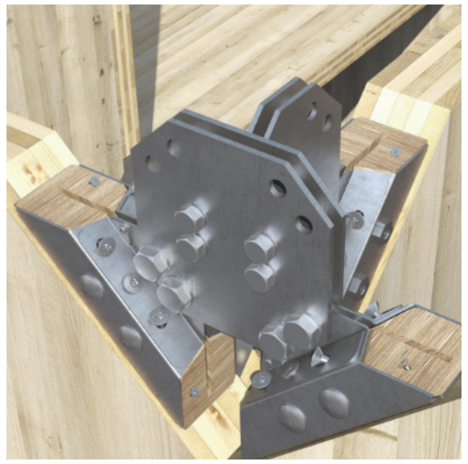


figure 23: X-ONE

2.3.4 X-RAD SYSTEM

The X-RAD System by Rothoblaas is one made up of 3 parts, the X-ONE, the X-PLATE, and the X-SEAL. The X-ONE is the base, or the universal connector, attached to the CLT wherever a connection will take place. The X-PLATE is the interchangeable connecting piece with different plates for wall to wall, wall to floor, panel to panel and wall to base. The plate sits between the X-ONE bases and joins them together. Following this, there is the X-SEAL, a rock wool structure with an aluminium finish that covers and seals the system providing insulation for acoustic and thermal comfort (Rothoblaas, 2017). The system is designed to simplify on-site assembly optimise mechanical, thermal and acoustic performance, it is; "a system that ensure simplicity, rapidity and safety" (Rothoblaas, 2017). The system requires the corners of each panel to be cut at 45o 255mm from the edge to allow the X-ONE to be attached on the angle by 6 self-tapping screws. Though the attaching of the X-ONE can be done on or off-site the time taken to do so needs to be factored in.

A key benefit of the X-RAD system is the number of connection points, or lack of as the connections are on the corners of each panel. This does mean that each connection point is larger than that of other systems such as the SHERPA connector. Each X-ONE piece is triangle-shaped with a size of 273mm x 255mm x 255mm and a thickness of 102mm, quite a jump from a screw or bracket connection. Once the plate element is attached with more bolts, the system needs covering as there are large gaps within the construction. This is where the X-SEAL comes in, however, this does nothing for the aesthetic qualities of the building, attached with black and white checked tape over every joint and being large enough to cover the connection, the only option is to cover the whole wall and hide any notion of CLT. The system is very successful in minimising the number of connection points, and it has proven to be a structurally viable way to build with CLT yet the number of pieces, steps to take, and need to completely cover and seal the construction means that it isn't as efficient as it could be.

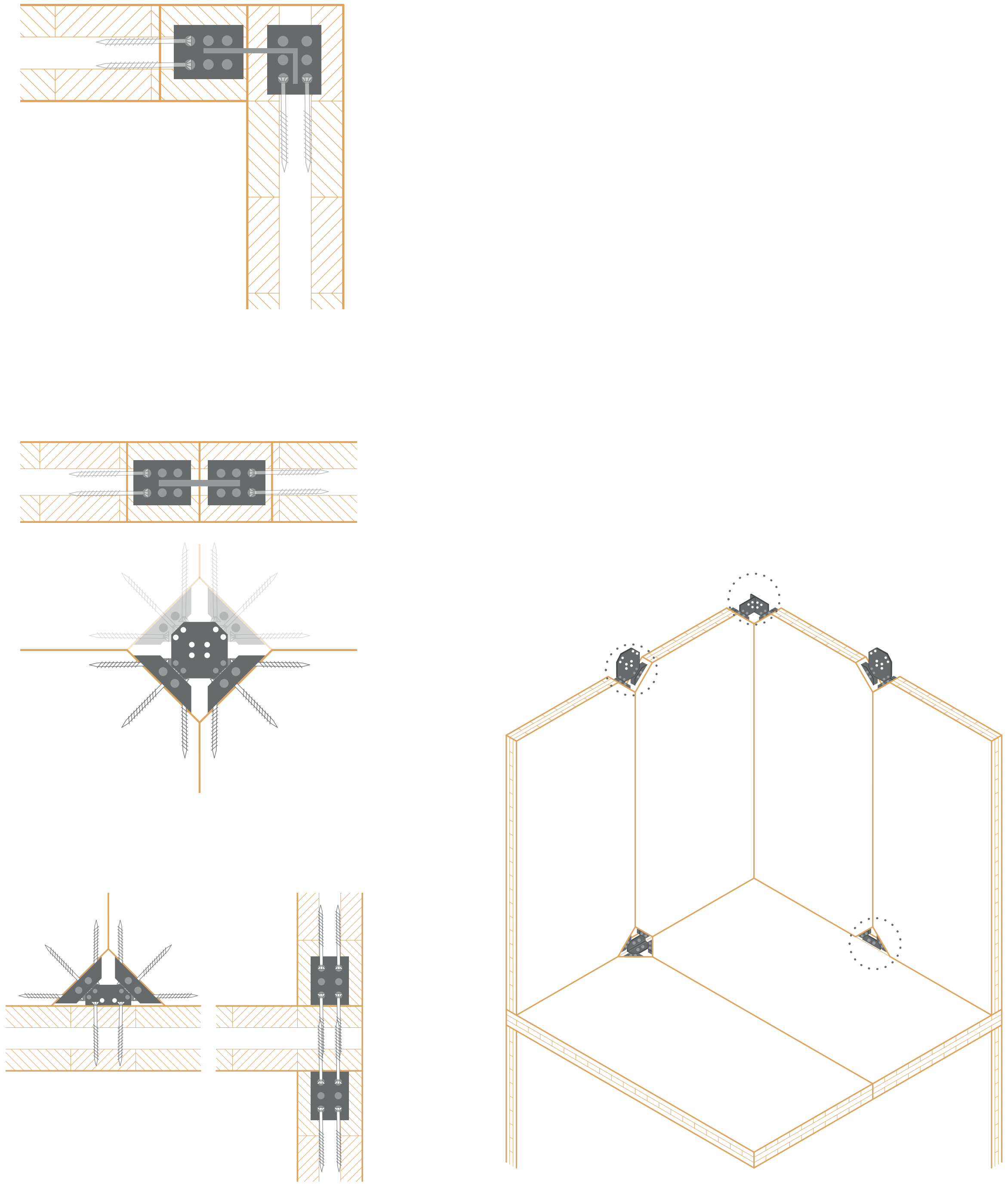
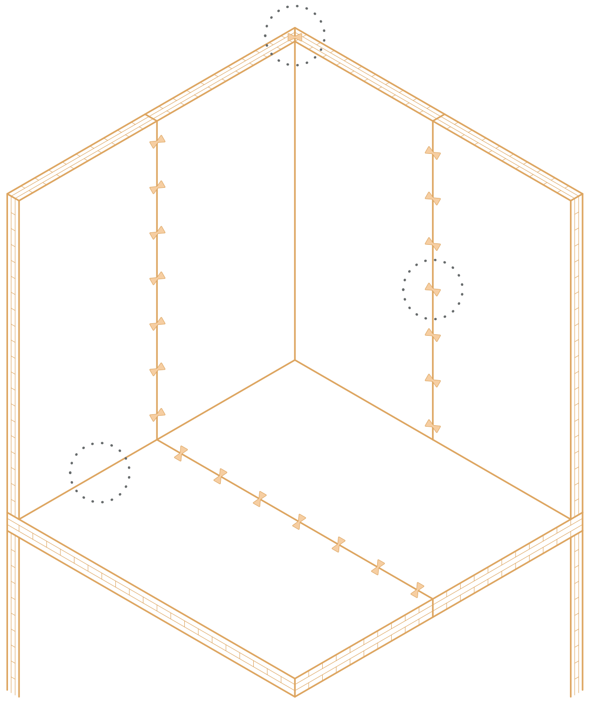


figure 24: (top) wall to wall, (middle) panel to panel, (bottom) wall to floor, (left) X-RAD connection system



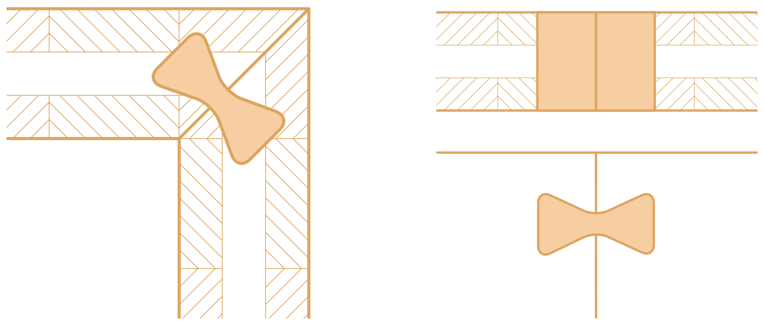


figure 25: (top) X-fix connection system, (left) wall to wall, (right) panel to panel

2.3.5 X-FIX SYSTEM

figure 26: X-fix C

The X-fix system is one that most closely resembles the outcome of this research with the primary idea being wood on wood connections. It is a timber coupling system that uses a dovetail shaped connector to join CLT elements in wall to wall connections and ceiling joints (Schilcher Tading & Engineering GmbH, 2016). There are two types of X-fix, the X-fix C for ceiling joints and, the X-fix L for wall to wall joints. Each contains two dovetail wedge shape pieces that allow it to act as a self-tightening connection. The pieces are hammered into place allowing the wedges to tighten together and lock into place (Hasslacher Norica Timber, n.d.). Though the ceiling joint system is easy to install and requires only a hammer to fix it in place, the X-fix L is more difficult. The idea is the same but the dovetail pieces are the same length as the walls they join which means a considerable amount of force and time is required to hammer the pieces into place.

The success of the system is seen in the lack of metal connections or screws, a feature that mitigates the need to cover the CLT. This also means that the connection pieces can become part of the aesthetic appeal of the building. The X-fix C system can also be used to join wall elements. This allows walls with window or door cut-outs to be made out of separate pieces of CLT as opposed to full panels saving on CLT waste. In most circumstances, the milling for the connection occurs off-site in the fabrication stage however a portable vertical milling tool can also be bought to site for on-site cutting. Of all the case studies, the X-fix system is the most effective in achieving a functional system that doesn't need covering or sealing whilst also adding to the aesthetic qualities of the space.

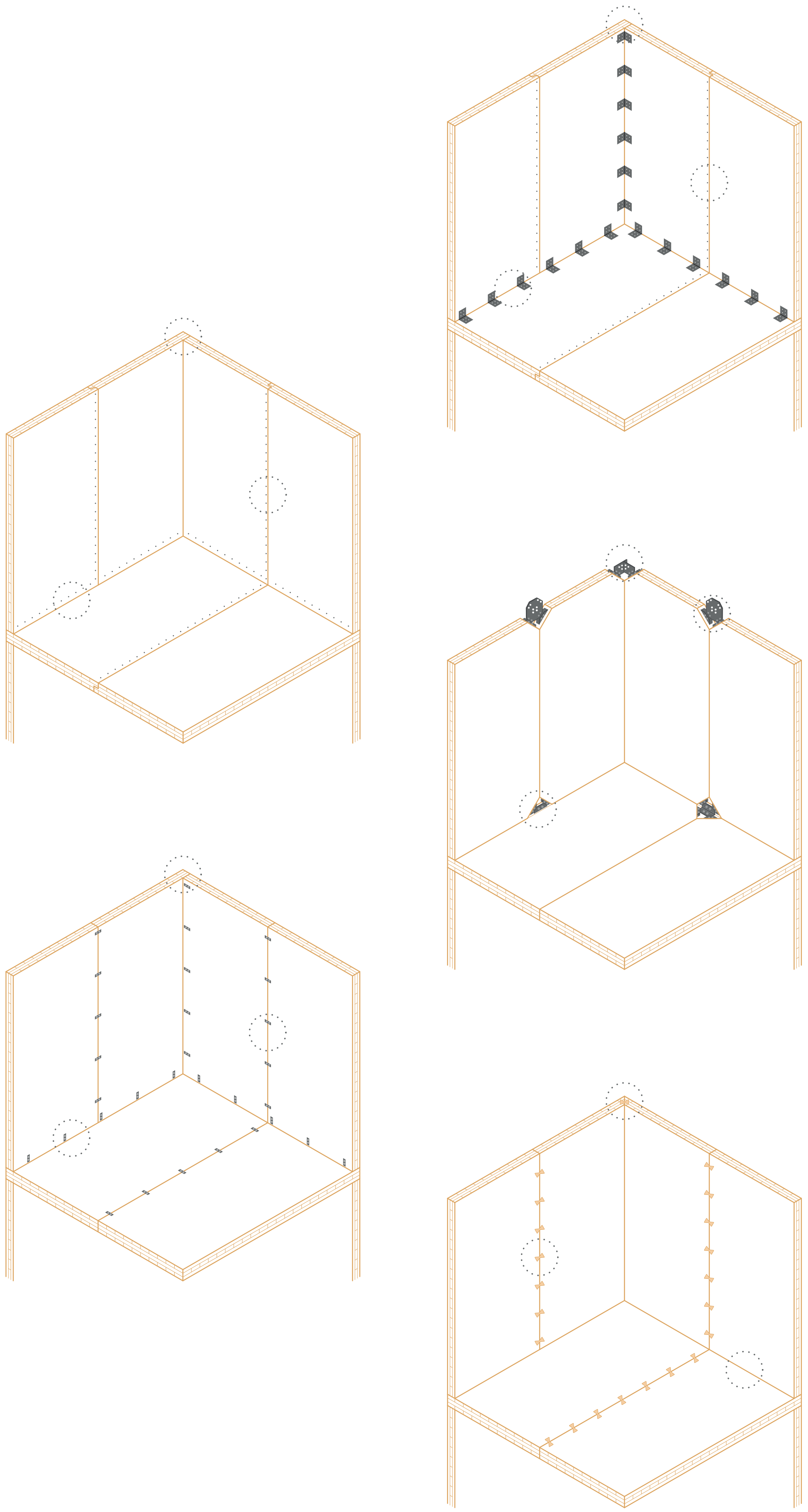


figure 27: all systems

2.3.6 ISSUE IDENTIFICATION

Having studied each system individually, metallic connectors is a clear theme that runs through 4 out of 5 systems. All but the x-fix system use some sort of metal fasteners to connect the panels. This, along with similarities in the type of construction and material requirements, allowed for the creation of a list of key criteria. They are as follows:

AESTHETICS

What impact the system has on the interior aesthetics of the space. All metal fasteners require covering and sealing meaning the CLT is also covered, altering the interior qualities of the building.

NUMBER OF PIECES

How many parts are required to use the connection system and how often they are needed. For example, the X-RAD system has far fewer repetitions of the connection than angle brackets, yet it requires 3 main pieces as well as numerous screws.

WASTAGE

How much material is wasted in the process of construction and how much extra material is needed to complete the connection, i.e. extra plasterboard needed to cover connections.

EASE OF BUILDING

In line with the number of pieces, the number of people required to complete the connection, the time it takes to complete and the ease (or simplicity) of the connection to complete.

THERMAL BRIDGE

The potential for thermal bridging through the connections and the size of the bridge, for example, the thermal bridge through the x-fix is minimal to none due to the connection being wood.

SECONDARY CONSIDERATIONS

There are three more issues that arose through the exploration of the systems. They are; the acoustic and fire performance of the structure, the structural integrity of the connection and the way in which services are distributed throughout the structure. Though each of these issues will have an effect on the structure and the design of a possible connection system, research into these effects is outside the scope of this thesis.

2.4.0 REFLECTION

The literature review conducted at the start of this chapter allowed for the research question to be situated in a clear gap in the industry. It is clear from the review that the need for effective and sustainable building techniques is more present than ever before and that although huge steps have been made, there are more needed. It has also shown that this might be done by combining the old and the new. The traditional approach of Japanese joinery in conjunction with the newest advances in digital manufacturing and fabrication creates the ideal situation to find a solution.

The building precedents reinforce the notion that a lot has been done in the way of progressing timber construction, using digital manufacturing to do so. They also highlight the ways in which these timber structures can be achieved through innovative means, with the focus on connections used to enhance the aesthetic qualities of the buildings.

The exploration of existing connection systems becomes the base for the thesis as it sets the mark and highlights what is already being done. It is clear that the standard systems are no longer good enough and that each bespoke system has found its own way to correct this. Despite this, there are weaknesses in each system, many of which are the same across multiple connections. These weaknesses allowed for the identification of criteria to inform the following design process.

This chapter has highlighted the relevance of the research and provided insight into how the research could progress within the current market. It also identified two overarching factors that have proven to be key drivers of the research as it progresses, the benefits of timber and the need to reduce wastage in construction.

CHAPTER THREE

DESIGN & FABRICATION

3.1.0 INTRODUCTION

The following chapter explores the design process and investigates connection possibilities for CLT panels. The existing systems are used as a base for design before adding in Japanese influences and extrapolating the most effective way to join CLT panels through traditional and new means. Initial designs were built upon to produce a range of design outcomes ranging in complexity and feasibility, allowing for evaluations and comparisons to be made between them. Selected designs are then prototyped using a robotic arm in order to test both the designs and the fabrication technique.

STRAIGHT KEY

- laser cut

STRAIGHT W/ TWIST

- laser cut

WEDGED KEY

- CNC machined

figure 28: initial test models

3.1.1 INITIAL PROTOTYPING

THE DESIGN

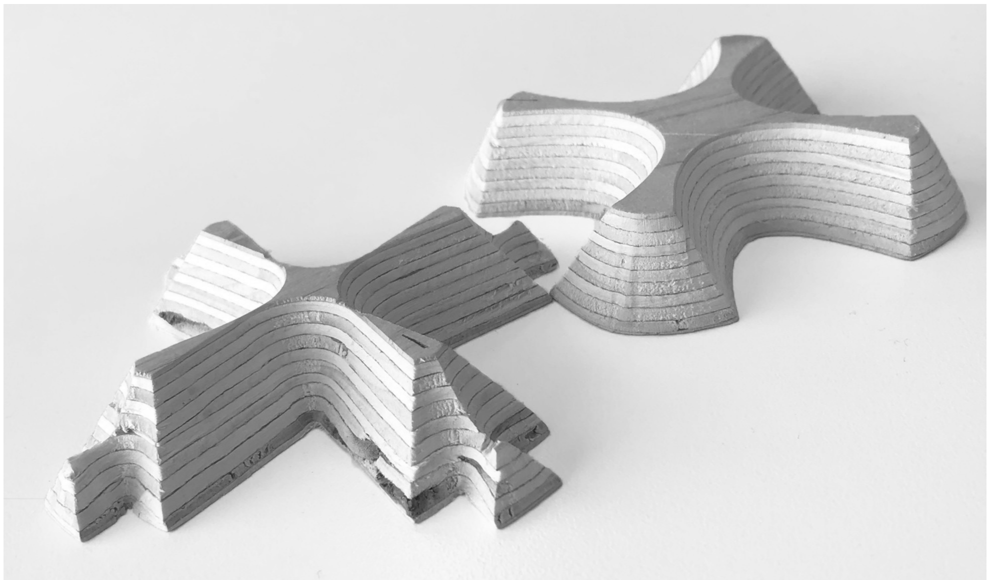
The designs for these initial tests were developed based on the existing system studies. Particular focus was given to the dovetail shape of the x-fix and the 'star' like form created by the X-RAD system. The first tests, the straight key, connected 2 'panels' with a simple stamped out shape. The second tests used slightly more complex forms in two layers to create a lock system thanks to rotated pieces. The final test used the same forms but added an angled cut to create a wedged key.

THE FABRICATION

The initial two tests were undertaken using a laser cutter and though there are limitations, this fabrication method was always intended for small scale tests as opposed to full-scale prototyping or fabrication. The third test was undertaken on a 3-axis CNC machine with a 30 degree angled milling bit. This test exposed issues that had not been previously considered. The first of these was the need to consider the angled cut and the way in which this decreases the size of the initial shape as it cuts. This second is the need to consider tolerances associated with both the form and the bit. The milling bits are round meaning that when creating an inside cut, such as on the base panel, the corners become rounded due to the bit radius. However, when creating an outside cut, such as the key, this rounding is avoided as the bit can move completely past the corner. This change in cut means that the pieces don't fit together as the shapes are different which creates an unsuccessful connection.

THE CONNECTION

There were varying degrees of success within the connections themselves. The straight keys are very successful in the x and y directions and keep the panels together with little movement, but fail in the z-direction as the hole created matches that of the key so they can slide through with ease. This effect is lessened with the addition of more keys but more keys mean more waste, fabrication and assembly time so is not ideal. The keys with a rotation solved this issue as the shape is different on each layer, however, they required adhesives to hold the keys together in the centre which is an added material that could be avoided. As previously mentioned, issues with tolerances on the wedged key created a mismatch in test 3 pieces meaning they didn't fit. Despite this, the wedge shape stopped the issue of sliding along the z-axis and proved to be the most successful way to join the panels.



SHAPED WEDGED KEYS

- CNC machined

figure 29: test model pieces

3.1.2 DEFINING A RESEARCH FOCUS

Following the initial prototypes, it was necessary to define where the focus of the thesis should be, specifically, on which connection. The first designs were created with a panel to panel connection in mind, however, upon reflection of the existing connection systems, it is apparent that this is not a major concern when looking at the construction process as a whole. Having highlighted the key criteria as; aesthetic qualities, number of pieces, wastage, ease of building, and thermal bridge potential, the panel to panel connection doesn't require too much focus in these areas.

As shown in the adjacent figure, the connection commonly consists of a simple screw and spline system, with the spline often being added at panel fabrication. The connection system is fairly quick and easy to build, and despite the high number of pieces, they are small and provide minimal thermal bridging with little to no wastage. The biggest issue would be that of aesthetics, yet, the nature of the connections means that it can be undertaken on the outside or on hidden surfaces meaning there is no impact on the interior space.

When evaluating the existing systems against the highlighted criteria, it is apparent that the focus should be on the wall to wall or 90-degree connections. The connection is commonly achieved with metal angle brackets, of which there are many, that hugely affect the aesthetics of the space as well as creating a thermal bridge in the structure. The proprietary systems, Sherpa and X-RAD, show the same issues, with the thermal bridge and aesthetic issues being more prominent than the brackets and a more complex building process. Given that the wall to wall connection has shown to be the most problematic, it was only natural that it became the focus of the joint-specific research within the thesis.

