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Designing Guidelines for Moisture-Responsive Wood Veneer

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Preface

Dear reader,

This thesis presents my graduation project and marks the end of my studies at Industrial Design Engineering.

As a designer, I mostly enjoy working hands-on. Experimenting, testing and learning through doing. I wanted to bring this approach into my graduation project as much as possible.

Material design has always intrigued me, especially exploring possibilities of material in new and novel ways. Research on responsive wood veneer caught my interest. Wood is a material that has been used for centuries to build and design with. However, it is still possible to find new ways to work with it.

Choosing this direction for my graduation project was both very interesting and challenging. As a design student, material research was not something I had much experience with. Although a lack of knowledge in this area made certain aspects of this project challenging, it also created many opportunities to learn.

I hope the result of this project, the design guidelines, can support some of you with your design projects. And maybe inspire you to explore and design with the responsive wood veneer material.

Ruby

Acknowledgements

This project would not have been possible without the guidance and support of so many people.

First of all, thank you to my supervisors, Sepideh Ghodrat and Freerk Wilbers, for all your help and support. Meeting with me almost every week and providing me with so many opportunities to bring this project to a higher level. I am truly grateful to have had the chance to work with both of you and learn from you.

Sepideh, thank you for your encouragement and endless enthusiasm for this project. For spending so much time with me reviewing my work in detail and being available to answer all of my questions. I aspire to have as much joy in dedication in my future work as you do.

Freerk, thank you for all your creative ideas and challenging me to explore directions I would never have considered on my own. For continuously reminding me to step back and look at the bigger picture and for all your thoughtful feedback and excitement about this project.

Thank you to everyone from the Materials Lab for helping me with anything I needed during this project. Special thanks to Tim for your endless patience. Spending hours fixing equipment for me to use and brainstorming with me on ideas for testing methods.

I also want to thank my other graduating friends. Working with you almost every single day and being able to share our struggles and successes made these last few months so much easier and more fun.

Finally, thank you to the best family and friends I could wish for. For always being there for me and supporting me through everything that I do.

Abstract

Wood is a material that displays a natural curvature response to its interaction with moisture. In design and building practices this behaviour is usually minimized. However in the form of wood veneer it can be used to create a responsive material system. Existing research on wood veneer is often application-specific, where only the findings relevant to the research outcome are documented. As a result, there is a lack of accessible knowledge about the influence of variables on resulting material behaviour. Information that is necessary for designers who wish to design with the material.

This project addresses this knowledge transfer gap between material research and design practice. Using a Material Driven Design approach, the research of this project investigates the moisture-responsive bending behaviour of wood veneer and translates the findings into actionable design guidelines. The project is structured in three domains: material exploration, performance development, and knowledge translation.

In the first domain, variables such as wood species, cutting orientation, fiber direction, programming conditions, and coating strategies are tested. Determining their influence on the curvature response of programmed wood veneer. Providing results that show the curvature behaviour is strongly dependent on the internal material structure and the bilayer system.

The second domain explores the dynamic performance of the material through cyclic humidity tests. Resulting in a material with a controllable bidirectional curvature response to humidity changes.

The primary contribution of the project, the third domain translated the insights on the material performance into structured design guidelines. The relationship between material variables and their resulting performance is communicated into actionable designer-oriented knowledge. Through a workshop evaluation and expert interview, the guidelines show potential as a design tool enabling designers to work with moisture-responsive wood veneer in various design contexts. By documenting experimental findings and presenting them as actionable, design-oriented format, the guidelines act as a bridge between material research and design practice.

AI declaration

In this thesis AI tools such as ChatGPT and Gemini have been used for brainstorming, image generation, structuring and language refinement.

Table of contents

Abbreviations

EMC - Equilibrium Moisture Content	The moisture content of a material when in balance with the surrounding environment. Where no gain or loss of moisture occurs.
FSP - Fibre Saturation Point	Moisture content of wood at which the cell walls are completely saturated with bound water, but no free water is present.
NIC - Natural Inside Curve	The side of the veneer that forms the inside of the curve when the sample bends in its natural curvature direction.
NOC - Natural Outside Curve	The side of the veneer that forms the outside of the curve when the sample bends in its natural curvature direction.
RH - Relative Humidity	The amount of water vapor in the air expressed as a percentage of the maximum amount at a given temperature.
Tg - Glass Transition Temperature	Temperature range at which materials transition to a soft and flexible state.

