Building Technology
Graduation Studio

WOOD WELDING

Hot pressure welding as a viable alternative to synthethic adhesives in Engineered Wood Products

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ACKNOWLEDGEMENTS

I want to thank the following people:

- Floor and Bas from the Green Village for allowing me to use the heat press.
- Bram, Warre, Merel, Lisa and Jorrit for joining me during the endless trips to the heat press at the Green Village.
- Isa for aiding me in manufacturing multiple steel moulds for my experiments in the heat press.
- Henk, Thomas and Roan from Lignitec for leading an insightful conversation and for supplying the additional powdered lignin.
- My father and siblings for supporting me throughout my challenging academic journey that took me across international borders.

I would like to sincerely thank Stijn Brancart and Marcel Bilow for their mentorship throughout this demanding and challenging period. Their guidance, support, and expertise have been invaluable, especially at times when I needed direction beyond my own abilities.

I am also deeply grateful to everyone who contributed to this project through their encouragement, knowledge, and support. Your help made this work possible, particularly during moments when I needed guidance beyond what I could do on my own.

ABSTRACT

The increasing use of timber in architecture has intensified concerns regarding the reliance on synthetic adhesives, particularly in relation to environmental impact and indoor air quality. This thesis explores whether hot-pressure welding can be a viable alternative for synthetic adhesives in Engineered Wood Products. An exploratory experimental approach was used to identify key manufacturing parameters and evaluate the performance of welded wood, validated by the development of a proof-of-concept and a minimum viable product. The results indicate although limited bonding can be achieved under specific conditions, hot-pressure welded wood is not yet a viable alternative to synthetic adhesives in Engineered Wood Products. The technique is limited to thin veneers, has a low moisture resistance and lacks mechanical validation. These findings are relevant for both researchers and practitioners in sustainable construction, as it establishes a third wood welding technique, with its respective limitations. Future research should focus on understanding bonding mechanisms, conducting mechanical and durability testing, optimising processing conditions, and assessing scalability and environmental performance.

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PART 1
INTRODUCTION

1 PROBLEM DISCOVERY

This thesis aims to tackle the reliance on synthetic adhesives in wood engineered products (EWPs) in the built environment. Even though the adhesives improve the performance of wood products, they create environmental and health problems. Hot pressure welding could be a viable alternative to these.

1.1 PROBLEM CONTEXT

Human beings have been building their homes with wood since the dawn of time. For centuries, wood was considered the first choice in building materials, but it lost favour with the rise of steel and concrete during the industrial revolution (Lennartz & Jacob-Freitag, 2015). These materials were considered more fire resistant, more durable and could achieve larger spans than wood (Ong, 2015). It is only with the introduction of adhesives in wood engineered products, that the strength of wood was improved, initiating a renaissance of wood architecture in the late 20th century (Lennartz & Jacob-Freitag, 2015). Since then, the wood industry has continued to expand, the European Timber Construction Market is set to grow with a compound annual growth rate of 9,8 % between 2025 and 2030 (Grand View Research, 2022). This economic trend is also translated into local and national legislation. For example, under the “Houtbouw Pact” at least 20% of new residential buildings in Amsterdam will be built with timber or other bio-based materials (AMS Institute, 2025).

However, the synthetic adhesives, that are used in wood products, are now considered harmful to human health and have a huge environmental impact (Adamova et al., 2020; Kutnar & Muthu, 2016).

Figure 1.1 Camoni de la Heurta, Spain by Ábaton Architects and Stora Enso. From Stora Enso. (n.d.).

1.1.1 ADHESIVES IN WOOD PRODUCTS

HISTORY

After wandering around as nomads, human beings looked for ways to make structures more permanent by assembling them with mechanical connections but also by gluing them together (Frihart, 2015). Wall carvings in Thebes, dating back more than 3000 years, depicted a pot with a paint brush, displaying the Egyptians' use of adhesives to attach veneers to wood (Skeist & Miron, 1990). These first adhesives were made from plants and animal products, using blood, pitch, gums, milk, soybean and collagen. The first adhesives for wood had little strength so they were mostly used in furniture and other indoor applications (Frihart, 2015).

Over the centuries, synthetic adhesives were improved and its use eventually expanded to the wood construction. A major step in this evolution came at the beginning of the 20th century, where Otto Hertzer filed a patent for a wooden structural system. The system consisted of several layers of wood being glued together with a natural adhesive made of casein, a milk protein (Hertzer, 1901). Figure 1.2 displays the patent by Hertzer, where an actively bent wooden element is laminated into a larger, straight component, effectively producing the first functional glued laminated timber prototype. However, the natural adhesives were sensitive to moisture and lacked strength in comparison to steel and concrete, keeping its applications indoors. Eventually, started looking into other kinds of adhesives (Moody et al., 1999). These natural adhesives would eventually be replaced by synthetic adhesives in the 1930's (Eckelman, 1997).

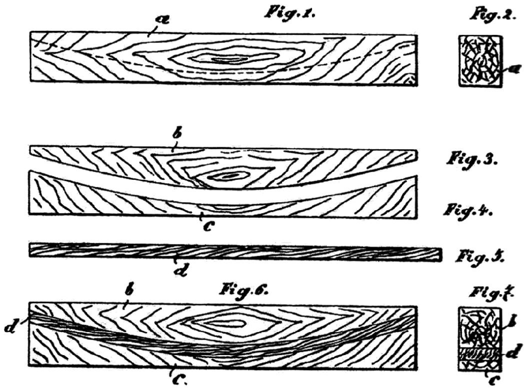


Figure 1.2 Patent from Otto Hertzer, 1905. From Müller, 2004.

The newly developed synthetic adhesives were first made to resemble the characteristics of natural adhesives but were later altered to be used in more structural applications. This development would be boosted during World War II. The petroleum industry, that had heavily expanded during the war, had to find better uses for their surplus of fossil-based products (Eckelman, 1997). These products were developed into synthetic adhesives, with a wide range of properties due to its beneficial polymer structure, improving the moisture resistance and mechanical performance (Frihart, 2015).

The introduction of synthetic glues would improve the development of stronger wood and wood-based products. Phenol-formaldehyde (PF) was discovered in the 1930's and was first used in durable exterior plywood. As the adhesive developed, similar adhesives such as resorcinol-formaldehyde (RF) and phenol resorcinol-formaldehyde (PRF) were derived, supporting the development of glulam (Frihart, 2015). Compared to the natural adhesives, the synthetic alternatives were water-resistant, which allowed for exterior applications like bridges, or high-humidity environments, such as in swimming-pools (Moody et al. 1999).

Since then, adhesives have had a firm grip on the wood sector. In 2016, roughly 80% of all wood and wood-based products contained adhesives (Sandberg, 2016). Today, the global wood adhesives market has reached a value of USD 8.7 billion and is forecast to grow to USD 19.6 billion by 2035, reflecting a compound annual growth rate of 8.5% (Future Market Insights, 2025).

ADVANTAGES OF SYNTHETHIC ADHESIVE USAGE

The usage of adhesives in wood products offers many advantages (Frihart, 2011; Skeist & Miron, 1990):

- Adhesives enable the bonding of thin films, fibres or veneers that cannot be joined using mechanical connections and would otherwise be considered waste.
- Adhesives provide for a high strength-to-weight ratio compared to structures with only nails and screws, as it evenly distributes stresses across the bonded surfaces.
- Adhesive bonding contributes to reducing wood consumption per product.
- They provide a durable bond that is resistant to moisture, heat and long-term loading. Adhesives can reduce warping, swelling and cracking caused by moisture and temperature changes.
- Thanks to faster bonding compared to mechanical fastening, wood remains cost competitive with steel and concrete.

These advantages allow for further development of Engineered Wood Products, such as particleboard, medium-density fibreboard (MDF), plywood, glued laminated timber (glulam), Cross Laminated Timber (CLT) and more (Frihart, 2015; Sandberg, 2016).

DISADVANTAGES OF SYNTHETHIC ADHESIVE USAGE

Due to the chemical composition of synthetic adhesives, there are a series of disadvantages that generate sustainability impacts and cause harm to the health of users and manufacturers. Firstly, the manufacturing of synthetic glues requires a big energy consumption and depletes non-renewable sources. This emits a massive amount of greenhouse gasses, further accelerating climate change (Eisen et al., 2020).

Futhermore, synthethic adhesives are slow to degrade in their end-of-life scenario, shattering the renewable aspect of wood (Gharhi et al., 2025). The addition of adhesives pushes wood further away from its monolithic nature and turns it into a processed or refined product. Its negative environmental impact per unit of mass is confirmed by life cycle assessments (LCA's). Although the data sources vary per study, some say that adhesives contribute about 5 to 10% of the greenhouse gas emissions of the total life cycle of a glulam beam. Yet synthetic adhesives are only 1 to 3% of the mass, highlighting the evirnomental impact of the petroleum extraction and high energy intensive production processes (Pedrero Zazo et al., 2025).

Figure 1.3 Wood waste. From Building, 2015.

Secondly, synthetic adhesives in wood products cause harm to the health of users, due to their emissions of volatile organic compounds (VOC's). In today's western society, most time is spent indoor, which leads to a long exposure to aldehydes (Gonçalves et al., 2025). This can contribute to the "sick building syndrome". It causes irritation to the eyes and throat, trigger asthma and could potentially cause cancer in humans (EPA, 2025; Adamova et al., 2020). This negatively impacts the end-users (such as the residents at the end-stage) and manufacturers (workers during the production).

1.1.2 RISE OF MORE SUSTAINABLE ALTERNATIVES

The negative effects of synthetic adhesive usage have caused a push away from them on both a regulatory and commercial level. For example, the European Union (2023) has released legislation to limit the formaldehyde emission to 0,062 mg/m^3 in furniture wood-based products. Additionally, Future Market Insights (FMI, 2025) have identified a market trend towards more bio-based alternatives. Manufactures are searching to counter the disadvantages of synthetic adhesives, looking for a high-performance, heat and moisture resistant bio-based alternatives, improving the natural adhesives that were widely used before the Industrial Revolution.

Although these bio-based adhesives have yet to achieve a similar performance as the synthetic adhesives, a few have shown promise, such as protein-, carbohydrate-, lignin-, tannin-based adhesives. Protein-based adhesives, derived from animal or plant proteins, are mostly used for plywood and particle board. Within these wood products, they have a similar performance as synthetic adhesives. Carbohydrate-based adhesives are made of plant-based polysaccharides like glucose, starch, chitosan and cellulose. They are biodegradable, renewable, and especially good with porous materials, hence its application in the wood industry. Lignin-based adhesives can be manufactured in large scales, as it is derived from the large waste stream of paper. They are thermally stable and have a good resistance to microbial degradation, making them suitable for wood composites. Generally, they are enhanced with crosslinking agents such as glycol, formaldehyde and phenol, though this removes the environmentally friendly and non-toxic aspects of bio-based adhesives. Finally, tannin-based adhesives can be found in bark, wood, leaves and fruit. They can cure rapidly, already replacing some synthetic adhesives (Gharhi et al., 2025). Tanin-based adhesives and resins are already used to produce particleboards, as illustrated by Figure 1.4.

Figure 1.4 Particleboard produced with tanin-based adhesives. From Zhou & Du, 2019. Licensed under Creative Commons Attribution 3.0 Unported.

Ultimately, bio-based adhesives have a lower environmental impact and are less toxic than synthetic ones. For example, lignin- and tannin-based adhesives, have a lower environmental impact in glulam applications compared to synthetic adhesives, such as MUF, PF and PRF. In a life cycle assessment, the bio-based adhesives contribute 8 to 12% during the sourcing modules (A1-A2) and 5% during the total life cycle. This is lower than the impact of synthetic adhesives, with an environmental impact of 23 to 43% during the sourcing modules and 10% in total (Pedrero Zazo et al., 2025).

However, bio-based adhesives are not an all-encompassing solution. Even though, they have shown promise, they are still lacking in aspects of cost, consistency, performance, resource availability, shelf life and scalability. Especially the latter is a challenge, as there is difficulty to find a consistent formulation and moisture resistant (Gharhi et al., 2025; Kumar & Leggate, 2022).

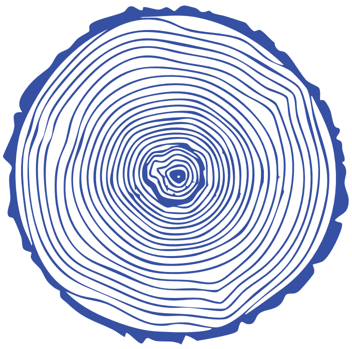
1.1.3 WOOD WELDING AS AN ALTERNATIVE

Wood welding is a bonding technique in which two or more wooden elements are joined through time, pressure, heat, or a combination of all three parameters. This is done without the use of adhesives (Stamm, 2005). Instead of relying on adhesives, the process exploits the thermoplastic behaviour of wood's natural polymers lignin and hemicellulose, which are located in the cell wall of the wood. These soften at their glass transition temperature, subsequently re-solidify to form a bond (Gfeller et al., 2003; Stamm, 2005).

The technique was first identified approximately 25 years ago and has since been investigated mainly at laboratory scale, with early research focusing on friction and ultrasonic welding of wood (Suthoff et al., 1997). These studies demonstrated that welded wood joints can achieve high initial mechanical strength and offer advantages such as rapid bonding, short processing times, and the elimination of chemical additives. Despite these promising results, wood welding has not yet been widely adopted in industrial or architectural applications. This limited application can be attributed to challenges related to scalability, sensitivity to moisture, process control, and the absence of standardised performance data for building-scale applications

(Stamm, 2005; Hahn, 2014). Consequently, wood welding remains an underexplored yet high potential approach for producing adhesive-free wood products in the built environment.

This thesis proposes hot-pressure welding as a third wood welding technique, in addition to friction and ultra-sonic welding. Unlike the two established techniques, hot-pressure welding does not rely on vibration.



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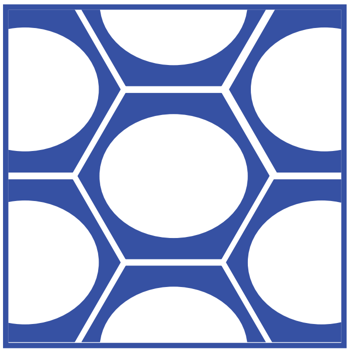

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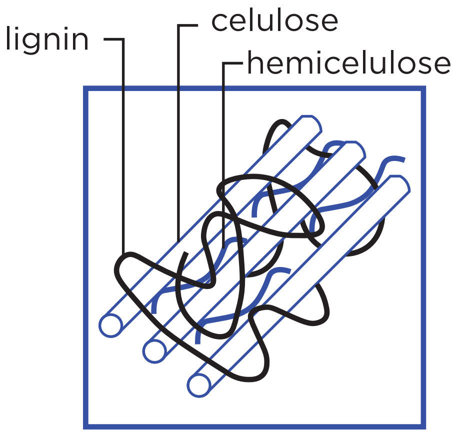


CELL WALL

Figure 1.5 The structure of the wooden cell wall.
Based on Yuan et al., 2022.

2 RELEVANCE

This research aims to discover whether hot pressure welding can be an alternative to synthetic adhesives in EWPs, by trying to maintain a similar mechanical performance and moisture resistance, while improving its environmental impact and mitigating the risks to the occupant's health.

From a societal perspective, the research aligns with broader demands for healthier building materials and more sustainable construction. As regulations and consumer awareness increasingly prioritise low-emission and non-toxic materials, adhesive-free EWPs could contribute to safer living environment without compromising material performance.

Additionally, the development of hot pressure welded wood addresses a growing concern related to the indoor environmental quality. If hot pressure welding can fully replace synthetic adhesives, it could eliminate the indoor release of VOC emissions, improving the indoor air quality, avoid respiratory issues of occupants and remedy the "sick building syndrome".

The scientific relevance of this thesis lies in its contribution to the development of adhesive-free bonding techniques for EWPs. Currently there is a rise timber usage in the built environment, however the addition of synthetic adhesives pushes the greenhouse emissions of the construction even higher.

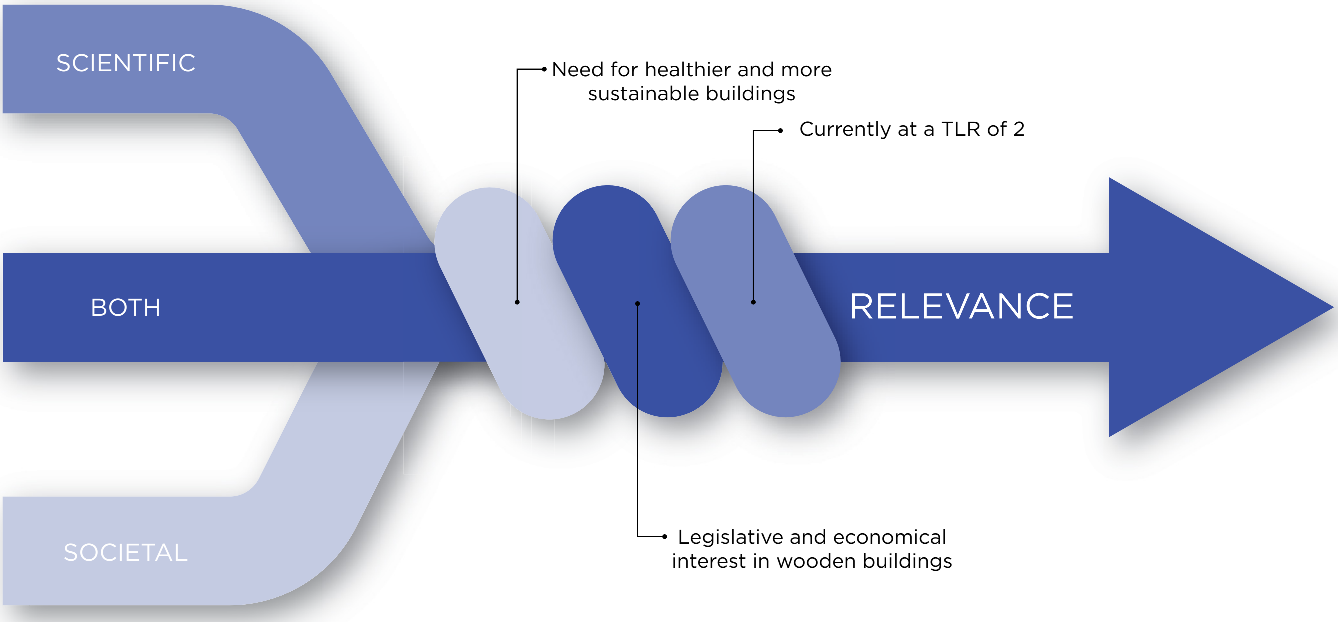


Figure 1.6 Scientific and societal relevance of research.

Friction and ultra-sonic welding have been previously investigated but have yet to be fully upscaled. While the development of these two techniques remains stagnant, the exploration of hot pressure welding could offer a pathway to the adhesive-free bonding of EWPs. By decoupling heat generation from vibration, this approach has the potential to overcome limitations related to joint geometry, material damage, and process scalability, thereby expanding the technological scope of wood welding for structural and architectural applications.

Within the framework of Technology Readiness Level (TLR), the hot pressure welding of wood is currently at a level of TLR 1, where the basic principle was observed. During the thesis the technique was pushed from formulated a technology concept and application (TLR 2), to an experimental proof of concept (TRL 3) and a laboratory-scale validation of key functional properties (TRL 4) including mechanical bending strength and moisture resistance. The thesis does not aim at industrial implementation, but rather at generating fundamental performance data and identifying critical process parameters that influence bond quality.

Focusing on EWPs, this thesis drives hot pressure welding toward higher Technology Readiness Levels (TRLs) by establishing foundations for the manufacturing processes, upscaled production, and performance tests. Ultimately, its value lies in a dual contribution: proving this new bonding method can match synthetic adhesive's performance while reducing environmental impact and human toxicity. In doing so, it supports both sustainable material advancement and the transition toward healthier, more circular built environments.

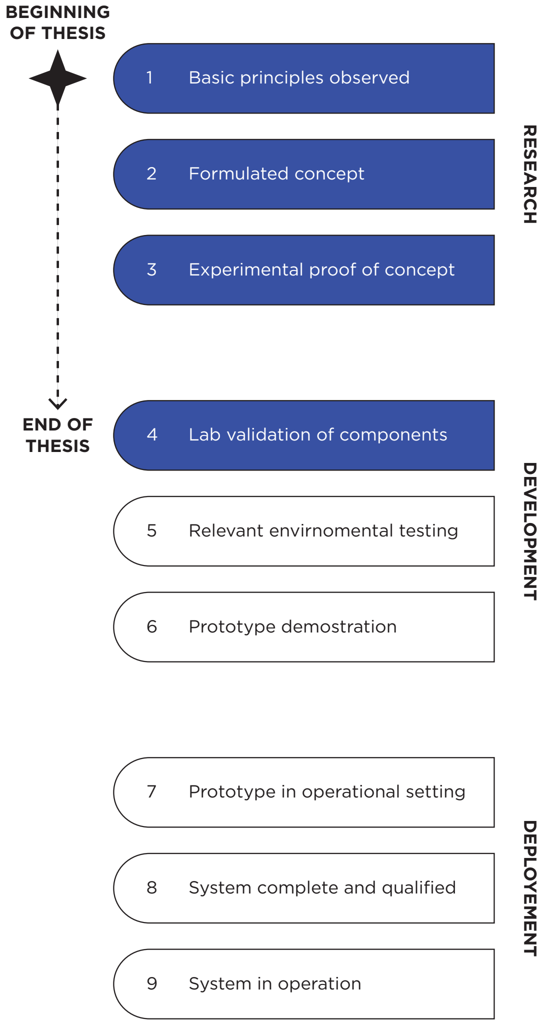


Figure 1.7 Technological Readiness Level. Based on NP Energy Group. (n.d.).

3 OBJECTIVE AND MOTIVATIONS

Although the friction welding and ultra-sonic welding have been around for more than twenty years, it has yet to be widely applied to furniture or structural applications. This thesis proposes a potential third technique of wood welding, namely hot pressure welding.

The main objective of this thesis is to research whether hot pressure welding is a viable alternative to synthetic adhesives in EWPs. However, hot pressure welded wood not only needs to address the environmental and health problems associated with synthetic adhesives, but it also needs to achieve a similar performance in terms of moisture and mechanical bending strength. In parallel, the thesis examines which EWP typologies (e.g. particleboard, OSB and related engineered EWP's) are technically and practically suitable for implementation of hot pressure welding in the built environment.

The following sub-objectives are derived:

- Defining hot pressure welded wood.
- Establishing key performance requirements for wood plating in the built environment
- Asses the manufacturability of hot pressure welded wood and identify key process parameters.
- Determine the performance of hot pressure welded wood in terms of moisture and mechanical bending strength.
- Evaluate its potential viability and the applications in the built environment.

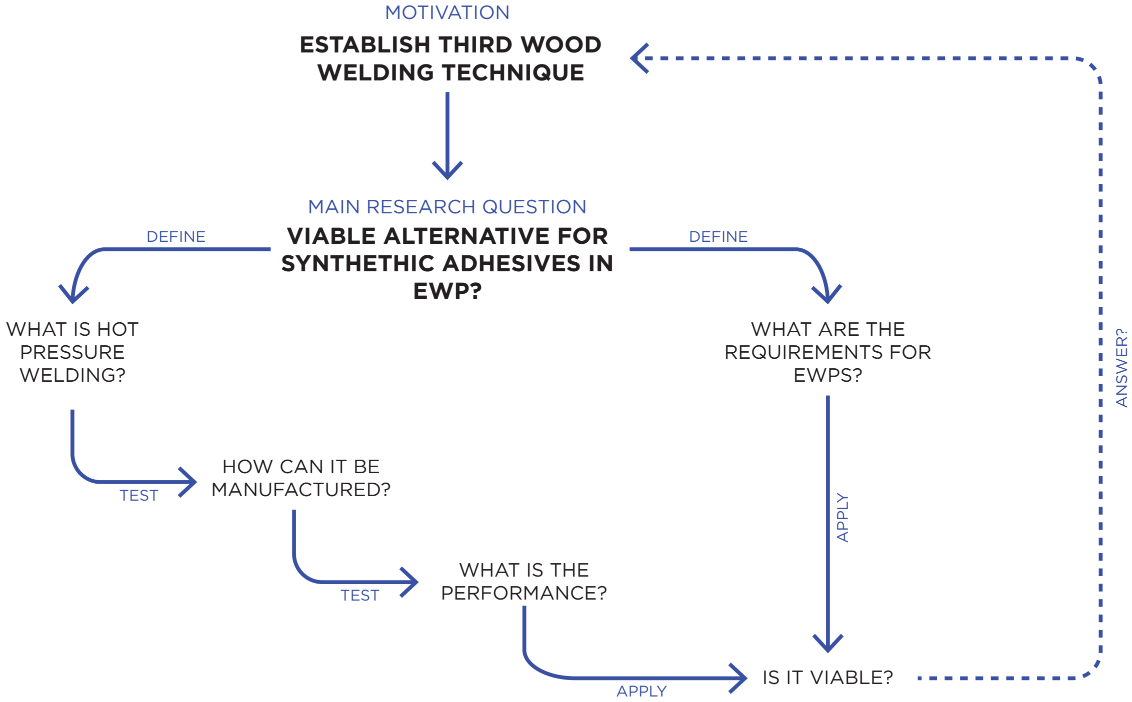


Figure 1.8 Objectives and motivation in relation to research question.

4 RESEARCH QUESTIONS

The problem statement and main objective give way to the following main research question: "can hot pressure welded wood be an alternative to synthetic adhesives in wood plating that is used in the built environment?"

From this the following sub-research questions can be derived:

- Sub question 1: "what is hot pressure welded wood?"
- Sub question 2: "what are the performance requirements for engineered wood products in the built environment?"
- Sub question 3: "under which parameters can wood be hot pressure welded?"
- Sub question 4: "what is the moisture and mechanical performance of hot pressure welded wood?"
- Sub question 5: "Is the performance sufficient for the use in the built environment and what applications are feasible?"

5 SCOPE OF THESIS

The scope of this master thesis is constrained by several practical and methodological boundaries.

Firstly, the theoretical framework relies on literature that is older than five years, as the development of welded wood has stalled and recent publications remain scarce. These sources, while still having a scientific impact, often lack integration in today's industrial standards or applications. It shows a slight resistance to adopt the technique. Secondly, the experiments must be carried out with the machinery currently available at the TU Delft, which could limit the needed pressure and temperatures to achieve a complete weld.

Furthermore, the thesis is carried out within a timeframe of three academic quarters. This restricts the number of iterations that can be performed for each test, blemishing the scientific rigour of the research. It also reduces the number of tests that can be performed, for example fire resistance test or more thorough testing in the indoor environment.
The novelty of hot pressure welding as an additional wood welding technique pushes the research into an exploratory phase, where the experiments are more about establishing dominant trends than establishing optimised conditions.