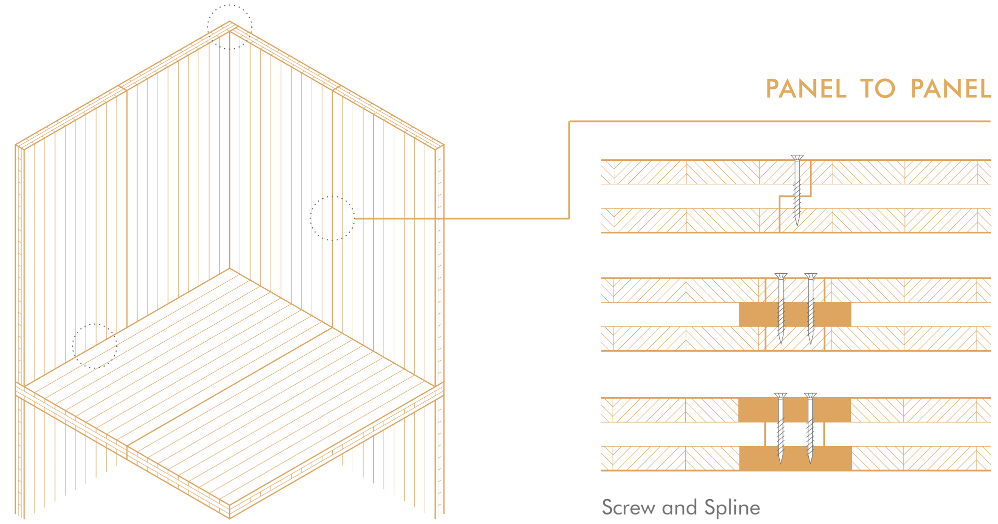


figure 30: panel to panel common connections

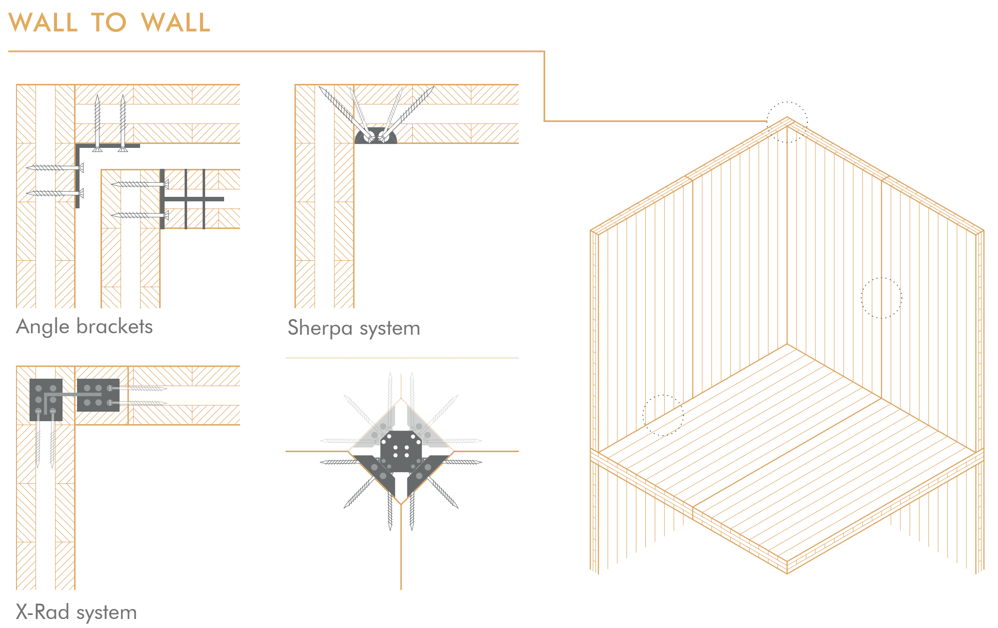


figure 31: wall to wall common connections

3.1.3 DESIGN DEVELOPMENT

When entering the design development phase it was important to have a solid base in which to begin the design process. Having explored various precedents and existing jointing systems the groundwork had been laid to progress, however, it was the combination of two ideas that provided the initial inspirations. Given that two of the key criteria are the thermal bridge potential and the aesthetic qualities, the first step in the process was to completely remove any metal fasteners. Though this was a big step away from most of the existing systems, it would have an immediate effect on addressing these criteria. This decision could also reduce the number of pieces required to join the panels as well as having the potential to reduce wastage.

This is where the influence of Japanese architecture and joinery comes in. The traditional wood on wood joints provide an ideal base for design exploration as they incorporate principles that can be mimicked and adapted to create a connection for CLT panels. Many of the traditional joints are splicing joints, used to connect pieces of timber to create a longer beam in a single line. There are also traditional connecting joints that were used to connect beams and columns at 90-degree angles, similar to the connection focus of this thesis. However, these were designed to connect a single beam and column as opposed to connecting two large panels.

The first design challenge consisted of finding a way in which these traditional, and very successful, joints and techniques could be applied to panel construction. A selection of splicing and connecting joints were chosen as a starting point to create the first iterations of panel connections. A key consideration was to maintain the proportions and shapes seen in the traditional joints as these are part of what makes them so successful. In the first prototypes, it was found that more connections made the joint stronger, this finding inspired the first exploration into the adaptation of the traditional forms, repetition.

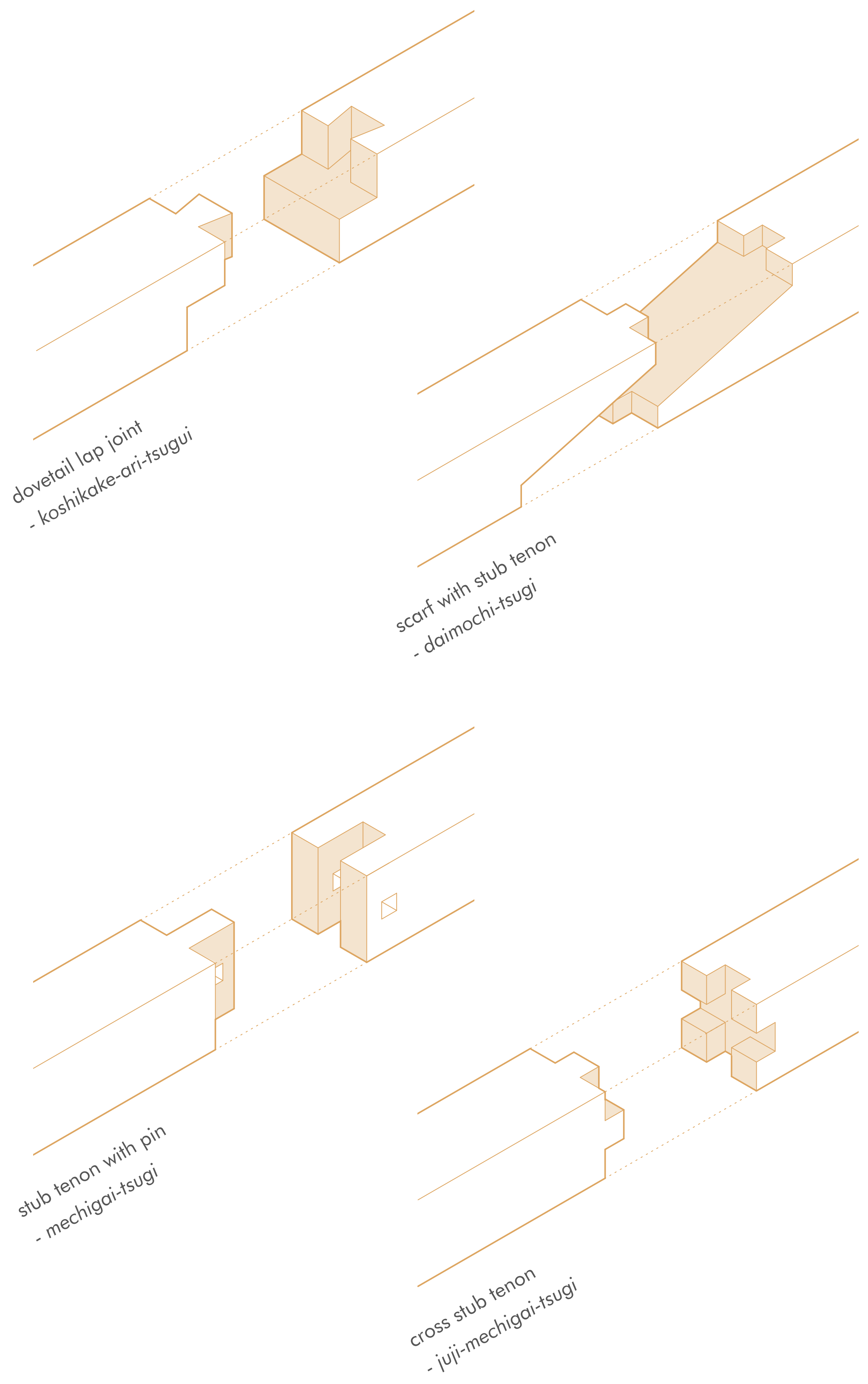


figure 32: traditional japanese joints

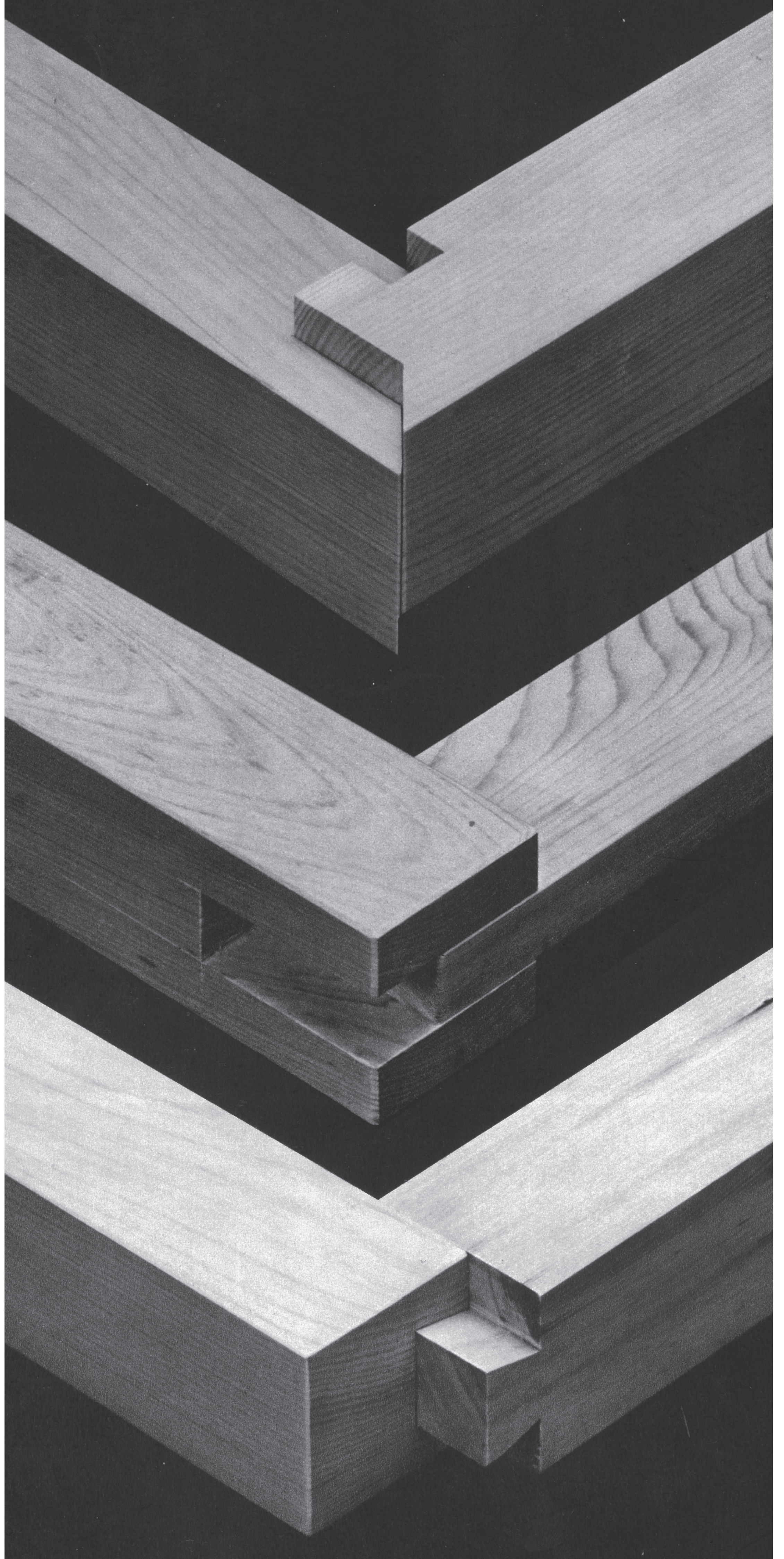


figure 33: tenon miter joint, finger joint, half lapped dovetail joint

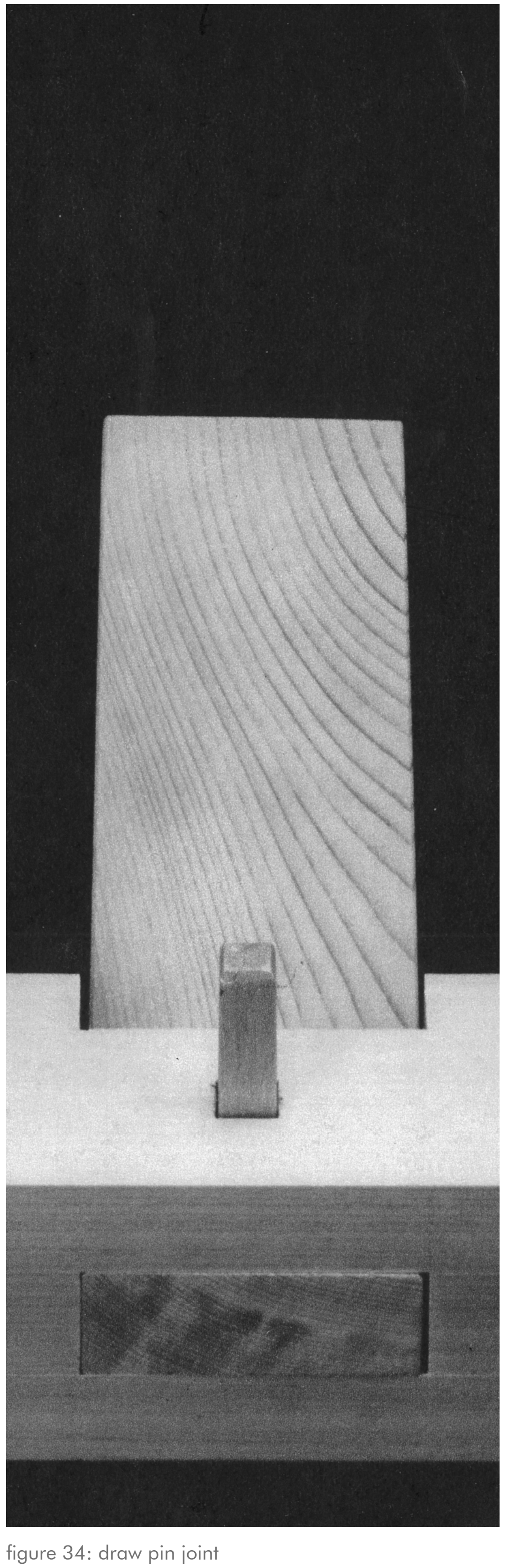


figure 34: draw pin joint

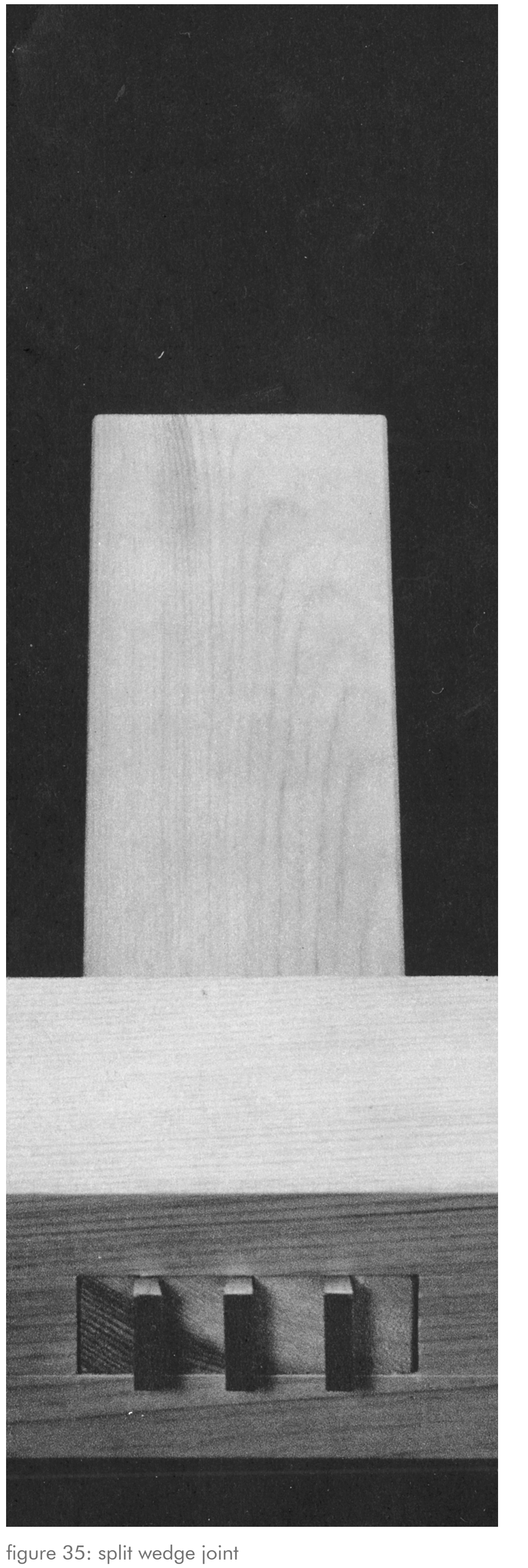


figure 35: split wedge joint

3.1.4 TRADITIONAL JOINTS

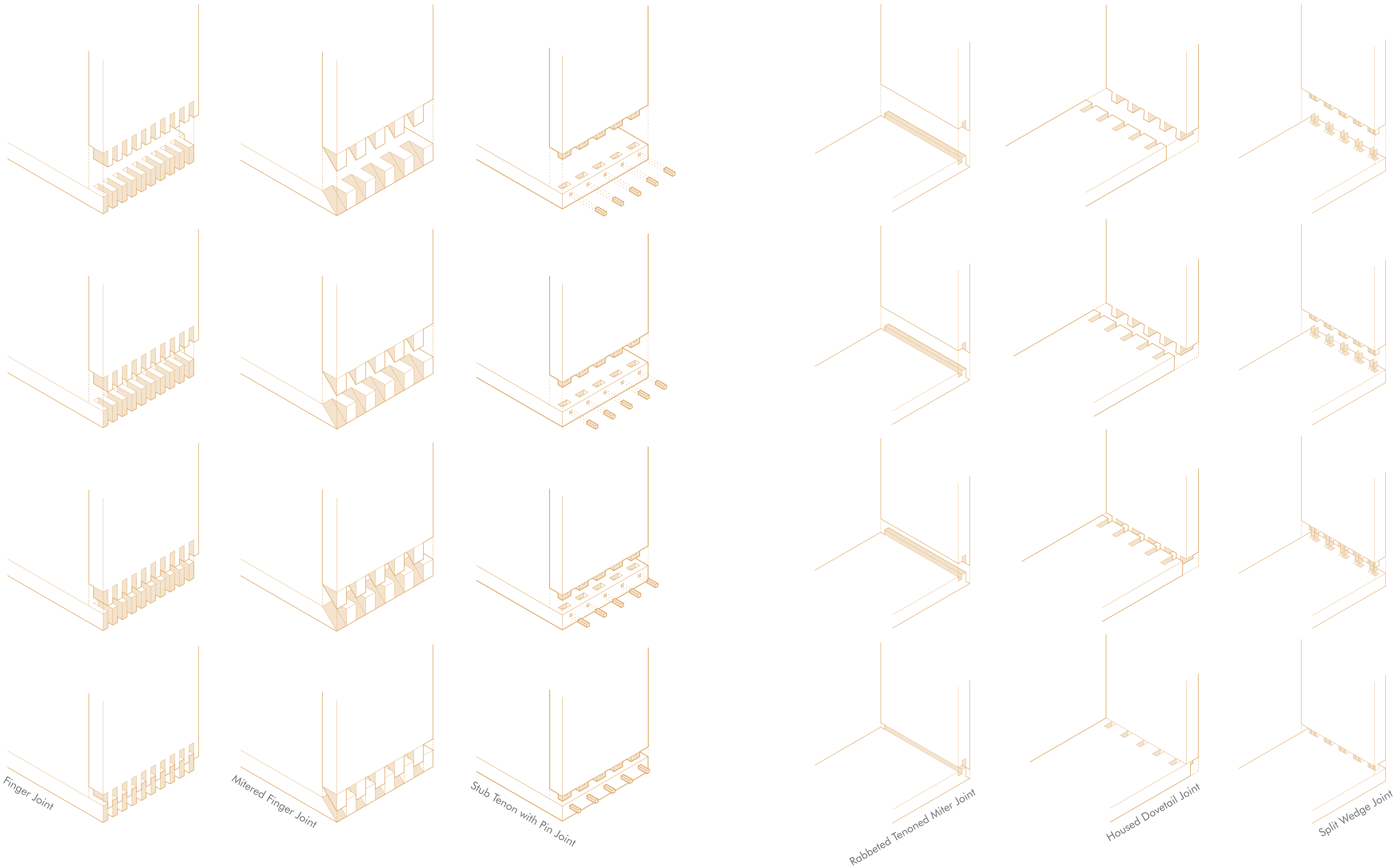


figure 36: joint repitition diagrams

3.1.5 JOINTING SYSTEM DEVELOPMENT

Having explored various adaptations of traditional forms through repetition, there were a few concerns, primarily, the number of connection points. Where in traditional joinery there would be a single dovetail or pin joint, the repetition meant that there was now 5, and that was only limited by the size of the panel created. This excess number of connections meant more time would be required to mill them when fabricating and, most likely, more time to put them together as there are many more pieces to put in and align.

These concerns led to the development of an assessment system to evaluate the success of each joint design and can be used to immediately identify the most successful designs. The assessment system was extrapolated from the key criteria identified previously. They are as follows:

AESTHETICS

A short description of what is seen once the connection is made and how many faces it is seen on.

NUMBER OF PIECES

Stating how many pieces are used to create the connection or whether it is a continuous repetition.