Glossary

Actuation speed	The rate at which a material changes shape in response to a stimulus.
Amplitude retention	The maintained percentage of deformation amplitude after repeated humidity cycles.
Anisotropic swelling	Unequal swelling behaviour in different directions.
Bidirectional curvature	Bending in two opposite directions.
Bilayer structure	A structure made from two layers with different material properties.
Calibration cycle	The first cycle of a climate chamber program, used to allow the sample to acclimatize.
Chord	The straight-line distance between the two ends of a curved sample.
Cyclic fatigue test	Testing multiple humidity cycles to test material durability and performance retention.
Deformation amplitude	The magnitude of bending between two opposite curvature extremes.
History dependency	The influence of a previous state on the current material response.
Isotropic swelling	Swelling that occurs equally in all directions.
Linear regression	Statistical method used to model the relationship between variables.
Moisture fatigue	Loss of performance or deformation amplitude after repeated moisture cycles.
Sagitta	The height of an arc measured from the midpoint of the chord to the arc.
Stress relaxation	The decrease in internal stress in a material over time.
Wood programming	The process of creating curvature in wood through hot water treatment.

1

INTRODUCTION

1.1 Research context and motivation

Wood is a material that's used extensively in various contexts, including design and architecture. The hygroscopic nature of the material results in absorption and release of moisture with changes in relative humidity, leading to dimensional changes. In building practices this behaviour is often unwanted, however when this quality is used and enhanced, it presents opportunities for designing responsive systems.

Existing research on wood veneer is mostly application-specific, where the material research documented only describes the findings relevant for the application outcome of the research. As a result, designers who wish to work with the material are limited by the lack of accessible knowledge about findings that describe the relationship between variables and resulting material behaviour. This creates a knowledge transfer gap between material research and design practice.

This project addresses this gap by documenting the material research findings of moisture-responsive wood veneer to a broader context and structuring this information to be actionable for designers in a design process. Resulting in design guidelines that bridge material research and design practice.

This project follows a Material Driven Design approach. Starting with material exploration, through which the behaviour and performance of the material are defined, shaping the following design process.

1.2 Research aim and questions

The goal of this project is therefore:

To explore the moisture-responsive bending behaviors of wood veneer and to combine these findings into actionable guidelines that inform and inspire designers in working with the material.

To achieve this goal, the following main research question is defined:

How can the moisture-responsive behaviour of wood veneer be translated into actionable design guidelines for designers?

The project is structured in three domains: material exploration, performance development and knowledge translation. They are addressed through the following subquestions:

1. How do material variables such as wood species, cutting orientation, fiber direction, and programming conditions influence the curvature response of wood veneer?
2. How can a bilayer coating strategy be used to create controllable bidirectional curvature behaviour in moisture-responsive wood veneer?
3. How can insights from experimental material research be translated into structured design guidelines that are useful and accessible for designers?

1.3 Societal relevance

In design sectors, there is an increasing demand for bio-based and renewable materials as alternatives to resource-intensive materials. Wood is a widely available renewable material that has been used for centuries in building and design practices. While the natural movement of wood is often aimed to be minimized through intensive material treatment strategies, exploring new ways of working with the material that emphasize this natural quality can contribute to more sustainable material systems.
Responsive materials can offer opportunities for adaptive and climate-responsive systems. With a passive reaction to environmental conditions, the need for mechanical systems or energy input to create movement is reduced. Moisture-responsive wood veneer shows how natural material behaviour can be used and amplified to create movement without the need for external energy input.
The integration of new material systems such as moisture-responsive wood veneer in design, requires designers to understand the material behaviour in order to work with it. Without accessible design knowledge, it is complex to apply the material in new design contexts. By translating material findings into structured guidelines, this research supports designers in working with moisture-responsive wood veneer and enables the integration of bio-based adaptive material systems in design practice.

1.4 Project approach

Chapter 2 provides an overview of relevant literature. It explains the main principles of wood as a hygroscopic material, the effects of material geometry on curvature, various material treatment methods and environmental influences on the material.