PART 2
APPROACH

1 RESEARCH FIELDS

To evaluate whether hot pressure welding is a viable alternative to replace synthetic adhesives in EWP's, an iterative process with three fields is undertaken. As illustrated by Figure 2.1, each field has a distinct methodology and action.

Firstly, the theoretical framework needs to be set, contributing to formulating research hypotheses and defining the experimental boundaries. These will then be applied during the experiments, before they will be analysed in the synthesis. Finally, all results must be supported by the theoretical framework, creating a feedback loop. However, this iterative process needs to eventually be stopped, as it does not fit within the time constraint of the thesis. At that stage the results must be visualised and presented.

It is important to note that the research fields do not address a research question specifically, as an interplay between each field is needed to formulate an answer.

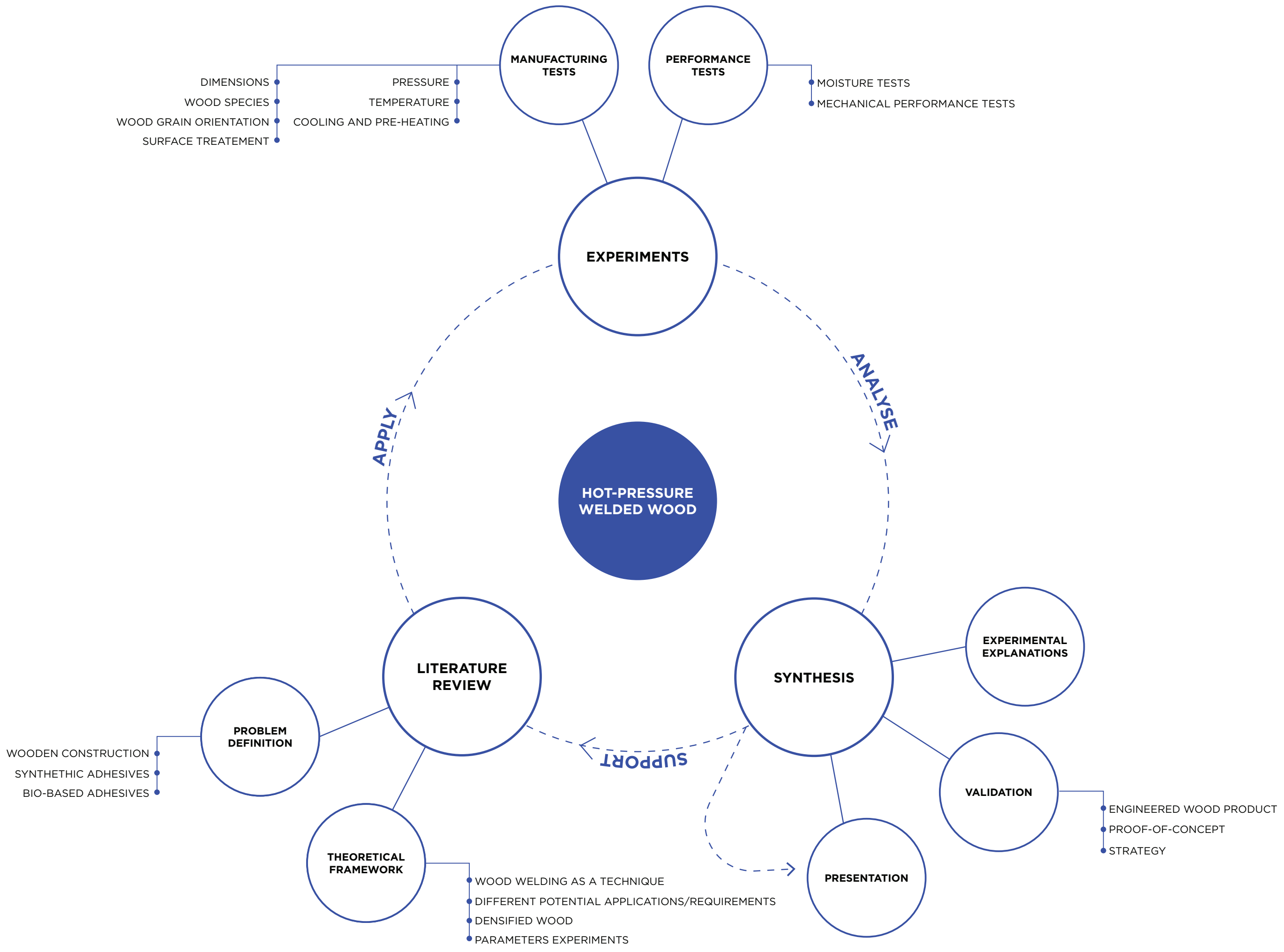


Figure 2.1 Research fields in an "iterative" loop.

1.1 LITERATURE REVIEW

A literature review was used to discover the problem context and to define the theoretical framework. A wide range of sources was consulted, including standards, journal articles, patents, books and legislation. Older sources were also included as development of wood welding has remained stagnant over time, and hot pressure welding has yet to be fully established as a wood welding technique. The literature review was focused on key areas such as synthetic adhesives, bio-based adhesives, wood welding, friction welding, ultra-sonic welding, hot pressing, EWP products and performance. Additionally, a literature review was conducted to try to find an explanation for certain observations made during the experiments. These were used to support the key conclusions, yet they were not used to fully rationalise the observations themselves, but to support the next design and research steps.

Scientific vigour was ensured throughout the literature review by adopting a structured and transparent approach to source selection and analysis. Relevant and more dated sources were cross referenced with other sources, clearly identifying limitations and gaps in existing literature, so that the research can provide a reliable and well-founded theoretical basis for the experiments.

1.2 EXPERIMENTS

The experimental field were divided into two phases that were not started simultaneously but would have flowed into each other. The manufacturing testing was started first by using a hot-press. Here the hot-pressure weldability of wood was evaluated, by playing around with several parameters: wood species, wood grain orientation, number of layers, thickness of each layer, surface treatments, the pressure and temperature applied by the machine, and the cooling or pre-heating of the samples. The objective is to weld a multi-layered wood engineered product, of which multiple samples can be made.

Before the performance tests took place, the manufacturing tests took majority of the time. As synthetic adhesives offer mostly advantages for the mechanical performance and moisture resistance of EWP's, the samples that were manufactured were tested for these two aspects. Firstly, to evaluate whether the welded wood could be used in outdoor applications, moisture tests must be conducted. To assess the moisture-induced degradation and potential delamination of the welded wood samples, a controlled humid environment test was conducted using a tupperware box. Additionally, this information was crucial for the mechanical performance tests. These were supposed to be evaluated with a three-point bending test, as most wood engineered products are used in beams or floor slabs applications, evaluating their flexural performance is essential. However, the mechanical tests could not be performed due to time constraints.

The detailed experimental set-ups of these experiments are explained in their respective section in Chapter 4.

Despite this research's exploratory nature and time constraints, the scientific vigour was ensured to some extent. The experimental design prioritized control of the parameters with a structured testing process, ensuring that observed effects could directly be linked to specific parameter changes. Parameter combinations were selected strategically to cover the most influential factors, rather than attempting exhaustive repetition. The results from the experiments were thoroughly documented. Since repetition was limited, the results were interpreted comparatively, focusing more on trends, correlations and performance ranges, rather than statistical generalisation or optimisations. By being transparent, critical and methodical, the scientific vigour was maintained, while keeping the research within its exploratory framework. This allows for the results to be repetitive and reliable.

1.3 SYNTHESIS

During the synthesis the results from the experiments and theoretical framework were analysed, by comparing them together. The theoretical framework established the composition and the minimum performance requirements for each EWP application, while the experiments showed the actual performance and potential composition of the wood welded EWPs. This comparison helped to deduct which EWP application is viable for hot pressure welded wood. Then, to validate these results, a proof of concept, minimum viable product and implementation strategy was constructed. The proof of concept was a chair that highlighted the potential EWP application and showed the potential to upscale hot pressure welded wood as an adhesive-free technique.

2 APPROACHES

2.1 TOP-DOWN

The methodology used a mainly top-down approach with bottom-up validation of the results. It was defined by an overarching societal and technical problem: the negative impact on human health and the environment of synthetic adhesives in wood products. From this problem definition, a theoretical framework was established through literature review, defining hot pressure welded wood, researching potential applications and setting performance requirements.

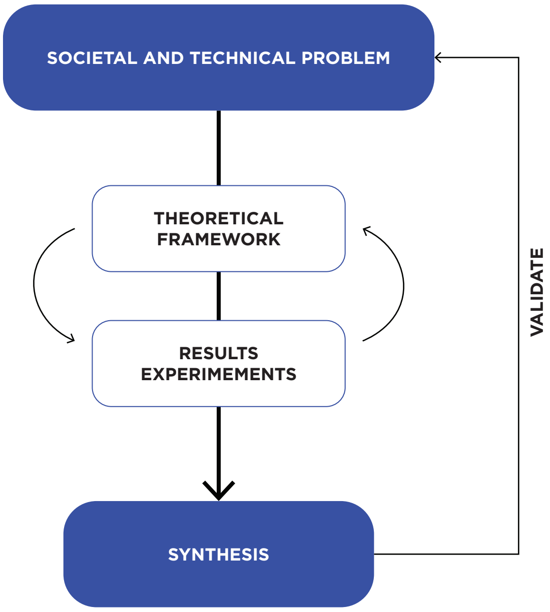


Figure 2.3 Top-down approach with bottom-up validation.

With the top-down structure the experiments and design-research development were not successive steps, but they reinforced each other. It was an iterative process where the experiments were explicitly framed to test whether hot pressure welded wood could fulfil the performance requirements derived from existing wood products and building applications. At the same time, the material behaviour observed during the experiments of manufacturing and performance testing actively informed the feasibility, constraints, and direction of the design exploration. This created a controlled feedback loop between literature-based requirements and empirical findings.

While the research was not bottom-up in the sense of open-ended material discovery, it incorporated bottom-up insights by allowing experimental results to shape realistic applications and design decisions. However, these insights refined and contextualised the research rather than redefine its core objectives.

2.2 DESIGN-RESEARCH

Hot-pressure welding is at a low TLR, as it is a new bonding technique for wood. This means that it is stuck in a research stage rather than a development or implementation stage. As a result, it was difficult to directly “design” with hot-pressure welded wood in the same way as with traditional construction materials. Unlike conventional wood products, there were no existing design guidelines, standardised connection details, or proven construction methods that could reliably inform the design process. The material behaviour was still uncertain and depended heavily on the experimental outcomes. Because of this, the design process could not begin with fixed assumptions, the design had to continuously adapt to the findings of the experiments, making research and design strongly dependent on one another throughout the project. This iterative process ensured a continues exchange of theory and practise. Thus, design became a tool for smooth conversation between the two counterparts.

The experimental phase was determined by a handful of parameters to achieve a complete weld or an adequate structural and moisture performance. However, these may not have been possible to achieve, requiring a design-forward solution, such as adding an additional lignin or changing the relief of the surface.

The synthesis phase shaped the results and analysis of the experiments into a physical object, forcing decisions in regards of geometry, loading, manufacturing and connections. This highlighted limitations, trade-offs and hypothesis, which could not fully be observed in a laboratory. For example, how the panel behaves when assembled into a larger structure, how variations in manual handling or joinery affect bending performance, how heat and pressure inconsistencies during production influence the visual quality of the wood surface.

The final design of the chair did not become only a demonstrative object but it also was research one. It embodied the performance requirements, experimental constraints, and material behaviours identified throughout the study. By designing and manufacturing a detail of the chair, the research tested whether hot pressure welded wood can function under realistic structural and production conditions, thereby validating the relevance of the experimental results within an applied context.

By designing and developing an development strategy that extended beyond the scope of this thesis and the current time, the technique went beyond the results. The strategy included aspects such as scalability, manufacturing feasibility, business potential, and future research directions. By framing the development strategy as both a business plan and a roadmap for future development, the thesis addressed how hot-pressure welding could move from experimental research toward practical adoption within the construction industry.

This integration of experimental research and design strengthened the thesis by bridging the gap between material science and architectural application. It ensured that conclusions are not only scientifically grounded but also materially and practically meaningful for the built environment.

PART 3

THEORETICAL FRAMEWORK

1 WELDED WOOD

1.1 WELDING GENERAL

Welding is a process where two or more surfaces are fused together, either with time and heat, pressure or all three (Phillips, 2023). The processes that rely on only extreme heat are called fusion welding, here the surfaces are melted and sometimes a molten filler material is added. Most common techniques are arc welding, gas welding, and laser beam welding.

Pressure welding processes cause a plastic deformation of both surfaces due to the application of outer forces. Sometimes the surfaces are heated to allow for better bonding of the two (Weman, 2011). According to the standard ISO 4063:2023 (2023), pressure welding includes friction welding, ultrasonic welding, friction stir welding, cold pressure welding and hot pressure welding.

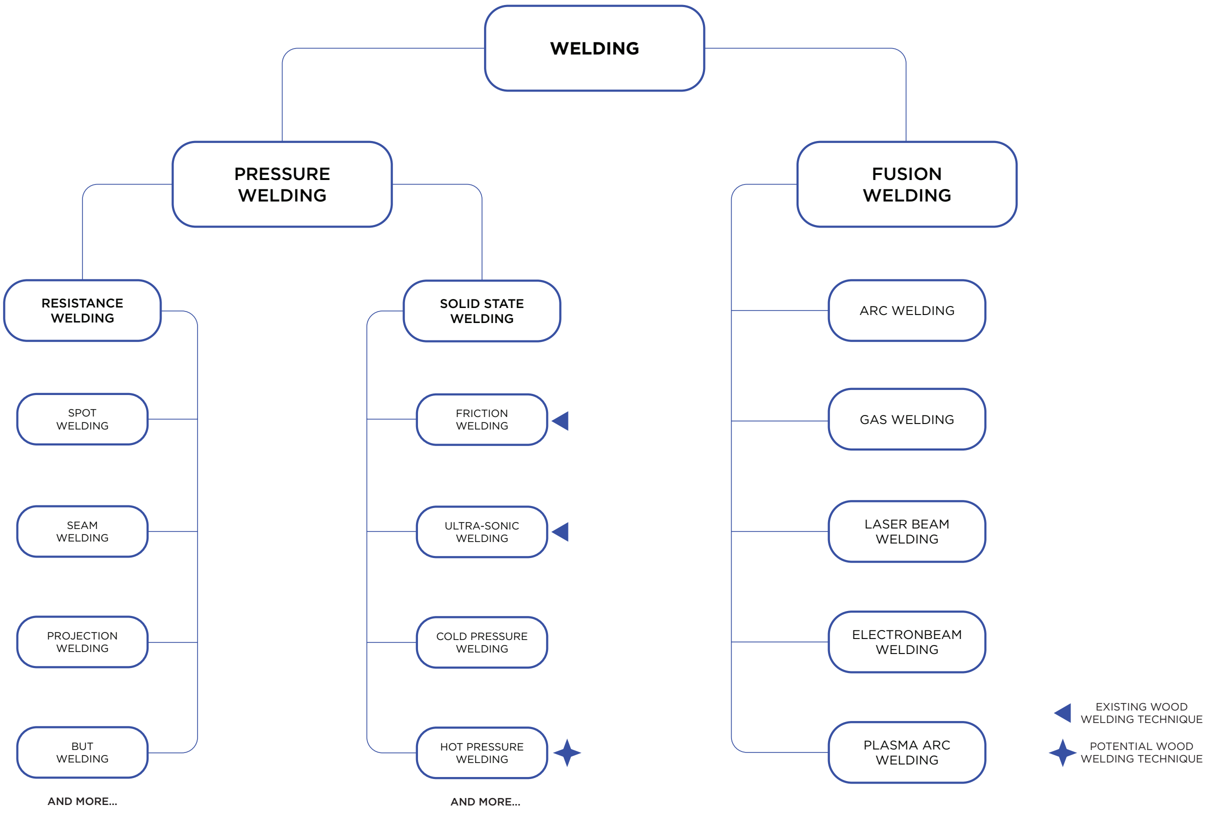


Figure 3.1 Welding techniques. Based on International Organization for Standardization, 2023 and Weman, 2012.

1.2 WOOD WELDING

Although welding is a common technique used on metals and thermoplastics, it can also be applied on wood. The weldability of wood can be contributed to its microscopic structure. Wood has a natural polymeric substrate, existing of lignin, cellulose and hemicellulose. Especially the lignin and hemicellulose react like thermoplastics; softening under thermal energy, which pushes them above their glass transition temperature. This means that the wood changes from a hard and brittle state to a softer and more pliable one (Stamm, 2005). The temperatures, where this state can be reached, are quite high, ranging from 100 °C to 170 °C for lignin and 54 to 142 °C for hemicellulose. Moisture can lower the glass transition temperature; moist lignin softens at 54°C and hemicellulose at 54-142 °C (Yang et al., 2019; Goring, 1963).

The material will start to flow, even though cellulose has a crystalline structure and lignin has a high molecular weight. Under a temperature of 450 °C and pressure, the polyoses break down into acetic acid, furfural and formaldehyde, while the lignin splits its ether links to make free phenolic hydroxyl groups. These reactive compounds will mix at the connecting surface where the pressure will eventually push them together, creating a bond with methylene bridges and diphenylmethane structure. This forms a layer of dense and stable phenolic resins, creating a strong wood-to-wood connection without any adhesives (Stamm, 2005).

Figure 3.2 Microscopy images of lignin, hemicellulose and wood fibres. From Gfeller at al., 2003.

In conclusion, welding irreversibly changes the cell-structure of the wood, caused by chemical degradation and re-crosslinking of the biopolymers. This is where wood welding drastically differs from the welding of metal and thermoplastics. With metal welding, the alloys are melted, reaching a true liquid phase, and solidified in a metallic lattice (Messler, 2008). On the other hand, the welding of thermoplastics constitutes of the reversible heating and melting of polymer chains, where the material softens and flows and bonds through molecular interdiffusion (Regnier & Le Corre, 2016). Thus, both the welding of metal and thermoplastics does not cause chemical degradation of the material, unlike wood welding.

The aim of wood welding is to have the lignin and polysemes reach the glass transition temperature. So far, only two different welding techniques have been applied on wood: friction welding and ultrasonic welding.

1.3 FRICTION WOOD WELDING

Friction welding involves pressing two surfaces together while moving them relatively to each other. This generates heat, causing the surfaces to soften, eventually forming a molecular bond between them (NEN-EN-ISO 15620:2019). The main parameters in this process are pressure, velocity of the movement, temperature and time (Stamm, 2005). There are three movements that are mainly used in frictional wood welding: linear, rotational and friction stir welding (Tondi et al., 2007).

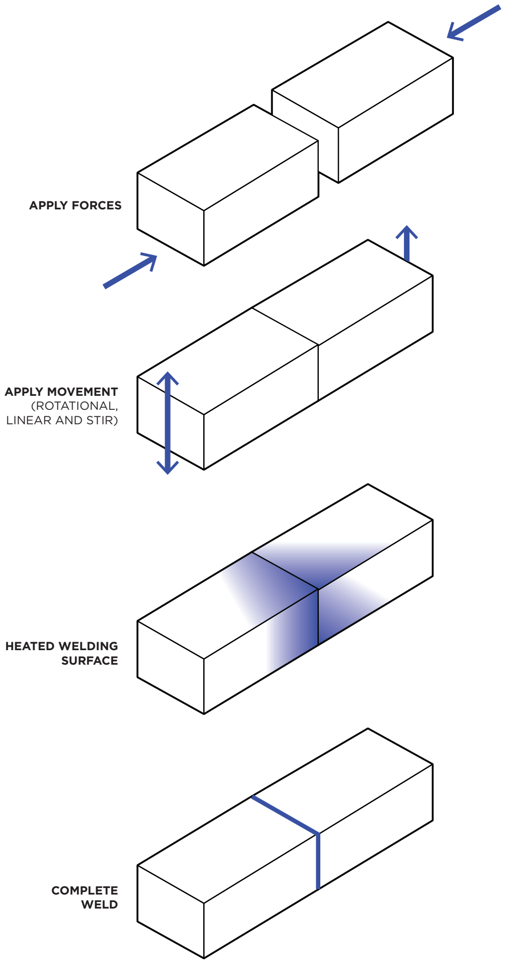


Figure 3.3 Friction welding diagrams.

Linear friction welding was the first technique with whom they tried to weld wood. In 1993, the Research and Development department of SWOOD launched research where they added a thermoplastic layer between two pieces of wood before friction welding them together. This created a strong bond; however, questions were raised about the recyclability and the need for specialized machinery. One day, the researchers forgot to add the thermoplastic, and they discovered that two wood pieces could be bonded together without the middle layer (Gerber & Gfeller, 2000).

In Germany, Suthoff et al. (1997) were the first to research friction welding for wood and file (currently expired) two patents for it. The first patent was filed in 1996 and recognized the potential for one of the two surfaces to be wood when friction welding in both linear and rotational movements (Suthoff et al., 1996). The second patent, filed one year later, describes the friction stir welding of wooden cone-shaped dowels. These are drilled into a slightly smaller hole, due to the rotational movement and pressure to dowels adhere to the wood (Suthoff & Kutzner, 1997). Since then, the friction welding of wood has mostly been researched in Switzerland and France (Leban et al., 2005).

Gfeller et al. (2003) applies principles of metal friction welding to create a bond between two pieces of wood. Additionally, the used machinery, a Branson welding machine, type 2700, 1000 HZ, was intended for only metal. So, the authors adjusted the parameters of the machine to achieve complete bonds, concluding that a higher vibrational amplitude, higher welding pressure, a longer welding time and a longer holding time contribute to a stronger bond with a higher tensile strength. They tried lowering the glass transition temperature by spraying water on the pieces of wood, however this was unsuccessful. Finally, they observed that complete bonds were created because the cell materials, mostly lignin, became entangled into each other, creating a network between the wood pieces. As it cooled, the joint solidified. Some wood cells, which were unable to connect themselves, were pushed out of the joint, as shown in Figure 3.4. Gfeller et al. identified that these joints could be used in furniture and interior applications.

At the Ecole Polytechnique de Lausanne (EPFL), two major PhD's were published, framing most of the research on wood welding. Stamm (2005) discusses the laminar wood connections that were achieved with linear wood welding. He notes that there are similarities with the process of friction welding of metals and thermoplastics, where the process can be divided into dry friction, transition and viscous states. The parameters of welding frequency and pressure were analyzed, he discusses that they influence the process duration, frictional force and temperature development at the surfaces. The moisture content of the wood is shown to play a critical role in processing stability and joint strength.

Figure 3.4 Welded wood connection with pushed out wood fibres. Laboratory for Timber Construction, IBOIS. (n.d.).

Stamm's (2005) microscopic and chemical analyses reveal that the joint consists of a consolidated mass of thermally degraded wood components. The cellulose in the wood remains stable and is abundantly present in the connection, while hemicellulose largely decomposes and the lignin is changed drastically, likely contributing to the cohesion through chemical interactions. Although the welded joints do not reach the strength of synthethic adhesive bonds, their high initial strength enables continuous multilayer welding without damaging existing joints. The study concludes that friction welding of wood offers advantages in speed, environmental compatibility, and machinability, but is limited to applications involving relatively low interfacial stresses due to reduced joint strength compared to glued connections.

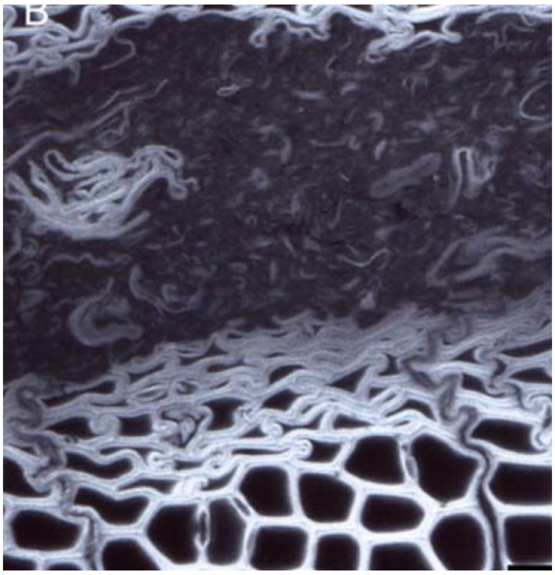


Figure 3.5 Microscopic images from welded area. From Stamm, (2005).

Hahn (2014), the second PhD performed at the EPFL, is the first to upscale friction welding to a level that is comparable to other structural applications of wood. With a machine, developed especially for the friction welding of wood, he analyses the correlation between the size of the sample and the occurrence of larger areas within the sample that have not been welded correctly. Firstly, Hahn tried to understand and to remedy the inconsistencies of welding on the wood surface. This is caused by the internal gas pressure that is generated by the degradation of the wood surface and by moisture evaporation. This can be remedied by drying the wood prior to welding or by making groves on the wood surface (Figure 3.6), which can guide the gas outwards. Secondly, he tried to find an algorithm that could predict the strength by considering the brittle failure mode. Thirdly, Hahn tried to improve the moisture stability under changing conditions. Moisture caused internal stresses due to the wood swelling or shrinking, making the mechanical capacity of the bond disappear completely. This problem could be mitigated by changing the shape of the joint, for example the surface could have a jagged surface made of triangles.

By using both this numerical and experimental approach Hahn (2014) concludes that friction wood welding is not suitable for lap joints, but that the technique can be scaled up to more structural applications such as laminated beams and CLT, as bending stresses govern failure rather than interface shear. However, Hahn is critical when it comes to the environmental and economic impact of the technique. During the welding process VOCs are released, he even speculates that these can still be present during the use phase. A lot of energy is used by the machinery but also during the drying time. Additionally, Hahn estimates that around 15% of the wood volume is lost due to the degradation of the wood at its surface. Yet, although the costs for the machinery are high, the technique of friction welding wood is still quicker than letting adhesives cure.

Figure 3.6 Small scale prototype of a friction welded laminated beam section with groves. From Hahn,. (2014).

1.4 ULTRA-SONIC WOOD WELDING

Ultra-sonic welding is mostly applied on thermoplastics which are welded together by mechanical vibrations that are within a high frequency range, usually between 20 to 70 kHZ (NEN-EN 14674:2003). The main parameters of ultra-sonic welding are frequency, amplitude, pressure and time (Neppiras, 1965).