WASTAGE

A calculated percentage of how much material is wasted when cutting into the panel for the connection

EASE OF BUILDING

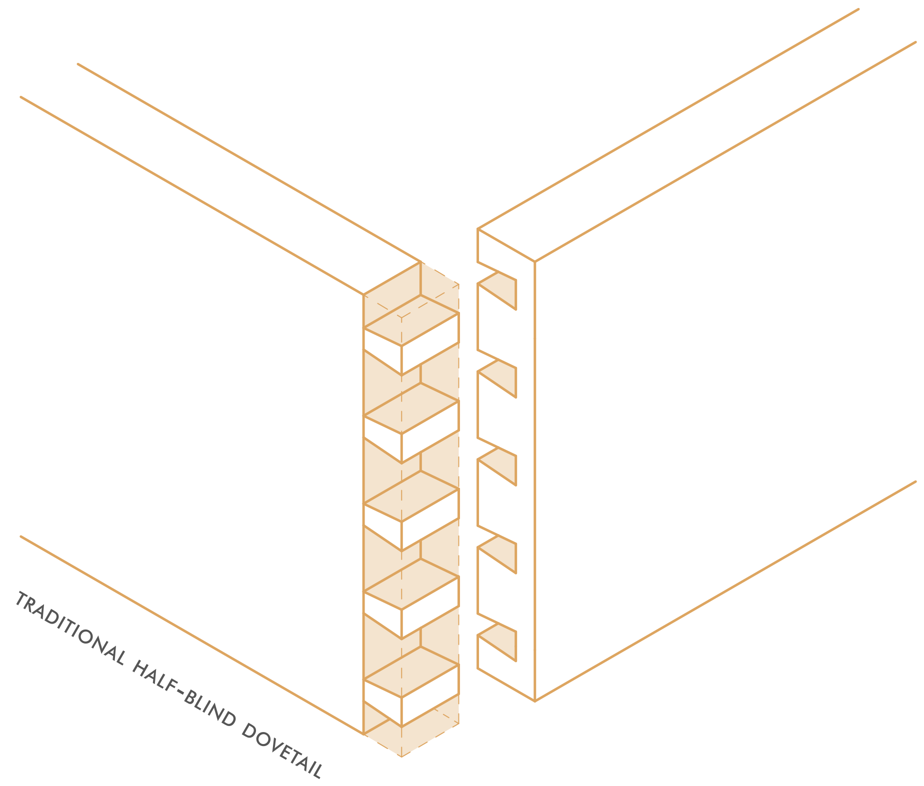
A rating given based on how easy the joint is to put together based on prototypes.

EASE OF FABRICATION

A rating based on the ease of which the joint and pieces can be fabricated, considers time and simplicity.

THERMAL BRIDGE

A yes or no with rating given if yes, usually n/a as the joints are wood.



Aesthetics	repeated, one face
No. of pieces	continuous
Wastage	45 %
Ease of building	4/10
Ease of fabrication	2/10
Thermal bridge	-

When these assessment criteria are applied to a repeated traditional design, the half-blind dovetail, it is clear that wastage and ease of fabrication are key issues. The number of connection points is high and each of these has to be milled. This consists of the machine cutting along the path of the joint on the top of the panel before moving down and repeating the action until it has cut all the way through or has achieved the required depth, a process that takes a long time. The process also cuts away the excess material creating a small bit of wood that cannot be reused in the process, becoming excess waste.

figure 37: traditonal half-blind dovetail

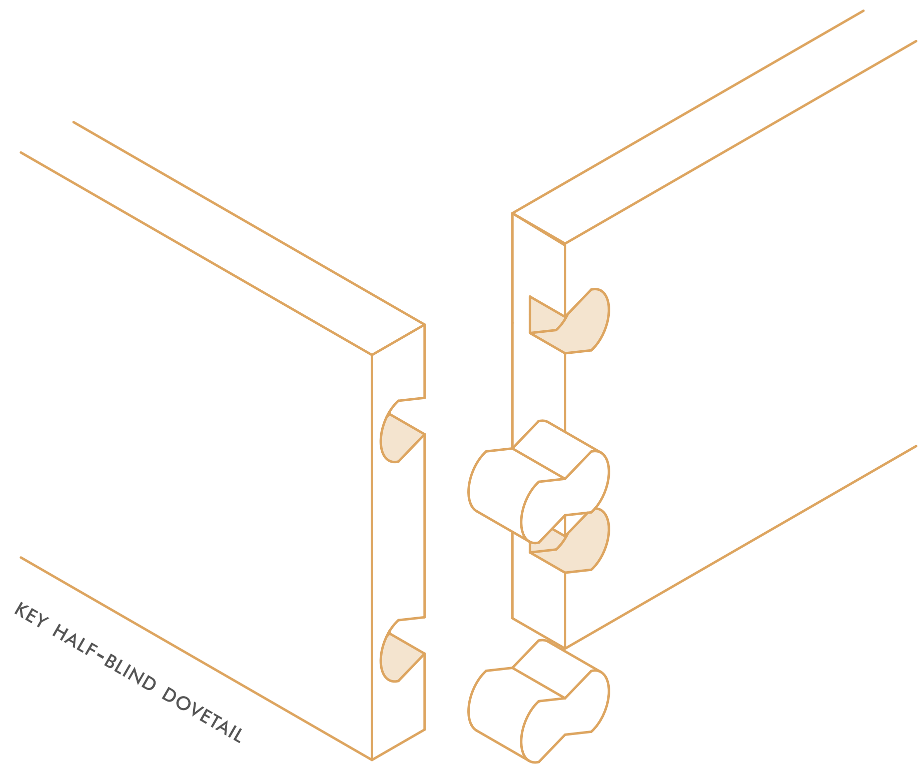
3.1.6 jointing system development

Based on the assessment of the traditional half-blind dovetail, it is clear that the idea of simple repetition will not be successful. When looking again at the existing joinery systems, they are all achieved by adding external pieces to the construction, a key of sorts. Though using metal pieces such as these is not the goal of this thesis, the idea of a key stood out as being particularly interesting. The traditional Japanese joinery ideas could be adapted into a key as opposed to being adapted for repetition.

Taking the traditional dovetail again, the joint was adapted to create a key whilst maintaining the proportions of the traditional joint. The new key joint was assessed against the criteria which showed the new joint was much more successful in terms of wastage, ease of building and ease of fabrication. Fabrication became a lot simpler as there were far fewer pieces to cut around, despite the need to also cut the key.

Most interesting, however, was the reduction in wastage potential. A massive 28% of the wastage is avoided by using a key instead of a repeating system. Though this is dependent on the number of keys required and their size, it is nevertheless, a huge reduction. This design also opened a new window of inquiry, what is the key made from? The answer comes back to waste. Through the manufacturing of CLT panels in factories, there are often large pieces of CLT cut off throughout fabrication as well as pieces deemed to be not up to standard. It is pieces such as these that were donated to the university as test materials which allow the prototyping of the designs created in this thesis. These 'waste' panels came to the university in the form of a number of panels around 1.5m x 3m in size.

Thanks to this 'waste' being donated to the university, it is being used, but it is safe to assume there is a lot more waste such as this that is simply being burnt or thrown away. So, being presented with excess waste and a joint that requires extra material, it was only natural to decide that the keys needed to create the joints would be made out of waste CLT, reducing the amount of waste again.



Aesthetics	repeated, one face
No. of pieces	2
Wastage	17 %
Ease of building	8/10
Ease of fabrication	4/10
Thermal bridge	-

figure 38: key half-blind dovetail

3.1.7 FINDING THE KEY

Having concluded that a key would be the most successful way to create a connection system, the next stage was to find that key. What shape was it? How did it connect the panels? How many pieces did it have? How is it made? The following categories allowed for the development of this key within each category as well as by combining them to find the key.

SLOT

straight key of various shapes

WEDGE

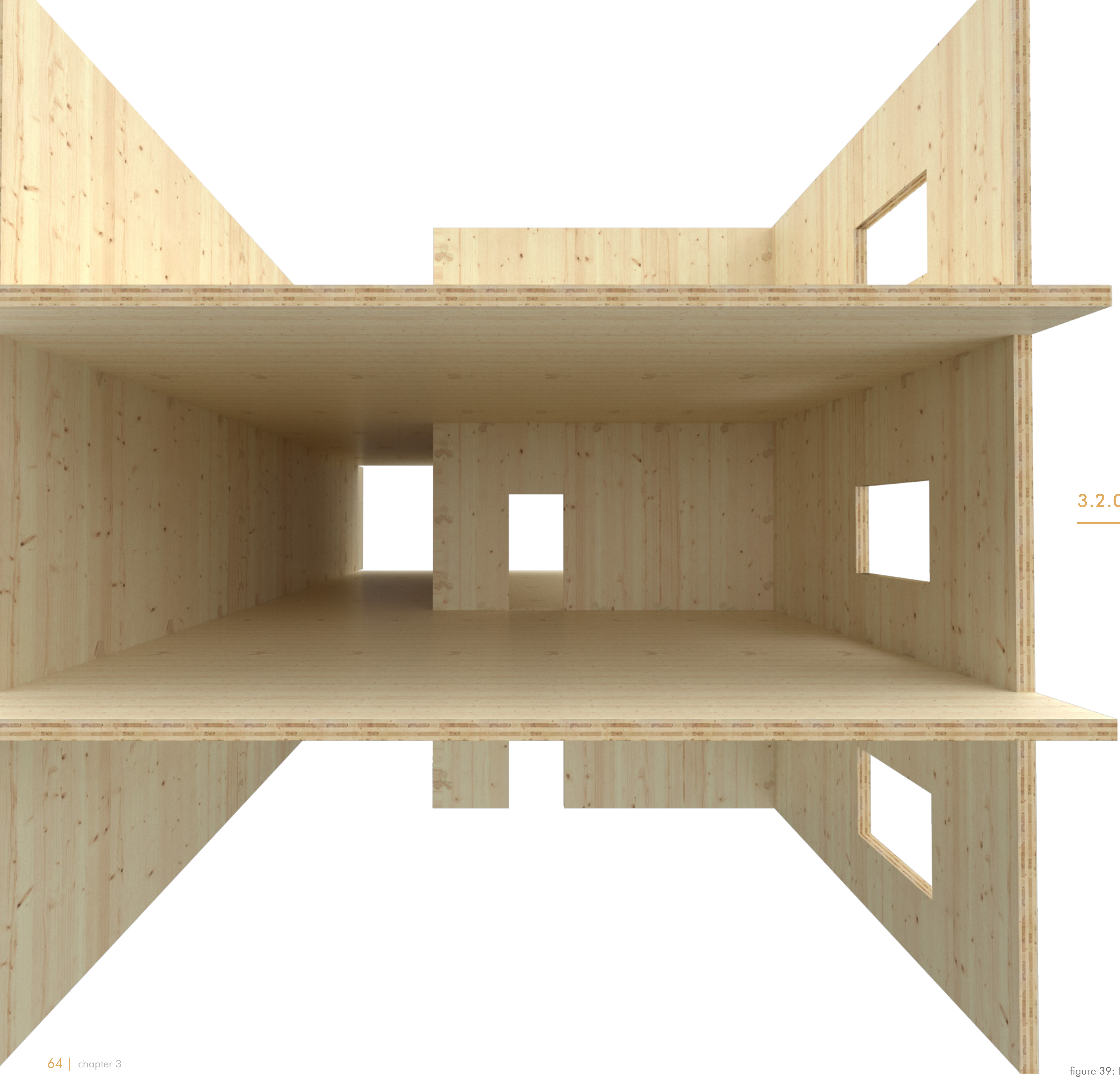
wedged keys locking together

PIN

pin locks to support main key

NOTCH

tenon additons to main key



3.2.0

CONNECTION DEVELOPMENT

figure 39: key construction overview

3.2.1 DOVETAIL KEY

INFLUENCES

Inspired by the traditional Japanese dovetail and the x-fix, the key is designed to use the dovetail shape to pull the 2 panels together whilst providing rigidity thanks to the maintaining the traditional proportions of 1:3 to 1:2.

TESTING

The strength of the traditional shape and the importance of an exact fit when connecting the panels.

CONSIDERATIONS

Though the traditional shape was kept, the edges and corners are rounded to account for tolerances when milling.

STRENGTHS

The simple shape means it is easy to mill and put together and can be replicated easily.

WEAKNESSESS

The joint relies on a very tight fit of the key in the panels, without this, the joint moves easily.

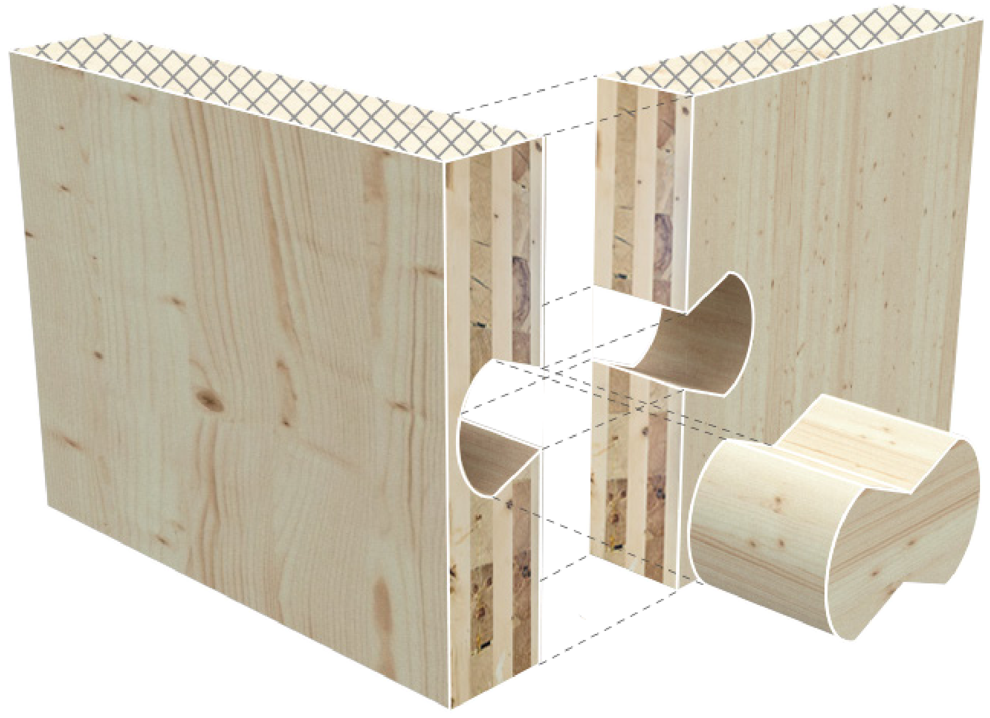


figure 40: dovetail key

3.2.2 ANGLED SLOT KEY

INFLUENCES

This key set uses the simplicity of dowel type fasteners combined with the connector angles seen in the Sherpa and X-RAD systems. The alternating angle provides stronger resistance to forces in 2 directions.

TESTING

Looking at what impact angles have on the joint and whether less is more when it comes to the size of the key.

CONSIDERATIONS

Simplicity can be achieved if the hole for the key is the same size as the milling bit as it requires only one simple curve to follow.

STRENGTHS

There is very minimal cutting waste as the shape is so simple, this also means a quick fabrication time.

WEAKNESSESS

It is more difficult to cut the keys from waste CLT as it is so thin, plywood or another sheet material would work better but this could create more wastage.

figure 41: angled slot key

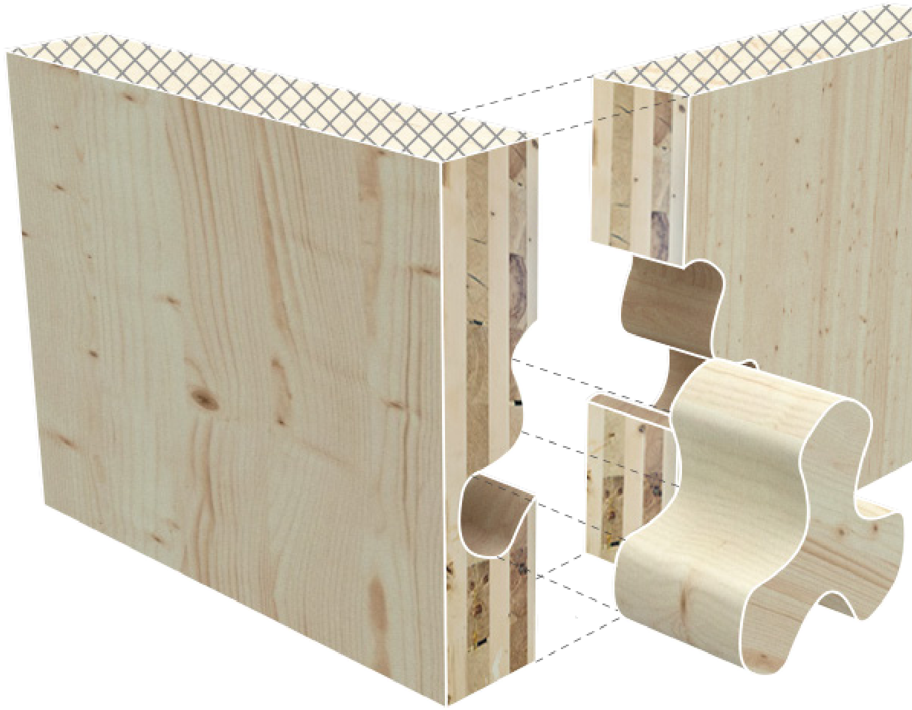


figure 42: star key

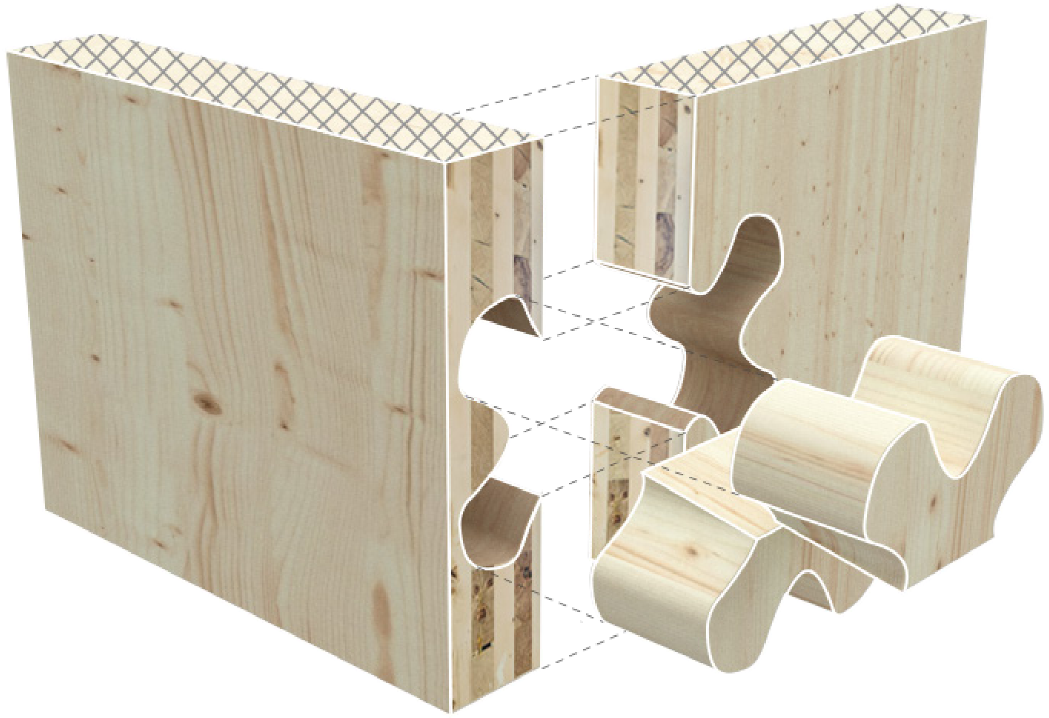


figure 43: wedge star key

3.2.3 STAR KEY

INFLUENCES

The star key is a progression of the simple dovetail, it maintains the traditional proportions on each dovetail arm but explores form and rotational composition.

TESTING

Whether additional dovetail arms make the joint stronger than two and if this affects the need for exact tolerances.

CONSIDERATIONS

Continuing an even curve that matches the radius of the milling bit to ensure the pieces fit together and deciding on an orientation that would best hold the panels together.

STRENGTHS

Simple cutting shape with no angles meaning a 3-axis CNC machine could be used.

WEAKNESSESS

Again, requires a very tight fit to work well and ensure no movement occurs.

3.2.4 WEDGE STAR KEY

INFLUENCES

This key also uses dovetail principles but also incorporates the wedge idea seen in the x-fix, the four arms allow for a symmetrical shape on both sides of the wedge.

TESTING

The wedge addition tests whether the increased friction and locking potential usually seen with wedges will have the same effect when connecting the panels

CONSIDERATIONS

Create an angle that creates enough friction to lock the pieces in without making the pieces too small. It is also important to create pieces that are taller than the hole in the panel so the wedge can be hammered in enough to lock.

STRENGTHS

This is the strongest system yet and prevents sliding along the z-axis whilst pulling the 2 panels together.

WEAKNESSESS

Requires a bit of labour to hammer in and excess material has to be cut off the top creating extra waste.

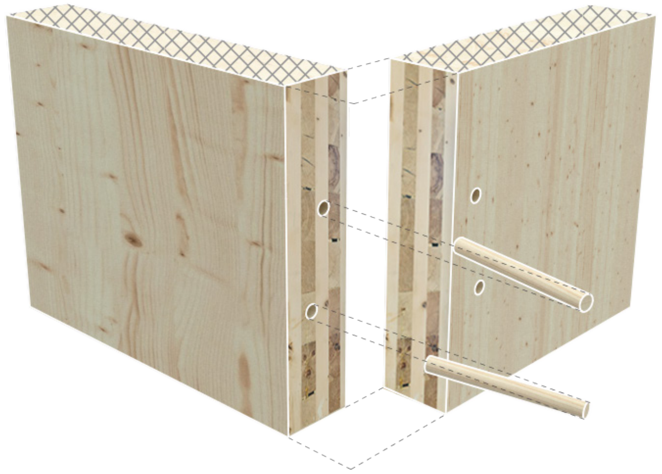
figure 44: key construction interior

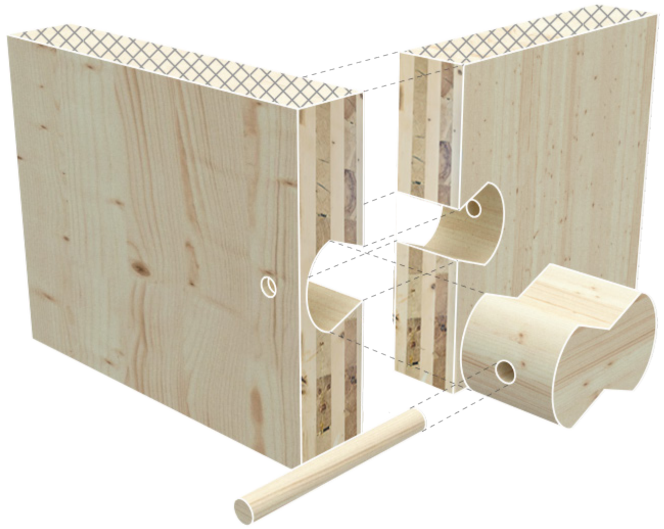
3.2.5 JOINT DESIGNS

This selection of designs builds upon the previous and develops them further with influence from the existing systems and traditional connections. Each looks to explore form in a different way whilst also challenging the way in which the joint can connect the panels and keep them in place. The use of pins, alone and with other keys, can act as a lock for the joint. When alone but on an angle they can resist multi-directional forces, combined with existing keys they lock the key into place, reducing the need for a perfect fit. The simplification of the wedge shape and additions to the star key compare whether it is more effective to be complex or simple.