Chapter 3 outlines the experimental testing phase of the material in this project. It explains the effect of a large range of variables on the resulting curvature of the material and introduces the dynamic bidirectional curvature performance.

Chapter 4 describes the climate chamber testing phase of the project. Here, the material performance is tested through varying humidity cycles. From defining the response to specific humidities to optimizing the test method and testing the fatigue of the material.

Chapter 5 introduces the design phase of the project, where the finding of the material research from the previous chapters are implemented in a design. This chapter explains the design process of the guidelines after the material performance was defined.

Chapter 6 explains the testing phase of a section of the guidelines, the sample structure examples. These samples were tested on their functionality in order to provide relevant insights on their performance as content for the guidelines.

Chapter 7 describes the testing phase of the guidelines themselves. Through a workshop test with design students the guidelines were tested on their ability to transfer material research insights effectively to designers.

Chapter 8 presents the design of the final guidelines, based on the design and testing phase described in earlier chapters and built on the designed moisture-responsive wood veneer material developed in Chapters 3 and 4. This chapter demonstrated the guidelines through annotated pages, highlighting the content included in the guidelines.

Chapter 9 evaluates the design on its desirability, feasibility and viability. It highlights the main limitations of the project and recommendations for future research.

Lastly, Chapter 10 presents the final conclusion, providing an overview of the entire project including a personal reflection.

2

LITERATURE RESEARCH

2.1 Material structure

Wood structure

The structure of wood is organized in a hierarchy, from visible growth rings to individual cells. At the macroscale, the growth rings are visible alternating between earlywood and latewood, reflecting the difference in growth between seasons. In one singular growth ring there is a matrix of cells that extend in the longitudinal direction, with a slight gradient from earlywood to latewood in the radial direction. Figure 1 explains these directions.

Earlywood, which is formed during rapid growth, consists of larger cells with thin cell walls and a low density. In comparison, latewood cells are smaller with thicker cell walls and a relatively high density. The cells elongated along the longitudinal direction, wood fibers, consist of a central open space called the lumen. The lumen is surrounded by a primary cell wall and a multilayered secondary cell wall, composed of cellulose, hemicellulose and lignin (Chen et al., 2020; Ross, 2010).

Moisture induced curvature

Wood is a naturally hygroscopic material, it can take up moisture from its surroundings. The dynamic moisture changes in wood cause the material to swell and shrink, impacting the dimensions of the wood in multiple directions Rüggeberg and Burgert (2015).

The majority of swelling and shrinking interaction happens in the tangential direction, following the direction of the growth-rings (figure 1). Radial swelling is approximately half of the tangential swelling, while deformation in the longitudinal direction is minimal (Ross, 2010).

Moisture in wood exists in two forms: bound water, which is absorbed within the cell walls. And free water, which is held in the lumen of the cell (figure 1). The content of moisture can be described by three conditions: the maximum moisture content, the equilibrium moisture content (EMC) and the fibre saturation point (FSP). When the cell walls and lumen are both saturated with water, the maximum moisture content is reached. The EMC is reached when the wood is in equilibrium with the relative humidity of the surroundings and there is no exchange of moisture in or out of the wood. The FSP is the state where there is only water inside of the cell walls, bound water, and not in the lumen. The FSP differs per species of wood but generally falls between 25 to 30%. The FSP is important when looking at the behaviour of wood. Swelling and shrinking only happens with a change in cell wall moisture content (Pournou, 2020).

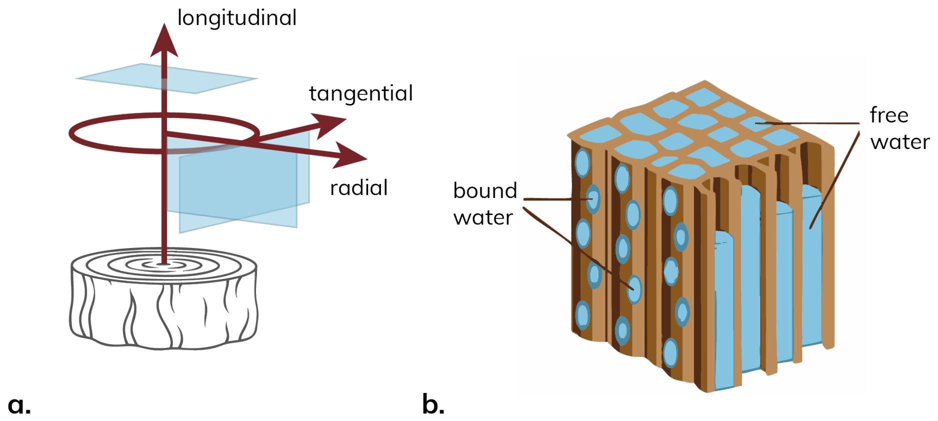


Fig 1. (a) The three dimensional directions and respective planes; (b) Bound and free water in wood (Pournou, 2020).