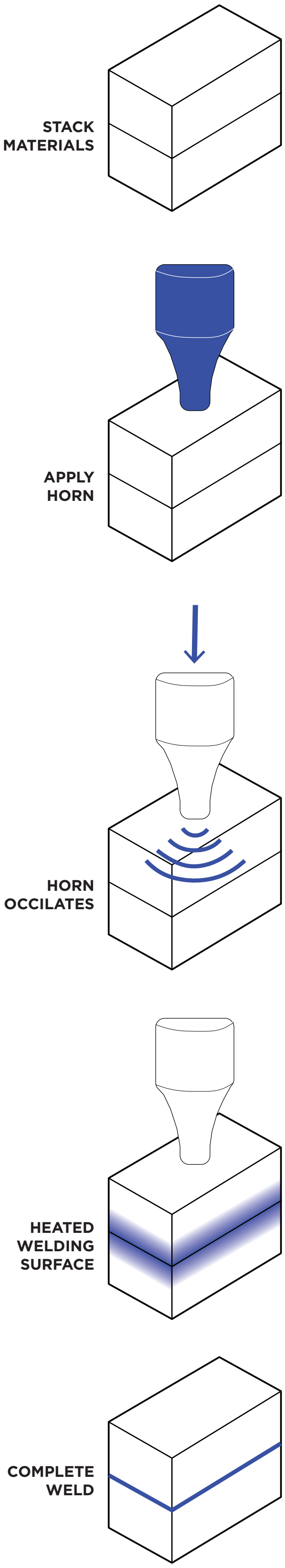


Figure 3.7 Ultra-sonic welding.

Gerber and Gfeller (2000) were the first to identify ultrasonic welding as a potential technique to weld two wooden pieces together. Instead of connecting two wooden surfaces together, they suggested that the vibrations could either be perpendicular (surface joints) or be used to shoot in dowels. Only small and thin pieces of wood were welded together, as the ultra-sonic vibrations could not penetrate the layers, due to the heterogeneous structure of the wood. However, ultra-sonic welding could be used in the plywood industry. It could be used for temporary spot joining to hold the thin veneers together during the assembly before tehy are hot pressed (Tondi et al., 2007).

Amani et al. (2025) suggests a 3D printed lignin-based structure to improve the adhesion between the thin veneer. The lignin-based structure directs the energy equally across the surface, improving the low mechanical performance and poor durability in wet conditions. By optimizing lignin fusion at the weld interface, the method enhances lap shear strength and moisture resistance, making it comparable to traditional adhesives. Additionally, this approach allows for the creation of complex geometries while maintaining the structural integrity of ultra-sonic welded wood.

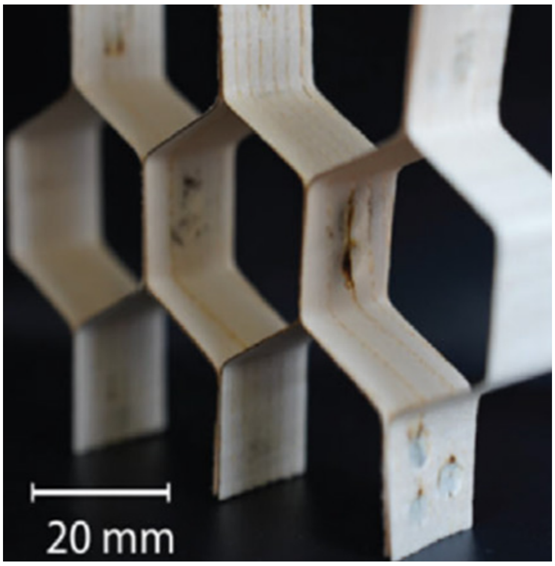


Figure 3.8 Ultra-sonic welded 3d structures with lignin. From Amani et al., 2025

The ultra-sonic welding showed mostly promise in another wood-related industry. In 2019, ultra-sonic welding was applied to paper, a byproduct of wood. Paper, made of 100% lignocelluloses, was completely bonded together using ultra-sonic welding and without using an adhesive. The researchers observed that the welds were stronger when the paper contained larger amounts of lignin and Hemicellulose, highlighting that ultra-sonic welding relied on the same principle of adhesion as vibrational welding. Eventually, the ultra-sonic welding of paper would be expanded to higher frequencies and different kinds of paper. This research continues to move forward, as the packaging industry has shown immense interest, funding future research (Turpin et al., 2026).

1.6 HOT PRESSURE WELDING

This thesis proposes hot-pressure welding as an additional wood welding technique. With hot pressure welding two or more materials are joined together by using heat and pressure, causing a plastic deformation (NPR-ISO/TR 25901-3:2016). Compared to friction welding and ultra-sonic welding this technique does not use vibrations to generate heat.

Hot pressure welding has yet to be applied on wood as a joining technique. Currently under the term “wood welding” friction welding (linear, stir and ultra-sonic) welding is understood. This thesis is the first to explore hot pressure as a third wood welding technique.

Hot-pressure welding differs from hot pressing, where pressing and sintering are integrated into a single operation (Eray, 2020). In the wood industry, resin is added to the wood particles as a binder to achieve a solid bond. Since the 1950’s hot pressing has been used to develop an array of EWP’s, such as plywood, particleboard and fiberboard (Wei et al., 2015). In recent years, hot pressing has been used to manufacture binderless boards. These boards are made with a wide array of bio-raw materials such as wood bark, rice and wheat straw, banana stems, coconut husk and bamboo.

The mechanical and physical properties of the boards are influenced by the material properties (geometry, particle size, chemical composition...) and machinery settings (pressure, pressing time and pressing temperature) (Börcsök & Pásztory, 2020).

In conclusion, hot-pressure welding joins two separate components relying on the natural properties of the wood, while hot pressing tries to join powder materials into dense solids, using synthetic or bio-based adhesives and resins.

1.7 COMPARISSON TECHNIQUES

Although wood welding has been around for more than two decades, it has yet to be widely applied. This can be attributed to the difficulty to scale up while using the two different techniques friction welding and ultra-sonic welding. Table 3.1 summarises the process steps, advantages and disadvantages of each technique.

The table shows that hot-pressure welded wood remains largely undiscovered and -developed.

Table 3.1 Comparisson of the welding techniques based on the theoretical framework, hot-pressure welding remained an open question.

	FRICTION WELDING	**ULTRA-SONIC WELDING**	**HOT-PRESSURE WELDING**
BASIC PRINCIPLE	Joins pieces by rubbing surfaces together at high speed, generating heat through mechanical friction.	Uses high-frequency vibrations to create frictional heat at the interface.	Relies on heated plates and pressure to generate complete welds.
HEAT GENERATION	On a macroscale.	On a microscale	On a macroscale.
COMPOSITION REQUIREMENTS	Dry surface with ridfes to optimise connections.	Two thin veneers, must be smooth and dry.	Unknown
LIMITATIONS	Difficult to upscale because the joints are sensitive to moisture.	Only connects thin veneers, which does not allow for layering and adhering the whole surface, only spots.	Unkown

2 POTENTIAL APPLICATIONS

2.1 ENGINEERED WOOD PRODUCTS

This thesis aims to replace synthetic adhesives in EWP's. Table 3.2 makes an inventory of all different typologies of EWP's, categorising them with their intended usage and bonding surfaces. Each EWP heavily relies on synthetic adhesives to create strong bonds between the wooden particles, veneers or lamellae. As hot-pressure welding bonds two separate components, rather than powder or particles, particleboard, MDF, HDF and Oriented Strand Board cannot be produced with hot-pressure welding.

Table 3.2 EWP Inventory. Based on Popescu (2017), Castanie et al. (2024), and Brandner et al. (2016).

PRODUCT	**DEFINITION**	**IMAGE**
Particleboard or chipboard	Particleboard is made of wood particles that are mixed with synthetic adhesives and are pressed under heat and pressure to form a flat board.	 From Bord, n.d.
Medium-Density Fibreboard (MDF) or High-Density FIbreboard (HDF)	MDF and HDF are made of wood pulp, which is combined with wax and resin binder, before it is hot pressed into dense and uniform panels. Their density is usually higher than particleboard.	 From Prinshouthandel, n.d.
Oriented Strand Board (OSB)	OSB has three layers made of wooden strands, which are debarked from round wooden logs. A resin is added, before it is pressed at a high temperature. Each layer is rotated 90 degrees from the one below.	 From Eco-logisch, n.d.

Table 3.2 EWP Inventory (continued).

Laminated Veneer Lumber	LVL is made of adhesives and veneers, thin sheets of wood.	 From Pollmeier, n.d.
Plywood	Plywood is made by gluing thin wood veneers in layers, with the grain of each layer typically oriented cross-grain from the next.	 From Ply Direct, n.d.
Glued laminated timber (glulam)	Glulam is made by bonding thicker layers of wood with the grain parallel to each other.	 From Timber Building Specialists. (n.d.).
Cross-Laminated Timber (CLT)	A quasi-rigid, plate-like engineered timber composite, typically consisting of an odd number of layers, with each layer formed from boards placed edge-to-edge and oriented perpendicular (90°) to the adjacent layers.	 From Woodteq, n.d.

2.2 MANUFACTURING PROCESSES

LVL and plywood

The manufacturing processes of plywood and LVL has remained practically the same since its invention. However there are some local differences in the manufacturing process, which are related to the used wood species (Hughes, 2015; Baldwin, 1995). LVL and plywood share the same first steps in their respective manufacturing processes. Logs are debarked, cut into blocks and peeled on a lathe into thin veneer sheets (Vladimirova & Meng, 2022). In Nordic countries, the wood is soaked before it is debarked, this softens the wood, improving the bond between its layers (Hughes, 2015; Rohumaa et al., 2016). The veneer sheets are clipped to remove defects, sorted and dried to lower its moisture content. The dried veneers are then cut to size and coated with adhesives, commonly phenol-formaldehyde for structural applications or urea-formaldehyde for indoor uses (Vladimirova & Meng, 2022).

At this step, the manufacturing processes for plywood and LVL start to diverge. In plywood production, the veneers are arranged in alternating grain directions, giving the material strength in two directions. The layered sheets are then hot-pressed under heat and pressure to cure the adhesive, forming flat panels that are later cut, sanded, and graded. In contrast, LVL uses veneers that are oriented in the same grain direction, which maximised strength along the length. The veneers are joined in long billets, which are pressed at slightly lower temperatures than

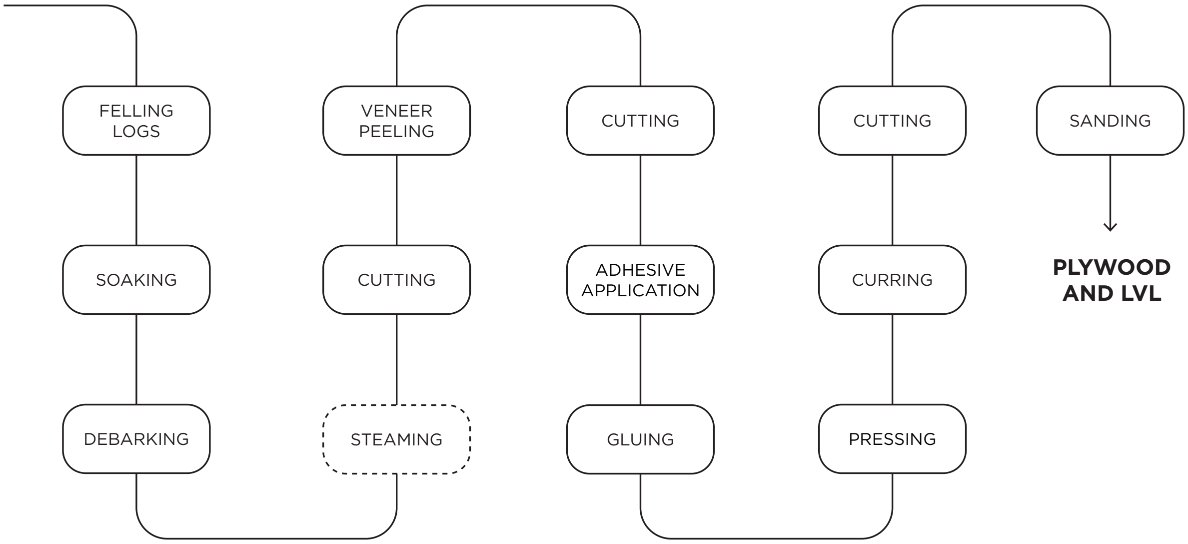


Figure 3.9 Production process plywood and LVL. Based on Vladimirova & Meng, 2022; Hughes, 2015; Rohumaa et al., 2016

plywood. Then they are pressed at a lower temperature, compared to the manufacturing of plywood, and then cut into structural elements such as beams and columns. Overall, while plywood and LVL share common veneer preparation processes, they differ mainly in veneer orientation, pressing methods, and final form, highlighting that plywood is more suitable for panels and sheathing, and LVL for high-strength structural components (Vladimirova & Meng, 2022).

Glulam and CLT

The manufacturing processes of glulam and CLT are broadly similar to those of plywood and LVL, although they rely on finger joining techniques and on sawn timber elements rather than thin veneers (Ong, 2015). Both glulam and CLT start with kiln drying of the laminations after they have been felled and sawed. This is done to reduce the moisture content to 8% and 14%, so that suitable conditions for adhesive bonding are ensured. Then, the dried timber undergoes a strength grading using non-destructive methods such as machine stress grader, natural frequency tools or visual grading. Defective sections are removed and the timber pieces are extended through finger jointing, creating continuous lengths for further processing. Subsequently, the laminations are planed to achieve smooth surfaces and uniform dimensions, improving adhesive bonding. Adhesive is then applied uniformly, after which the laminations are assembled and clamped together using mechanical systems such as clamps, screws, or bolts. Depending on the application, elements may be cold-pressed, hot-pressed, or even curved during the laminating process. After pressing, the elements undergo curing before final finishing processes, including trimming, cutting to size, and removal of excess adhesive (How et al., 2016; Brandner et al., 2016).

The manufacturing of CLT and glulam differ when it comes to the orientation of the laminations. During the production of glulam, all laminations are orientated parallel to the grain directions, forming high strength linear members such as beams and columns. In contrast, CLT consists of layers that are stacked cross wise at 90-degree angles, producing panels that can span in two directions, mostly used for walls, floors and roofs (Ong, 2016; Brandner et al., 2016). Overall, while glulam and CLT share similar bonding and processing techniques, they differ primarily in grain orientation and structural application, with glulam optimized for linear load-bearing elements and CLT for panelised construction systems.

2.3 CHARACTERISTICS AND REQUIREMENTS

LVL, plywood, glulam and CLT are the four potential EWP's that could be manufactured with hot pressure welding. Table 3.3 organizes different engineered wood products by describing their key defining parameters rather than directly comparing performance values. It distinguishes wood species, grain orientation, and whether layers are cross laminated, then details how each product is built in terms of veneers or massive lamellas, number of layers, and individual layer thickness. Adhesive types are listed to indicate typical bonding systems used in production, followed by broad ranges for flexural strength and stiffness that characterize structural behaviour.

Finally, common applications link these material and manufacturing choices to suitable environmental conditions and structural uses. The service class connects each EWP to an environmental moisture condition. According to Eurocode 5 (European Committee for Standardisation) The service class is crucial for assigning strength values and calculating deformations under certain environmental conditions. Service Class 1 is for dry interior environments, 2 covers protected exterior or occasionally damp areas, and 3 represents exposed humid conditions.

As the composition and manufacturing parameters vary so much between products, but also producers or geographic location, they strongly influence both the performance and suitable applications per product. As a result, many of the mechanical and service related values are given as broad ranges rather than single numbers, reflecting the spectrum of possible configurations rather than one fixed, representative value.

Table 3.3 EWP's production, composition and performance characteristics. Based on Brander et al., 2016; Swedish Wood, 2024; Hughes, 2015; Ong, 2016; Meng, 2022; Vladimirova & Meng, 2022; Granta EduPack, 2024; Steico, n.d.; European Committee for Standardization, 2004.

		LVL	PLYWOOD	GLULAM	CLT
COMPOSITION	**WOOD SPECIES**	Softwood	Both softwood and hardwood	Mostly softwood, hardwood	Softwood
	GRAIN ORIENTATION	Cross-grain	Cross-grain	Cross-grain	Cross-grain
	CROSS LAMINATION	No	Yes	No	Yes
	WOOD COMPOSITION	Veneers	Veneers	Lamellae	Lamellae
	NUMBER OF LAYERS	10+	Odd number (3,5,7...)	Variable	Odd number (3,5,7...)
	THICKNESS OF LAYERS	1,5-6,4mm	1-4mm, but 4mm is universal	6-45mm	6-45mm
	ADHESIVES	Phenol-formaldehyde (PF, outdoor) urea-formaldehyde (UF, indoor)	Phenol-formaldehyde (PF, outdoor) urea-formaldehyde (UF, indoor), phenol-resorcinol-formaldehyde (PRF)	polyurethane (PUR) adhesives and emulsion polymer isocyanate (EPI)	Melamine-urea–formaldehyde (MUF), polyurethane adhesives (1K-PUR), emulsion polymer isocyanate adhesives (EPI)
PERFORMANCE	**FLEXURAL STRENGTH**	40-80 MPa	25-55 MPa	13,8-16,5 MPa	14-30 MPa
	STIFNESS	10-12 GPa	3-5,7 GPa	12-14 GPa	7-12 GPa
	SERVICE CLASS	1-2	1-3	1-3	1-3
APPLICATION		Beams and columns	Panels, sheathing, furniture	Beams and columns	Walls, floors and roofs

2.4 DENSIFIED WOOD

As the hot pressure welding of wood relies on pressure to create a complete bond between the layers of wood, the wood will ultimately become densified under mechanical pressure. Densified wood has been used since the 1930s to replace metal in military settings as wood could not be detected on a radar (Wang & Huang, 2011). Today, densified wood is utilised to improve the characteristics of low- and medium-strength wood species, because high-strength wood species are hard to get by. To improve the strength of the low-strength species, their density could be increased mechanically, chemically or both (Chen et al., 2020; Luan et al., 2021). The chemical method involves impregnating the wood spores with chemical liquids that destroy the recyclable characteristics of wood, releases greenhouse gas emissions and pushes up the cost (Sandberg et al., 2017).

At a fundamental level, the densification of wood reduces the volume of wood. With mechanically densified wood a load is added which changes the internal microstructure and reduces the void volume (Luan et al., 2021). Wood can be compressed in the three grain directions: tangential, longitudinal and radial. However, compression in some direction can cause damage to the integrity of the wood. In the tangential direction, the annual rings of the wood buckle, while in the longitudinal direction folds are created, damaging the cell structure of the wood (Kutnar et al., 2015). Thus, most wood is densified in the radial direction of the grain. The annual rings give way in such a manner that the wood remains unfractured (Luan et al., 2021).

Figure 3.10 Lignostone, a laminated densified wood. From Röchling Industrial, n.d.

The mechanical compression of wood can be done by adding steam or not during or before the process. As hot-pressure welding does not involve steam, it is crucial to understand how wood is densified without steam. First the wood softens and plasticises, then it compresses before the wood is cooled. It can be done in bulk or not. Bulk compression densifies the whole wood in one direction, reducing the volume around 40% to 60%, while non-bulk densification involves only one layer of wood, creating a sandwich panel with un-densified and densified wood. This reduced the volume of wood with 6% to 30% (Luan et al., 2021; Laine et al, 2015).

Even though mechanical compression improves the strength of the wood, the technique has two problems. Firstly, the wood does not contain it's shape, warping when only one side is compressed. It bounces back or swells after being compressed. Adding steam could be a potential solution as it improves the dimensional stability without damaging the wood. Secondly, the process of compressing the wood is long and highly energy intensive. The wood needs to cool down in the machine to avoid damage from the internal steam pressure, then the machine needs to be reheated to produce another batch, utilising a lot of energy. These problems can be solved by applying faster cooling methods (like water cooling) or initiating continuous production systems that heat, compress and cool the wood in one workflow that saves time and energy (Luan et al., 2021).

PART 4
EXPERIMENTS

1 MANUFACTURING EXPERIMENTS

As this research and design process was an exploratory one, the aim of the manufacturing experiments was simple: achieve a complete weld. This was assessed in a qualitative manner. Through visual inspection and simple mechanical observation, a complete weld was indicated by the absence of delamination.

1.1 EXPERIMENTAL SET-UP

1.1.1 PROCESS

At the start of each experiment, wood samples were stacked on a steel plate lined with Teflon (PTFE) paper to prevent adhesion. An additional Teflon layer was placed on top of the samples to protect the upper press bed.
The press was preheated to the target temperature with the press beds closed to ensure optimal thermal efficiency. Only once the system indicated a "Ready" status, the press bed was lowered, and the sample assembly was centered within the heated zone. After closing the safety doors, the hydraulic system was activated to apply a specified compressive force, monitored via a manometer and adjusted using a handwheel. Upon completion of the designated pressing time, the pressure was released, and the press bed was fully lowered. For safety and to preserve material integrity, the samples should have only been removed using heat-resistant gloves after the "Ready to Open" indicator confirmed that the cycle has been completed.

This process is displayed by Figure 4.1.

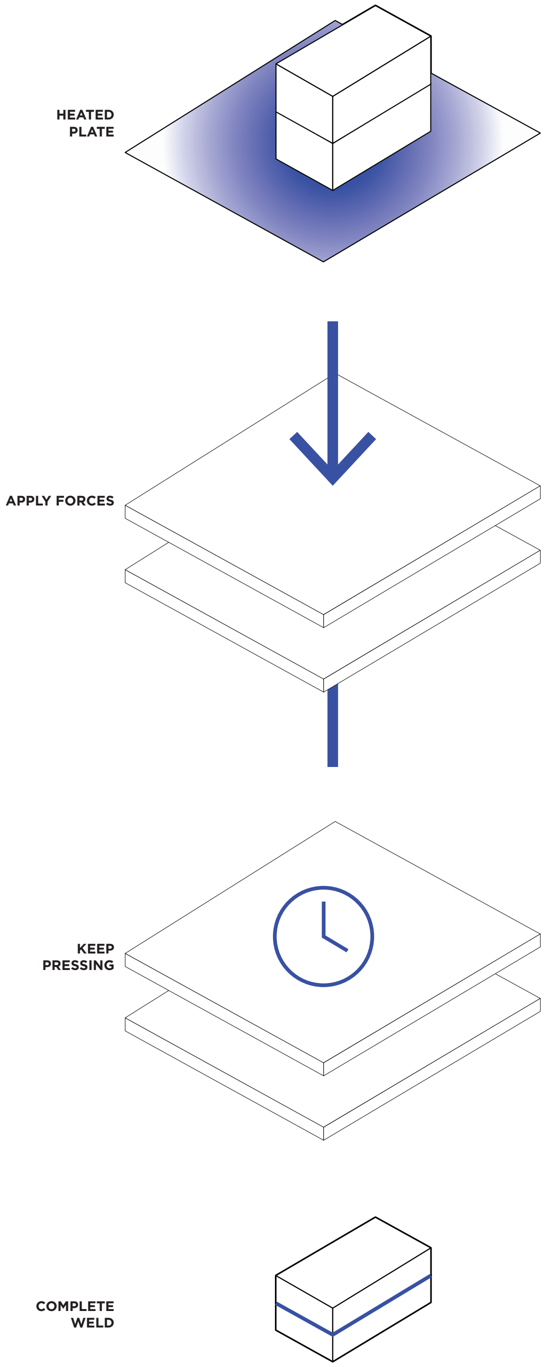


Figure 4.1 Hot-pressure welding process with heat press.

1.1.2 MACHINERY AND TOOLS

Before starting the manufacturing process, the wooden layers needed to be prepared. These were cut and assembled in the Maquette Hall of the Faculty of Architecture.

There are currently two available hot-press machines on the campus of the TU Delft: at the Green Village and the Faculty of Aerospace. Both can reach similar temperatures, but the latter can use a higher pressure.

The Green Village currently has a BIO SheetPress 70 44T with a pressing plate of 700x700mm. Table 4.1 displays the technical information from the machine. It is important to note that this machine is normally only available to make bio-composite plates and has yet to be used on wood. Additionally, this heat press does not allow for humid materials to be pressed together, due to vapour that can build up in the materials, causing potential explosions.

Figure 4.2 BIO SheetPress 70 44T from the Green Village.

Table 4.1 Machine specifics BIO SheetPress 70 44T from the Green Village.

BIO SHEETPRESS 70 44T	
Maximum pressing force	44 ton
Temperature heated press bed	250°C
Press bed dimensions	700x700mm
Maximum pressure of hydraulic system	180 bar

The Aerospace Faculty has a LAP 100 Press Gottfried Joos Machinefabrik. This hot press was not used during this thesis, but could be used for future research.

Besides the hot press, a humidity meter and an infrared thermometer would be needed to measure the humidity and temperature of the welded surfaces.

1.1.3 PARAMETERS

There are a series of parameters that were tested, by making them a constant or variable factor in each experimental set-up. Table 4.2 dispalys their relation to the material properties, composition, machinery or process.

Initially, it was thought that these parameters would have the biggest influence, but as displayed in the following experiments, there are plenty of other parameters that impact the completeness of a weld.

Table 4.2 Parameters manufacturing experiments.

PARAMETER	RELATION
Species of wood	Material related
Orientation of wood grain	
Profile of the veneer	Composition related
Thickness of the veneer	
Number of layers	
Surface preparation	
Pressure applied by machine	Machinery related
Temperature applied by machine	
Pressing time	Process related
Cooling time	
Pre-heating time	

Table 4.3 Wood class chemical characteristics. Based on Schutyser et al., 2017 and Granta Design, 2024.

PROPERTIES	SOFTWOOD	HARDWOOD
Lignin content	21-29%	18-25%
Hemicellulose content	19-22%	17-23%
Cellulose content	46-50%	40-46%
Density	450-550 kg/m^3	600-700 kg/m^3

SPECIES OF WOOD

The distinction between softwood and hardwood is a determinant parameter, as each species has a different amount of lignin and hemicellulose present. Meranti, a hardwood, and pine, a softwood, were chosen as the two tested species of wood because they are already readily used in engineered wood products in the built environment. Each species of wood also has a different density which influences how much the wood will compress in the heat press

ORIENTATION OF WOOD GRAIN

The orientation of the wood grain could play a role in achieving a complete weld, as the cell structure is exposed in a different manner. This influences the flow of lignin and hemicellulose.

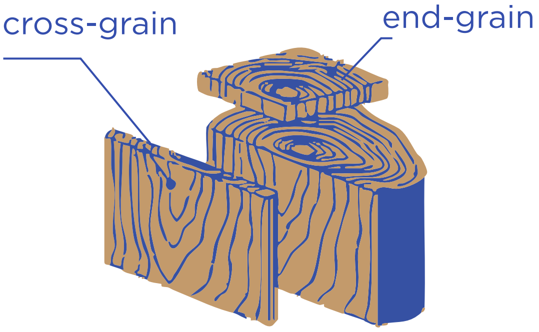


Figure 4.3 Wood grain orientation in end- and cross-grain.