PIN KEYS

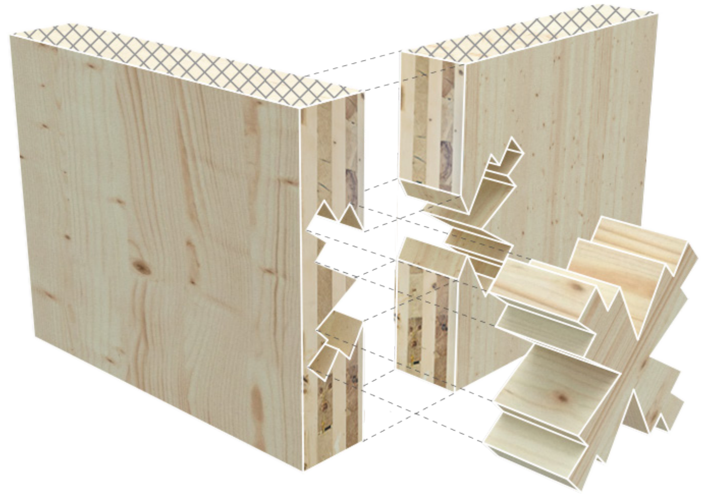
Aesthetics	regular pin holes
No. of pieces	2
Wastage	2 %
Ease of building	5/10
Ease of fabrication	3/10
Thermal bridge	-





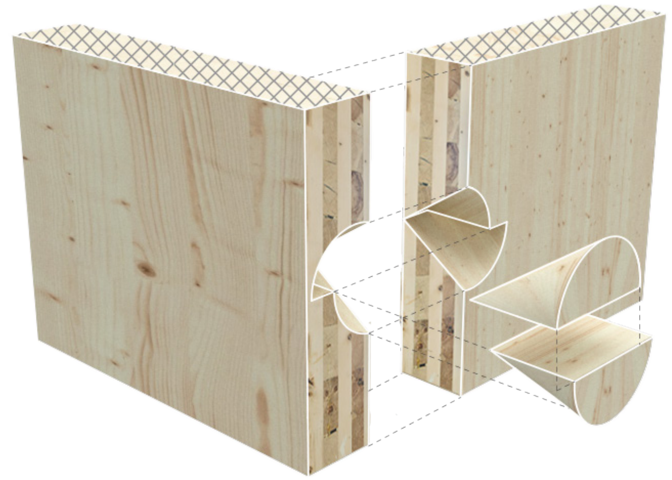
DOVETAIL PIN KEY

Aesthetics	regular dovetail and pin hole
No. of pieces	2
Wastage	19 %
Ease of building	6/10
Ease of fabrication	6/10
Thermal bridge	-



TENON STAR KEY

Aesthetics	regular angled star
No. of pieces	1
Wastage	27 %
Ease of building	5/10
Ease of fabrication	4/10
Thermal bridge	-



CIRCLE WEDGE KEY

Aesthetics	regular circle
No. of pieces	2
Wastage	12 %
Ease of building	7/10
Ease of fabrication	4/10
Thermal bridge	-

figure 45: joint designs 0.1

3.2.6 JOINT DESIGNS

NOTCHED DOVETAIL KEY

Aesthetics	regular dove
No. of pieces	1
Wastage	13 %
Ease of building	4/10
Ease of fabrication	2/10
Thermal bridge	-

CIRCLE SLOT KEY

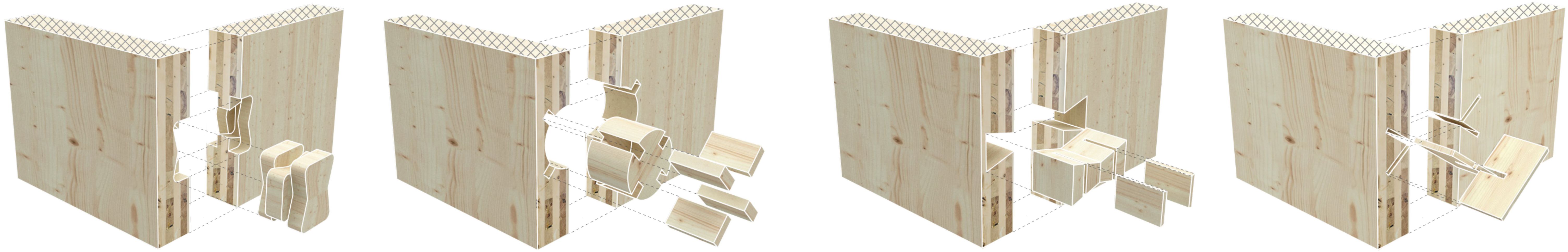
Aesthetics	regular circle and locks
No. of pieces	5
Wastage	21 %
Ease of building	6/10
Ease of fabrication	3/10
Thermal bridge	-

DOVETAIL WEDGE KEY

Aesthetics	regular half star
No. of pieces	3
Wastage	12 %
Ease of building	4/10
Ease of fabrication	4/10
Thermal bridge	-

CUTOUT SLOT KEY

Aesthetics	regular angled ply
No. of pieces	2
Wastage	4 %
Ease of building	4/10
Ease of fabrication	7/10
Thermal bridge	-



Adding another layer of complexity, these designs use forms and techniques used in previous designs in a different way. Employing the use of a twisted notch system allows for locking without pins yet is far more complex in fabrication and building. Building on more successful designs using slots and wedges, these designs explore whether more pieces will create a stronger joint without over-complicating the fabrication and construction process.

figure 46: joint designs 0.2

3.2.7 REFLECTION

Finding a base in traditional Japanese joinery allowed for the exploration of design ideas with proven connection methods at the core of the design process. Combining the traditional with the modern bespoke allowed for the joint design to developed and evaluated against proven techniques as well as speculative ideas.

By beginning with simple designs with clear testing purposes and influences, the designs that followed could be explored on a more conceptual level whilst also being aware of structural and fabrication implications. These designs were evaluated against the previously defined assessment criteria.

The results of the assessment indicated that the fewer the pieces, the simpler the connection – both in fabrication and building. Though not always the case, as with the pin keys, it is reasonable to state that fewer pieces would lead to more efficient construction. There is also the effect on wastage that more pieces have; though more material is used which could mean less waste, there is the potential for increased waste from cutting around multiple small pieces as opposed to one larger key.

When it comes to fabrication, the initial assessments are estimates based on the previous small scale testing. In order to understand these criteria more fully, the initial four designs were taken forward to be prototyped through robotic fabrications.

3.3.0

ROBOTIC FABRICTAION

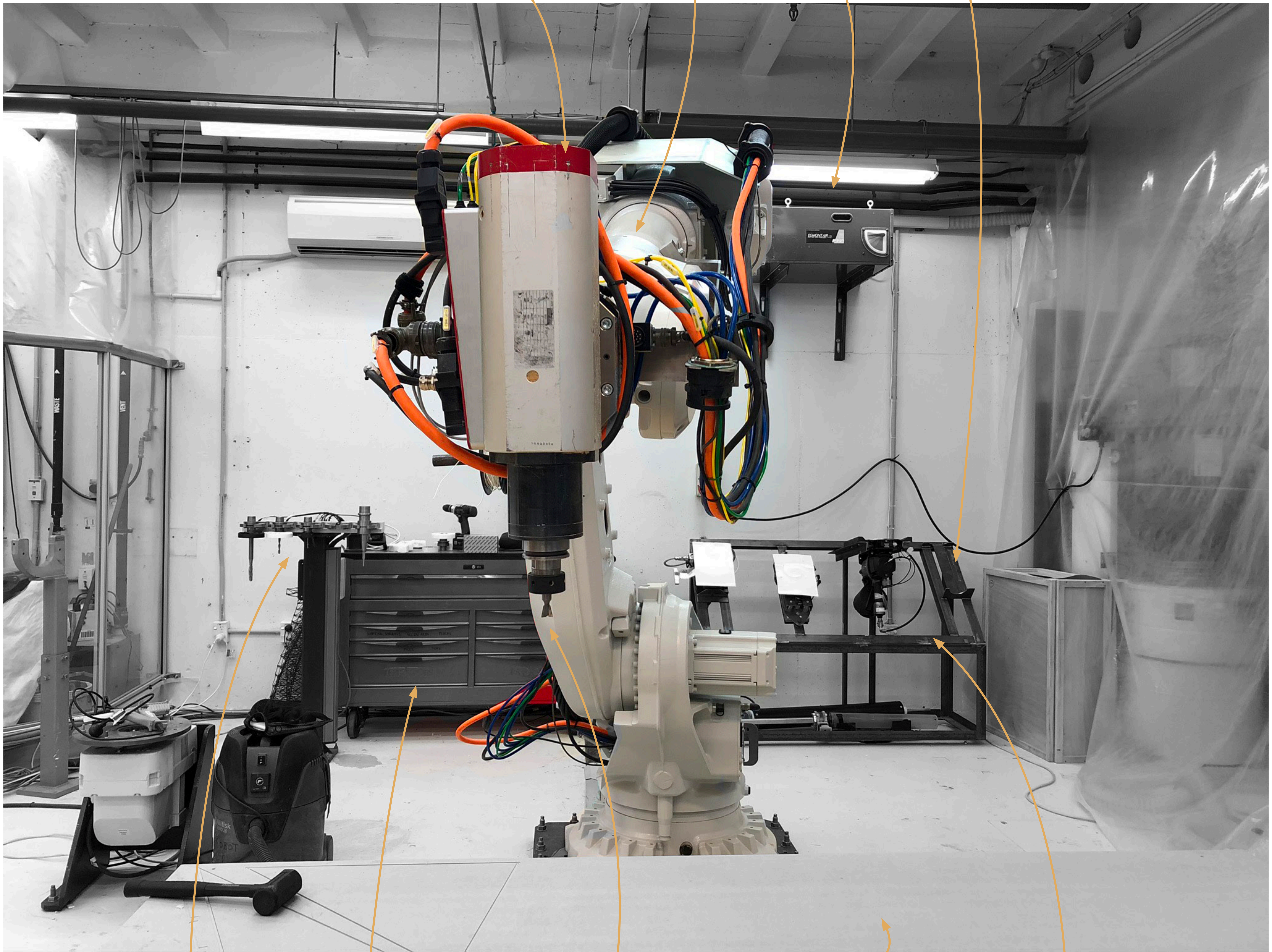
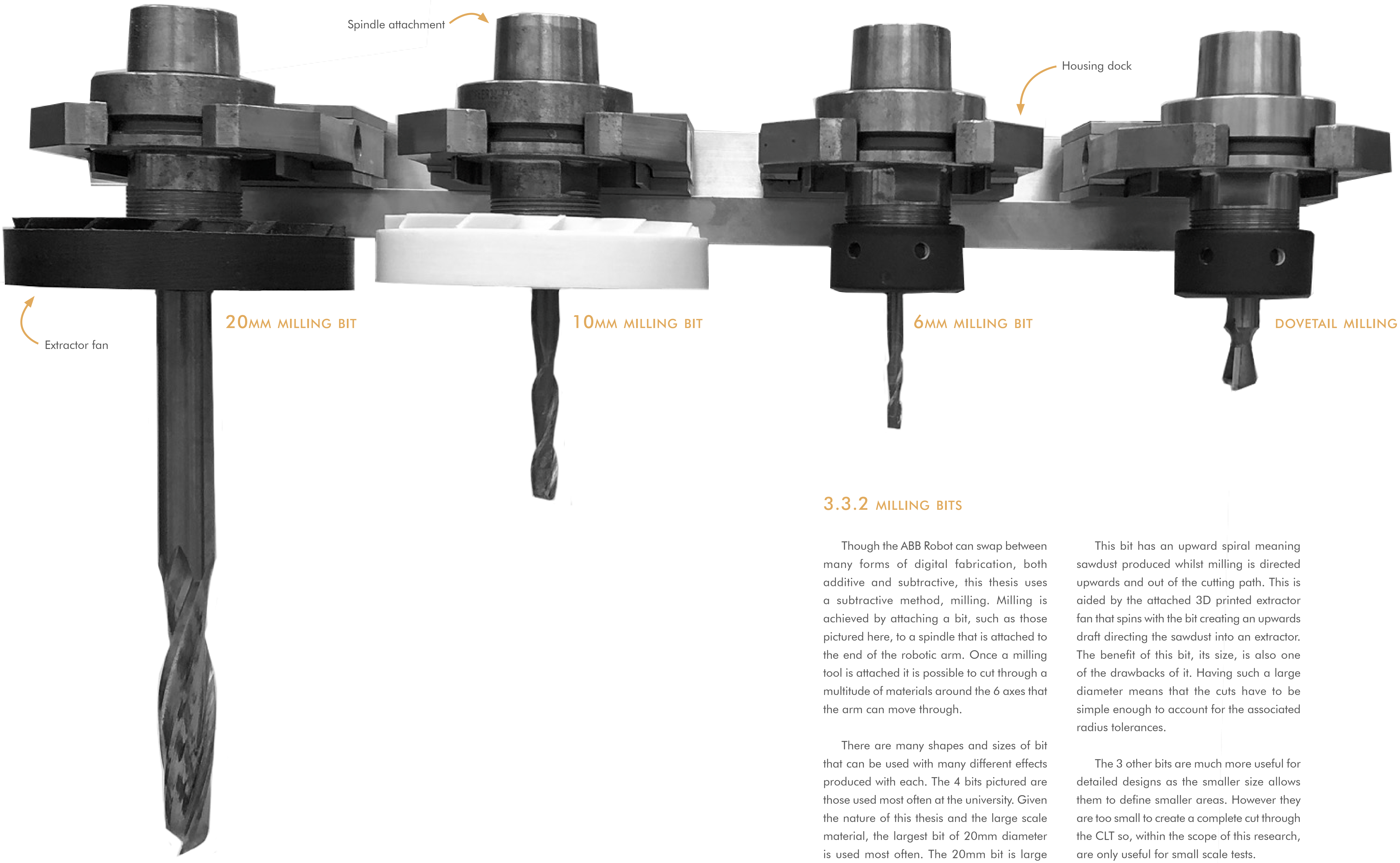


figure 47: ABB robotic arm

3.3.1 Robotics workshop

The robotics workshop at Victoria University is home to an ABB IRB 6700 robotic arm. The workshop houses the end adapter tools, work surfaces and extraction machines needed when operating the robot. It is set up to allow 360-degree rotation of the robot with tools positioned within reach to allow the robot to perform programmed tool changes that require no human interference. The cutting table is situated close to the robot base to allow for complete use of the 6 axes of the robotic arm. With access to a spindle, table saw, gripper and two 3d printing extractors, the robotics workshop allows for a wide range of fabrication.



3.3.2 MILLING BITS

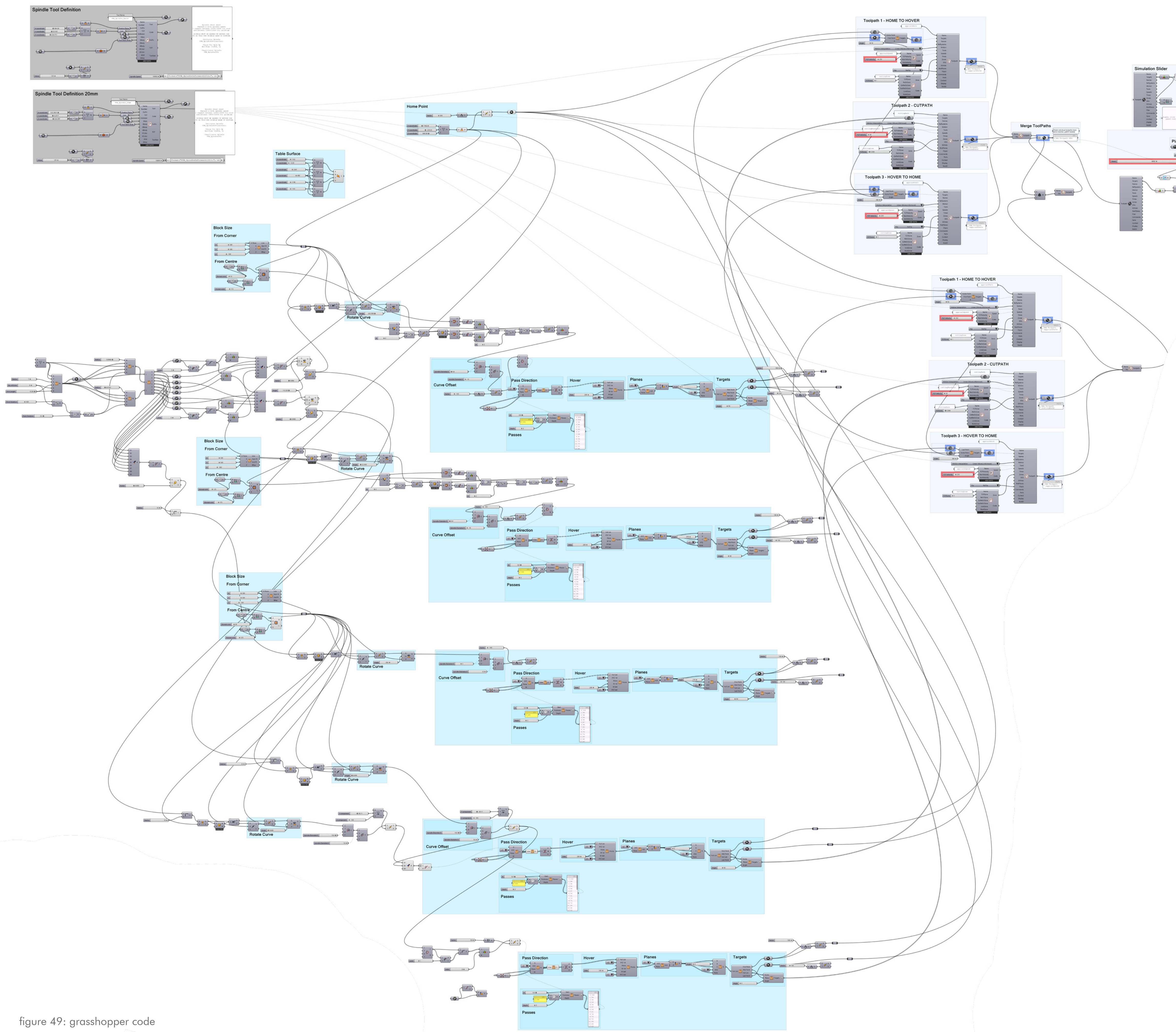
Though the ABB Robot can swap between many forms of digital fabrication, both additive and subtractive, this thesis uses a subtractive method, milling. Milling is achieved by attaching a bit, such as those pictured here, to a spindle that is attached to the end of the robotic arm. Once a milling tool is attached it is possible to cut through a multitude of materials around the 6 axes that the arm can move through.

There are many shapes and sizes of bit that can be used with many different effects produced with each. The 4 bits pictured are those used most often at the university. Given the nature of this thesis and the large scale material, the largest bit of 20mm diameter is used most often. The 20mm bit is large enough to cut all the way through CLT and thanks to its larger diameter, the toolpaths can be simpler. This bit size also means the cutting time is reduced significantly.

This bit has an upward spiral meaning sawdust produced whilst milling is directed upwards and out of the cutting path. This is aided by the attached 3D printed extractor fan that spins with the bit creating an upwards draft directing the sawdust into an extractor. The benefit of this bit, its size, is also one of the drawbacks of it. Having such a large diameter means that the cuts have to be simple enough to account for the associated radius tolerances.

The 3 other bits are much more useful for detailed designs as the smaller size allows them to define smaller areas. However they are too small to create a complete cut through the CLT so, within the scope of this research, are only useful for small scale tests.

figure 48: milling bits



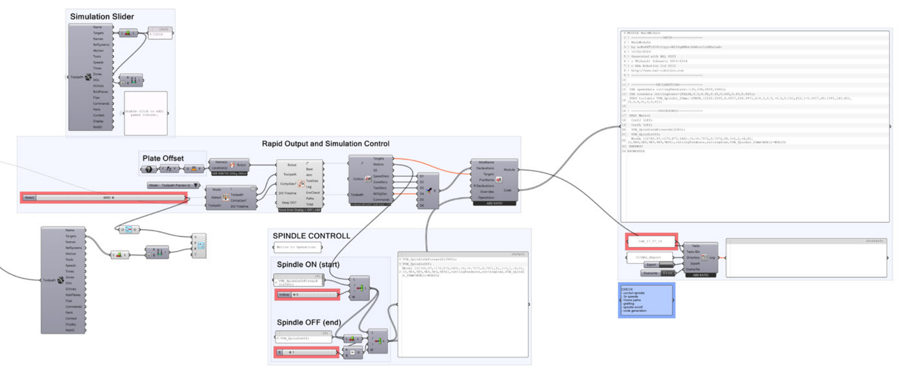


figure 49: grasshopper code

3.3.3 CODING THE ROBOT

In order to use the robotic arm, you need a code. This code is made using Grasshopper for Rhino and a plugin, HAL Robotics. There are many benefits of this coding method, first, is the visual nature of the coding system. Grasshopper allows you to create code that you can see through the use of components and clusters, allowing a novice coder to create a language that the robot can understand. The nature of this coding means that the user has absolute control over every part of the robotic movement, from the design, the way the robot moves, the speed in which it does so and much more.