Patera et al. (2017) studied the swelling behaviour of wood at a cellular level, particularly the interactions of earlywood and latewood. The swelling behaviour of three regions of interest were compared. One containing pure earlywood, one containing pure latewood, and one region of interest consisting of both earlywood and latewood with the natural transition intact. Comparing the behaviour of each piece of wood, the combined tissue showed some interesting results. The amount of swelling in the combined tissue was less than the amount of swelling in either homogeneous tissues. Meaning that the swelling behaviour is restricted in the combined tissue.

The cells in the earlywood structure are relatively large with large lumen, with a high porosity and low density. The latewood structure has low porosity, a high density and a high stiffness. The stiffness of the latewood cells exerts resistance to the earlywood cells, restricting their swelling behaviour in the radial direction.

Wood species

Wood comes in a large variety of species, categorized as hard woods and soft woods. Each species has its own unique combination of properties and thereby resulting interaction with moisture. Wood density and porosity are two properties that greatly influence the material's moisture swelling response. The density of wood relates to the thickness and amount of cell wall material. When moisture is absorbed in the wood, the swelling response occurs primarily in the cell walls. Resulting in the density affecting the amount of swelling of the material. Porosity mainly affects the rate of swelling, a porous wood species is able to distribute the water faster through the material, thereby increasing the speed of absorption and swelling (Pournou, 2020; Ross, 2010; Thybring & Fredriksson, 2021). Table 1 shows the density values of various wood species based on ~12% moisture content (MC).

These material properties vary significantly between wood species, with the result of extremely varying moisture-induced swelling responses. Similar variations also occur within a singular wood species. Earlywood and latewood have different densities and porosities, leading to differences in swelling behaviour even in the same growth ring (Patera et al., 2017; Ross, 2010).

Wood species	**Density (kg/m³, ~12% MC)**
Rosewood (East Indian)	~830
Oak (European)	~720
Beech (European)	~720
Ash (European)	~690
Teak	~650
Maple	~705

Table 1. Density values of various wood species at ~12% Moisture Content (MC). The data for this table came from Ross, 2010 and Zanne et al., 2009.

2.2 Sample geometry

Cut orientation effects

The manner in which wood is cut strongly influences the directionality of the material's bending response. Each wood cutting direction produces a different alignment of the material structure, such as the fiber directions and year-rings relative to the cut. The anisotropic swelling in both the tangential and radial direction creates a bending response of the material. Depending on how a piece of wood is cut, the direction of the bending response differs as can be seen in figure 2 (Ross, 2010). Similarly, cutting wood veneer can be done in different methods as can be seen in figure 2 (Wagenführ et al., 2023). Each type of cut results in both a different structural orientation as well as a different textural appearance.

The type of veneer cut does not only influence the bending direction. It also affects the predictability and stability of the bending response. The orientation of the fibers is much more uniform in quarter cut veneer than flat sawn veneer. This uniformity improves the stability of the material because the swelling response throughout the material is similar. This improves the predictability of the bending performance (Wagenführ et al., 2023).