SURFACE PREPARATION

By treating the surface of the wood veneer, complete welds could be achieved. This could be done by sanding the welding surface or adding ridges. Sanding the welding surface damaged the wood grain. This deteriorated the cell structure, potentially influencing the flow of lignin and hemicellulose. Adding ridges to the wood surface, exposes the end-grain characteristics. Or, adding additional lignin may also improve weld quality. This was acquired from Thomas and Henk at Lignitec

NUMBER AND THICKNESS OF LAYERS

The heat could not penetrate fully from a certain distance, so it is crucial to see at what thickness the welds can become incomplete, limiting the applications where hot-pressure welding could be an alternative to synthetic adhesives in EWPs.

TEMPERATURE AND PRESSURE OF HEAT PRESS

The aim of the process is to bring the lignin and hemicellulose within the wood to their glass transition temperature through the application of heat and pressure. Therefore, it is important to determine the press settings required to achieve the appropriate temperature at the welding interface.

TIME

The welds will not occur immediately; the question is how long the pressure needs to be applied to achieve a complete weld or whether the samples need to be cooled or pre-heated in a controlled manner.

1.1.4 QUALITATIVE ASSESMENT

A weld is considered complete when full adhesion has been achieved. However, this is a qualitative observation rather than a quantitive observation, done through a visual inspection. Indicators of a complete weld include a lack of delamination and no edge deterioration, as too much deterioration could negatively impact the applications.

To assess the completeness of a weld, a ranking system from 1 to 3 is applied:

- 1: this represents an incomplete weld where there is no full adhesion and a clear continuous delamination along the surface. The veneers separate easily without resistance.
- 2: this represents a moderate weld, where majority of the welding surface is adhered. There is limited delamination.
- 3: this is a complete weld, with full adhesion across the entire welding surface. It is difficult to separate under mechanical pressure.

Deterioration was graded as follows:

- 1: there is no splintering or crumbling at the edges and the sample expanded minimally.
- 2: there is slight splintering, crumbling and expansion at the edges, most of the surface of the wood retains its integrity.
- 3: there is a lot of splintering, crumbling and expansion at the edges, rendering most of the sample's surface damaged.

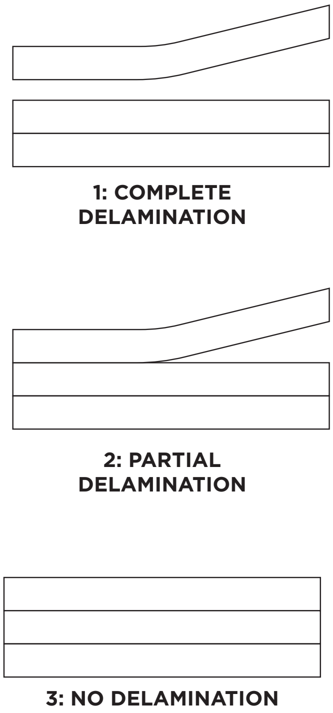


Figure 4.4 Grading delamination.

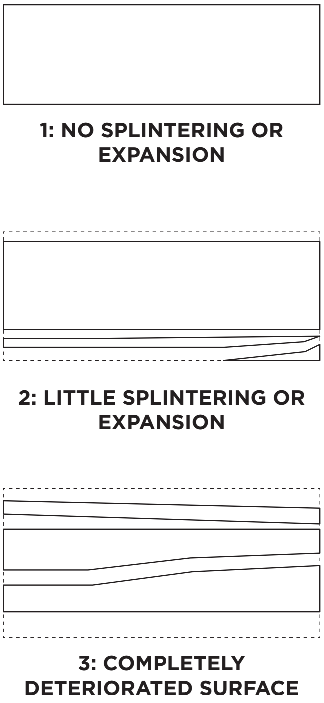


Figure 4.5 Grading deterioration.

1.2 PRELIMINARY EXPERIMENTS

Over a span of three weeks, preliminary experiments were conducted to define the baseline for the parameters. The first series of experiments were used to familiarize oneself with the heat press of the Green Village. Here the first few welded samples were manufactured, sketching the framework for a series of parameters, the temperature of the heat press, the pressure of the heat press and the orientation of the wood grain.

Subsequently, the next series of experiments were conducted to harden the borders of the parameter framework. These series of experiments can be divided into two different studies: one tests what material properties of wood contribute to completeness welds, while the other tests the settings of the machinery.

1.2.1 MATERIAL PROPERTIES TESTING

The objective of these experiments was to evaluate how different material properties affect the quality of the welds, while the machinery settings remain the same.

PARAMETERS

To successfully study what material properties of wood, contribute to a complete weld, it is crucial to have a set of absolute parameters that remain unchanged during the series of tests. Table 4.4 highlights that mostly the settings of machinery remained the same. The temperature, pressure, and pressing time were selected based on preliminary trials that indicated these conditions were sufficient to activate the thermoplastic behaviour of lignin and hemicellulose without causing excessive thermal degradation of the wood.

Table 4.4 Constant parameters material properties tests.

PARAMETER	VALUE
Temperature of press	100 °C
Pressure on press plate	100 bar
Pressure on veneer	35573 bar
Pressing time	15 minutes
Profile of veneers	23mm x 44mm

Table 4.5 displays the variable parameters that were tested in this experimental series.

Wood samples were prepared in the Maquette Hall.

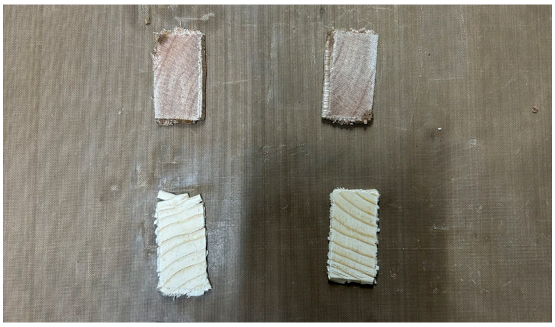
Table 4.5 Variable parameters material properties tests.

PARAMETER	VALUE
Wood species	Meranti (hardwood, pine (softwood)
Grain orientation	End-grain, cross-grain
Surface treatement	Sanded, unsanded
Thickness	2, 3 or 5mm

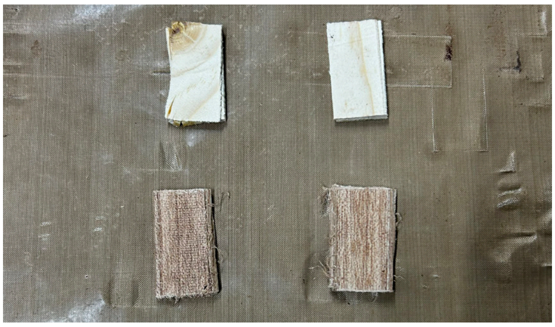
OBSERVATIONS

As can be seen on Figure 4.9, the end-grain specimens (samples 1.1, 1.2, 1.3 and 1.4), pressed at 100 °C and 100 bar for 15 minutes generally produced complete welds. These had limited edge deterioration, indicating that grain orientation is a dominant factor in achieving stable bonds. Increasing the number of layers did not improve overall weld performance and instead resulted in more brittle samples with deterioration, or completely shattered surfaces. This suggests that additional interfaces may promote internal weakness rather than enhanced adhesion. Slightly sanding down the samples did not visually influence the completeness of the weld. Mechanical testing would be needed to see whether the surface treatement had any influence.

For cross-grain configurations (samples 1.5, 1.6, 1.7, 1.8), adhesion was obtained but the joints tended to be more brittle and prone to splintering, with Meranti showing morre complete welds but but also a greater degree of deterioration compared to Pine. Very thin Meranti veneers (sample 1.9) with a thickness of 1 mm, yielded comparatively better weld quality, with complete bonds and no deterioration. This implies that reduced veneer thickness can enhance weld efficiency and mitigate damage at the edges.

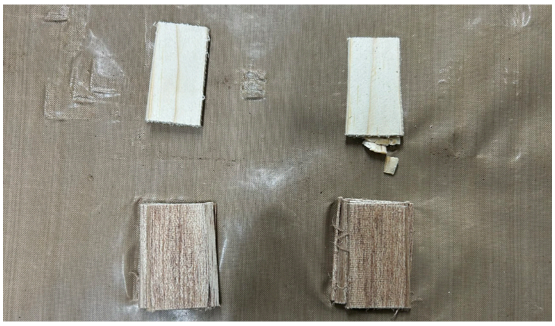


Sample 1.1 Meranti (top), pine (bottom)



Sample 1.5 Meranti (top), pine (bottom)

Sample 1.2 Meranti (top), pine (bottom)

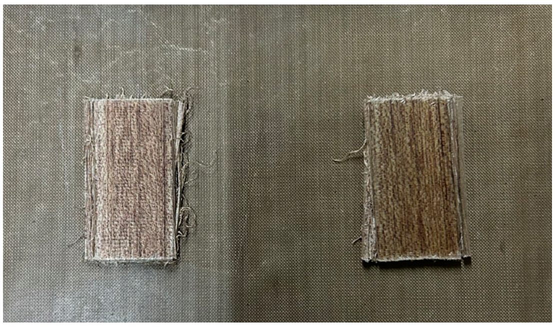


Sample 1.6 Meranti (top), pine (bottom)

Sample 1.3 Meranti (top), pine (bottom)

Sample 1.7 Meranti (top), pine (bottom)

Sample 1.4 Meranti (top), pine (bottom)



Sample 1.8 Meranti (top), pine (bottom)

Figure 4.6 Results prelimanary tests on material propertie (continued).

Table 4.6 (Appendix) displays a summary of these parameters and results.

From this series of experiments of the material properties the following three conclusions can be drawn:

- The end grain samples yielded more complete welds than cross-grain samples.
- The thin veneers of 3mm and samples with less layers had less deterioration at the edges and surface.
- The meranti wood samples showed more deterioration than the pine wood.

In conclusion, this series of testing showed that the grain orientation, the thickness of the samples and wood species are instrumental in achieving complete welds. These parameters are influenced by heat penetration, cell structure accessibility, moisture and vapor escape and chemical stability of hemicellulose.

EXPLANTATIONS

After consulting literature and accessing the aerospace material database of EduPack Granta, the results were analyzed and substantiated. Firstly, the end grain samples yielded more complete welds than cross-grain samples. Properzi et al. (2004) also found that cross-grain welded joints were about half as strong as joints welded along the grain. During wood welding, hemicelluloses and lignin soften and flow under heat and pressure, creating a mixed, molten layer that binds the wood. Because vessels and tracheid's run mainly along the grain, this suggests that end-grain welds let heat and molten material move into the joint more effectively than cross-grain welds. Additionally, end grain samples compress more easily as the cell tubes are collapsing axially, while cross grain samples are stiffer (Sun et al., 2022; Sandberg et al., 2017). This allows for better welds of end-grain samples under less pressure.

Secondly, the thin veneers of 3mm and samples with less layers had less deterioration at the edges and surface, as heat can penetrate faster and more uniformly due to the cores needing less time to heat up. In thicker samples, there is more internal vapor that needs to escape, causing surface degradation, especially at the edges. This is similar to what was observed with friction wood welding. When the internal pressure cannot escape efficiently, especially in larger or thicker samples, it can contribute to irregular bond formation and localized degradation at the surface and edges. Lower moisture content also reduces these scale effects because less heat is consumed by moisture evaporation, allowing thermal degradation and bonding processes to occur more uniformly (Hahn, 2014).

Thirdly, the meranti wood samples showed more deterioration than the pine wood. Meranti is a hardwood with a higher density of 510 to 630 kg/m^3, compared to the density of pine (350 to 430 kg/m^3) (Granta Design, 2024). This means that it has a lower thermal conductivity and can resist compression better, so surface layers may degrade instead of densifying under pressure (Mauranen et al., 2015).

1.2.2 MACHINERY SETTING TESTING

After performing the experiments related to the material properties, a second series of preliminary experiments was conducted to examine how the settings of the heat press influence the quality of a weld. The objective was to determine the ranges of temperature and pressure that would consistently produce a stable and uniform weld while minimizing deterioration of the wood surfaces.

PARAMETERS

To ensure that the results could be attributed primarily to the machinery settings, the parameters related to the material properties remained constant. Pine was selected as the wood species because it showed relatively less deterioration during the previous series of tests. Additionally, the use of a single species helped eliminate variability caused by differences in density, cellular structure, and chemical composition between hardwoods and softwoods.

Additionally, the pressing time was set to 15 minutes, ensuring that sufficient time was available for heat to penetrate the veneers and to soften the lignin and hemicellulose.

By making the pressing time a constant variable, this series of experiments isolates and evaluates the effects of the heat press’

Table 4.7 Constant parameters machinery settings tests.

PARAMETER	VALUE
Wood species	Pine
Thickness of veneer	3mm
Profile	28mm x 44mm
Number of layers	3
Pressing time	15 minutes

temperature and pressure on the weld quality, without adding complexity to the process.

Therefore, all samples were manufactured using pine veneers with a profile of 28mm x 44mm and a thickness of 3mm. Each sample consisted of a layer of 3 veneers, forming a multi-layered configuration, that can be used in potential applications.

The variable parameters were related to the machinery settings, such as the temperature and the pressure of the heat press, as shown in Table 4.8. By systematically varying these parameters while maintaining consistent material conditions, the experiments aimed to establish a clearer understanding of the processing window within which complete welded joints can be achieved.

Table 4.8 Variable parameters machinery settings tests.

PARAMETER	VALUE
Temperature of machinery	100 °C , 125 °C, 150 °C
Pressure on press plate	50 bar, 100 bar, 150 bar
Grain orientation	End-grain, cross-grain

Although the focus of this series of experiments is on the machinery settings, the orientation of the wood was also included as a variable parameter. This decision was made because grain orientation influences how heat and pressure are transferred through the cellular structure of the wood. As a result, it can interact with the machinery settings and affect the resulting weld quality, even though it is not itself a parameter controlled by the machine.

OBSERVATIONS

All tests achieved complete welds, however there are clear differences in the weld quality, as shown in Table 4.9 (Appendix). End-grain samples generally exhibited brittle edges and surface darkening, especially at the higher temperatures (125 to 150 °C). Cross-grain samples showed weaker welds and splintering along the fibre edge. As the pressure increases, samples 2.2, 2.3, 2.5, and 2.7 showed stronger welds, but more pronounced edge brittleness and compression effect, unrelated to the grain orientation of the samples.

However, the deterioration happens in a different manner. For end-grain samples, the material crumbles at the edges, while cross-grain samples splinter at the edges. The temperature of the heat press influences both the visual and structural characteristics. At 125 °C, samples 2.4 and 2.5 surface displayed a darker coloration. This points to pyrolysis, the thermal decomposition of the wooden samples. Thus, while higher temperatures appeared to facilitate more reliable cross-grain welding by enhancing the softening and flow of lignin, they also increased the risk of discoloration and surface deterioration.

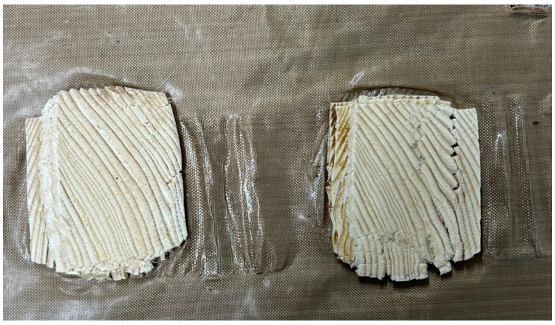
Overall, both the pressure and temperature generated by the heat press are dominant parameters to achieve a complete weld. It was observed that moderate conditions allowed sufficient softening of the bonding components within the wood while limiting excessive compression, fibre expansion, or thermal degradation. Excessively high temperatures primarily increased discoloration and deterioration, whereas excessive pressure tended to produce brittle edges and extreme compression of the cellular structure.

From the series of experiments on the machinery settings, three conclusions can be drawn:

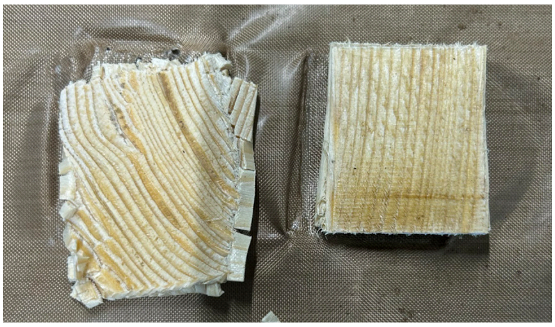
- The balance between temperature and pressure needs to be carefully controlled to prevent problems like weak welds, discoloration, too much compression, and brittle edges. Higher pressure tends to cause brittle edges, while higher temperature mainly leads to discoloration.
- Cross-grain samples benefit from higher temperature.
- The middle layer appears to soften en be partially absorbed into the adjacent layer, acting as a boding medium that contributed to a complete weld.

Sample 2.1 Both end-grain

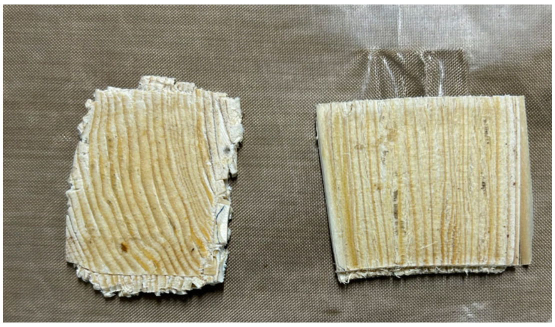
Sample 2.2 Both end-grain



Sample 2.3 Both end-grain

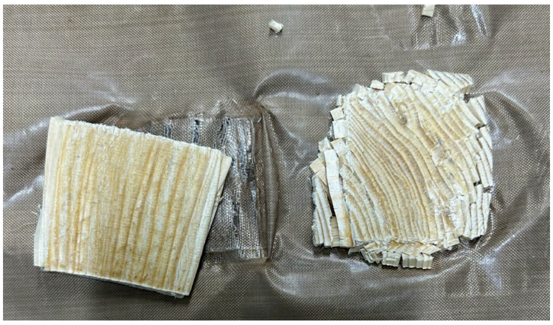


Sample 2.4 End-grain (left), cross-grain (right)



Sample 2.5 End-grain (left), cross-grain (right)

Sample 2.6 End-grain (left), cross-grain (right)



Sample 2.7 Cross-grain (left), end-grain (right)

Figure 4.7 Results prelimanary tests on machinery settings.

EXPLANATIONS

By consulting literature, the main conclusions of the observations are supported and rationalized.

Firstly, the relationship between the temperature and pressure of the heat press is fickle, as it can cause incomplete welds, discoloration, brittle edges and excessive compression. By exposing wood to temperatures higher than 65 °C, the chemical compounds (including lignin and hemicelluloses) degrade. The heat reduces the strength and modulus of elasticity, depending on the exposure time and temperature levels (Dietenberger & Hasburgh, 2016).

However, some literature claims that pressure is the most determinant factor that contributes to the rate of deterioration of wood, compared to the peak temperature applied. Experiments performed in a closed reactor, compressed wood at 0,14 MPa to 0,79 MPa and heated the wood from 150-180 °C. Here, they estimated that wood lost more mass under higher pressure than under higher temperatures. This could potentially affect the chemical composition of wood, especially the lignin (Altgen et al., 2016).

Secondly, cross-grain samples benefit from higher temperature for complete welds. At higher temperatures the lignin and hemicellulose are activated more, as their glass transition temperature range is broad: from 100 °C to 170 °C for lignin and 54 to 142 °C for hemicellulose (Yang et al., 2019; Goring, 1963).

Finally, the middle layer appears to soften en be partially absorbed into the adjacent layer, acting as a boding medium that contributed to a complete weld. This could be contributed to the mechanical set-up of the experiments. As both outer layers are mostly loaded by the respective plate of the press, they likely directed and concentrated pressure toward the middle layer. As a result, the middle layer experienced greater compressive deformation, promoting softening, densification, and enhanced interfacial bonding.

1.3.3 CONCLUSIONS

The preliminary tests displayed that an array of parameters are crucial in achieving complete welds. For the material properties, the wood species, thickness of the sample and the wood grain orientation played a major role, while for the machinery settings the temperature and pressure shaped the completeness of the welds. However, both experimental series reveal that grain orientation and the thickness of the veneer remained the most significant factor; it fundamentally governed the rate of heat penetration and the accessibility of the cellular structure for molten lignin and hemicellulose flow.

Having established a baseline for the parameters related to material properties and machinery settings, the next experiments should be focused on upscaling. Bigger samples should be produced to evaluate the potential applications of hot-pressure welding as an alternative to synthetic adhesives.

To facilitate this upscaling, the next steps were centred around the successful welding of cross-grain wood veneers rather than end-grain wood. Firstly, end-grain wood is rarely used in EWPs such as plywood, LVL, CLT or glulam (Gong, 2022; Popescu, 2017; Ong, 2015). The production of end-grain wood is dependant of the size of the trunk; large panels cannot be produced. Secondly, end-grain wood has a comparatively lower strength than cross grain wood, limiting the potential high-loaded applications of welded wood (Sun et al., 2022; Sandberg et al., 2017).

Thus, the welds need to be improved so that cross-grain and thicker wood veneers could be used in larger and high-loaded applications.

1.3 CROSS-GRAIN WOOD EXPERIMENTS

To support the upscaling of hot-pressure welded wood and enhance joint strength, a new series of tests will focus on adapting cross-grain and thicker wood veneers for welding applications. Since end-grain configurations have shown more favourable welding behaviour, these experiments aim to modify cross-grain wood to replicate key characteristics of end-grain structures.

The first set explored surface modifications designed to expose end-grain features within the cross-grain wood. The second set of tests investigated the effect of introducing an additional lignin layer to the bonding surface, with the goal of improving material flow and interfacial bonding. The textured surface emulated the ridges observed when the end-grain samples are broken open.

PARAMETERS

Each testing set had a treated sample and an untreated sample, to investigate the influence of the treatment on achieving complete welds with scientific vigour.

To observe the behaviour of the additional lignin and the ridges in the welding surface, a series of

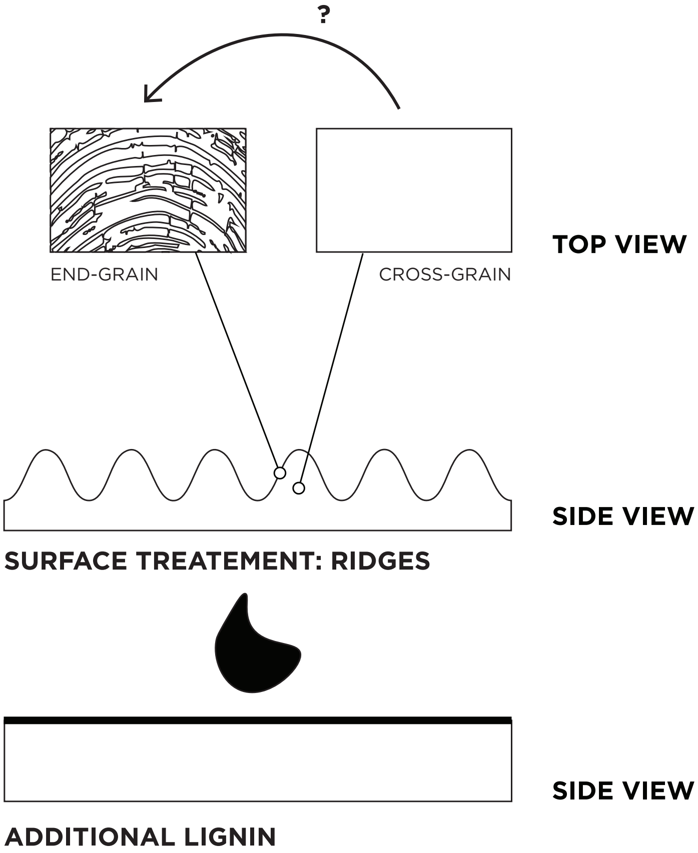


Figure 4.8 Cross-grain treatements

parameters stayed unchanged. Table 4.10 highlights that both material properties and machinery settings remain the same.

The variable parameters are displayed in Table 4.11. These are related to the surface treatment and the thickness of each layer. This allows to evaluate the influence of the ridges and additional lignin on a complete weld of thicker veneers.

Table 4.10 Constant parameters cross-grain tests.

PARAMETER	VALUE
Wood species	Pine
Wood grain orientation	Cross-grain
Temperature of press	125 °C
Pressure on press plate	50 bar
Pressure on veneer	14610 bar
Pressing time	15 minutes
Profile	28mm x 44mm

Table 4.11 Variable parameters cross-grain tests.

PARAMETER	VALUE
Thickness of veneer	4mm, 10mm
Number of layers	2,3
Ridges	Yes, no
Additional lignin	Yes, no

For the treated samples containing ridges (3.1 and 3.2), each layer was hand carved with piece cutting knives, as the profile and thickness of the samples did not allow for easy use of a milling machine. For the lignin focused samples (3.3 and 3.4), the lignin was coated richly on the whole welding surface, without adding a binding medium.

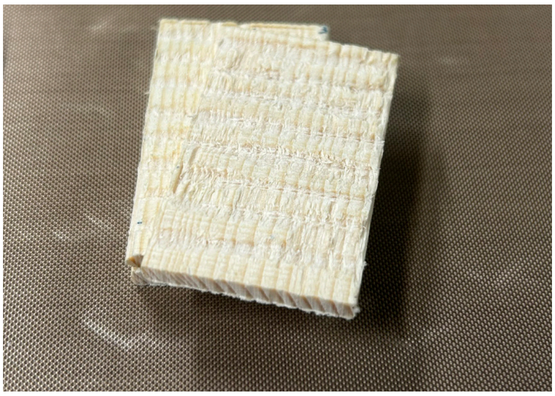


Table 4.9 Hand carved ridges made with carving knives.

OBSERVATIONS

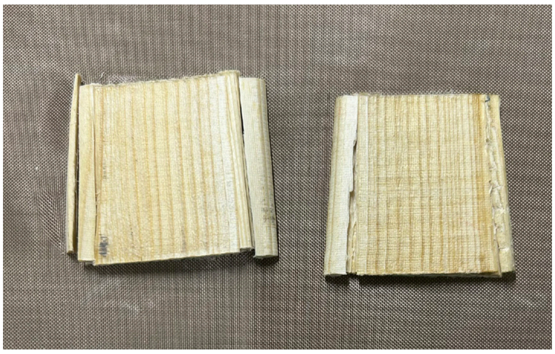
The observations presented in Table 4.12 (Appendix) indicate that the veneer thickness had the most significant influence on the weld quality under the constant variables of 125 °C, 50 bar pressure, and 15 minutes pressing time. Samples, made from thinner veneers (tests 3.1 and 3.2, using 4mm layers) achieved complete welds, scored with a 3, whereas samples produced from thicker veneers (tests 3.3 and 3.4, using 10mm layers) showed a lower quality of welds, scoring 1 and 2. This suggests that increasing veneer thickness negatively affects heat transfer and material flow at the welding interface, reducing weld quality. During test 3.3 an exploding sound emitted from the heat press, so to avoid breaking the machinery, test 3.4 used two layers of veneers rather than three.