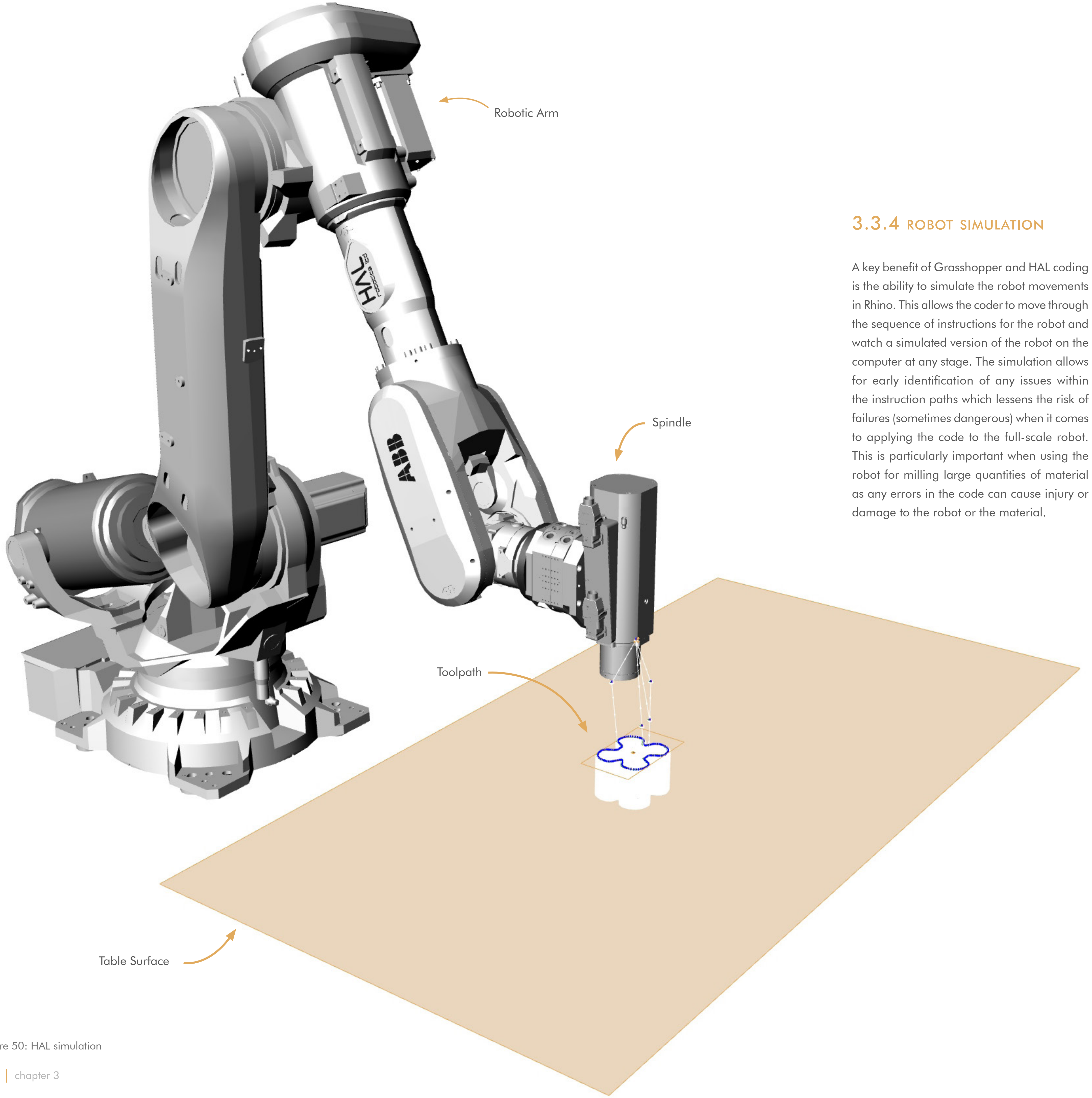
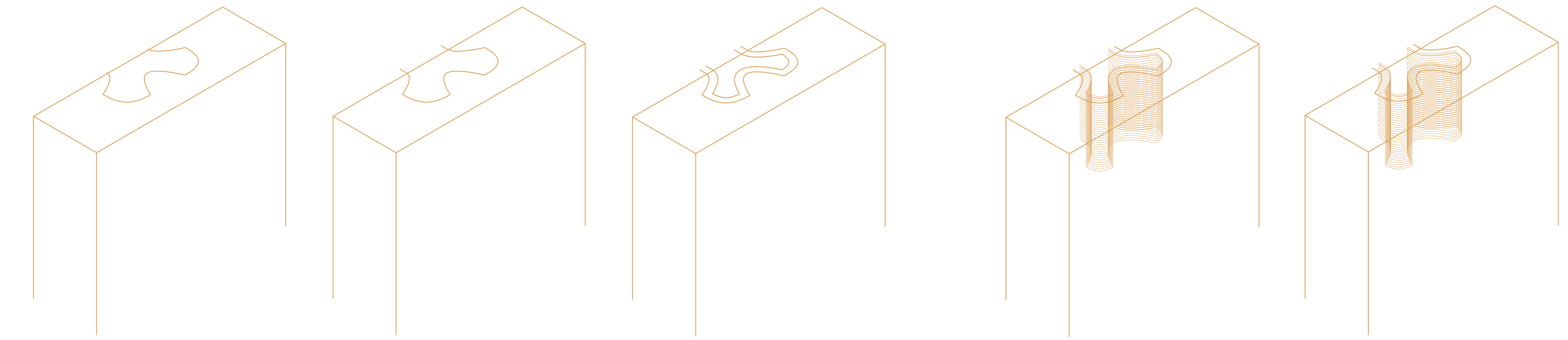


figure 50: HAL simulation

3.3.4 ROBOT SIMULATION

A key benefit of Grasshopper and HAL coding is the ability to simulate the robot movements in Rhino. This allows the coder to move through the sequence of instructions for the robot and watch a simulated version of the robot on the computer at any stage. The simulation allows for early identification of any issues within the instruction paths which lessens the risk of failures (sometimes dangerous) when it comes to applying the code to the full-scale robot. This is particularly important when using the robot for milling large quantities of material as any errors in the code can cause injury or damage to the robot or the material.



3.3.5 ROBOT TOOLPATH CREATION

The robotic arm executes tasks by following a defined toolpath. This toolpath is the visual product of the code created in Grasshopper and gets converted into RAPID code along with the tool and speed instructions to inform the robot of the actions it needs to take.

The toolpath is created through these diagrammed steps, the more complex the shape, the longer the toolpath. In order for the robot to understand the instructions, the curves created are translated into targets that contain a directional plane. These targets define where the robot moves to create the desired action. As the robotic arm can move around 6 axes, the directional plane is key to ensuring that it is moving in the correct way. For example, if the plane has a –z orientation, the robot will move directly down. If the plane has a +y axis it will move forward with the spindle at 90 degrees to the z axis, creating an entirely different cut.

This toolpath creation process is also where tolerances are crucial, both for correcting forms to account for the bit radius and for the spacing of targets. If the targets are too far from one other, the robot will find the simplest way from one to another. In the case of a straight line, this is not an issue as the robot will move from one end of the line to the other in a straight line. However, for more curved forms, this is an issue as the robot could create a straight line where there was meant to be a curve as there were not enough targets to define the curve.

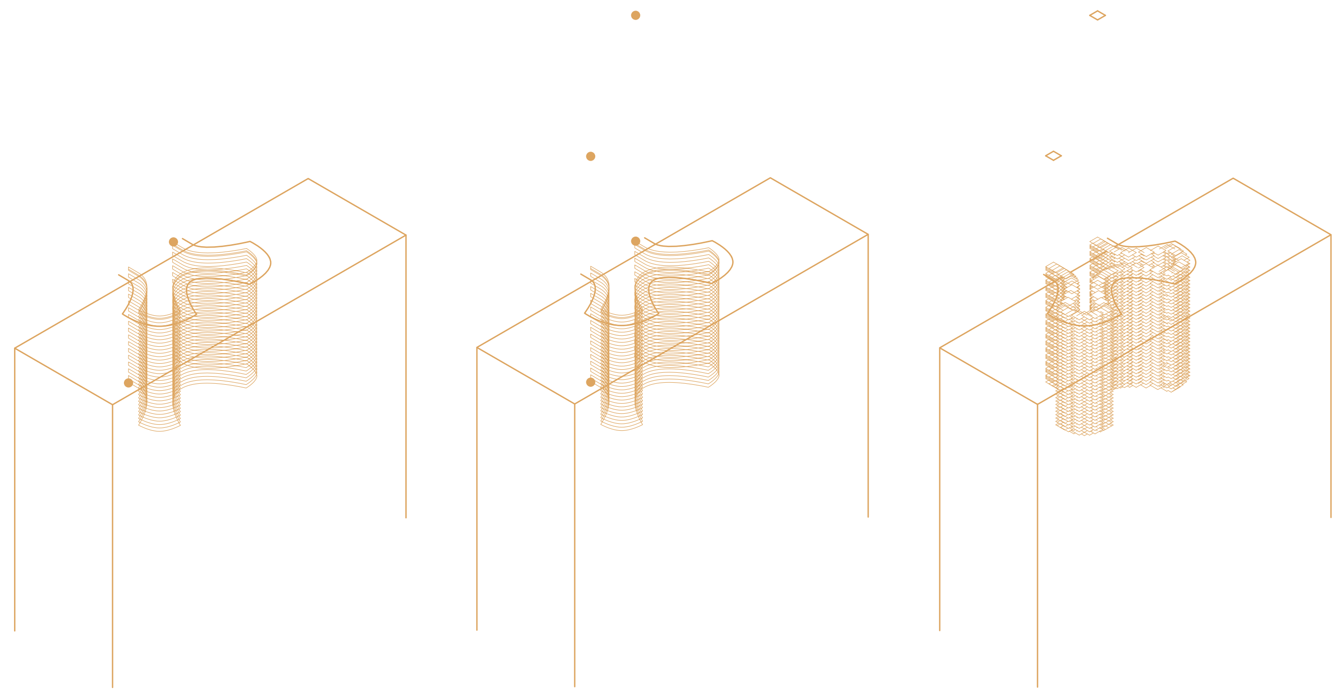


figure 51: toolpath creation

figure 52: robotic milling

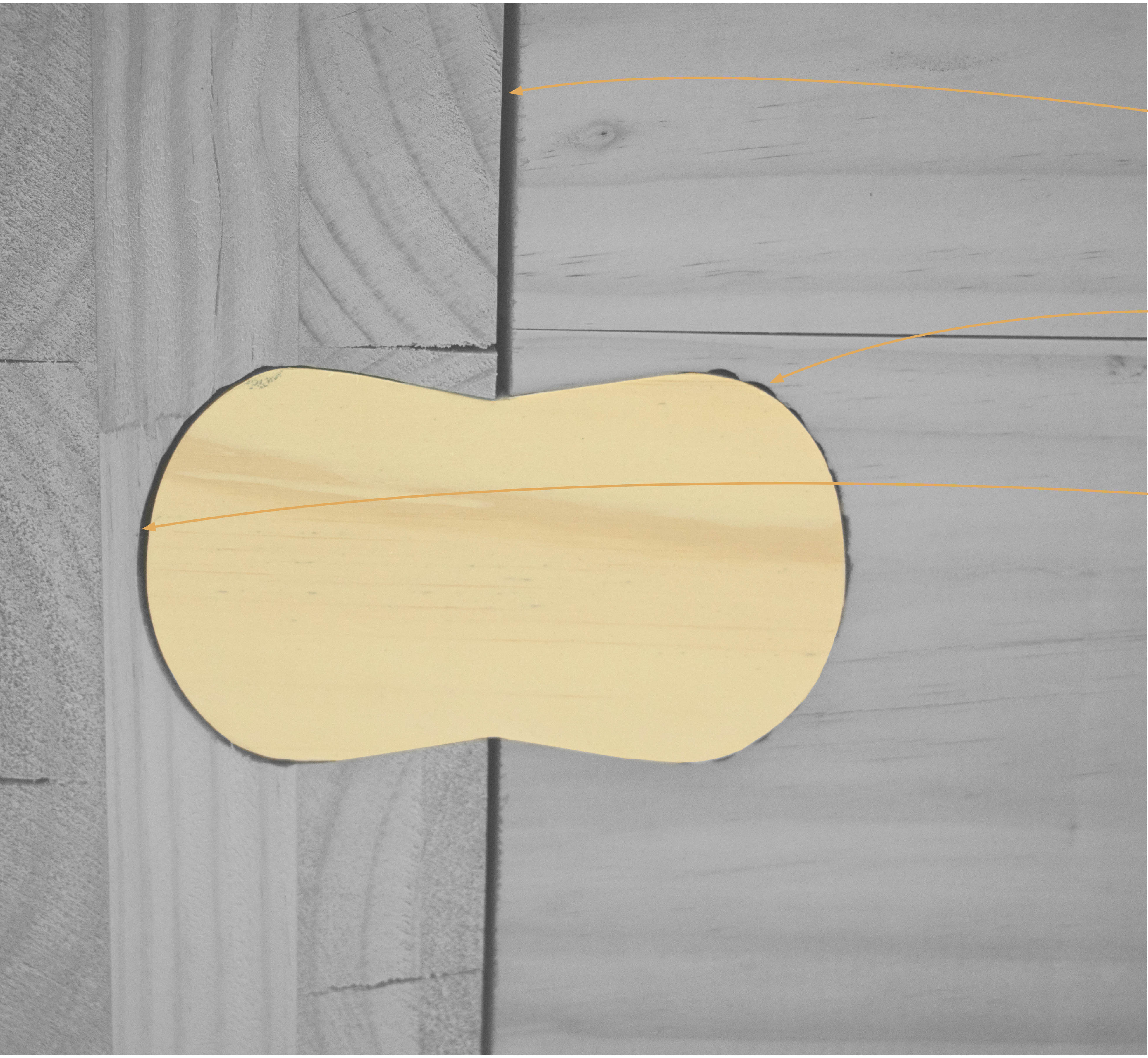
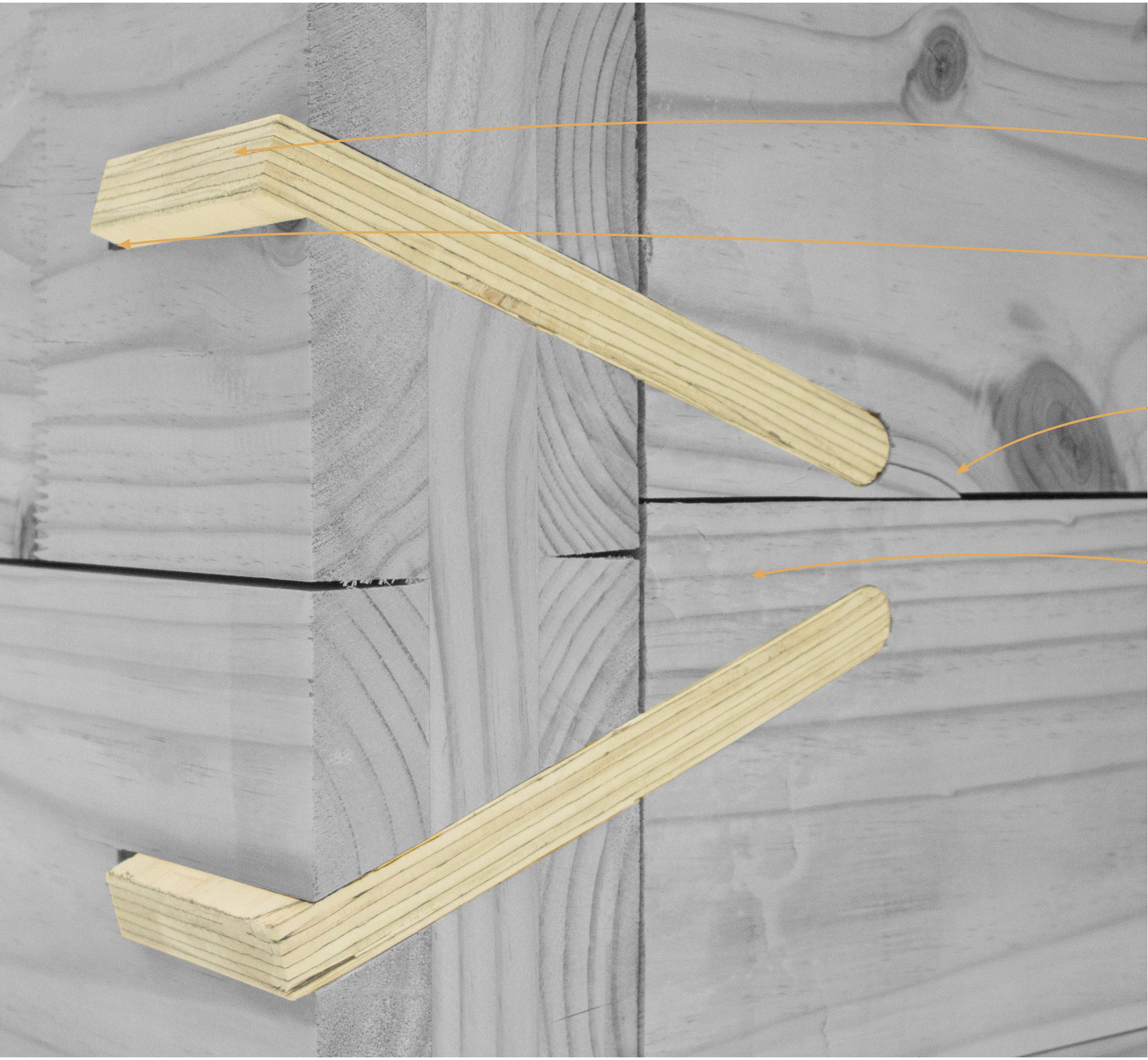


figure 53: prototype dovetail key

3.3.6 DOVETAIL KEY

Aesthetics	repeated, one face
No. of pieces	1
Wastage	17 %
Ease of building	8/10
Ease of fabrication	4/10
Thermal bridge	-



3.3.7 Angled slot key

Aesthetics	regular simple timber
No. of pieces	2
Wastage	14 %
Ease of building	6/10
Ease of fabrication	9/10
Thermal bridge	-

figure 54: prototype angled slot key

Panels pulled together

Continuous gaps where tolerances were slightly out - despite this the key fits tightly in the slot

3.3.8 STAR KEY

Aesthetics	regular star
No. of pieces	1
Wastage	16 %
Ease of building	7/10
Ease of fabrication	7/10
Thermal bridge	-

figure 55: prototype star key

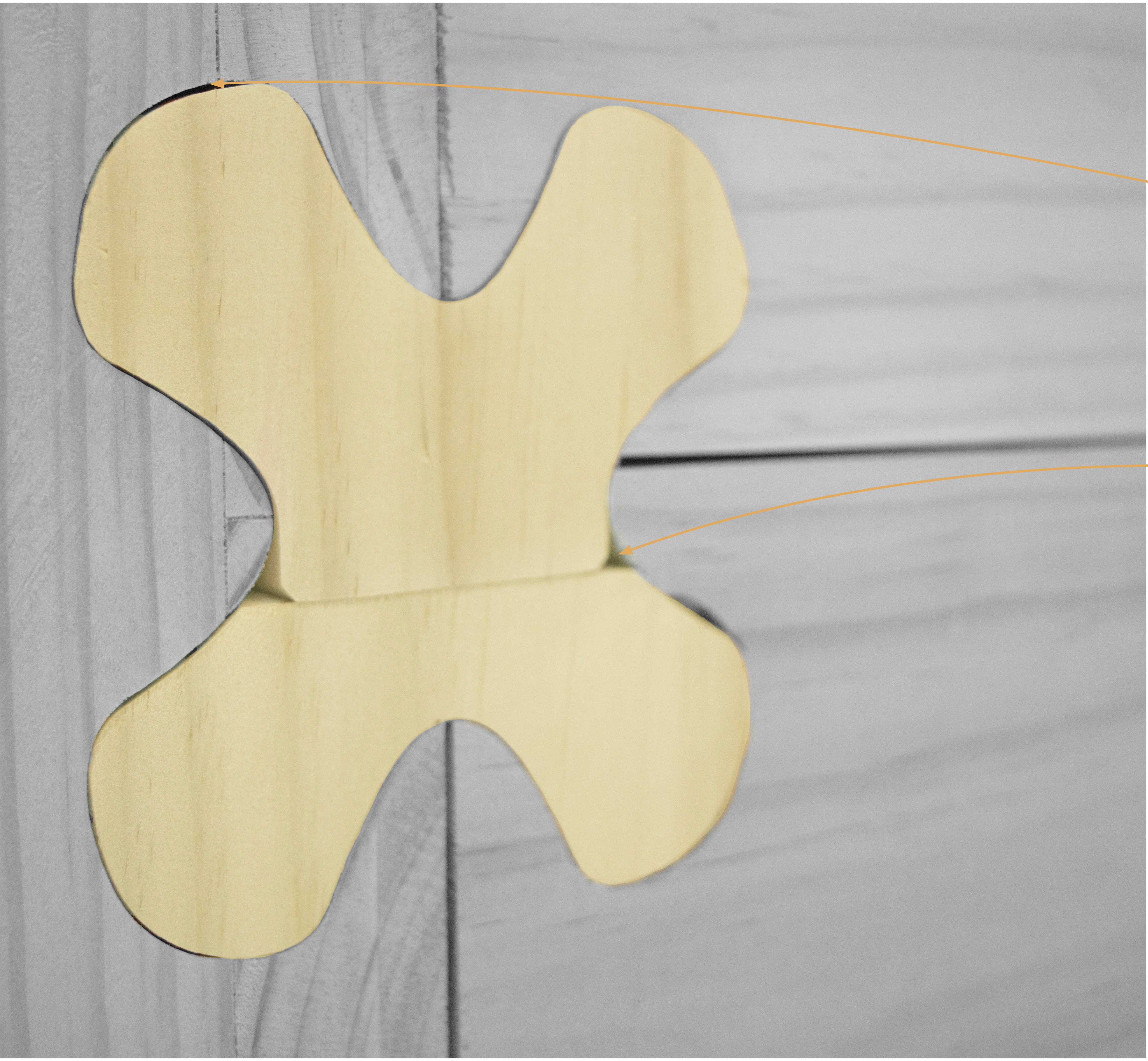


figure 56: prototype wedged star key

Smaller but still evident gaps around the edges

Curved edges created by bit movement - curve needs to be extended to allow for the radial tolerance

3.3.9 WEDGED STAR KEY

Aesthetics	regular wedge star
No. of pieces	2
Wastage	24 %
Ease of building	7/10
Ease of fabrication	4/10
Thermal bridge	-

figure 57: star prototype

figure 58: dovetail prototype

figure 59: angled slot prototype

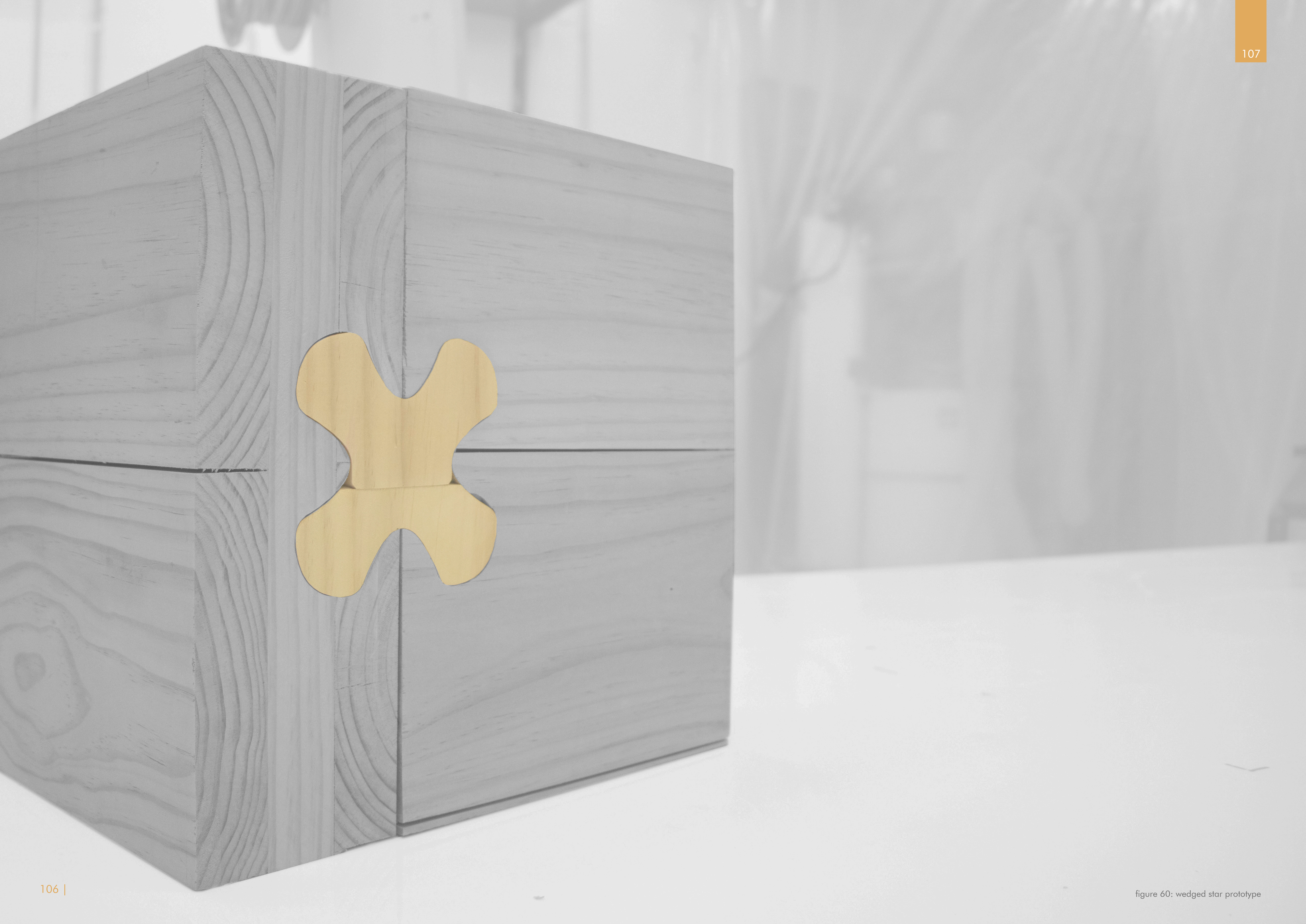


figure 60: wedged star prototype

3.4.0 REFLECTION

Upon completion of the prototypes, there was one clear outcome, the key needs to be a perfect fit. Too tight it needs a lot of labour to complete, too loose and the joint is weak. Along with this, there was a lot to be learned from both a design and fabrication point of view.