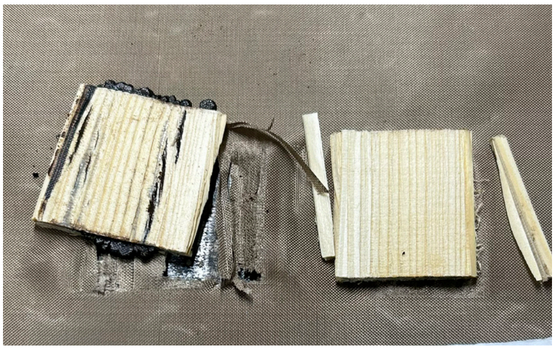
A key observation across all samples was the severe deterioration present not only at the specimen edges but across the entire welded interface, indicating that the selected welding parameters were too aggressive for cross-grain pine veneers.

The addition of ridges to the thicker samples did not improve the weld quality, indicating that the surface texture alone was insufficient to remedy the limitations of the thicker veneers. similarly, the additional lignin layer did not produce a clear structural improvement during visual assessment, although in some thinner samples it appeared to slightly enhance the weld surface. The lignin darkened a lot when taken out of the heat press.

From these observations three conclusions can be drawn:

- Increased veneer thickness resulted in severe deterioration at both the welding interface and the specimen edges.
- The incorporation of ridges in thicker sections did not contribute to stronger weld formation.
- The addition of lignin appeared to visually improve weld quality.


Sample 3.1


Sample 3.2


Sample 3.3

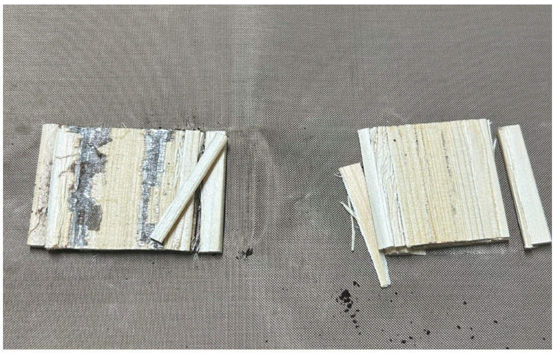

Sample 3.4

Figure 4.10 Results prelimanary tests on cross-grain.

EXPLANATIONS

Firstly, the increased thickness of the cross-grain veneers resulted in severe deterioration at both the welding surface and the specimen edges. This can be explained with the low thermal conductivity of wood. According to the Aerospace Universe of EduPack, pine has a thermal conductivity of 0,21 to 0,26 W/m.°C, meaning that heat can penetrate less easily through the layers of material (Granta Design, 2024). As a result, the edges of the welding surface, closest to the heated plates of the press, experience higher temperatures and compression. The inner core remains cooler, causing stress in the wood. Additionally, thicker specimens contain a larger volume of moisture and internal vapour pressure, which cannot escape efficiently during pressing. The trapped vapour increases internal stresses and contributes to edge deterioration. This is similar to the findings of Hahn (2014) on friction welding of wood.

Secondly, the incorporation of ridges in thicker sections did not contribute to stronger weld formation and led to dramatic splintering of the wood. The ridges broke the integrity of the wood. Thus, the load was not well distributed across the surface of the wood and became concentrated at the peaks of the ridges.

Finally, the addition of lignin appeared to visually improve weld quality. This observation is consistent with the role of lignin as a natural thermoplastic polymer within wood. When heated to its glass transition temperature, lignin softens and can flow under pressure, helping to fill voids and create a continuous matrix between adjacent wood surfaces. Upon cooling, the lignin re-solidifies and contributes to bonding strength (Gfeller et al., 2004; Pizzi et al., 2004). Therefore, the added lignin enhanced the weld by increasing the amount of flowable bonding material available during pressing.

CONCLUSIONS

The experimental series, building on the findings of the earlier tests, confirmed that cross-grain configurations with thin veneers offer the most potential for upscaling towards applications in engineered wood products (EWPs). Lignin showed potential as a valuable surface treatment, while the ridges only destroyed the wood's surface, negatively impacting the welding quality.

Further experiments focused on lignin-treated and untreated samples using thin veneers, while maintaining constant processing parameters (125 °C, 100 bar, pine, 15 minutes pressing time)

1.4 UPSCALED MANUFACTURING TESTS

After having established that cross-grain wood could be used during the process of hot pressure welding, the next step was to scale up the welding surface; the width of the samples stayed the same at 44mm, but the length extended to 143mm.

This upscaling step was intended to evaluate whether the hot-pressure welding process remained effective on larger samples that are more representative of potential practical applications, such as an alternative bonding system for engineered wood products.

Based on the results from the previous tests, the heat press' pressure, grain orientation and presence of lignin were evaluated.

The samples created during this series of tests were eventually used in the performance tests, described in chapter 4.2.

PARAMETERS

A series of parameters remained unchanged, as illustrated by Table 4.13. The choice to keep these parameters fixed was important because it limited the number of influencing factors and made it possible to compare the results more reliably. At the same time, this setup also meant that any visible defects or differences in weld quality could be linked to the changed variables. Some parameters did vary between each sample (Table 4.14).

Four samples were manufactured during this series of tests. Samples 4.1, 4.2 and 4.3 were produced at 100 bar, while sample 4.4 was produced at 200 bar to investigate the effect of increased pressure. Sample 4.3 included an added lignin layer, while sample 4.2 was produced with end-grain orientation for comparison with the cross-grain samples.

Table 4.13 Constant parameters upscaling tests.

PARAMETER	VALUE
Wood species	Pine
Wood grain orientation	Cross-grain
Temperature of press	125 °C
Pressing time	15 minutes
Profile	143 mm x 44 mm
Thickness	3mm

Table 4.14. Variable parameters upscaling tests.

PARAMETER	VALUE
Grain orientation	End-grain, cross-grain
Pressure of heat press	50 bar, 100 bar
Pressure on veneer	14610 bar, 29220 bar
Additional lignin	Yes, no

OBSERVATIONS

The results (Table 4.15, Appendix A) indicate that upscaling the welding surface was feasible, although the weld quality remained dependent on the grain orientation and the process parameters. In general, all the samples showed limited deterioration at the edges, which is an improvement compared with some of the smaller samples from the previous series. This suggests that scaling up does not damage the wood surface more.

Sample 4.2, the only sample manufactured with end-grain wood, achieved the most complete weld, receiving the highest score of 3, while the other samples only scored a 2. The cross-grain samples all had minor lifting at the edges. Sample 4.3, which included additional lignin, showed no clear visual improvement in bond quality, although discoloration of the lignin layer was observed after pressing. Increasing the pressure from 50 bar to 100 bar in sample 4.4 did not resolve the lifting observed at the edges of the cross-grain specimens. This indicates that simply increasing pressure is insufficient to overcome the bonding limitations associated with cross-grain orientation at this scale. Noticeable across all the samples is that the samples get warped once taken out of the heat press. They curved and did not lay flat anymore.

Four conclusions can be drawn from these observations:

- There is little deterioration at the edges of the bigger samples.
- The end-grain sample was the only sample to show full adherence.
- Adding more pressure did not improve the lifting at the edges in cross-grain samples.
- All samples got warped when taken out of the heat press.

Sample 4.1

Sample 4.2

Sample 4.3

Sample 4.1 warped

Figure 4.11 Results prelimanary tests on upscaled manufacturing.

EXPLANATIONS

Firstly, there was little deterioration at the edges of the samples with larger welding surfaces. This is likely caused by an even distribution of pressure across the welding surface. In the larger samples, the compressive load is spread over a larger area, reducing deterioration at the edges and safeguarding the integrity of the cellular structure of the wood. Additionally, the larger surface area has a lower edge to surface area, which means that the deterioration could be less pronounced as the lignin can distribute more evenly.

Secondly, the end-grain sample was the only one to show a complete weld. This aligns with the previous results from the first experimental series. Because the vessels and tracheids are oriented along the grain, the end-grain orientation allowed heat and softened material to penetrate the weld. Additionally, end-grain wood compresses more easily due to the axial collapse of the cell structure, whereas cross-grain samples are mechanically stiffer, resulting in less efficient bonding under the same pressure conditions (Sun et al., 2022; Sandberg et al., 2017). This allows for the lignin and hemicelluloses the flow better under heat and pressure.

Additionally, adding more pressure did not improve the lifting at the edges in cross-grain samples, causing the unsuccessful welds. Instead, higher pressure appeared to further damage the wood surface. Due to the anisotropic nature of wood, it has different resistance depending on its grain orientation. Wood undergoes less dimensional change in the cross-grain direction, which is half as much as in the end-grain direction (Glass & Zelinka, 2010). So, in cross-grain orientation, the fibres resist compression more strongly, causing stresses to concentrate near the edges and along the fibre boundaries. As pressure increases, the rigid fibre structure will splinter and fracture rather than densify.

Finally, all samples warped after they were removed from the heat press, causing them to curve instead of lying flat. This likely happened because the wood cooled down too quickly, making its components harden unevenly and trapping internal stresses. Additionally, some of the compressed wood may have partly returned to its original shape, a phenomenon called spring-back (Scharf et al., 2023). This could have contributed to the bending of the samples, especially in the larger samples as bigger pieces of wood cool less evenly than smaller ones.

CONCLUSION

In conclusion, upscaling the welding surface is possible. End-grain samples still achieved more complete welds than cross-grain samples, which aligned with the findings from the previous experimental series. However, the upscaling still had two problems: the deterioration at the edges of the samples remained and the samples warped after being taken out of the oven. The next experimental series revolved around finding solutions for these problems.

1.5 MOULD PRESSING TESTING

Almost all previous experiments showed samples with edge deterioration. This occurred because the edges experienced the highest heat and pressure during welding. Heat and vapour could not spread evenly through the wood, especially in thicker or cross-grain samples, creating internal stresses that caused expansion, splintering, or crumbling at the edges. To prevent this from happening, a framed mould was used to prevent the edges from deteriorating and expanding. The mould was made from steel, which was laser cut at the Faculty Workshop of the Faculty of Mechanical Engineering at the TU Delft. The mould had a thickness of two 2mm steel plates, based on the measured thickness of the achieved previous tests.

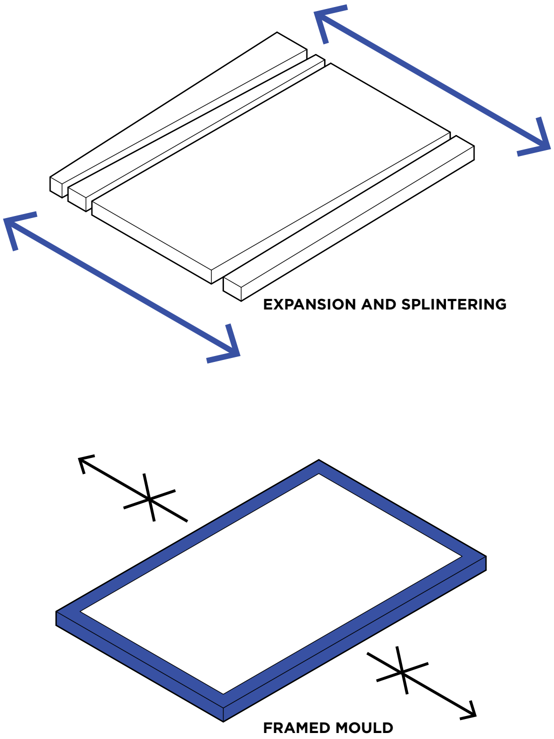


Figure 4.12 Framed mould.

PARAMETERS

To reduce the costs of laser cutting and materials, this test tried to produce a successful weld with a smaller sample size of 28mmx44mm and a thickness of 4mm. Table 4.15 shows the constant parameters of the experiments.

Table 4.15 Constant parameters mould pressing tests.

PARAMETER	VALUE
Number of layers	3
Thickness of layer	4mm
Profile	28mmx44mm
Grain orientation	Cross-grain
Wood species	Pine
Temperature of press	125 °C
Pressure on press plate	75 bar
Pressure on veneer	21915 bar
Pressing time	15 minutes

The only variable parameter is the presence of a mould.

OBSERVATIONS

Only one samples was successfully produced as the mould broke due to the wood expanding under the high pressure. Sample 5.1 did not achieve a complete weld as the two bottom layers did adhere fully to each other, but the top veneer fell off. The edges also showed a certain rate of deterioration, but in terms of extreme expansion. There was no crumbling or splintering at the edges.

The main observation was that the mould did mitigate the splintering at the edges, yet a fully complete weld was not achieved.

Figure 4.13 Sample 5.1

CONCLUSIONS

This experiment could be deemed as a failed one, as it did not achieve a successful weld however, the results should be placed within their aim. The mould had to prevent the splintering and extreme expansion at the edges of the samples, which it achieved to a certain extent. It prevented splintering and crumbling at the edges, except the sample still expanded to an extreme rate. This could have been prevented by making the edges of the frame thicker, so that it could resist the compression of the wood better. Maybe, with a new mould, the expansion of the edges could be mitigated.

1.6 PRE-HEATED AND CONTROLED COOLING

The aim of this series of experiments was to mitigate the warping of the upscaled samples when they were taken out of the heat press. This occurred because the wood cooled down to fast, causing parts of the sample to harden unevenly and creating internal stresses.In addition, part of the compressed wood may have partially recovered its original shape through a phenomenon known as spring-back. These effects likely caused the samples to bend.To attempt to diminish the warping of the samples, the wood was pre-heated and cooled off in the heat press. This intervention could assist the upscaling of hot pressure welded wood.

PARAMETERS

Figure 4.16 displays the constant variables of this series of experiments.

However, this time two additional parameters were added: pre-heating time and cooling time, each being 15 minutes or 0 minutes. Sample 6.1 was only pre-heated, sample 6.2 was only cooled off in the heat press, and sample 6.3 did both. It should be noted that, unlike in previous experiments, the wood used in this series contained medium sized knots. This introduced additional variability due to local differences in density, grain deviation, and resin content.

Table 4.16 Constant parameters controlled cooling and pre-heating tests.

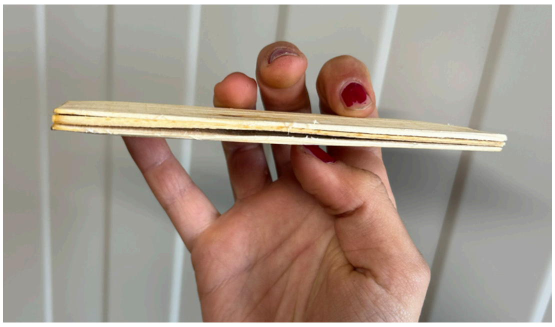
PARAMETER	VALUE
Number of layers	3
Thickness of layer	4mm
Profile	143mm x44mm
Grain orientation	Cross-grain
Wood species	Pine
Temperature of press	125 °C
Pressure on press plate	50 bar
Pressure on sample	2860 bar
Pressing time	15 minutes

The temperature of the wood was an independent parameter, which was measured with an infra-red thermometer after it has been cooled down or pre-heated. The aim of these experiments was to evaluate whether controlling the thermal transition before and after pressing could improve weld quality and reduce the warping of samples.

OBSERVATIONS

As illustrated by table 4.20 (Appendix), Sample 6.1, which was only pre-heated, did not achieve a complete weld, with all three layers delaminating. In contrast, sample 6.2, which was cooled within the heat press after pressing, produced a complete weld with improved adhesion across the interface. Sample 6.3, which combined both pre-heating and controlled cooling, also achieved a complete weld, although significant expansion near knots and resin release were observed.

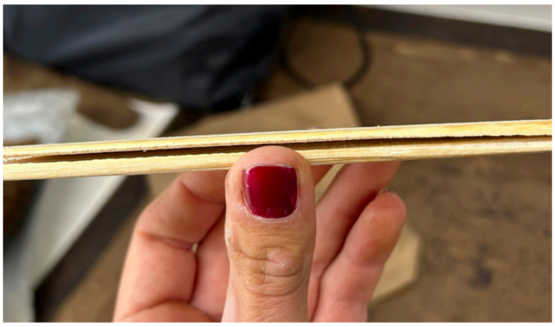
All three samples did not warp after being taken out of the oven and remain flat on both the top and bottom surface. Interestingly, in all three samples resin was released from the wood.



Sample 5.1

Sample 5.2 (left) and 5.3 (right)

Sample 5.2 without warping



Sample 5.2 without warping

Figure 4.14 Results pre-heated and cooled samples.

EXPLANATIONS

The improved weld quality and lack of warping of the samples 6.2 and 6.3 suggest that controlled cooling inside the heat press played an important role. When the samples were removed from the press immediately after pressing, the material were still thermally unstable. The internal stresses caused by uneven moisture and temperature gradients remained present within the wood. As the samples cooled freely in ambient conditions, rapid shrinkage and elastic recovery of the compressed fibres could disrupt the newly formed bond, leading to edge lifting and incomplete adhesion. This could have reduced the warping of the samples

CONCLUSIONS

The results from this experimental series did not provide a definitive answer regarding the influence of pre-heating or cooling the samples on the weld quality. Sample 6.1, which was only pre-heated, failed to achieve a complete bond, despite earlier experiments (4.1.4) demonstrating successful welding under identical parameters. The inconsistency suggests that the process may be sensitive to uncontrolled variables, moisture content, air temperature, or material variability. This limits the reliability of pre-heating as an intervention to improve weld completeness. In contrast, the results do indicate that cooling and pre-heating within the press reduce the warping of the samples. Both samples subjected to in-press cooling (6.2 and 6.3) achieved complete welds and showed no warping. This finding highlights cooling rate as a critical parameter in the upscaling process.

Additionally, the wood used in this experimental series contained knots, unlike in the other experiments. The knots introduced material variations in density and grain orientation, which could have influenced the heat transfer, lignin content and the overall welding behaviour. As a result, the presence of knots reduces the comparability of the results with previous tests. This reduced the reliability of the results.

1.7 VENEER SANDWICH PRESSED SAMPLES

The results from the experimental series on machinery settings, displayed that the middle layer of each test seemed to disappear, as if it is the glue that adheres the top and bottom veneer together. This led to the question whether reducing the thickness of the middle layer contributes to a more complete weld.

Figure 4.15 Dissepeared middle layer.

PARAMETERS

Almost all parameters were constant, only two parameters were variable: the thickness of the middle layer and the presence of lignin. The addition of lignin was included because it appeared to contribute to the most complete welds in earlier tests.

In addition, the thin veneer used in this series was birch, which was purchased through Amazon. They had a shine to them, which implied they were shaved off.

Table 4.18 Constant parameters sandwich samples.

PARAMETER	VALUE
Number of layers	3
Profile	143mm x44mm
Grain orientation	Cross-grain
Wood species	Pine with birch veneer
Temperature of press	125 °C
Pressure on press plate	50 bar
Pressure on sample	2860 bar
Pressing time	15 minutes

Table 4.19 Variable parameters sandwich samples.

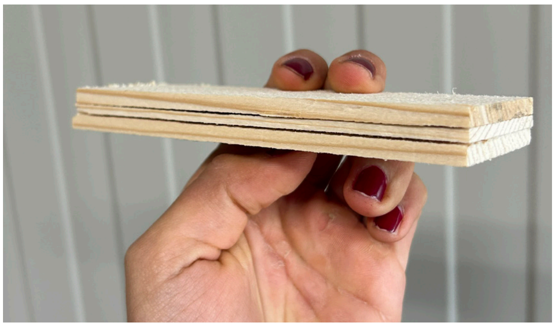
PARAMETER	VALUE
Thickness layers	4mm with 1mm or 0,5mm
Addition of lignin	Yes, no

OBSERVATIONS

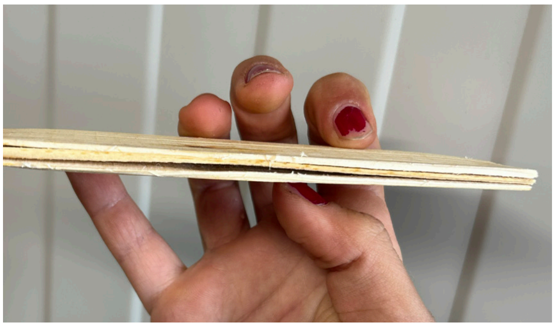
Three samples were tested with different configurations and thickness of the middle layer. Sample 7.1, with a middle layer of 0,5mm and no added lignin, did not achieve a complete weld. The thin layer came loose and did not adhere at all to the other layers. Sample 7.2, also with a 0,5mm veneer layer but with added lignin, showed partial adhesion, although the weld was still incomplete, especially at the edges. Sample 7.3, with a 1mm middle layer and no lignin, also did not achieve a complete weld. The middle layer appeared to adhere to the bottom layer, while the top layer completely detached. Overall, the results did not show a consistent improvement in weld quality as the middle layer became thinner. The sample with lignin performed somewhat better than the samples without lignin, yet the bond was not fully successful.

Sample 7.1 (left) and 7.2 (right)

Sample 7.2



Sample 7.3 before welding



Sample 7.3

Figure 4.14 Results pre-heated and cooled samples.

CONCLUSIONS

This experimental series does not provide clear evidence that reducing the thickness of the middle layer improves the weld quality. All samples did not show complete welds, as a result, the effect of middle-layer thickness remains inconclusive. The results do suggest that the added lignin may have positive influence on the bonding.

1.8 LIMITATIONS AND FUTURE STEPS

The results from the manufacturing tests had a few limitations. Firstly, although a numerical rating system was applied, it lacked quantitative assessment. The completeness of a weld was determined mainly by visual inspection, without standardized quantitative strength testing. Without shear, tensile, bending, or delamination tests, the actual structural performance of the joints remains unknown, and the "completeness" of a weld is relative. A weld that appears sound may still fail under load. Hence, why further performance testing is described in the next section.

Only a small number of samples were tested and no repeated trails for identical parameters sets were performed. This made it impossible to assess statistical significance of certain results. The trends that were observed could be random variabilities rather than an objective outcome.

Wood is not a homogeneous material. It can vary in density, moisture content, grain orientation, lignin content between samples. These factors may have influenced the results influenced the results independently of the tested parameters. Some material loss occurred during preparation due to badly cut samples, which may also have affected consistency and precision. This was also the case for the samples with the ridges.

Additionally, the last series of tests showed less complete welds. All these experiments were conducted during a rainy and cold day, with a relatively high humidity, compared to the days where other experiments took place. Series 5 to 7 took place on May 12, on which the temperature ranged from 7 to 13 °C with a humidity of 61%. Series 4 were done on April 14, a sunny day with temperatures between 6 to 14 °C and a humidity of 56% (World Weather Info, n.d.) These uncontrolled parameters could have heavily influenced the completeness of certain welds.

Explanations such as lignin softening, pyrolysis, and layer absorption were based on literature rather than measurements. Since no internal temperature monitoring, microscopic imaging, or chemical analysis was performed, these explanations remain hypothetical and unconfirmed. Therefore, these explanations remain unconfirmed and speculative. As the experiments became more exploratory and the tested parameter combinations increasingly unconventional, it also became more difficult to identify literature that fully supported the observed behaviour, resulting in a greater reliance on hypotheses and interpretation.

Future research should therefore focus on improving the scientific rigour of the results. Repetition of the experiments and the use of more precise manufacturing equipment would turn the current results from hypotheses to reliable and reproducible results. The effect of longer pressing time, higher pressure and higher temperatures should be researched more extensively. In addition, microscopic and chemical analyses should be conducted to verify the assumptions made to explain certain observations. Finally, the influence of air temperature and moisture fluctuations, particularly during the final experimental series where weld quality decreased, should also be investigated further and mitigated by conducting the experiments in a climatised room. Without all his, the results remain practically scientifically imprecise.

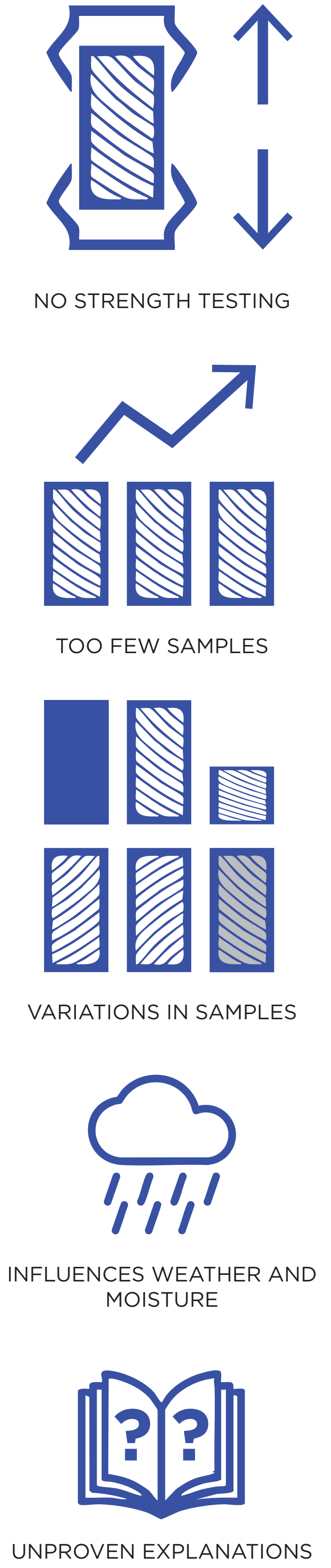


Figure 4.16 Limitations.

1.9 CONCLUSIONS

The results of the manufacturing experiments demonstrate that wood can be successfully hot pressure welded under a specific combination of parameters. The series of experiments showed that most complete welds, with the least edge deterioration, were achieved with thin veneers (3 to 4mm thick), moderate heat (125 °C), pressure at around 50 bar and a pressing time of 15 minutes. Addtional lignin that was sprinkled on the surface also contributed to more complete welds.

The orientation of the wood grain proved to be the most influential parameter. The end-grain samples repeatedly achieved more complete welds, because the exposure of the annual rings allowed lignin and hemicelluloses to flow better under heat. Cross-grain samples could also be welded but they were more susceptible to splintering due lifting and incomplete welds because of the higher mechanical resistance of the fibres in this orientation.

Figure 4.17 Cross-grain (right) sample shows extreme expansion compared to the end-grain (left).

Nevertheless, the experiments demonstrated that cross-grain samples could be welded, as long as the veneers were thin and the temperature high enough.

The thickness of the veneers also strongly influenced the completeness of a weld. Thin veneers performed better because heat penetrated more evenly though the material, uniformly bonding the welding surfaces together. In contrast, thicker veneers led to severe edge deterioration and incomplete welds. Increasing the number of layers also damamaged the weld quality, as the heat transfer became inconsistent.

Figure 4.18 Two-layered sample of 1 cm veneers shatered in press.

The manufacturing experiments showed that the excessively high temperatures and pressures had a negative influence on the weld quality. Higher temperatures improved the softening of lignin and hemicellulose, especially in cross-grain samples, but it also increased the risk of surface deterioration, pyrolysis and discoloration. Similarly, higher pressures bettered the adhesion, however it also further deteriorated the edges of the wood, causing splintering, brittle edges and excessive compression. As a result, the relationship between the temperature and the pressure of the press remained fickle.

Some measures were taken to improve the weld quality. Controlled cooling and pre-heating of the samples reduced the warping of the samples. The additional lignin showed to improve the weld quality, although its structural contribution needed to be evaluated in performance tests.

Figure 4.19 Surface treated sample with additional lignin.

Overall, the research concluded that wood can be hot pressure welded, but it is most successful with thin wood veneers, moderate pressure and temperature and the addition of lignin. It is most effective for end-grain samples, while cross-grain application remains more challenging and require further testing so it can become suitable for the larger scale.

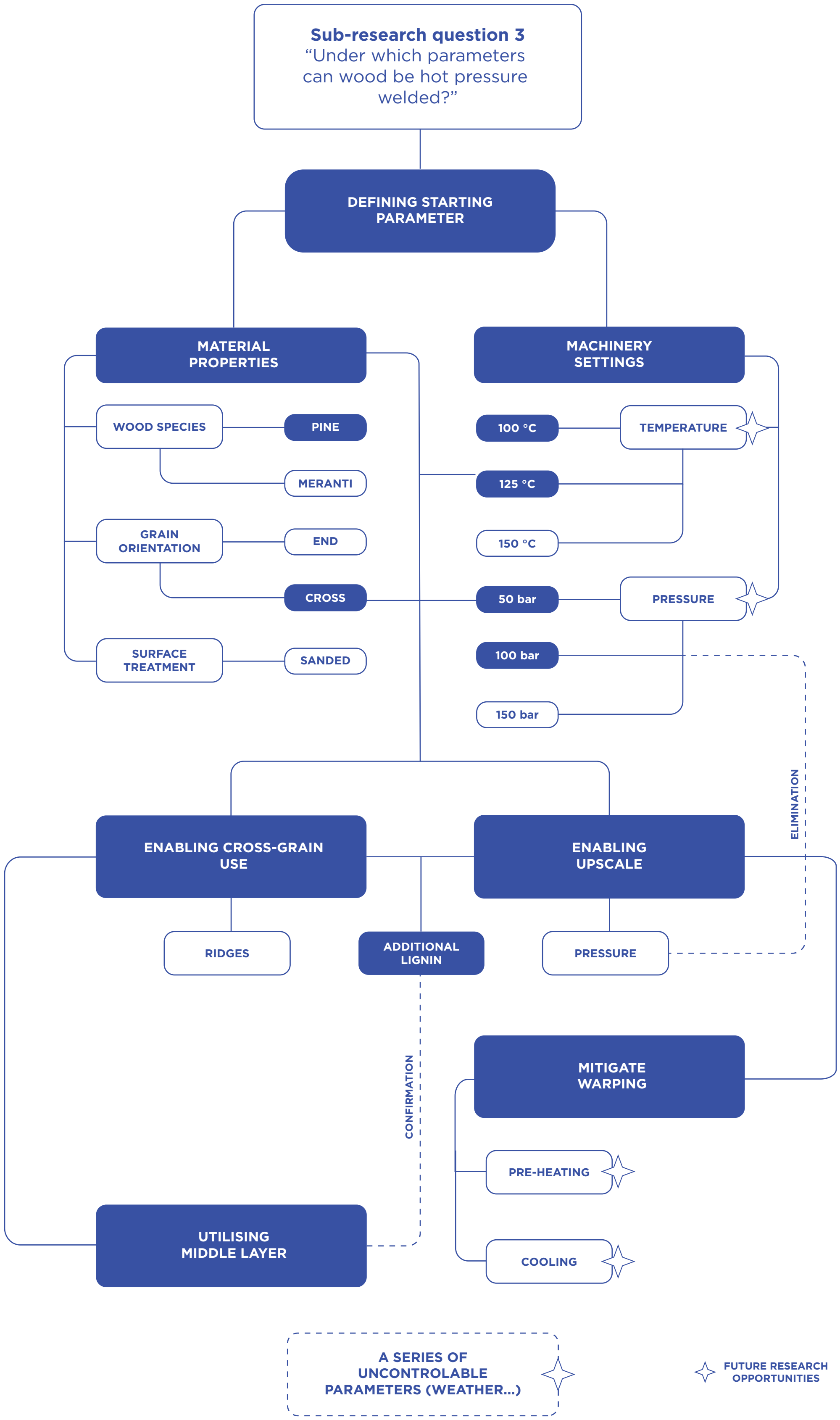


Figure 4.20 Iteration proces of the manufacturing process.

2 PERFORMANCE TESTS

After having established that wood can be hot-pressure welded and its crucial parameters for complete welds, the performance of the welds could finally be tested. As the completeness of a weld was evaluated in a qualitative manner, more quantitive research was needed.

2.1 MOISTURE TESTS

The aim of the moisture tests was to establish the moisture resistance of hot-pressure welded wood, pointing towards the potential service class, as stated in Eurocode 5 (EN 1995-1-1), and application possibilities. The tests focused on evaluating whether the welded wood samples would delaminate after repeated exposure to moisture and elevated humidity conditions over time.

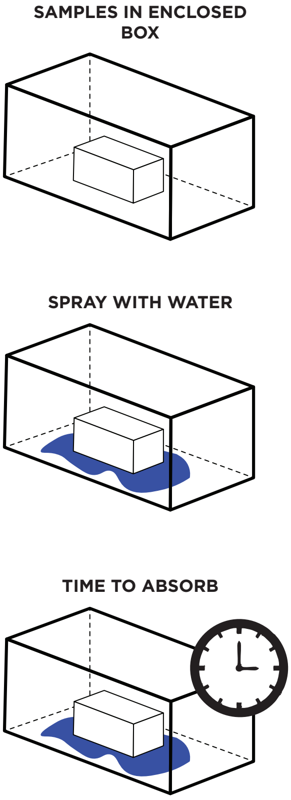


Figure 4.21 Moisture tests process.

2.1.1 EXPERIMENTAL SET-UP

The welded specimens were placed inside a closed plastic container, where water was sprayed to create a saturated humidity environment without full immersion. The samples were exposed for predefined duration of 24 hours, 72 hours and 10 days. This approach resembled the prolonged exposure to high relative humidity conditions commonly encountered in interior or semi-exterior building applications. The closed boxes with the samples were placed in a location where there was a minimal sunlight exposure to reduce temperature fluctuations, namely a living room with little windows.

To contextualize the findings within the broader research scope, comparable non-welded or glue bonded wood samples were subjected to the same conditioning protocol, allowing a relative assessment of welded wood performance.

MACHINERY AND TOOLS

This test was not conducted in a laboratory setting, requiring mostly household equipment, such as a plastic container and spray bottle. The moisture content of the wood was measured with a pin-type humidity meter.

QUALITATIVE AND QUANTATIVE ASSESMENT

The effects of moisture were evaluated in both a qualitative and quantitative manner. Firstly, the presence of delamination was observed visually, and scored from 1 to 3.

- 1: the sample showed no delamination, its whole surface remained welded.
- 2: the sample showed a moderate amount of delamination, with less than 50 percent of its surface becoming unwelded.
- 3: the sample showed complete delamination, with more than 50 percent of its surface becoming un-welded.

Additionally, the relative moisture content of the wood was measured with an electrode moisture meter. The mass of each specimen was also recorded before and after the experiment. This gave an indication in which service class the hot-pressure welded wood could be applied.

PARAMETERS

The data on the used samples is shown in Table 4.21. The tested samples consisted of benchmark glued specimens and hot-pressure welded specimens, with variations in grain orientation, machinery pressure and lignin presence to evaluate the influence of these parameters on moisture resistance, as shown in Table 4.21.

Table 4.21 Sample information moisture tests.

CONSTANT SAMPLE DATA	
Number of layers	3
Thickness of layer	4mm
Profile	143 mmx44mm
Wood species	Pine
Temperature of press	125 °C
Pressing time	15 minutes
VARIABLE SAMPLE DATA	
Grain orientation	Cross-, end-grain
Additional lignin	Yes, no
Pressure of press	50 bar, 100 bar
Welded or glued	Glued, welded

Table 4.22 shows the constant and variable parameters that were tested during the moisture tests.

Table 4.22 Parameters moisture tests.

PARAMETER	VALUE
Test duration	24 hours, 72 hours, 10 days
Amount of water sprayed at 0 hours	10 spritz per side, +- 10 ml per side

2.1.2 OBSERVATIONS

Table 4.23 (Appendix) displays that immediately after exposure, most samples showed visible delamination despite a high relative humidity, ranging from 14% to 40%. Only sample 2.2, a welded end-grain sample without lignin, displayed delamination directly after exposure.

After 24 hours, the glued samples (1.1 and 1.2) remained stable with no visible delamination, despite the relative humidity levels increasing. Similarly, the welded cross-grain samples without lignin (sample 2.1) and with lignin (sample 2.3) still showed a complete weld, with little deterioration at the edges. However, the welded end-grain sample without lignin (sample 2.2) and the double-pressed welded sample (sample 2.4) exhibited significant delamination.

At the 72 hour mark, the same tendency was observed. Samples 2.2 and 2.4 showed extreme delamination, while sample 2.1 showed the first sign of delamination. The glued samples and the lignin sample still showed complete adhesion.

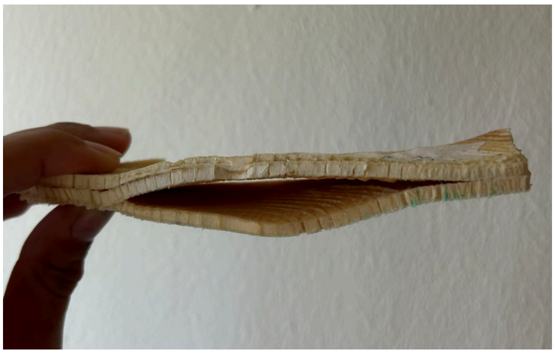
After 10 days, most samples showed the same pattern. The glued samples maintained complete adhesion, without visible delamination. The welded cross-grain sample with lignin (sample 2.3) showed its first sign of delamination, whereas the other samples continued to show major delamination. The end-grain sample (sample 2.2) showed signs of mould and extreme deterioration, as it crumbled at the edges .
When the samples were left to air dry for 24 hours, all welded samples delaminated fully, except the cross-grain sample with lignin (sample 2.3) and the glued samples.

Throughout the whole time frame of the moisture tests, it was observed that the glued samples showed the highest resistance to moisture. Among the welded samples, the cross-grain samples performed better than the end-grain samples. The addition of lignin appeared to improve the moisture resistance, while the higher amount of pressure did not improve its durability. It instead increased the chances of the samples delaminating.

Sample 1.1 and 1.2 (dry)

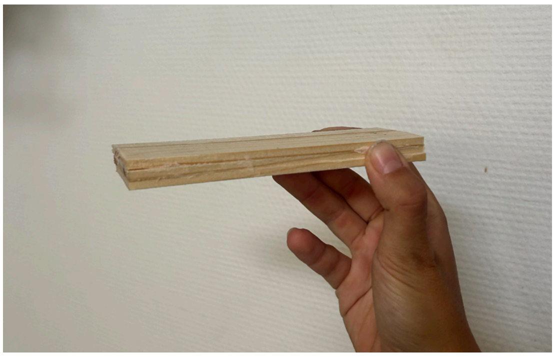
Sample 2.1, 2.2, 2.3 and 2.4 (dry)

Sample 2.1, 2.2, 2.3 and 2.4 (wet)

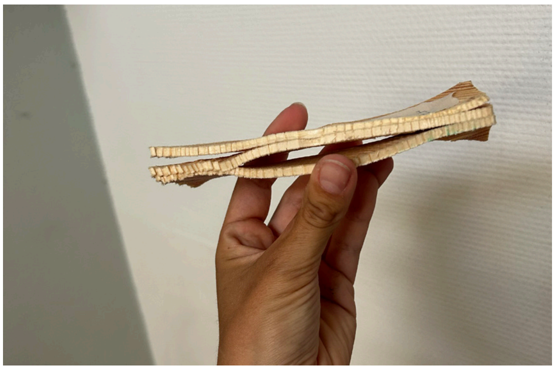


Sample 2.2 warped instantly

Figure 4.22 Samples at 0 hours.

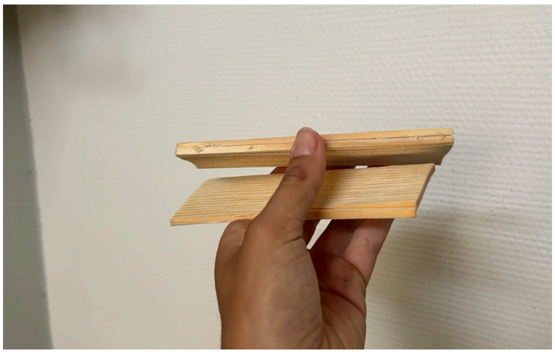


Sample 1.1



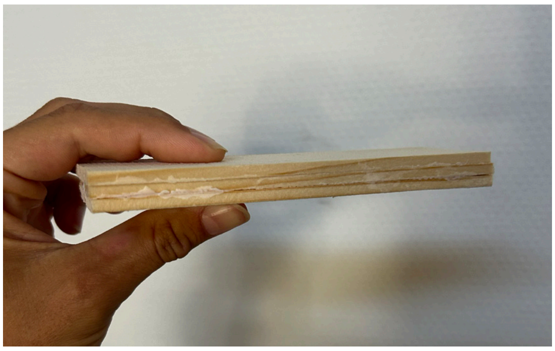
Sample 2.2

Sample 2.3

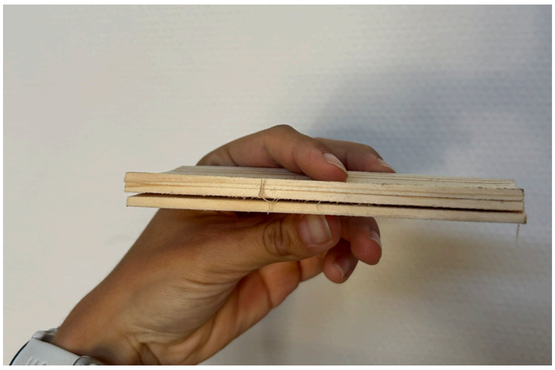


Sample 2.4

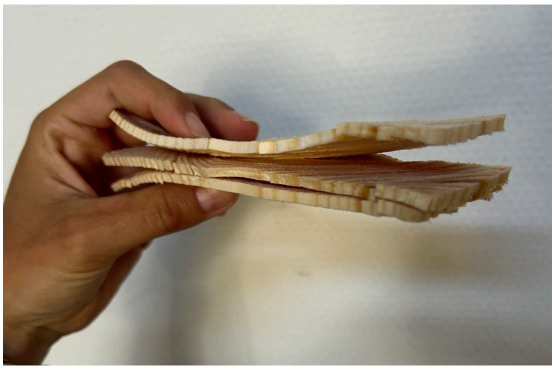
Figure 4.23 Samples at 24 hours.



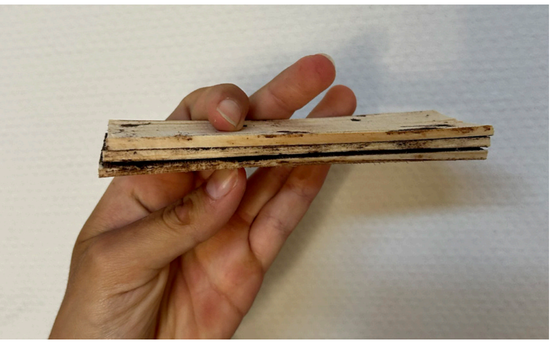
Sample 1.2



Sample 2.1

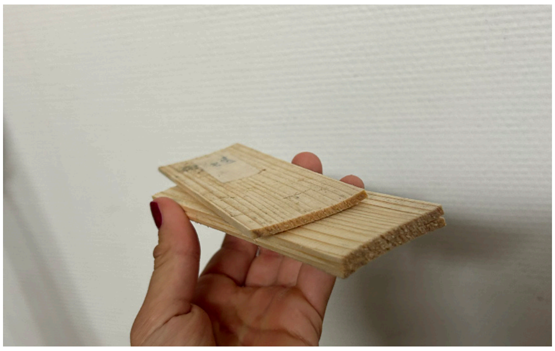


Sample 2.3



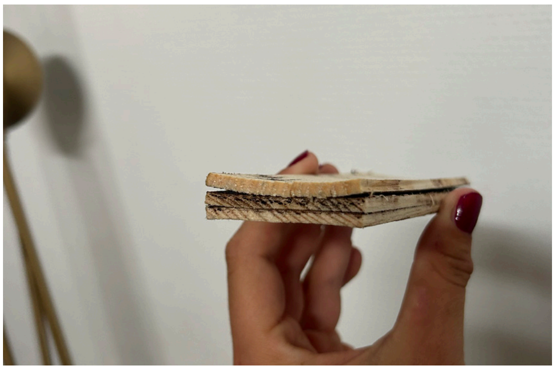
Sample 2.3

Figure 4.24 Samples at 72 hours.

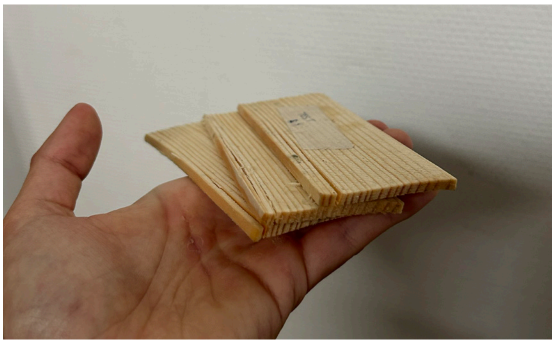


Sample 2.1

Sample 2.2



Sample 2.3



Sample 2.4

Figure 4.25 Samples after 10 days.

2.2.3 EXPLANTATIONS

The moisture resistance of the samples can mostly be related to the interaction between the humidity and cellular structure of wood. Wood is hygroscopic meaning that it absorbs moisture from its environment. This interaction is dependent on the relative humidity and temperature of the air. The moisture content of wood can cause the wood to swell, when it gains moisture or it can shrink, when it loses moisture. The changing dimensional stability can cause warping or splitting of wood or the welds between the layers (Glass & Zelinka, 2010).

The glued samples yielded more moisture resistant bonds compared to the hot-pressure welded samples. This can be contributed to the synthetic adhesives which are specifically engineers to resist moisture (Frihart, 2011; Skeist & Miron, 1990).

The end-grain sample performed worse than the cross-grain samples. Due to the anisotropic nature of wood, Glass and Zelinka (2010) noted that wood undergoes less dimensional change in the cross-grain direction, about half as much in the end-grain direction. End-grain surfaces expose the open ends of vessels and tracheid's, allowing moisture to penetrate deeper into the structure more rapidly (Sun et al., 2022; Sandberg et al., 2017). This increases swelling and internal stresses at the welded interface, contributing to delamination. Cross-grain samples, on the other hand, limit direct moisture penetration into the cell cavities and therefore showed greater resistance.

The addition of lignin appeared to improve the stability of the weld under humid conditions. Since lignin behaves as a thermoplastic polymer when heated, the additional lignin may have contributed to a denser more continuous bonding layer that resisted moisture better (Stamm, 2006).

2.2.4 LIMITATIONS

There are several limitations that affect the results of the moisture tests. Firstly, the environmental conditions were not constant. The room temperature and humidity fluctuated naturally throughout the testing period, despite the efforts to place the samples in a stable indoor location with limited sunlight exposure. These variations may have influenced the relative humidity levels within the boxes. Continuous exposure to the elevated humidity levels could lead to different degradation mechanisms and may further influence the long-term stability of welded wood joints.

Secondly, the moisture was applied using a spray bottle. This could have caused inconsistencies in the distribution and the penetration of the water. As a result, some samples may have experienced more moisture than others, potentially influencing the rate of delamination and swelling. A more controlled testing method, such as a climate chamber, would have provided more reliable and reproducible conditions.

Additionally, the duration of the tests was short compared to the larger time frame of standardised moisture tests. Moisture resistance in timber products is usually evaluated over prolonged exposure periods, including cyclic wetting and drying conditions. Therefore, the results primarily provide an indication of short-term moisture performance rather than definitive long-term durability.

Finally, it was difficult to relate the results directly to the service classes stated in the Eurocode 5, because the service classes depend on the material properties of wood rather than the connecting method of the wood layers. However, estimations could be made regarding potential applications based on the observed delamination behaviour.

2.2.5 CONCLUSIONS

The moisture tests showed that hot-pressure welded wood can maintain stable bonds under short-term humid conditions, although the performance relied heavily on the configuration of the weld. The cross-grain samples performed better than the end-grain samples, indicating that grain orientation remains a dominant parameter for the quality of the weld. The addition of lignin appeared to slightly improve the resistance to the moisture, while higher pressure did not enhance the durability and enhanced the chance of delamination.
However, the glued samples showed an overall better resistance to moisture, with little to no delamination during prolonged exposure. This highlights the benefits of using synthetic glue in EWPs, as these adhesives are specifically designed to maintain bond integrity under fluctuating moisture conditions and dimensional changes caused by swelling and shrinkage of the wood.

Future research on the moisture resistance of hot-pressure welded wood could be done in climate chambers using standardised testing method and more samples. This would provide reliable, reproducible and quantitative testing results rather than qualitative estimations, such as in this testing series.

In conclusion, at its current TLR, hot-pressure welded wood should only be used in dry environment, making it only applicable to Service Class 1.

PART 5

VALIDATION

1 ENGINEERED WOOD PRODUCTS

The results from the manufacturing and performance tests were validated by placing them in a real-life application: Engineered Wood Products. EWP's and their respective production process were defined in the theoretical framework. This theoretical knowledge was compared with the practical findings from the series of tests described in the previous chapter.

1.1 DEFINITION

The theoretical framework identified four different EWPs where hot-pressure welding could be used as an alternative bonding technique. Each of these have a different composition and performance requirements, which can be used as Key Performance Indicators. These were compared with the results from the manufacturing and the moisture tests. The mechanical performance was not taken in consideration as these were not tested.

In terms of composition, Table 5.1 and Figure 5.1 highlights that the hot-pressure welded wood could be an alternative bonding technique for plywood. Plywood is made of thin veneers (1 to 4mm thick) that are cross laminated in an uneven number of layers. This composition closely resembles the successful manufacturing results, suggesting that plywood is currently the most feasible EWP for which hot-pressure welding could be an alternative bonding system.

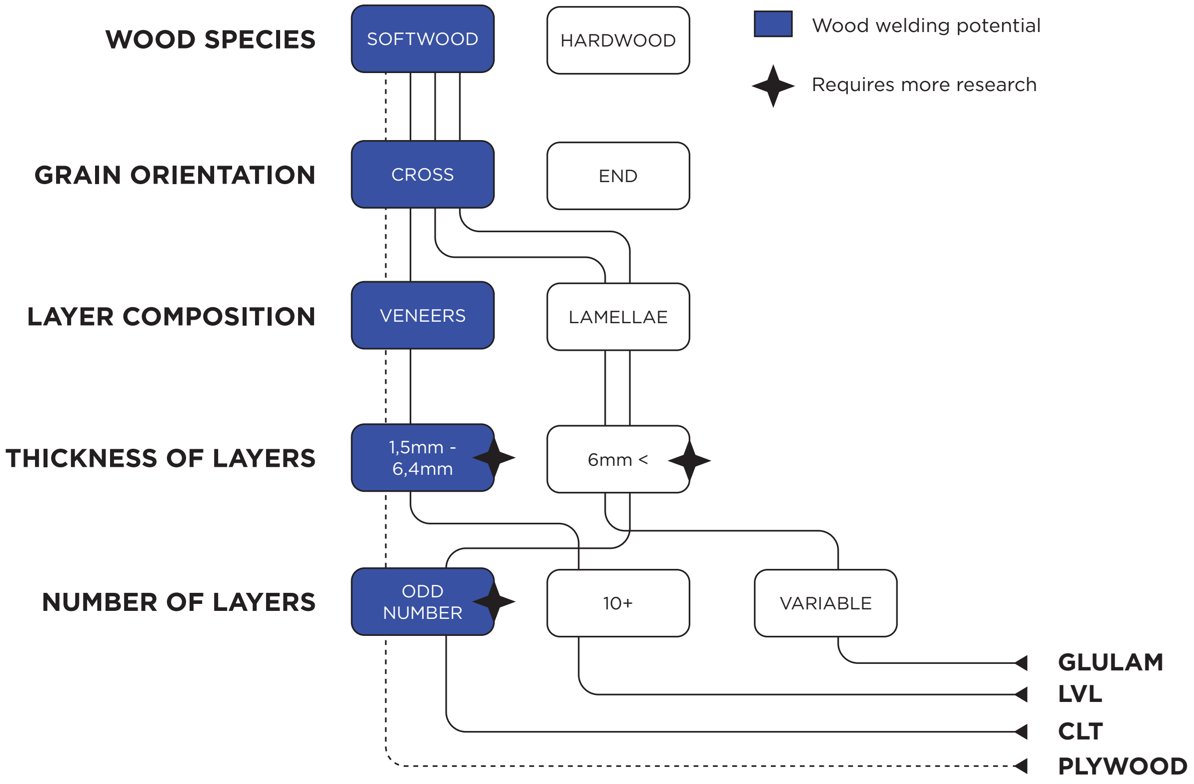


Figure 5.1 Comparisson table EWP requirements and experimental results.

In contrast, currently LVL, glulam and CLT cannot be manufactured with hot-pressure welding. Their composition is too complex for hot-pressure welding, especially at its current TRL. LVL also uses veneers, but it contains more than 10 layers, while the manufacturing tests only focussed on achieving complete welds with compositions of 3 to 5 layers. This makes the production of welded LVL uncertain at present, as its suitability has not yet been demonstrated under the tested layer configurations.

Glulam and CLT on the other hand use thick lamellae. During the manufacturing tests, the samples that went beyond a veneer thickness of 4mm were unable to achieve a complete weld. This suggests that sufficient heat penetration and material fusion cannot currently be achieved in thicker timber sections. Thus, upscaling from thin veneers to thick lamellae is currently not possible, drastically reducing the applicability of the technique.