Simplicity is key and wedges are stronger. Simplicity comes in the design and fabrication processes, though not always together. The simplest design is the angled slot key, and though this was also the simplest to cut out, the keys proved to be the most complex and required a lot of planing and sanding as well as 20 minutes with a mallet on order to get the keys in the slot. Though successful once complete, if this design were to be taken to site it would require far more labour than any other designs or existing systems.

Similarly, out of the 4, the wedged star key was the most complex design but relatively easy to fabricate and complete. The wedge also lessens the need for the key to be a perfect fit as the friction created in the wedge pulls all the pieces together creating an ultimately snugger fit as it is pushed to the limit. If this design were to be taken on-site, the pieces would have to be slightly larger than normal with the excess material cut off on-site once the joint is in place. Though this is slightly more labour than other designs, it was by far the most effective and is preferable to the required perfect fit of the other designs.

Although the wedged design isn't the simplest, the design is by no means complex, it uses simple ideas and forms to create the joint. The simplicity of all prototypes is purposeful as it allows for higher efficiency both in fabrication and on-site, as shown through the assessment criteria of previous designs. The simpler shapes also produced less waste in the cuts as less material had to be taken away and fewer pieces had to be made.

This efficiency of fabrication is also affected by the tools used. For the first prototype, the dovetail, the 6mm milling bit was used meaning with each movement less material was being removed. This meant that the cut required far more points and a much longer cutting time in order to complete the joint. This bit also limited the depth of the cut, the bit itself is shorter than the thickness of the CLT meaning it could not cut all the way through. After this, the 20mm but was used for the following joints. This decreased the cutting time and also created smother shapes with rounded curves that appeal to the aesthetics of the research.

Moving forward, the lessons of simplicity and reducing waste are continued through and become design drivers throughout the following design phase. The efficiency of fabrication is also bought forward as a driver to compliment the existing design drivers and becomes the focus of the next design stage.

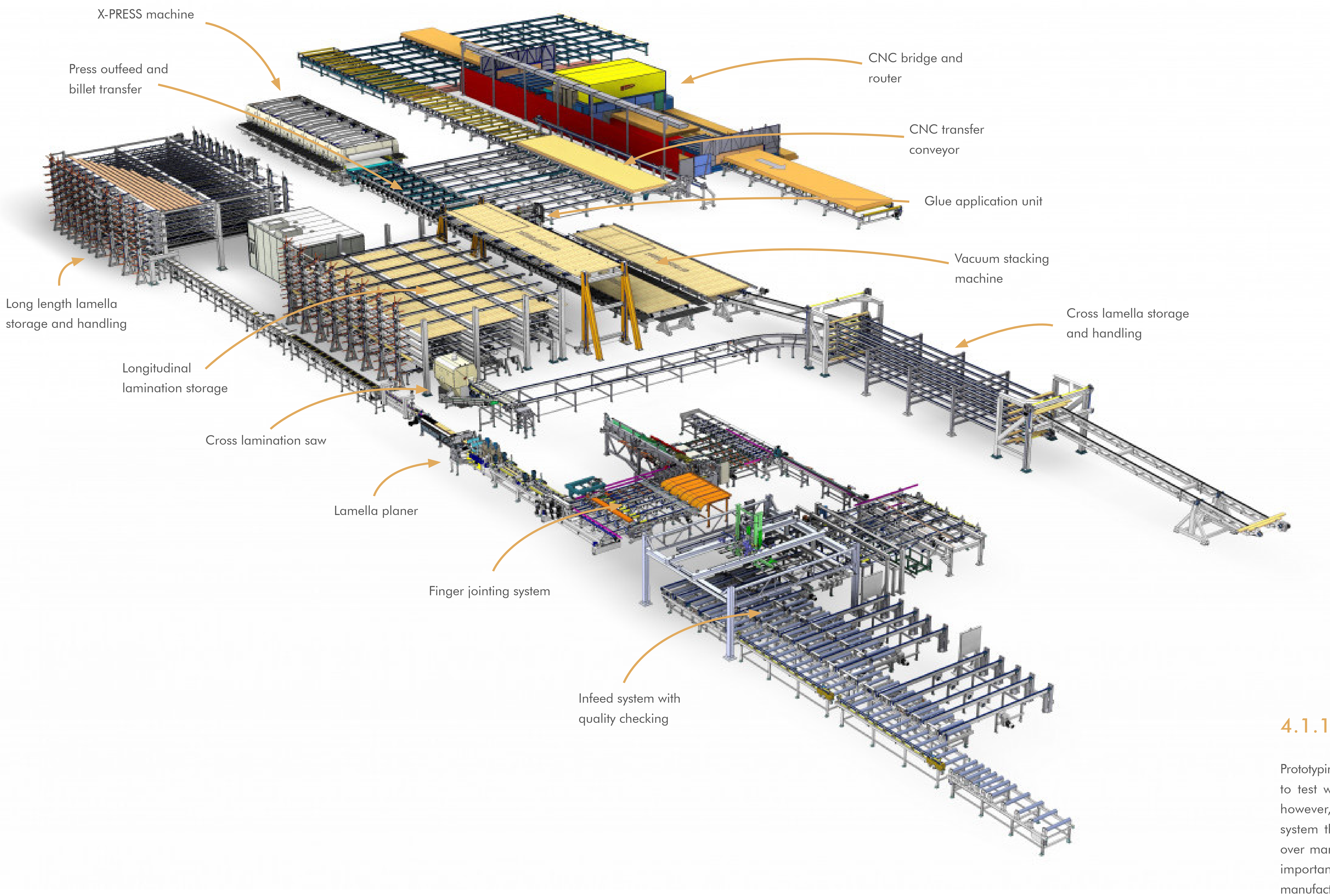
CHAPTER FOUR

INDUSTRY APPLICATION

4.1.0 INTRODUCTION

The design of a connection system means very little if it can't be applied to industry. The following chapter explores existing CLT factory tools and processes in order to develop the connection in line with what can be fabricated and eventually used for building. The developed designs consider how the connection will be fabricated, the material they are made out of, their ability to adapt and the structural integrity of the joint in order to define the best solution.

figure 61: CLT factory



4.1.1 CLT FACTORY

Prototyping at a small scale is hugely beneficial to test whether ideas are working or not, however, this research looked to create a system that can be used on a large scale over many projects. In order to do this, it is important to have an understanding of CLT manufacturing. Every factory is slightly different so one factory was chosen as a reference to understand the process. The chosen factory is the XLAM factory in Wodonga, NSW, Australia.

figure 62: CLT factory line

4.1.2 CLT FACTORY

Despite there being differences in each factory, the base procedure to create the panels is the same. The XLAM Australia production line was designed by Ledinek, who create the factory layout and a large amount of the machinery needed on this line.

As depicted on the previous page, there are a number of processes in which the timber lamellas go through in order for them to become a CLT panel. Once in the factory, the lamellas are finger-jointed together before being fed into multi-level storage. From there, they are planed, sized and sorted into cross laminations and longitudinal laminations and stored in separate multi-level storage units where they are ready to be placed into panels.

Vacuum stacking devices lift and place the groups of lamellas onto a moving conveyor, alternating between longitudinal and cross laminations to create a billet or panel. Between each layer, the conveyor moves back and forward underneath a polyurethane glue application unit before moving into the X-PRESS CLT press which applies pressure to the billet, bonding the layers together. Once bonded, the conveyor carries the billet out to be taken to the CNC router where it is cute to size and any extra details are added.

This process has been designed to produce as little waste as possible, after all, the creation of CLT was partly driven by the desire to use 'waste' timber. However, there is still waste produced in production such as this. Waste comes many forms but is most commonly used to make other wood products such as chipboard. The sawdust produced throughout the process is can be used to make compressed fire blocks or as stuffing for animal mattresses (J. Church, personal communication, October 18, 2019). Yet, there are still issues regarding a large amount of waste product that is created as it comes from treated panels which can contaminate untreated material meaning it often has to go to landfill.

Finding another use for these treated panels is where this research is key. Having deduced that using a timber on timber method for joinery is the most effective in terms of minimizing thermal bridging and increasing the aesthetic qualities of the space, the question can be asked; from what are these extra timber pieces made?

As these connections are for CLT panels, the fact that the timber is treated has no effect as it is used within a structure that is treated in the same way. This also allows for a much smoother manufacturing process as all the tools and materials required are already in the factory and there is no need to outsource the fabrication of the joints creating a one-stop-shop for both panel and joint manufacturing.

figure 63: finger jointing line

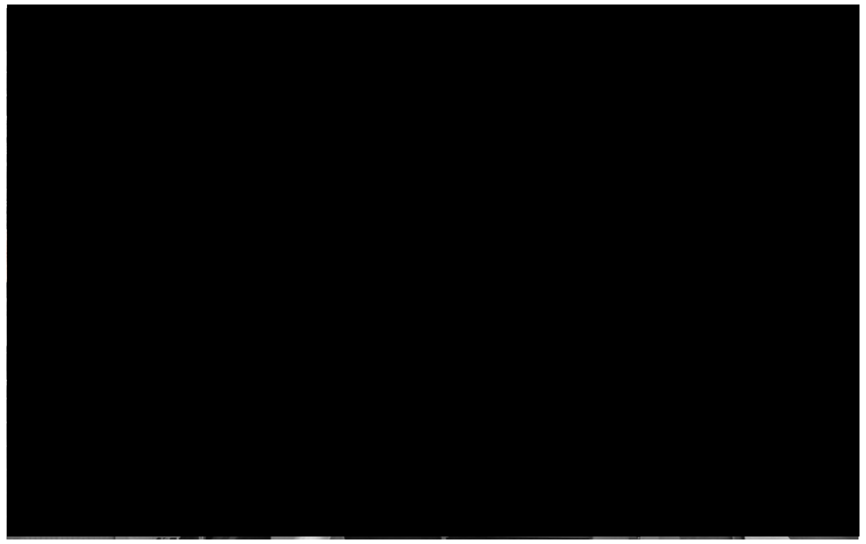


figure 65: moveable conveyor for billet assembly

figure 64: glue application unit

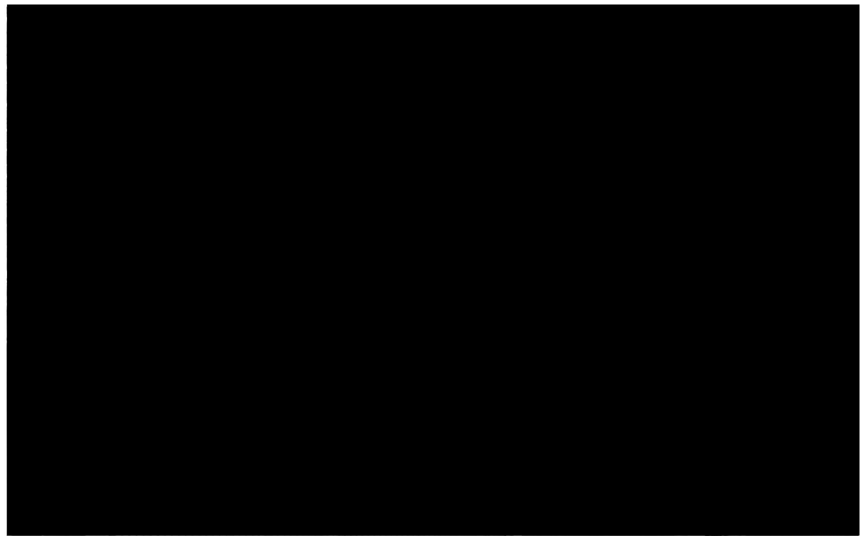


figure 66: X-PRESS timber press

4.1.3 CNC CUTTING

Within each CLT factory there are a number of machines and tools available for a wide range of jobs, yet, for the creation of joints such as those designed in this research, the job falls to the CNC router. The XLAM Australia factory uses a Hundegger PBA gantry style CNC router, a common choice in many CLT factories. This machine can process panels of between 8cm and 48 cm thick and is accurate to the millimeter (Hundegger, n.d.). This CNC router has the ability to move through 5 axis which creates flexible processing options that can be altered for various tasks.

There are 8 tool units available, they are; 5-axis chainsaw, circular saw, vertical milling, vertical drilling, 4-axis milling and drilling, circular saw planing, marking, and inkjet units. There is also a 5-axis milling unit with tool changer that is of most interest to this research. This unit allows for up to 11 tools, including milling, drilling and sawing tools, to be stored and automatically picked up to suit each task (Hundegger, n.d.). The milling bits, similar to those used with the ABB robot, just on a much larger scale, come in a variety of sizes and shapes, including cylindrical, end mill and dovetail cutters with diameters of up to 310mm. The milling bit used to create the joints will have a larger effect on the shape of the joint as the bigger the bit, the bigger the tolerance radius required.

figure 67: CNC machining CLT

4.2.0

DEVELOPED DESIGN

4.2.1 MANUFACTURING THE KEY

Being that CNC machines in CLT factories are gantry style and able to process 16m x 3.6m panels, it makes no sense to cut one key at a time. The slots for the keys can be cut as part of any other CNC processes such as creating windows or services holes however the manufacturing of the key itself will be separate.

As some of the waste produced by the factories is in panel form, it makes sense to use these to create the keys, reducing the waste and making use of material that would normally go to landfill. These 'waste' panels can be any shape and size so the keys need to be able to fit on as many of these as possible. When creating the small scale prototype joints, there was a lot of material waste around the key itself. This was reduced thanks to using a smaller piece of CLT but this might not always be the case in the factory, and, as previously mentioned, the large gantry scale CNC machine won't be suitable for one key at a time.

This is where the idea of tessellation comes in. If the key can be designed to not only create a strong joint but also follow a repetitive pattern, multiple keys can be manufactured at once. With a tessellated pattern, excess material waste is minimised as each cut will create multiple keys meaning the only full pieces on material waste will be on the outer edges where full keys cannot be made.

figure 68: example star key

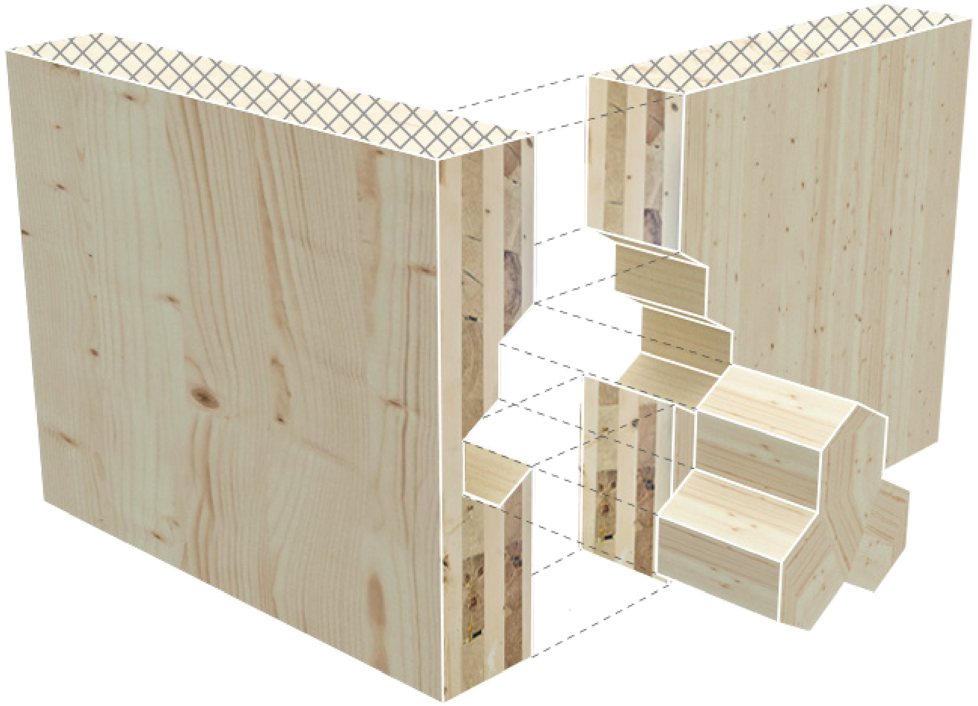


figure 69: star tessellation key

figure 70: star tessellation

4.2.2 STAR TESSELLATION

This key follows on from the previous star designs and adapts them to allow for a repeated pattern or tessellation. The benefit of this design is knowing already how it may work. As shown with the previous star key, an exact fit is needed to ensure rigidity and strength in the joint. It is also important to acknowledge the need to account for bit tolerances. This is particularly important where the designs have corners as these will not occur when cut in the factory.

Though this key has the potential to work well as a joint, fabrication may not be the simplest. Despite being a regular, tessellated design, the arrangement and design of the key means that there a lot of paths to follow in order to cut the key. The more paths, the more time to cut and the more wastage involved. There is, however, a benefit to this. Though the path is long, it can be followed in one continuous path without having to lift the milling bit out and down again meaning a smoother cutting process.

Aesthetics	regular angled star
No. of pieces	1
Wastage	17 %
Ease of building	7/10
Ease of fabrication	6/10
Thermal bridge	-

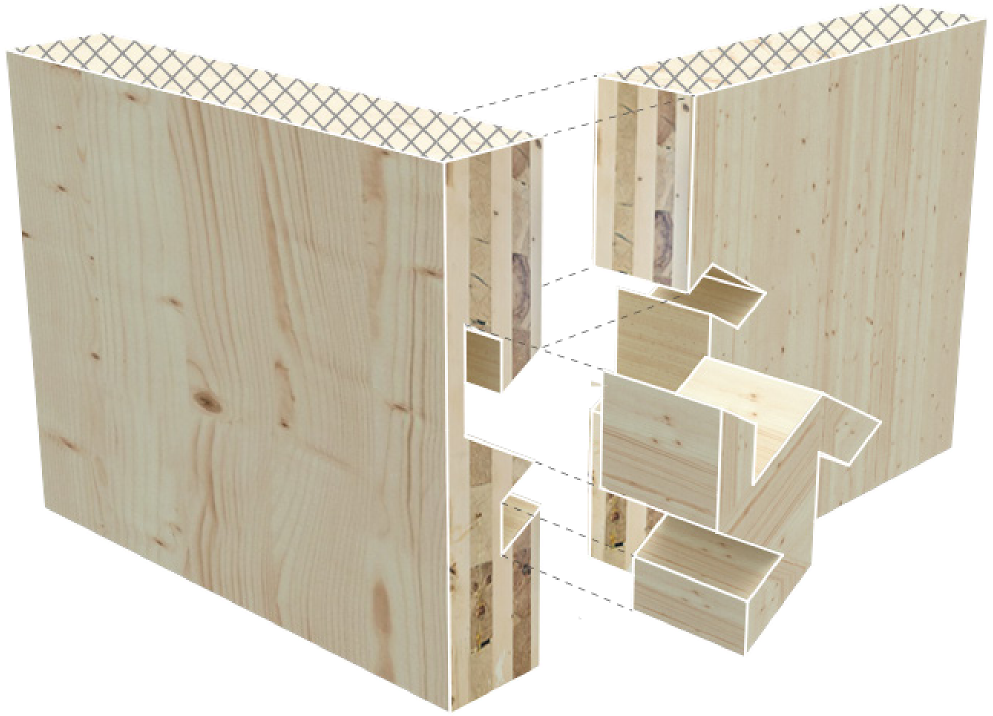
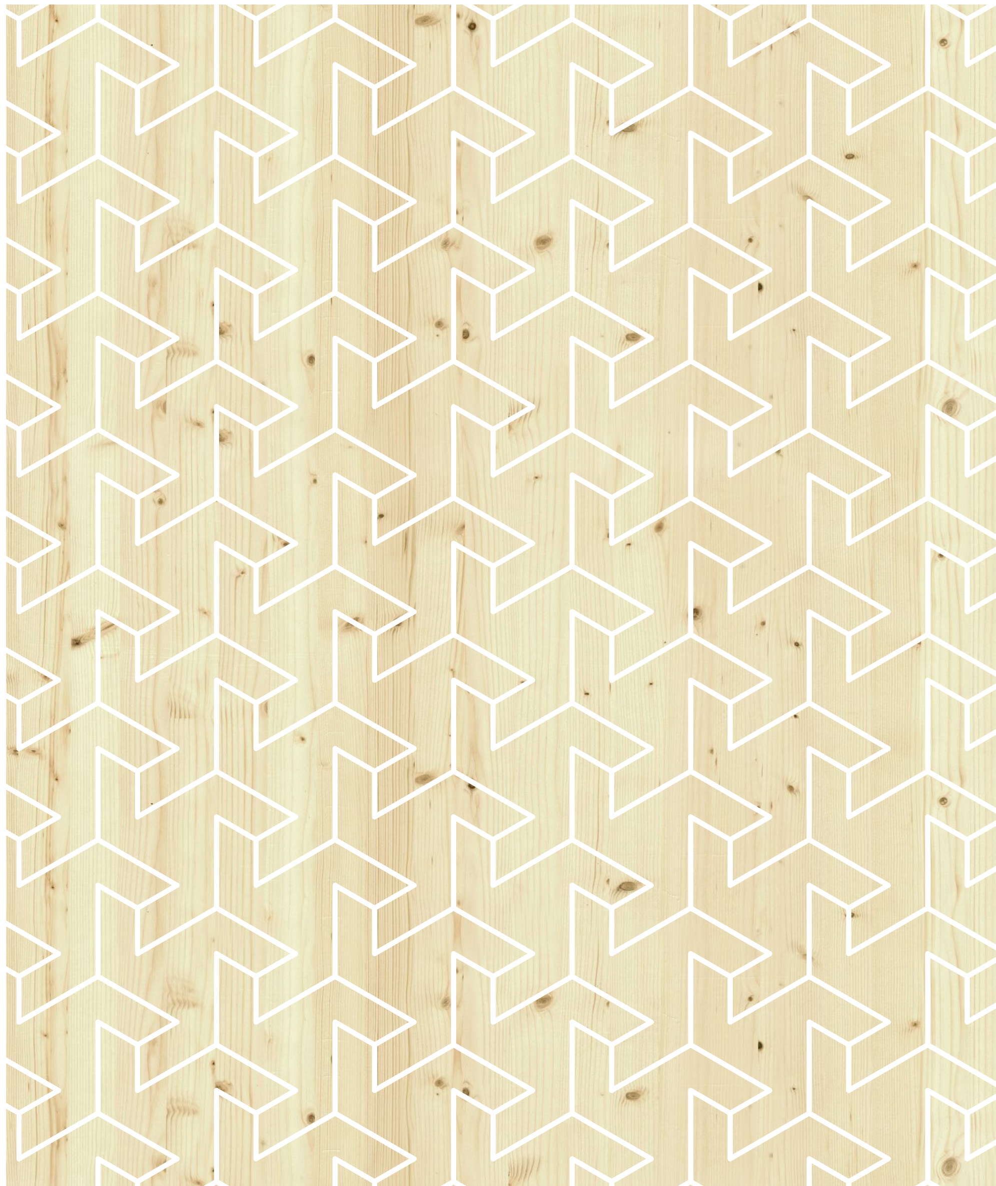


figure 71: point tessellation key

figure 72: point tessellation



4.2.3 POINT TESSELLATION

Following on from the previous star key, the design extends out each arm to creative 3 distinct branches. These new branches act in a similar way to the dovetail, by pulling the panels in towards a central point. Based on the prototypes of previous designs, it is safe to assume this joint will also require a very tight to be effective. This may be far more difficult given the more complex shape and added number of angles that need to fit together.