The moisture tests pointed out that hot-pressure welded products should only be used in a dry environment, hence giving it a Service Class of 1. This limits significantly the potential applications, as many structural EWPs are required to perform under Service Class 2 or 3 conditions where fluctuating humidity and outdoor exposure are present.

Another potential application for hot-pressure weldeding is densified wood. Both processes rely on pressure and heat. In hot-pressure welding, the pressure brings the wood layers into close contact and helps create a bond, while the heat softens the lignin and hemicelluloses so it can deform and consolidate. This means the wood is not only joined, but also compacted and densified in the process, which makes densification an important part of how the welding mechanism works. Hot-pressure welding could be used for bulk densification, as multiple samples can now also be connected.

As there are no results from the bending strength tests, it is difficult to confidently point towards a realistic applications. Without having an quantitative estimations of the strength, this definition remains hypothetical.

Table 5.1 Comparisson EWP rewquirements and experimental results.

		LVL	PLYWOOD	GLULAM	CLT	HOT-PRESSURE WELDED WOOD
COMPOSITION	**WOOD SPECIES**	Softwood	Both softwood and hardwood	Mostly softwood, sometimes hardwood	Softwood	Softwood
	GRAIN ORIENTATION	Cross-grain	Cross-grain	Cross-grain	Cross-grain	Cross-grain
	CROSS LAMINATION	No	Yes	No	Yes	Not tested
	VENEERS OR LAMELLAE	Veneers	Veneers	Lamellae	Lamellae	Veneers
	NUMBER OF LAYERS	10+	Odd number (3,5,7...)	Variable	Odd number (3,5,7...)	3 and 5
	THICKNESS OF LAYERS	1,5-6,4mm	1-4mm, but 4mm is universal	6-45mm	6-45mm	0,5mm - 4mm
PERFORMANCE REQUIREMENTS	**FLEXURAL STRENGTH**	40-80 MPa	25-55 MPa	13,8-16,5 MPa	14-30 MPa	NOT TESTED
	STIFNESS	10-12 GPa	3-5,7 GPa	12-14 GPa	7-12 GPa	NOT TESTED
	SERVICE CLASS	1-2	1-3	1-3	1-3	1
APPLICATION		Beams and columns	Panels, sheathing, furniture	Beams and columns	Walls, floors and roofs	

In conclusion, based on the possible composition and moisture performance of the hot-pressure welded wood, only plywood is possible. In contrast, other engineered wood products such as LVL, glulam, and CLT appear unsuitable under the present process conditions. Their more complex and thicker compositions exceed the limits of heat penetration.

However, this conclusion should be regarded as preliminary. The absence of mechanical performance data, particularly bending strength and load-bearing capacity, means that no definitive statements can yet be made regarding structural viability or long-term performance. Further testing is needed to confirm this hypothesis.

1.2 MANUFACTURING

PROCESS

If, in the future hot-pressure welded wood could be used to manufacture plywood, LVL, glulam and CLT, it would impact their traditional manufacturing process. The preparation of the veneers and lamellae, with the debarking, cutting and veneer peeling, would remain the same. However, the drying stage would become even more crucial as a higher moisture content in wood can increase the pressure in the heat press, causing explosions.

The most drastic change occurs when the veneers and lamellae are assembled: the gluing stage is eliminated, and the pressing step is the only one that remains. Before the veneers are pressed, a layer of additional lignin could be added. The post-processing would depend on the pressing method: if panels are pressed without a framed mould, they would require trimming and sanding, whereas pressing with mould would reduce or eliminate the need for sawing the edges. This is also dependent on the final application of the EWP.

Finally, the absence of a curing and gluing step, has the potential to reduce the production time significantly although these efficiency gains remain uncertain and would depend on the pressing time for larger panels. This requires more research.

Another question to take into consideration: “are there really efficiency gains in terms of energy consumption of the heat press and time profit?”.

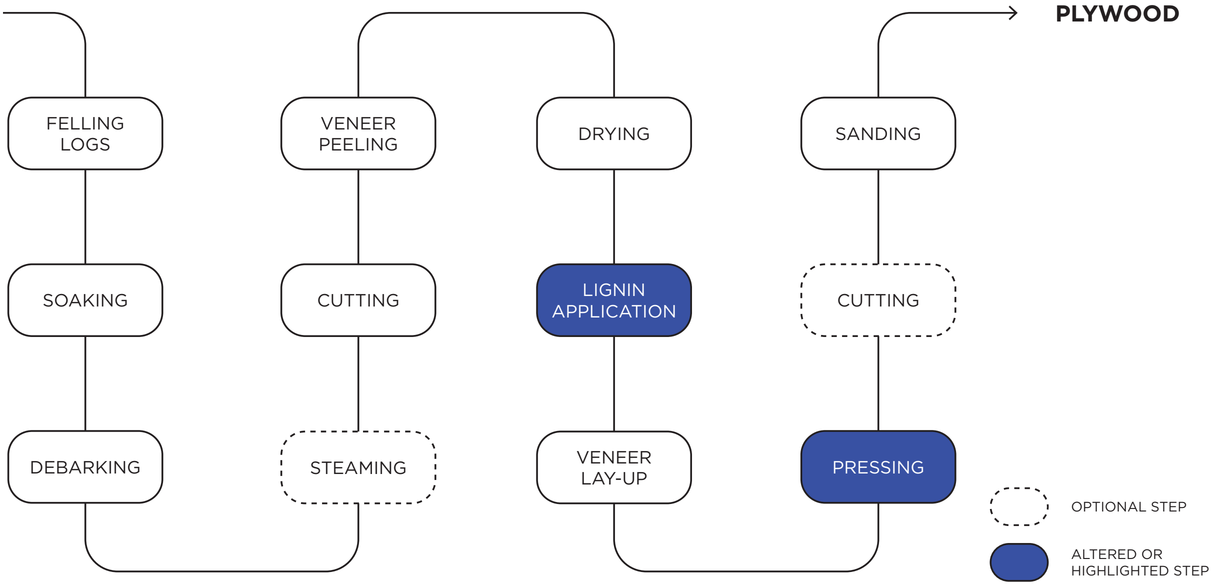


Figure 5.2. Manufacturing hot-pressure welded plywood and LVL.

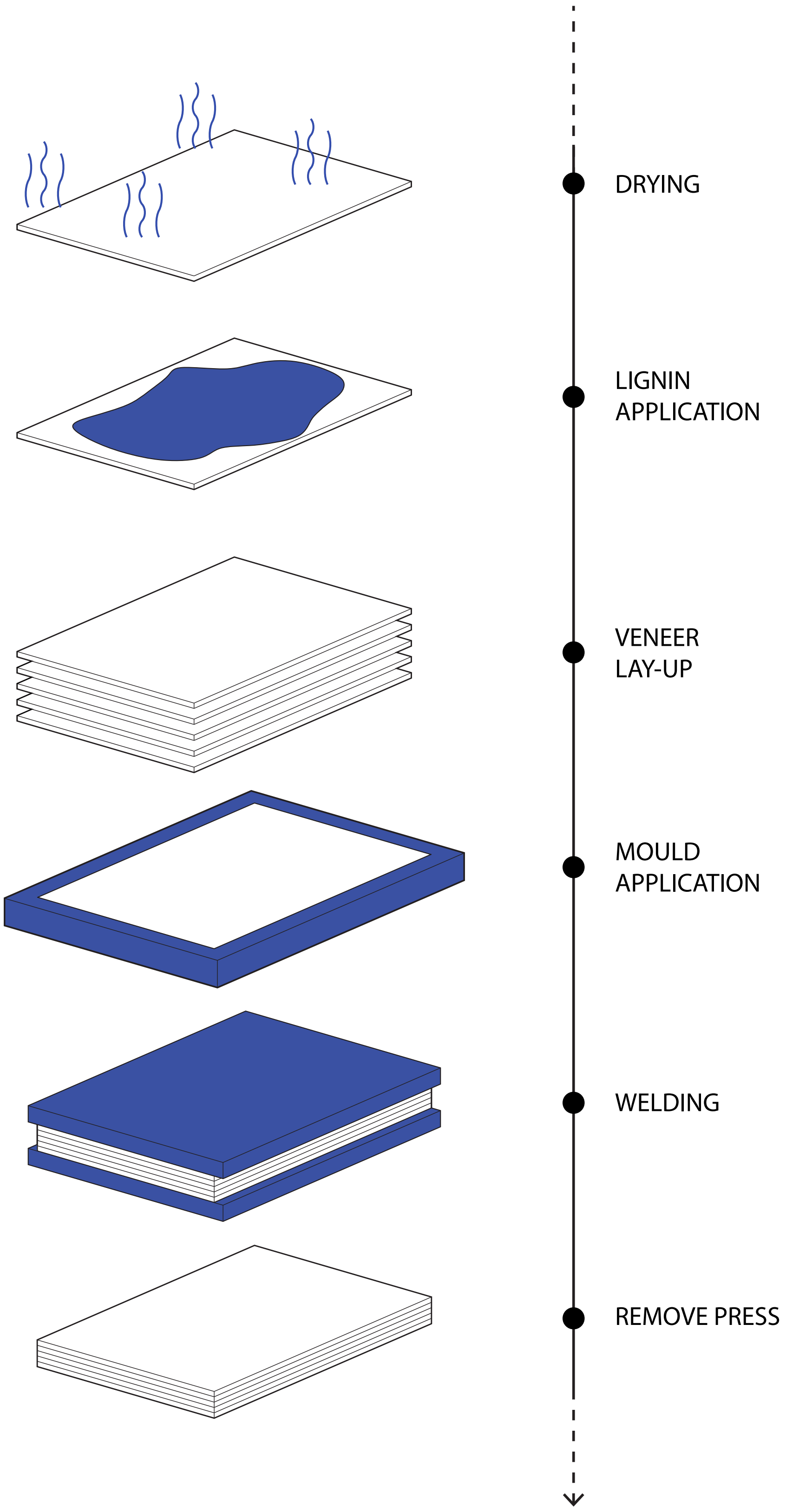


Figure 5.3 Altered steps in production process hot-pressure welded plywood.

MACHINERY

The machinery that is used to hot pressure weld veneers together is already readily available, underlining the upscaling potential of the technique. Because these industrial scaled heat presses are already standard equipment for plywood, LVL and other composite panel producers, there is no need to develop a new kind of machine.

To produce plywood and LVL, there are two different kinds of machinery that can be used to produce hot-pressure welded wood: a heat press with a dual plate and a heat press with multiple plates. The dual plate machine could be used for plywood that has less than 5 layers, as more layers would not allow heat to penetrate easily. The multiple plate machine could be used for both plywood and LVL as it heats up each layer individually.

These machines are available to buy (at Alibaba or more reputable sellers) or are already owned by manufacturers. For example, Trespa, a façade panel producer in the Netherlands, has a one of the largest heat presses in the world to produce their panels (Trespa International B.V., n.d.).

However, upscaling from thin veneers to lamellae, new machinery needs to be developed. To produce CLT and glulam, heat needs to effectively penetrate each thick lamella. This cannot be done with thin plates that remain on the surface. A new machine would introduce a heating element, before it is removed and the lamellae are pressed together, welding the surfaces of each lamella together.

Figure 5.4 Dual plate heat press. From Sublicool, n.d.

Figure 5.5 Multi plate heat press. From Alibaba.com, n.d.

1.3 CONCLUSIONS AND FUTURE STEPS

In conclusion, at its current TRL, hot-pressure welding has the potential to be used as an alternative bonding system for plywood with five or fewer layers. Hot-pressure welding has severe limitations for the thickness of veneers and number of layers, LVL, glulam and CLT are not possible, due to the heat not fully penetrating through the thickness. Due to its lacking moisture performance, hot-pressure welded wood can only be used in an indoor setting.

As there is no concrete data on the mechanical performance, it is unclear if hot-pressure welded wood can be used in a large structural applications.

The upscaling potential for plywood production is promising because there are industrial heat presses commercially available. However, applying hot-pressure welding to thicker lamellae and thus creating structural products would require the development of a new machine that is capable of heating the welding surfaces more effectively. Even though hot-pressure welding could potentially reduce the length of the production process, the energy consumption of the heat pressing should be evaluated.

To further validate the results more research is needed. This process is illustrated by Figure 5.6.

Firstly, manufacturing tests should establish whether larger panels of plywood can be manufactured, thus increasing the welding surface. This could be a Minimum Viable Product (MVP), as this could be the first profitable product that could further fund the research.

Then, the thickness of the overall panel should be increased, by adding thickness to the veneers or adding more layers. This would help determine the current limitations of heat penetration and assess whether the technique can gradually be adapted towards more advanced engineered wood products.

At the same time, life cycle assessments and energy consumption calculations should happen, to establish whether hot-pressure welding is a sustainable and viable alternative in terms of environmental impact and energy use.

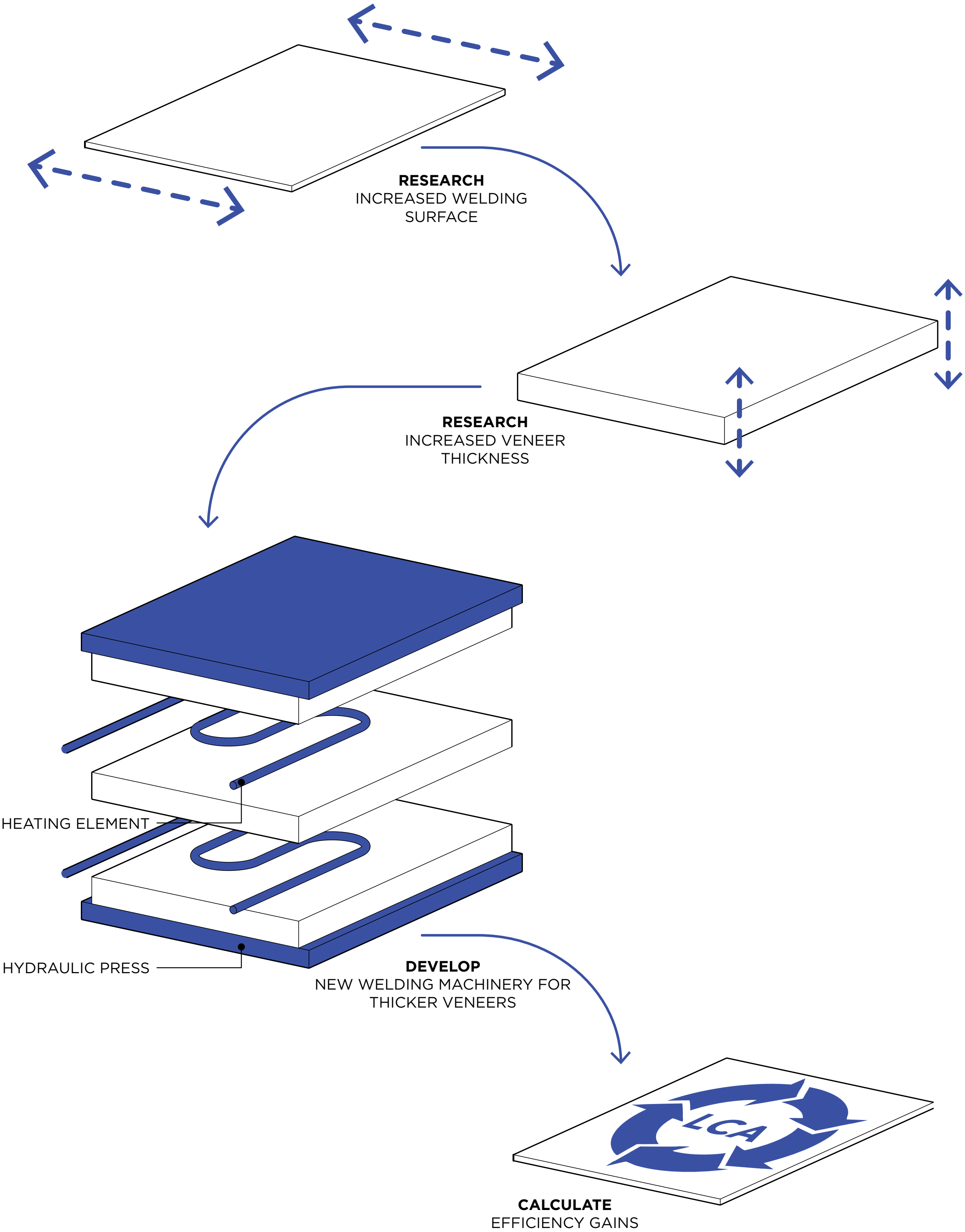


Figure 5.6 Further development of manufacturing of hot-pressure welded plywood.

2 PROOF-OF-CONCEPT

A proof-of-concept was developed to evaluate hot-pressure welding as a potential technology for bonding wood without the use of conventional adhesives, thereby increasing the Technology Readiness Level (TRL) of the process. The aim of the proof-of-concept is to see whether hot-pressure welded wood can go from laboratory experiment to a marketable product.

To investigate this, a stool and chair with its production process were designed. This was used as a case study to evaluate both the structural performance and the up-scaling potential of hot-pressure welded wood. However, the stool could not be fully manufactured. Only a small detail was manufactured within the time frame of the project, leaving the feasibility of full-scale implementation as an open question. Nevertheless, the design exploration and partial manufacturing process provided valuable insights into the opportunities and limitations of the technique when applied at product scale.

2.1 DESIGN ARGUMENTATION

The chair or stool needed to adhere to the following design requirements:

- Must be able to carry one person with average weight.
- At least the seating plate must be made from wood, the legs can be made from another material.
- Must display the characteristics of hot pressure welded wood.
- Must be limited to the dimensions of the heat press.
- Must be both functional as a piece of furniture but must also be a part of the experiments.

As the final shape of the chair is dependent of the performance tests and futher development, three different designs were developed, each highlightsing a different characteristic of hot pressure welded wood and manufacturing process.

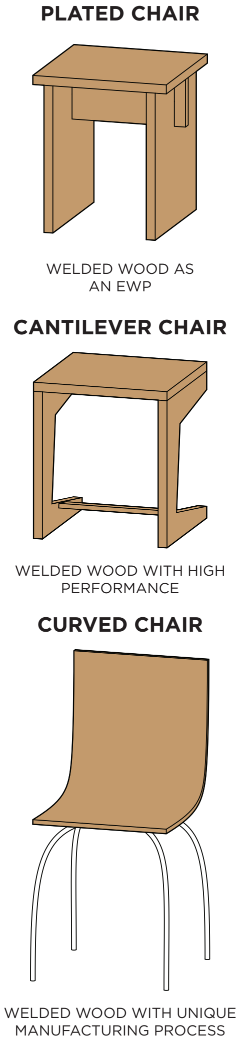


Figure 5.7 Different chair designs for proof-of-concept.

2.2 PLATED STOOL

The plated stool places wood pressure welded wood within its EWP application. It is constructed without glue or bolt and screws, highlighting hot pressure welded wood as an alternative connecting method. Its interlocking mechanism makes it a modular piece of furniture.

However, the stool is also still an object of testing both displaying the manufacturing testing and the performance testing. The orientation of the plates is loaded in two directions, perpendicular and parallel to the welds, displaying the bending strength of hot pressure welding.

This stool could be manufactured with the wood welded plywood highlighted in the previous section.

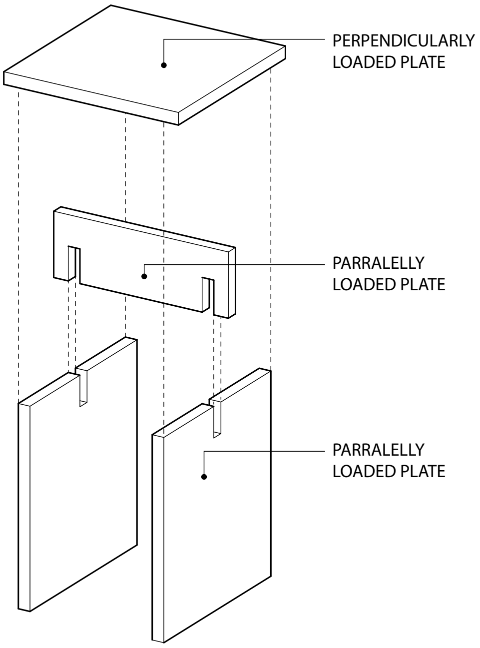


Figure 5.8 Exploded view of plated stool.

2.3 CANTILEVER STOOL

The cantilever stool highlights the mechanical performance of the hot pressure welded wood, namely its bending strength. Screws and bolts are allowed to fasten the connections within the stool. The design is centered overarching concept of resting the bending moment at the point where the seating plate meets the legs. This makes the design both a functional piece of furniture and a testing subject in terms of performance characteristics.

This stool could also be manufactured with wood welded plywood.

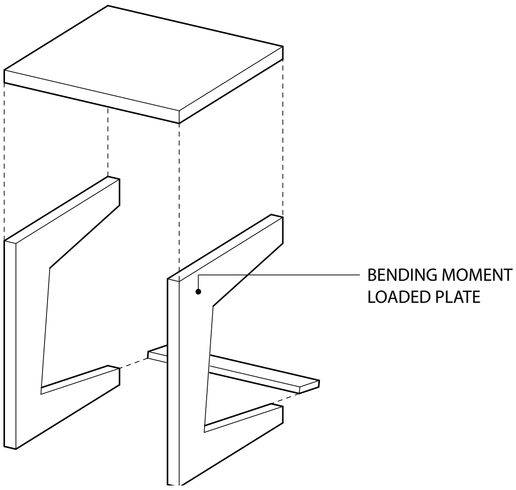


Figure 5.9 Exploded view of cantilever stool.

2.4 BENDED CHAIR

The chair design is inspired by the curved furniture pieces that were popularized during the 20th century by designers such as Alvar Aalto, Arne Jacobsen, Charles Eames and Ray Eames. The bended chair highlights the unique production process of hot-pressure welded wood.

In the 1930's, Alvar Aalto was the first to commercialize the 'L-leg' where pieces of plywood are curved to form the leg of a stool. These were manufactured by sawing slits height wise in pieces of solid wood, allowing the wood to bent to the angle. Then these slits were filled with sheets of veneer and glue. Aalto diverged from the traditional bulky furniture that was typical of the era, pushing the furniture industry away from solid wood and towards plywood (Buur, 2020; Parsons, 2022). This process heavily relies on synthethic adhesives.

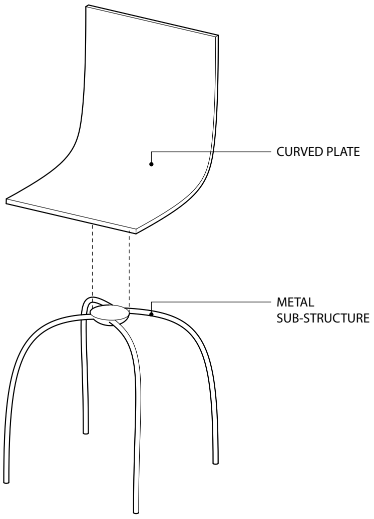


Figure 5.10 Exploded view of curved chair.

As illustrated by Figure 5.12, to produce the bended plate, the thin veneers (>1mm thickness) need to be cut and coated in additional lignin. Then they are placed on a curved would that is heated. Finally these veneers are pressed together, and the curve is achieved.

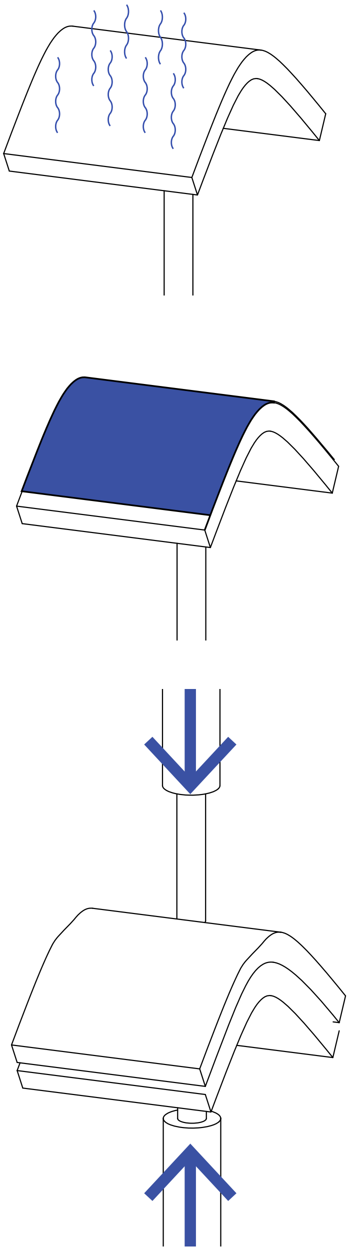
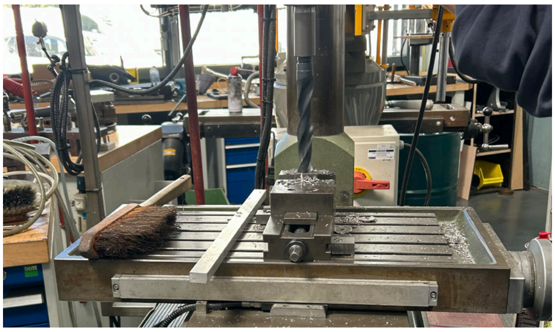


Figure 5.11 Production process of curved geometries.

To show that it is possible to achieve this curved geometry with welded wood, a detail of the curve was produced. A steel mould had to be manufactured. This was done in the metal workshop of the faculty of Mechanical Engineering of the TU Delft, with the help of my crewmate, Isa Zondag.

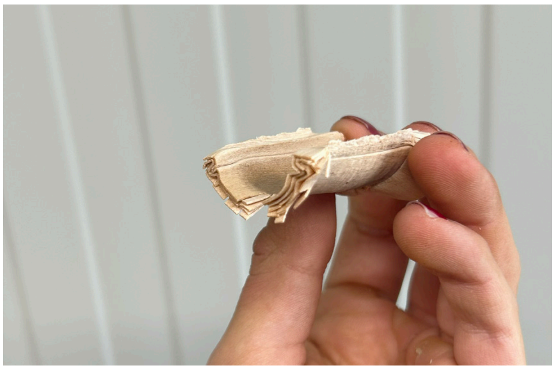
To create the bottom section of the mould, a steel beam with a profile of 30mm by 30mm was first cut into a cube. Then a hole was drilled with a 26mm auger bit, before the cube was cut in half, so a half circle shaped mould was manufactured. The top section of the mould was made of a round steel rod with a diameter of 20mm. This needed to be cut in half to achieve a half circle section, however this could not be done in the metal saw, as the rod would roll of the table. So the top part of the rod was milled of in a milling machine, where it could be secured in between some clams and metal pieces. With both the top and bottom section of the mould, the detail could be produced. These were pre-heated in the heat press untill they achieved a temperature of 125 degrees. Then five thin birch veneers were placed inside the mould and it was pressed together. Two mdf plates werre placed between the mould and the press to avoid damaging it. After the first run, the MDF plates were melded to the mould, thus a second experiment with lignin could not be performed.