More so than previously, tolerances will have a huge effect on this design as there are a number of smaller areas and an increased number of corners that will be affected. This increased complexity will also have an impact on fabrication time. Though the keys can be milled using a single path, this path is far more complex than the previous design and will require a much longer cutting time. The design will also require a smaller bit to cut around the branches which can often mean more cutting time than if using a bigger bit.

Aesthetics	regular pointed star
No. of pieces	1
Wastage	17 %
Ease of building	7/10
Ease of fabrication	5/10
Thermal bridge	-

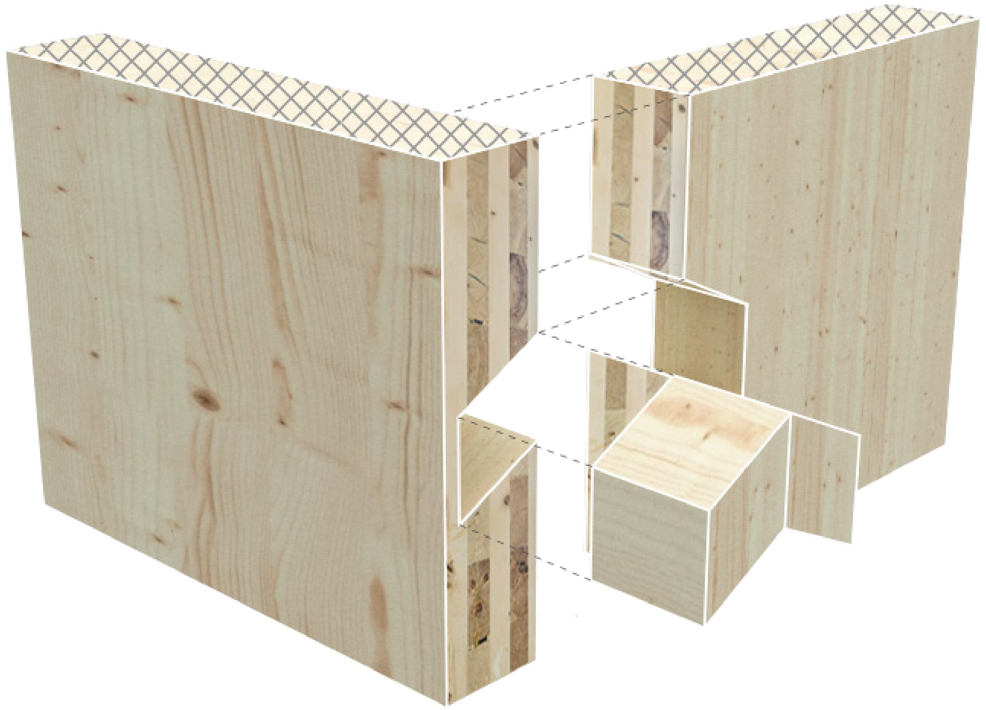
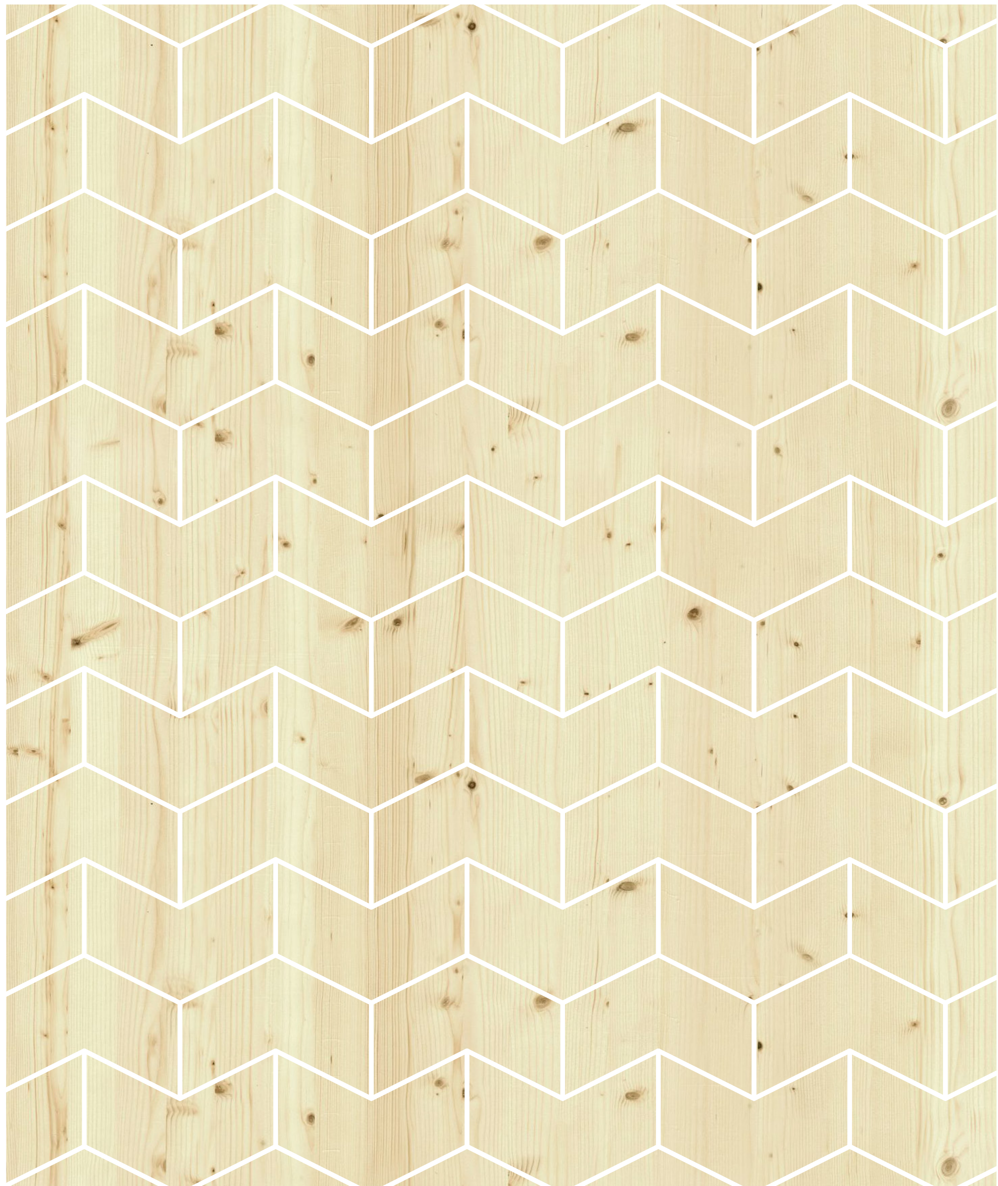


figure 73: arrow tessellation key

figure 74: arrow tessellation



4.2.4 ARROW TESSELLATION

This key design takes a step back to a more simple design. Inspired by the traditional dovetail that uses angles to lock and pull pieces into place, this design uses angles in a similar way. As the prototypes showed that simplicity is key, coming back to clean shapes using traditional techniques and applying tessellation should be the most effective jointing system. Again, a tight fit is required for this design, but, given the simplicity of the design, it is possible to add in a wedge, creating two pieces, to aid in creating a strong tight joint.

As the design is simpler, the tolerances are far easier to manage, despite the regular corners, and they won't alter the design too drastically. This simplicity also means the fabrication process will be far easier and quicker which is preferable when using the keys on a large scale. However, the tessellation of this design means that cutting path isn't one path and will require lifting and moving of the milling bit to cut around the keys which will slow down what could be a streamlined fabrication system.

Aesthetics	regular alternating arrow
No. of pieces	1
Wastage	17 %
Ease of building	8/10
Ease of fabrication	8/10
Thermal bridge	-

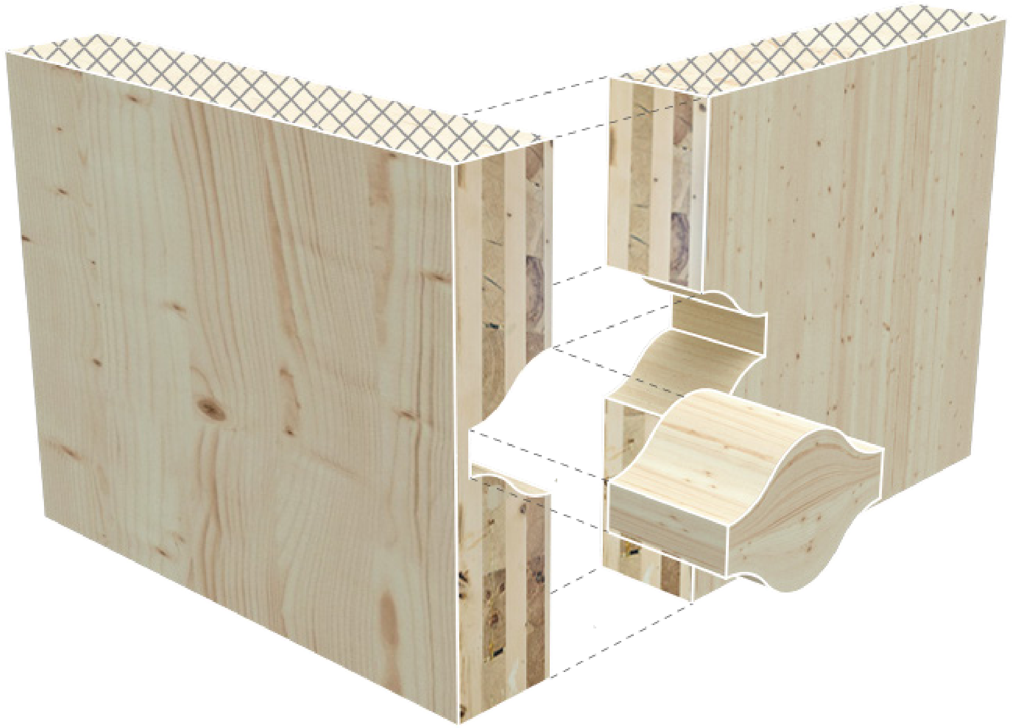


figure 75: leaf tessellation key

figure 76: leaf tessellation

4.2.5 LEAF TESSELLATION

Traditional Japanese joints have a base in nature and organic systems which influenced the design of this key to embrace a more organic form. Using a more rounded form such as this means that issues around tolerances are reduced as the milling bits are already rounded. It also creates a fluid path for the bit to follow. However, similar to the arrow, in order to separate the keys, the milling bit will be required to come up and back down again rather than following one path.

This primary concern with this design is its ability to pull the panels together. The most successful designs have a smaller central point with arms pulling in towards it whereas this design is the opposite. Based on the results of the prototypes and the precedent examples, it could be assumed that this design would fail to pull in the panels without the aid of metal fasteners which can be avoided with other designs.

Aesthetics	regular leaf
No. of pieces	1
Wastage	15 %
Ease of building	7/10
Ease of fabrication	7/10
Thermal bridge	-

figure 77: arrow key connection 0.1

figure 78: arrow key connection 0.2

4.2.6 DESIGN CHOICE

A key driving factor for the designing of this joint is the ability to fabricate it on a large scale within an existing factory, ideally with waste material. Based on this, and the results of the prototyping, the most successful design is the arrow tessellation. This design was also selected as it was the most effective when checked against the assessment criteria. Despite this, there are issues and improvements that can still be made.

Firstly, the prototyping of previous designs showed that the inclusion of wedge in the key was by far the most successful way to join the panels. As it stands the arrow design does not include this, but, this can easily be added in. The wedged star key was made by creating an angled cut through the middle of the joint. In order to account for the size of the bit, the arrow shape will have to be enlarged slightly but this will not have an effect on the tessellation. As the design is simple, this angled cut could be created in multiple keys at once using the 5-axis circular saw on a shallow angle so as to keep the key to 2 pieces.

There was also the issue of creating a simple cutting path that can be continuous. Thanks to the simplicity of the design, this can be achieved by simply aligning the straight edges of the keys to create a continuous line. Though it is hard to know conclusively, this could be achieved most effectively by using a vertical milling bit to cut the angles of the arrows followed by the circular saw to follow the straight line. This method may also create less sawdust waste as the circular saw is thinner than the milling bits, meaning less waste created in the cut.

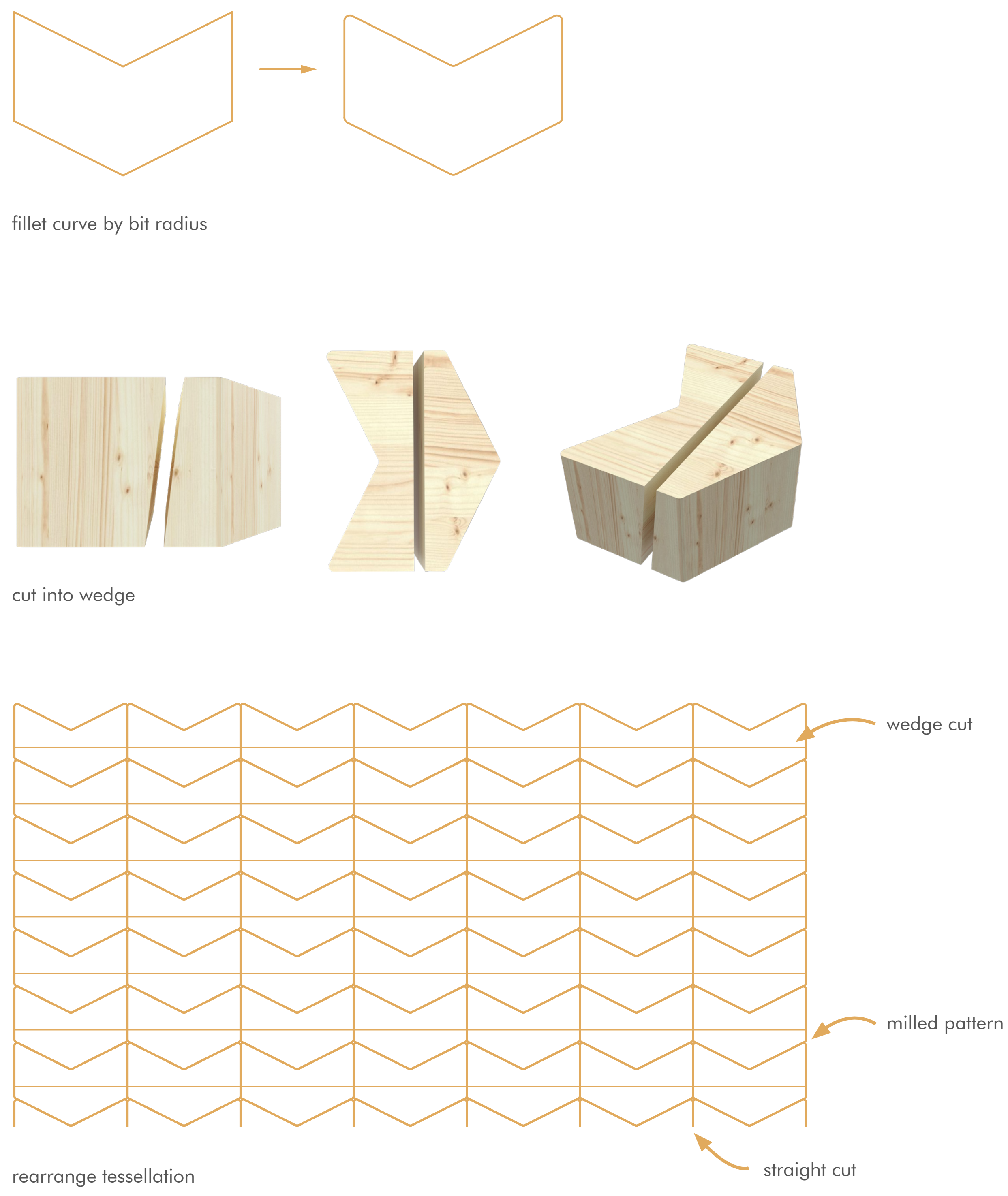


figure 79: design development

4.2.7 STRUCTURAL CONSIDERATIONS

It is also important to consider how the joint might perform structurally even if testing the structural capacity is not within the scope of this thesis. The dovetail joint is successful as its alternating angles work to resist forces in multiple directions. These angles also help to lock the joint in place and reduce movement. The arrow design has a single angle with a pointed end which will take loads differently. One way in which this joint system could be made stronger is by alternating the direction in which the arrow is facing when used to join full-scale panels. This mimics the effects of the alternate angles of the dovetail and could allow the joints to take multiple loads, alternating between being in tension and compression depending on the force applied. This is aided by the addition of the wedge as this works to not only ease the construction process but also lock the joint once in place.

figure 80: arrow connection 0.3

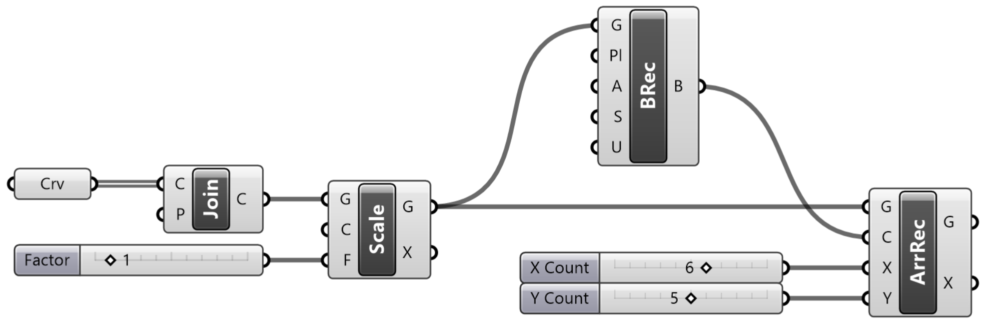
4.2.7 PARAMETRIC DESIGN

As the key will ideally be made from waste panel offcuts, it is important to consider that the size of these panels could vary greatly. This means that the design has to be flexible enough to be applied to any number of panel shapes and sizes. This flexibility can be achieved through parametric software whilst maintaining the tessellation design.

Using grasshopper, the arrow design can go through many adaptations based on the requirements of each design. Firstly the size of the key itself can be altered. This means that smaller or larger keys can be cut based on each project requirement. This will also be helpful if structural testing were to be undertaken as it would be simple to alter just the size of the key and test what difference this makes to its strength.

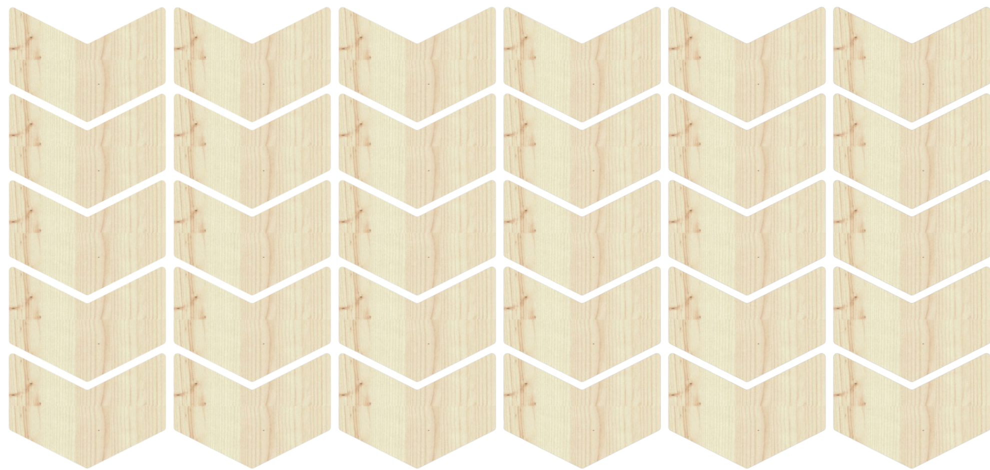
Along with this, two simple number inputs define how many rows and columns there are in the tessellation. This allows for the tessellation pattern to match the panel available. For example, if an offcut was a very long panel with a small width, the tessellation could be altered to have fewer columns and more rows.

These inputs work together to create the ideal tessellation of the base shape based on project, structural and panel requirements when manufacturing. It also means that waste is avoided as much as possible.



increase key size

add columns of keys



add rows of keys

figure 81: parametric design

4.3.0

BUILDING APPLICATION

4.3.1 TRANSPORT TO SITE

Manufacturing the keys is only one part of the process. It is also important to explore the transportation and on-site process involved in the construction of a CLT building. As shown in the adjacent image, CLT panels are transported on their flat on a trailer and taken to site. In cases where the CLT is imported from overseas, the panels are loaded into a container to be transported.

As the keys are individual pieces when cut, it begs the question, how will they be transported? Common connection systems such as screws and brackets arrive at site separately in their own boxes. Though this could work for the keys, it would require a much larger box that could be added to the existing trailer or container, however, it may take up more space and be an inefficient use of transportation. The main issue is that keys are cut into separate pieces despite originating for a panel much like those already being transported. As its panels that are being transported, it may be far simpler to transport the keys as panels too.

There are two ways in which the panel form can be kept whilst still cutting the keys out. One is to not cut all the way through. If most of the CLT has been cut through to make the key but a small amount of material is left, this will hold the panel form. The second is to create small notches in the cut paths where the milling bits don't cut, keeping a small amount of CLT joining each panel. Both of these methods require extra cutting once on-site to remove the keys from the panel.

Being that this process cannot be simulated it is difficult to say what is most successful. However, based on the desire to streamline the process, it seems that delivery in a box would be the most effective. This removes the need for onsite cutting which could lead to inaccuracies meaning the keys would not be as effective as well as slowing down the assembly process.

figure 83: CLT transport

figure 84: CLT installation

4.3.2 ON SITE

Once the keys and panels have arrived on site it is time to put them together. This part of the process resembles a large 3D puzzle with specific pieces required in specific places. CLT panels are moved into place using cranes and lifting straps attached to the panel through temporary holes. This requires a team of people on the ground and a team where the panel is to be placed in order to edge it into place. Once the panels are in place, they are attached using whichever system has been chosen for that project. It most cases, this involves lots of screws and attaching angle brackets to secure the panels. With the key design, this is replaced by a stack of keys and a mallet to hammer them into place.

CLT is known for being extremely quick and quiet once on site, one of its many benefits. It is also known for requiring far fewer deliveries to site compared to traditional steel or concrete structures. The key design is in keeping with these factors as it requires no loud electronic tools to assemble, requires no extra deliveries and takes up little space once on site.

CHAPTER FIVE

CONCLUSIONS

5.1.0 LIMITATIONS

As this research uses advanced technologies to design and prototype a connection system that could lead to full-scale application, it was predicted that some limitations would be encountered.

The first of these is the use of the robotic arm. The learning process undertaken to understand this technology became invaluable when designing for full scale application. Though the initial unfamiliarity of robotic controls and processes meant a large portion of time was spent learning the basics of this fabrication method before any prototypes could be made, it allowed for a more in depth understanding of machine processes. As large-scale factory machinery often has similar machining processes and limitations, this allowed for predications to be made as to how factory machinery would perform if the prototyped designs were to be taken forward. Additionally, the unforeseen closure of the university workshop and robotics lab meant that continued prototyping for design development could no longer be undertaken so assumptions had to be around the feasibility of the developed designs.

Another limitation was the inability to structurally test the connections. This was known at the start of the research and was defined as being out of the scope as at this stage it did not hinder the design progress. Despite this, it is an area that could be interesting to explore with the correct equipment and time.

As a design that is intended to be fabricated on a large scale, there are limitations regarding the feasibility of this fabrication in a factory setting. Though this has been speculated upon and investigated in conjunction with actual tools and factory services, it is impossible to know at this stage whether a design such as that produced in this research would be possible.

Similarly, in regards to building application, the ease of building and using this design on site is something that can only be hypothesized at this stage. All assumptions made are based on a single joint prototype as opposed to a full panel and therefore may not be an accurate representation of how the system might work.

5.1.1 FUTURE RESEARCH

The limitations identified offer many possibilities for future research into improving this connection system and applying it on a large scale.

Once more prototypes can be made, structural testing could be undertaken to determine the strength of the joint under more rigorous circumstances, including earthquake simulation. This research could be furthered with the advent of full scale in factory prototyping. If the speculated factory fabrication technique, using waste and the CNC router could be tested, it may become clearer as to whether or not this is a viable solution for waste minimisation and reuse.

Full scale prototyping would also allow for structural testing of the key system on a larger scale as test structures could be made and further examined against structural requirements.

This research could also lead into cost evaluations as well as the reality of building without internal finishes. It was assumed that with the use of a timber on timber connection, the interior surfaces of the walls would not need to be covered, meaning less cost and less time. It would be interesting to compare whether the cost of fabrication and installation is itself lower or if it is comparable to the cost saved through removal of interior finishes.

5.1.2 CONCLUSION

The aim of this research was to explore how digital fabrication and traditional timber joinery could be combined to create a connection system for cross laminated timber. Through the use of digital design and prototyping, this thesis has shown that an alternative timber connection system for CLT panels can be designed to reduce and re-use waste using existing fabrication methods.

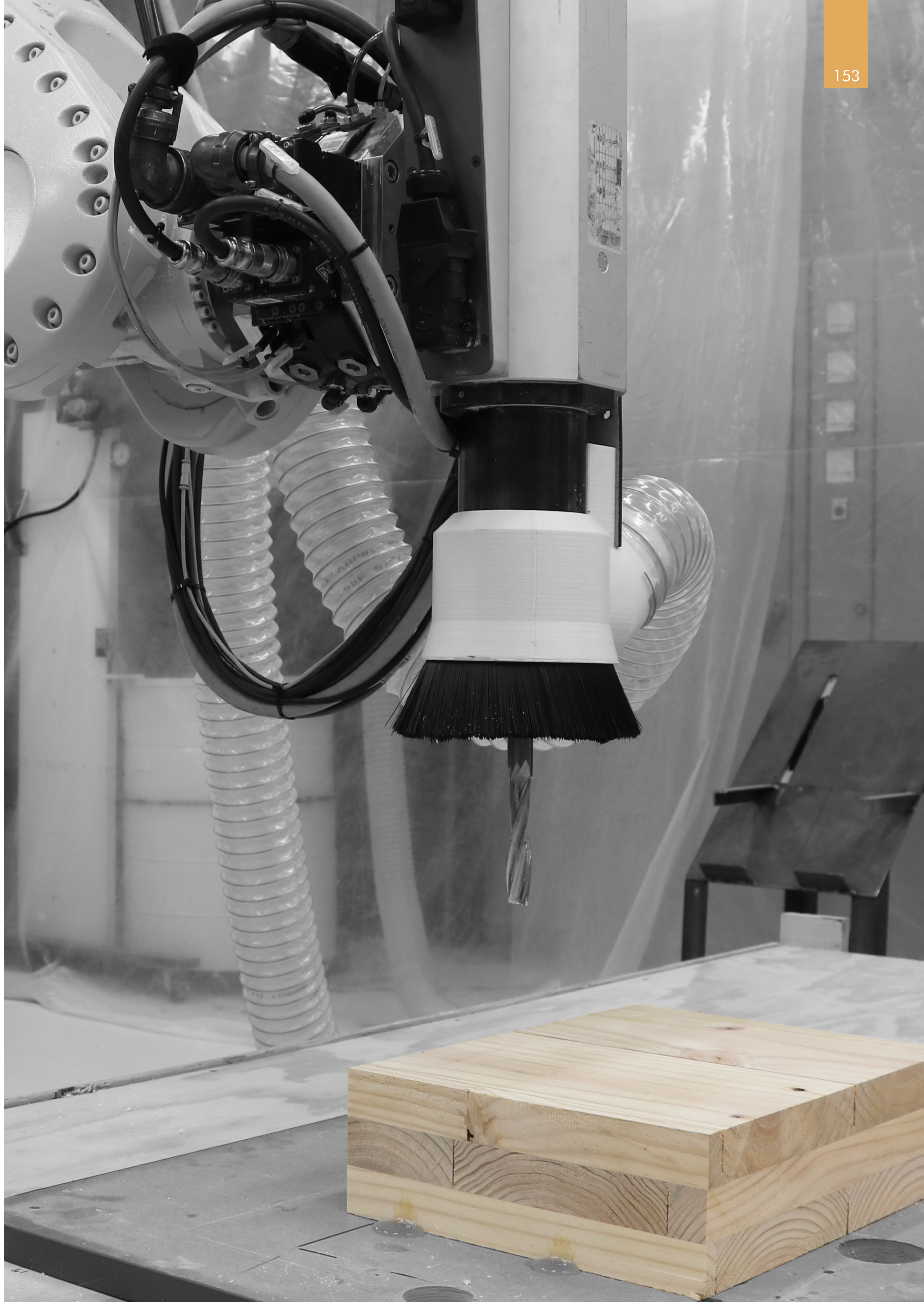
It became clear through the research that there is no one solution to this question and that there a number of factors to consider when designing an effective system. From the beginning of the research, it was evident that finding a solution would require using a combination of research methods. These were to evaluate existing systems and traditional Japanese joinery and combine these with digital manufacturing and fabrication.

The identification of criteria determined that aesthetics, number of pieces, wastage, ease of building and fabrication, and thermal bridge potential were the focus areas for design. Computer aided design became a large part of this research, both in the use of the robot for prototyping, and in the design development of the connection system. CAD provided new possibilities as manufacturing is no longer limited to hand tools and traditional techniques. Whilst designing within this digital workflow and the identified criteria, a defining conclusion was made; the connection required a timber key. Setting the course for the thesis, the task shifted from designing a connection to designing a key. Over the design process, robotic prototyping and simulation determined that maintaining simple forms and including wedged shapes would create the most successful system.

The inclusion of CLT factory analysis and production systems became a pivotal part of the research as it allowed for speculation into large-scale fabrication. The design of a connection for a material such as CLT means very little without considering full scale and built application. It was here that the goal to reduce waste in construction progressed. Not only has the cut out wastage been reduced, but the factory wastage now has a purpose; to become the key. The investigation into factory fabrication also gave way to an additional design parameter, tessellation. The development of tessellation in the design process answered many questions surrounding efficiency of fabrication and the application to full scale projects. Mitigating the need for one-by-one fabrication, it became both a limitation and an opportunity for design, and ultimately led to the most successful design outcome.

The research began as an exploration into a connection system to improve the aesthetics of CLT buildings. As this exploration continued, it developed into an investigation into building scale fabrication and waste reduction with the goal being to create a more efficient, environmentally friendly and beautiful CLT structure for modern construction. Though conclusive statements cannot be made in regards to the success of this system on a full building scale, the link between digital fabrication and connector technology has been made and has highlighted the potential for further exploration. This thesis has shown that timber connections for CLT can reduce construction wastage through the use of digital design and fabrication.

figure 85: ABB robot ready to mill



CHAPTER SIX

REFERENCES

6.1.1 REFERENCES

Agkathidis, A. (2010). From Design to Production. In Digital Manufacturing in Design and Architecture (pp. 118–121). Amsterdam: BIS.

Bernheimer, A. (Ed.). (2014). Timber in the City. New York: ORO Editions.

Blaser, W. (1963). Structure and Form in Japan. Zurich: Artemis Verlags.

Bock, T., & Langenberg, S. (2014). Changing Building Sites: Industrialisation and Automation of the Building Process. Architectural Design, (229), 88–99.

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): Overview and development. European Journal of Wood and Wood Products, 74(3), 331–351. https://doi.org/10.1007/s00107-015-0999-5

Branz. (n.d.). Why REBRI. Retrieved 28 October 2019, from https://www.branz.co.nz/cms_display.php?sn=113&st=1&pg=12513

Bruhl, F., & Kuhlmann, U. (2017, September 13). Consideration of Connection Ductility within the Design of Timber Structures (Reinhard Brandner, A. Ringhofer, & P. Dietsch, Eds.). Graz: Verlag der Technischen Universität Graz.

Brunauer, A. (2017, September 13). The Practical Design of Dowel-Type Connections in Timber Engineering Structures according to EC 5 (Reinhard Brandner, A. Ringhofer, & P. Dietsch, Eds.). Graz: Verlag der Technischen Universität Graz.

CMA+U. (n.d.). Mt Pleasant Community Centre – CMA+U. Retrieved 30 October 2019, from https://cma-u.com/mt-pleasant-community-centre/

Cohn, D. (2014). Inside Job. Architectural Record, 202(7), 110.

Daas, M. (2018). Being Thinking Doing Becoming: Framing Robotics in Architecture. In Towards a Robotic Architecture (pp. 12–27). California: Applied Research and Design Publishing.

Daas, M., & Wit, A. J. (2018). Robotic Production in Architecture. In Towards a Robotic Architecture (pp. 28–62). California: Applied Research and Design Publishing.

Dunn, N. (2012). Digital Fabrication in Architecture. Laurence King Publishing.

Gershenfeld, N. (2012). How to make almost anything: The digital fabrication revolution. Foreign Affairs, 91(6), 43–61.

Gramazio, F., Kohler, M., & Willmann, J. (2014). Authoring Robotic Processes. Architectural Design, (229), 14–21.

Green, M., & Taggart, J. (2017). Tall Wood Buildings: Design, Construction and Performance. Retrieved from http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=4851850

Harte, A. M. (2017). Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2(3), 121–132. https://doi.org/10.1080/24705314.2017.1354156

Hasslacher Norica Timber. (n.d.). X-fix: The Timber-to-Timber Connection System. Retrieved from https://www.hasslacher.com/data/_dateimanager/broschuere/HNT_News_XFix_EN_WEB.pdf

Helen & Hard. (n.d.). Bjergsted Financial Park, Stavanger. Retrieved 15 May 2019, from Helen & Hard website: http://www.helenhard.no/projects/bjergsted_financial_park_stavanger

Hudert, M. (2010). Fully Furnished. In Digital Manufacturing in Design and Architecture (pp. 126–129). Amsterdam: BIS.

Hundegger. (n.d.). CNC panel processing centre: PBA. Hans Hundegger AG.

Inglis, M. (2007). Construction and demolition waste—Best practice and cost saving. 12. Ministry for the Environment, New Zealand.

Izzi, M., & Fragiacomo, M. (2018). Hysteretic behaviour of connections and wall systems used in CLT structures. In G. Dill-Langer (Ed.), Timber: Bonds—Connections—Structures (pp. 257–270). University of Stuttgart - Material Testing Institute.

Jeska, S., & Pascha, K. S. (2015). Emergent Timber Technologies: Material, Structures, Engineering, Projects (R. Hascher, Ed.; P. Thrift, Trans.). Birkhauser Basel.

Jockwer, R., Fink, G., & Kohler, J. (2017, September 13). Assessment of Existing Safety Formats for Timber Connections – How Probabilistic Approaches can Influence Connection Design in Timber Engineering (Reinhard Brandner, A. Ringhofer, & P. Dietsch, Eds.). Graz: Verlag der Technischen Universität Graz.

John, A. O., & Itodo, D. E. (2013). Professionals' views of material wastage on construction sites and cost overruns. Organization, Technology & Management in Construction; Zagreb, 5(1), 747–756.

Kloft, H. (2010). Digital Manufacturing and Sustainability. In Digital Manufacturing in Design and Architecture (pp. 130–133). Amsterdam: BIS.

Kolarevic, B. (2003). Architecture in the Digital Age: Design and Manufacturing. New York: Spon Press.

Kremer, P. D., & Symmons, M. A. (2015). Mass timber construction as an alternative to concrete and steel in the Australia building industry: A PESTEL evaluation of the potential. International Wood Products Journal, 6(3), 138–147. https://doi.org/10.1179/2042645315Y.0000000010

Kuilen, J. W. G. V. D., Ceccotti, A., Xia, Z., & He, M. (2011). Very Tall Wooden Buildings with Cross Laminated Timber. Procedia Engineering, 14, 1621–1628. https://doi.org/10.1016/j.proeng.2011.07.204

Level. (n.da). Concrete. Retrieved from http://www.level.org.nz/fileadmin/downloads/Materials/LevelMCon1.pdf

Level. (n.db). Plasterboard. Retrieved from http://www.level.org.nz/fileadmin/downloads/Materials/LevelMPBoard.pdf

Level. (n.dc). Timber. Retrieved from http://www.level.org.nz/fileadmin/downloads/Materials/LevelMTimber.pdf

Locher, M., Simmons, B., & Kuma, K. (2010). Traditional Japanese Architecture: An Exploration of Elements and Forms. Retrieved from http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=895742

Macfarlane, B. (2003). Making Idea. In Architecture in the Digital Age: Design and Manufacturing (pp. 181–198). New York: Spon Press.

Mah, M., Fujiwara, T., & Ho, C. (2018). Environmental Impacts of Construction and Demolition Waste Management Alternatives. Chemical Engineering Transactions, 63. https://doi.org/10.3303/CET1863058

Mayo, J. (2015). Solid Wood: Case Studies in Mass Timber Architecture, Technology and Design. Routledge.

McGee, W., Velikov, K., Thün, G., & Tish, D. (2018). Prologue for a Robotic Architecture: Bridging design environments, robotic additive manufacturing and systemic controls for kinetic in-formation. In Towards a Robotic Architecture (pp. 190–203). California: Applied Research and Design Publishing.

Menges, A. (2011). Integrative Design Computation: Integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions. Integration through Computation, 72–81. Calgary: The University of Calgary.

Mohammad, M. (2011, August). Connection in CLT Assemblies. Presented at the Cross Laminated Timber Symposium, Vancouver. Retrieved from http://www.woodusematrix.com/database/rte/files/CLT-Connections.pdf

New Zealand Forest Owners Association Inc. (2017). Facts & Figures 2016/17: New Zealand Plantation Forest Industry. Ministry for Primary Industries.

Organschi, A. (2014). Timber City: Architectural Speculations in a Black Market. In A. Bernheimer (Ed.), Timber in the City: Design and construction in Mass Timber (pp. 13–25). ORO Editions.

Pozza, L., Saetta, A., Savoia, M., & Talledo, D. (2018). Angle bracket connections for CLT structures: Experimental characterization and numerical modelling. Construction and Building Materials, 191, 95–113. https://doi.org/10.1016/j.conbuildmat.2018.09.112

Rabagliati, J., Huber, C., & Linke, D. (2014). Balancing Complexity and Simplicity. In F. Gramazio, M. Kohler, & S. Langenberg (Eds.), Fabricate. Zurich: Swiss Federal Institute of Technology.

Ringhofer, A., Brandner, R., & Blaß, H. J. (2018). Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections. Engineering Structures, 171, 849–861. https://doi.org/10.1016/j.engstruct.2018.05.032

Rothoblaas. (2017). X-RAD. Retrieved from https://issuu.com/rothoblaas/docs/x-rad-en

Sadler, A. L. (2009). Japanese Architecture: A Short History. Vermont: Tuttle Publishing.

Scheurer, F. (2012). Digital Craftsmanship: From Thinking to Modeling to Building. In Design-Assembly-Industry (pp. 110–131).

Schilcher Tading & Engineering GmbH. (2016). X-fix / CLT Connectors. Retrieved 4 June 2019, from http://www.x-fix.at/

Schwinn, T., Krieg, O. D., & Menges, A. (2012). Robotically Fabricated Wood Plate Morphologies. Robotic Frabrication in Architecture, Art and Design, 48–61. Vienna: Springer.

Seike, K. (1977). The Art of Japanese Joinery (1st English Edition). New York: John Weatherhill, Inc.

Shen, Y.-L., Schneider, J., Tesfamariam, S., Stiemer, S. F., & Mu, Z.-G. (2013). Hysteresis behavior of bracket connection in cross-laminated-timber shear walls. Construction and Building Materials, 48, 980–991. https://doi.org/10.1016/j.conbuildmat.2013.07.050

Sherpa. (2013, June 20). Products [Text]. Retrieved 4 June 2019, from Www.sherpa-connector.com website: http://en.sherpa-connector.com/products

SHERPA. (n.d.). CLT Connector: Sherpa Connection Systems. Retrieved from http://en.sherpa-connector.com/dl/092018_CLT%20und%20Schallschutz_6-Seiter_EN_Einzelseiten_web.pdf

Silva, C. V., Branco, J. M., & Lourenço, P. B. (2013). A project contribution to the development of sustainable multi-storey timber buildings. 379–386. Retrieved from http://repositorium.sdum.uminho.pt/handle/1822/26947

Smith, R. E., Griffin, G., Rice, T., & Hagehofer-Daniell, B. (2018). Mass timber: Evaluating construction performance. Architectural Engineering and Design Management, 14(1–2), 127–138. https://doi.org/10.1080/17452007.2016.1273089

Stehling, H., Scheurer, F., & Roulier, J. (2014). Bridging the gap from CAD to CAM: Concepts, caveats and a new Grasshopper plug-in. In F. Gramazio, M. Kohler, & S. Langenberg (Eds.), Fabricate. Zurich: Swiss Federal Institute of Technology.

Steurer, A. (2006). Developments in Timber Engineering: The Swiss Contribution. Birkhauser.

Storey, J., Gjerde, M., Charleson, A., & Pedersen Zari, M. (2005). The State of Deconstruction in New Zealand

Sumiyoshi, T., & Matsui, G. (1991). Wood Joints in Classical Japanese Architecture. Retrieved from http://archive.org/details/wood-joints-in-classical-japanese-architecture

Tam, V. W. Y., Tam, C. M., Zeng, S. X., & Ng, W. C. Y. (2007). Towards adoption of prefabrication in construction. Building and Environment, 42(10), 3642–3654. https://doi.org/10.1016/j.buildenv.2006.10.003

Taylor, L. (2013). Building the future—With CLT. Innovative Timber Construction, (Autumn).

Tomasi, R., & Pasca, D. (2017, September 13). Summary and Recommendations Regarding the Seismic Design of Timber Connections (Reinhard Brandner, A. Ringhofer, & P. Dietsch, Eds.). Graz: Verlag der Technischen Universität Graz.

Tomasi Roberto, & Smith Ian. (2015). Experimental Characterization of Monotonic and Cyclic Loading Responses of CLT Panel-To-Foundation Angle Bracket Connections. Journal of Materials in Civil Engineering, 27(6), 04014189. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001144

Waugh, A. (2014). Twenty-First-Century Timber. In A. Bernheimer (Ed.), Timber in the City: Design and construction in Mass Timber (pp. 13–25). ORO Editions.

Waugh Thistleton Architects. (2018). 100 Projects UK CLT. Waugh Thistleton Architects.

Wegener, G. (2011). Forests and their significance. In H. Kaufmann & W. Nerdinger (Eds.), Building with Timber: Paths into the Future (pp. 10–17). Prestel.

Weinand, Y. (2016). Advanced Timber Structures: Architectural Designs and Digital Dimensioning. Retrieved from http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=4804381

Wood Solutions. (2012). Massive Timber Construction Systems (Vols 1–16). Australia: Forest and Wood Products Australia Limited.

6.1.2 LIST OF FIGURES