The final achieved sample was deemed succesful as a complete weld was achiieved. However, the sample remained brittle, as it broke after being handled. More research and more samples would be needed to fully understand the strength of these bent geometries.



Drilling of bottom mould.

Mould after taken out heat press.



Finished detail

Figure 5.12 Manufacturing of curved sample and its mould.

3 DEVELOPMENT STRATEGY

The previous sections tried to validate hot-pressure welding as an alternative to synthetic adhesive in EWPs, however, due to time and resource constraint, the validation was not successful. A development strategy is needed to direct future research and design, and to formulate a complete answer to the main research question.

This strategy is depicted by Figure 5.13. The development starts with the current knowledge of hot-pressure welded wood. Firstly, larger specimens need to be made with complete welds with the parameters which are currently identified as succesful. If this fails, these parameters need to be reformulated.

Mechanical testing can finally be undertaken with the right machinery and larger samples. This will help to finally establish whether hot-pressure welding can be an alternative for synthetic adhesives, but only when it has a comparable mechanical strength. Otherwise, testing should be terminated.

To place the results within its problem context and, scientific-societal relevance, it is crucial to conduct more performance tests. Firstly, the emissions of VOC during the manufacturing process needs to be evaluated. High temperatures are applied to the wood, which can also release volatile compounds due to the thermal degradation of lignin and hemicellulose. Secondly, the envirnomental impact of welded wood is unclear, so an Life Cycle Assesment (LCA) needs to performed.

Additionally, the technique goes from technical feasability to industrial readiness by developing the right machinery and manufacturing the MVP and proof-of-concept. These two are the milestones in the strategy, which ground the development to practise rather than theory.

In conclusion, if it was possible to have unlimited funds and time, it would be possible to further develop hot-pressure welded wood and push it towards a higher TLR. However, everything depends on the succesfull outcomes of the experiments. It is not realistic to pursue the technique when the results are not adequate.

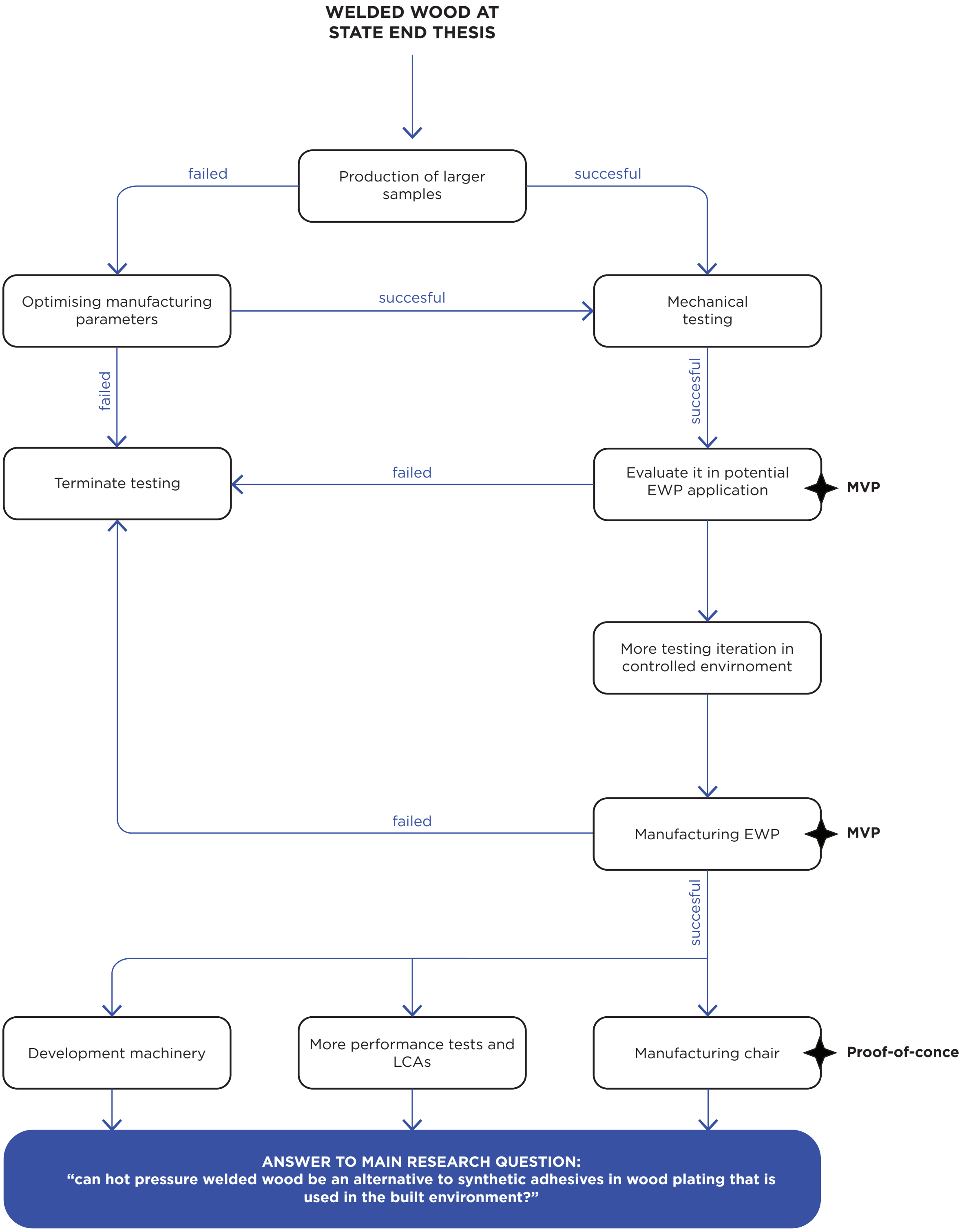


Figure 5.13 Development Strategy.

PART 6

CONCLUSIONS

1 LIMITATIONS AND RECOMMENDATIONS

This thesis explored hot-pressure welding as a potential alternative to synthetic adhesive in EWPs. The research and design were exploratory in nature and therefore the research and design process contains a series of limitations.

Firstly, the hot-pressure welding process is still not fully understood as the whole impact of each parameter is not fully known yet. More testing iterations are need, so that the relation between the pressure, temperature, surface treatment, heating and sample profile can be better understood. With this the scientific vigour can be improved as the results become reproducible and reliable.

A second limitation is that most samples with complete welds required additional lignin, which raises the question whether the process should be interpreted as the use of a bio-based adhesive in a heat pressing set-up rather than hot-pressure welding. This distinction matters because the observed weld performance may partly result from the added lignin acting as a bonding agent, instead of being produced solely by wood-to-wood welding phenomena. As a result, the conclusions about the technique should be treated with caution, since the contribution of true hot-pressure welding may be less dominant than initially assumed. More extensive microscopic research is needed to further validate the results.

Thirdly, several proposed explanations are grounded in literature but remain assumptions. Although the cited sources helped to interpret the results, the actual bonding mechanisms are not directly verified through chemical or microscopic analysis. Therefore, the explanations can suggest possible mechanisms, but it cannot fully confirm them. This means that the results should be viewed as an indication rather than a definitive answer.

In essence, hot-pressure welding behaves as thermally densified wood, however, rather than it solidifying one piece of wood, it presses multiple layers together. This layered structure means that the bond performance may depend not only on the material itself, but also on the quality of contact, pressure distribution, and consolidation between layers. As a result, the interpretation of the material behaviour is more complex than for a single, continuous wood piece, such as traditional densified wood.

Literature also pointed out that moisture can drastically lower the glass transition temperature of lignin and hemicellulose. This decrease would be beneficial to avoid discolouration on the welding surface and further deterioration of the wood matrix. However, the BIO SheetPress 70 44T from the Green Village does not allow the pressing of materials with a high moisture content, as this can lead to vapour formation in the layers, which increases the pressure and can cause an explosion. This constrained the experiments to dry wood. It limited the understanding of how moisture could potentially improve the completeness of a weld.

Furthermore, no mechanical testing took place due to time constraints. This obstructed the validation of hot-pressure welded wood, as it was not possible to establish if hot-pressure welded wood can even carry a load. More extensive mechanical testing is needed to evaluate structural reliability, long-term performance, creep behaviour, moisture resistance, and durability under realistic environmental conditions. In addition, when placed within its problem context, this thesis leaves a series of unanswered questions.

The environmental impact is still uncertain. Even though it could potentially remove synthetic adhesives, the manufacturing process requires a lot of heat and pressure. Thus, the environmental benefits gained from eliminating synthetic adhesives may partially be offset by the increased energy demand associated with the welding process. Especially when the wood has to be dried before welding an EWP, the long heating cycles could become highly energy intensive when scaled up industrially. So, the sustainability benefits of hot-pressure welding cannot yet be fully validated without a complete life cycle assessment.

Addtionally, hot-pressure welded wood is highly compressed. A relatively large volume of wood is required to produce a comparatively thin final product, creating uncertainty regarding whether the technique truly uses wood resources efficiently, especially when compared to conventional engineered wood products. Furthermore, this issue is directly related to the final mechanical performance of the welded material. If the structural strength and durability of the compressed product do not significantly outperform existing solutions, it becomes difficult to justify the amount of material and energy required to manufacture it.

It also remains uncertain to what extent hot-pressure welding improves the indoor environment of a building. One of the main motivations of this thesis was to reduce the harmful effects of synthetic adhesives, such as VOC and formaldehyde emissions, which negatively affect occupant health and contribute to the “sick building syndrome.” Removing adhesives could therefore improve indoor air quality and simplify the material composition of EWPs, potentially improving recyclability and circularity. However, this benefit must be considered critically. During the welding process, high temperatures are applied to the wood, which can also release volatile compounds due to the thermal degradation of lignin and hemicellulose. As a result, it remains unclear whether hot-pressure welded wood fully eliminates harmful emissions or merely shifts them to another stage of the process.

Finally, the research mainly demonstrates a technical feasibility rather than a industrial readiness. Hot-pressure welding remains at a low TLR, with a lot of assumptions made about scalability, structural performance, processes and economic viability. Like friction and ultrasonic welding, the technique still faces challenges related to upscaling, moisture sensitivity, and process consistency. The proposed implementation strategy therefore mainly functions as a future research direction rather than a directly applicable industrial solution.

From a broader societal perspective, the thesis contributes to ongoing discussions about healthier and sustainable materials. The project explores the possibility to reduce the reliance on synthetic adhesives and improves the circularity of timber construction.

However, the societal impact remains uncertain at this stage because the technique has yet to be validated at a an architectural and industrials cale. So, the research contributes more to the exploration of potential future possibilities within sustainable construction rather than providing a fully deployable solution for the built environment today.

2 CONCLUSION

This thesis examined whether hot-pressure welded wood could be a viable alternative to synthetic adhesive in Engineered Wood Products for use in the built environment. Based on the theoretical framework, experiments and validation, the research questions can be answered.

The hot-pressure welding of wood refers to a bonding technique where heat and pressure join two or more veneers of wood without using synthetic adhesives. The process relies on heating the wood to the glass transition temperature of lignin and hemicelluloses, which results in a bond formed through densification. It is possible within a wide set of parameters such as pressure, temperature, veneer thickness, grain orientation and surface treatment. Among these, thin pine veneers with additional lignin were found to have more complete welds.

In terms of performance, the welded samples demonstrated that they were very sensitive to moisture, irrespective of their wood grain orientation, thickness or densification. Compared to the glued samples, only those with additional lignin showed no extreme delamination. This limits the applications of hot-pressure wood to a controlled indoor environment.

Based on these results, hot-pressure welded wood is currently not sufficiently reliable to replace or be an alternative synthetic adhesive in Wood Engineered Products within the built environment. EWPs are required to meet strict performance criteria including mechanical strength, moisture resistance and structural reliability. These criteria are not fulfilled by the hot pressure welded wood, however with the development strategy that requires more research, the manufacturing of the proof-of-concept and the development of the welded plywood as an MVP, it is possible to push hot-pressure welded towards becoming a viable alternative for synthetic adhesives.

In conclusion, the thesis established hot-pressure welding as a third wood welding technique but ultimately it still suffers from the same problems as the other two techniques: difficulty to upscale due to a lacking moisture resistance and a limited veneer thickness. The technique is still at an exploratory stage. Although the principle has been validated experimentally, significant further development is required before it can function as a practical and scalable alternative to synthetic adhesives in Engineered Wood Products.

3 REFLECTION

My thesis explored the intersection of material innovation and architectural design by testing whether this new bonding technique could become a sustainable application represented by a proof-of-concept, a chair, and minimum viable product, hot-pressure welded plywood.

At the start of the project my research process appeared clear and structured. By using the framework of TRLs, it became possible to position the technique within an early research stage and define the steps needed to move it toward higher technical viability. The process was supposed to be iterative: first establishing a theoretical framework, then performing manufacturing and performance experiments, after which the results would be analysed and compared to literature in order to define the next experimental steps. In theory, this created a structured feedback loop between research, experimentation and design.

In reality, however, the process was far less controlled and iterative than expected. Much of the project became focused on trying to achieve complete welds that would not delaminate immediately and to guarantee the integrity of the surface. In addition, the performance tests were done a late state of the thesis process. The parameters of the manufacturing process could not be changed based on the performance results, to improve the overall performance. Ideally, the mechanical results would have informed new iterations of the manufacturing process, creating a stronger feedback loop between fabrication and evaluation. However, due to time limitations and the delayed testing phase, this iterative process remained incomplete.

As the research process was not truly iterative, much time was spent preparing manufacturing tests and trying to achieve complete welds, instead of optimising the technique by testing parameters individually. If there would have been more time,

Instead of continuously moving between reading, testing, improving and refining, the research process slowed down significantly due to the practical constraints. The availability of the heat press strongly dictated the pace of the project, forcing the research to move into a more linear process rather than the iterative which was initially anticipated. This highlighted the difference between the ideal academic framework proposed at the beginning of the thesis and the unpredictable nature of experimental material research in practice.

The main strength of the project was its exploratory foundation. The thesis pushed me to conduct material research with little to no prior knowledge. Existing literature on friction welding, densified wood, and engineered wood products provided a theoretical basis, but hot-pressure welding of wood remained largely unexplored. This created opportunities to contribute something genuinely new to the discussion surrounding adhesive-free wood bonding techniques. The research also demonstrated the value of combining architectural thinking with material experimentation. Design was not only used to represent results, but also to test the practical implications of the material behaviour.

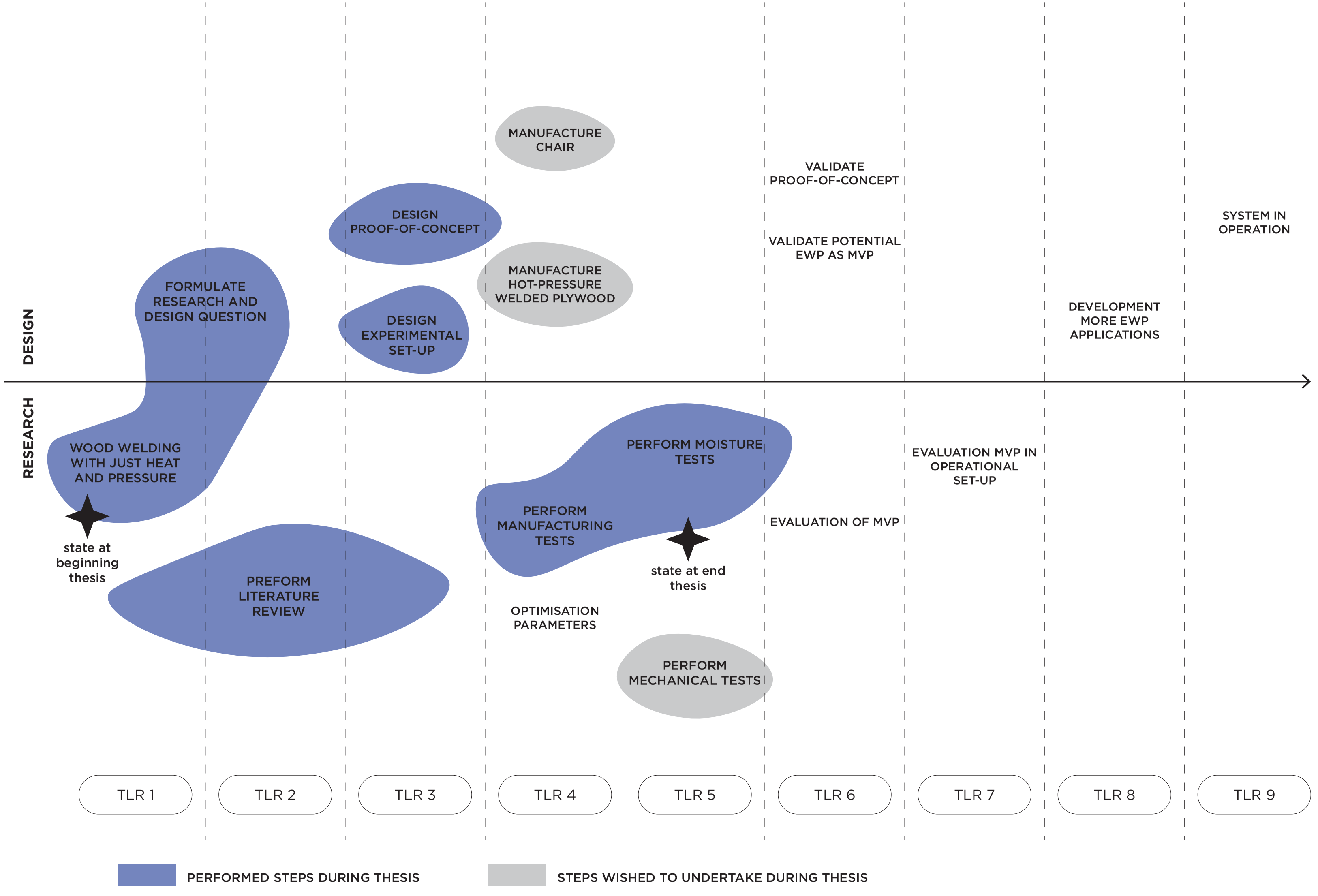
At the same time, the project revealed several weaknesses. These are mostly related to the time constraint. Figure 6.1 displays the design and research steps that could be undertaken to push hot-pressure welded wood to a higher TRL. Even though, the thesis checked the requirements of an achieved TRL of 5, there are still a few questions from the previous levels that remain unclear.

The limited access to machinery and the inconsistency of the samples reduced the possibility for systematic experimentation. Additionally, an important aspect of the research remained incomplete: the mechanical bending tests were either too limited or could not be fully carried out in a scientifically rigorous manner. As a result, an essential part of validating the structural performance of the material remained missing from the thesis.

The project also confronted me with the fact that designing can mean very different things within my graduation process. Initially, the architectural ambition of the project was strongly focused on designing the chair as a final object. However, as the research progressed, it became increasingly clear that directly designing with the material was unrealistic because the bonding technique itself remained unstable and underdeveloped. This was personally frustrating, as the project slowly shifted away from architecture toward experimental material research. At the same time, this shift also taught me that design does not always need to result in a finished building or object. In this thesis, design became a tool to frame research questions and explore future applications rather than only producing a final aesthetic outcome.

To me, the relationship between research and design became much more fluid than expected. Instead

Figure 6.1 Current and future research-design in relation with the TRLs.



of design following research, both continuously influenced one another. The experiments affected the feasibility of the chair, while the desire to create an architectural application influenced which material properties became important to investigate. This relationship reflects the broader approach of the graduation studio, where research and design are not separated but used together to explore emerging questions in architecture and building technology.

The process also raised several conceptual and ethical questions. One important dilemma concerned the sustainability claims surrounding the technique. Although the thesis aimed to replace synthetic adhesives and improve the environmental performance of engineered wood products, it became clear that the process itself required large amounts of heat, drying and pressure. This complicated the initial assumption that adhesive-free automatically means more sustainable. Additionally, questions emerged regarding whether the term “wood welding” is fully appropriate for the technique, since the process differs significantly from traditional friction and ultrasonic welding and may rely more heavily on densification and thermal compression mechanisms. The potential future addition of lignin or other bio-based additives also complicated the original ambition of creating a completely adhesive-free material.
Overall, the graduation process taught me that experimental research rarely develops in a straight line. Instead, it constantly shifts between success, failure, adaptation and uncertainty.

Although the thesis did not fully achieve the original ambition of creating a structurally reliable hot-pressure welded plywood application, it succeeded in establishing the basic feasibility of hot-pressure welding as a third wood welding technique and opened up new directions for future research. More importantly, the project fundamentally changed my understanding of research, design and architecture by showing how material experimentation itself can become a valid architectural exploration.

PART 7

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PART 8

APPENDIX

Table 4.6 Results manufacturing experiments on material properties.

	COMPOSITION AND MATERIAL PROPERTIES					OBSERVATION		
	WOOD SPECIES	GRAIN ORIENTATION	SURFACE TREATEMENT	THICKNESS	NUMBER OF LAYERS	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORA-TION (1 TO 3)
1.1	Meranti	End-grain	Sanded (left), unsanded (right)	3mm	3	4mm	3	1
	Pine						3	1
1.2	Meranti	End-grain	Sanded (left), unsanded (right)	3mm	3	4mm	3	2
	Pine						3	2
1.3	Meranti	End-grain	Sanded (left), unsanded (right)	6mm	3	5mm	3	2
	Pine						3	2
1.4	Meranti	End-grain	Sanded (left), unsanded (right)	10mm	3	4mm	2	2
	Pine						3	3
1.5	Meranti	Cross-grain	Sanded (left), unsanded (right)	3mm	3	5mm	2	1
	Pine						3	1
1.6	Meranti	Cross-grain	Sanded (left), unsanded (right)	6mm	3	5mm	1	2
	Pine						2	2
1.7	Meranti	Cross-grain	Sanded (left), unsanded (right)	10mm	2	10mm	1	2
	Pine						1	2
1.8	Meranti	Cross-grain	Sanded (left), unsanded (right)	1mm	5	2,5mm	3	1

Table 4.9 Results manufacturing experiments on machinery settings.

	COMPOSITION AND MATERIAL PROPERTIES	MACHINERY SETTINGS			OBSERVATION		
	GRAIN ORIENTATION	TEMPERATURE	PRESSURE HYDRAULIC SYSTEM	INDIVIDUAL PRESSURE ON VENEER	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORATION (1 TO 3)
2.1	End-grain	100 °C	50 bar	1461 bar	6mm	3	1
2.2	End-grain	100 °C	100 bar	29220 bar	3mm	3	2
2.3	End-grain	100 °C	150 bar	43830 bar	3mm	3	3
2.4	End-grain	125 °C	50 bar	1461 bar	4mm	3	2
	Cross-grain					2	1
2.5	End-grain	125 °C	100 bar	29220 bar	4mm	3	2
	Cross-grain					2	3
2.6	End-grain	150 °C	50 bar	1461 bar	4mm	3	2
	Cross-grain					3	1
2.7	End-grain	150 °C	100 bar	29220 bar	4mm	3	3
	Cross-grain					3	3

Table 4.12 Results manufacturing experiments on cross-grain orientation.

	COMPOSITION AND MATERIAL PROPERTIES				OBSERVATION		
	THICKNESS OF LAYERS	AMOUNT OF LAYERS	ADDITIONAL LIGNIN	RIDGES	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORATION (1 TO 3)
3.1	4mm	3	No	Yes	4mm	3	3
				No		2	3
3.2	4mm	3	Yes	No	4mm	3	3
			No			3	3
3.3	10mm	3	No	Yes	4mm	1	3
				No		1	3
3.4	10mm	2	Yes	No	4mm	2	3
			No			2	3

Table 4.15 Results manufacturing experiments on upscaling.

	COMPOSITION AND MATERIAL PROPERTIES		MACHINERY SETTINGS		OBSERVATION		
	GRAIN ORIENTATION	ADDITIONAL LIGNIN	PRESSURE HYDRAULIC SYSTEM	INDIVIDUAL PRESSURE ON VENEER	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORATION (1 TO 3)
4.1	Cross-grain	No	50 bar	2860 bar	5mm	2	2
4.2	End-grain	No	50 bar	2860 bar	4mm	3	2
4.3	Cross-grain	Yes	50 bar	2860 bar	5mm	2	1
4.4	Cross-grain	No	100 bar	5721 bar	5mm	2	2

Table 4.17 Results manufacturing experiments on pre-heating and controlled cooling.

	PROCESS		OBSERVATION		
	PRE-HEATING TIME	COOLING TIME	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORATION (1 TO 3)
6.1	15 minutes	0 minutes	4mm	1	2
6.2	0 minutes	15 minutes	4mm	3	2
6.3	15 minutes	15 minutes	4mm	3	2

Table 4.20 Results manufacturing experiments on pre-heating and controlled cooling.

	COMPOSITION AND MATERIAL PROPERTIES		OBSERVATION		
	THICKNESS OF LAYERS	ADDITIONAL LIGNIN	THICKNESS	COMPLETE WELD (1 TO 3)	DETERIORATION (1 TO 3)
7.1	4mm, with 0,5mm middle layer	No	5mm	1	2
7.2	4mm, with 0,5mm middle layer	Yes	5mm	2	2
7.3	4mm, with 0,5mm middle layer	No	5mm	1	2

Table 4.23 Results moisture performance tests.

	COMPOSITION AND MATERIAL PROPERTIES			HOUR 0: APRIL 29		HOUR 0: APRIL 29		HOUR 24: APRIL 30		HOUR 72: MAY 1		DAY 10: MAY 8	
	ADHESION	GRAIN ORIENTATION	ADDITIONAL LIGNIN	RELATIVE HUMIDITY	DELAMINATION	RELATIVE HUMIDITY	DELAMINATION	RELATIVE HUMIDITY	DELAMINATION	RELATIVE HUMIDITY	DELAMINATION	RELATIVE HUMIDITY	DELAMINATION
1.1	Glued	Cross-grain	No	0%	1	17,5%	1	14,1%	1	21,90%	1	23,90%	1
1.2	Glued	End-grain	No	0%	1	40%	1	43,80%	1	26,80%	1	25,80%	1
2.1	Welded	Cross-grain	No	0%	1	16,8%	1	14,10%	2	16,20%	2	17,90%	3
2.2	Welded	End-grain	No	0%	1	30%	3	14,50%	3	17,50%	3	17,50%	3
2.3	Welded	Cross-grain	Yes	0%	1	14,6%	1	13,80%	2	14,60%	2	14,40%	2
2.4	Welded (double pressure	Cross-grain	No	0%	1	14,4%	1	13,80%	3	16,60%	3	17,90%	3