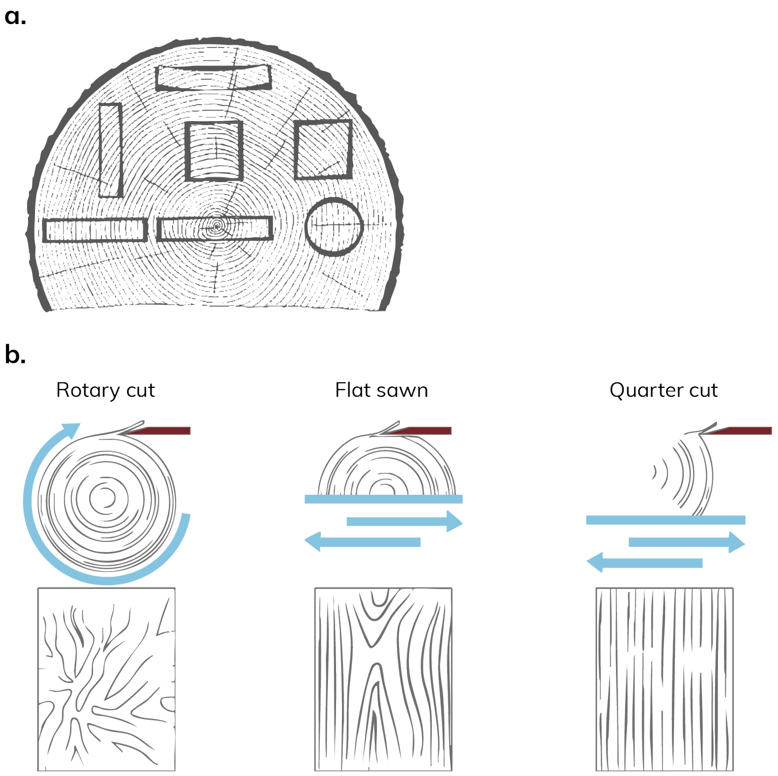


Fig 2. (a) Natural bending response of wood affected by the growth ring direction relative to the cut (Pournou, 2020); (b) Vener cut orientation with the resulting wood pattern.

Bilayer structures

Curvature of materials can be achieved through force or active controlling, but also through passive actuation. This is when a material bends in response to a specific external stimulus, for example the bending response of wood to moisture caused by the swelling in tangential and radial directions.

When working on an engineered material, a method often used to create bending, is making bilayer structures consisting of an active and passive layer (Rüggeberg & Burgert, 2015). The two layers of these structures each have different properties that respond differently to the chosen actuation. The active layer has a stronger response to the actuation than the passive layer. Examining for example a shrinking behaviour. The active layer would shrink more than the passive layer when actuated. Because the layers are stuck together, the passive layer has to move with the rate of shrinkage and will therefore curve (figure 3).

Connecting bilayer structures to wood, earlywood and latewood can be considered a natural bilayer structure. There is a clear distinction in research on methods of using bilayer structures of wood. There are some studies which already use the natural bilayer structure of earlywood and latewood (Luo et al., 2023; Luo et al., 2020). Then there are others which create multi material bilayers. For example Rüggeberg and Burgert (2015), making a wooden bilayer structure out of a layer of beech and a layer of spruce wood.

Comparing the two bilayer structure methods, there is one significant difference. Bilayer structures made from multiple materials have a very clear boundary between the two materials with different properties. For a natural bilayer structure like earlywood to latewood, there is a gradient where the earlywood cells transition to the latewood cells.

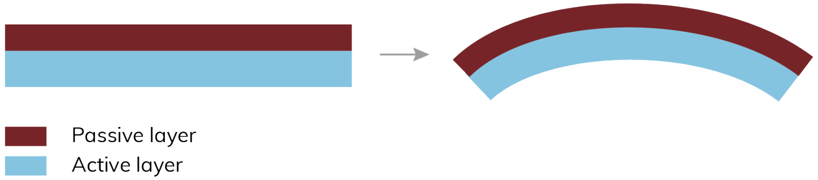


Fig 3. Bilayer structure representation

Thickness ratio influence

Rüggeberg and Burgert (2015) studied transverse wood curvature through induced moisture. The samples in this study are bilayer structures made from two different wood types. They created an equation calculating the curvature of the wood, with variables including the swelling coefficient difference, moisture content change, thickness ratio, stiffness ratio and total sample thickness. The results of this study show that the thickness ratio between the two layers had the largest impact on the curvature, rather than the stiffness ratio.

This finding can directly be related to designing with bilayer wood veneer. The thickness ratio between the two layers is an important variable in controlling the curvature response.

2.3 Material treatment

There are a variety of different methods to modify the structure of wood each with their own benefits. Chen et al. (2020) classifies wood modification into three categories: physical modification, chemical modification and combined modification. Where chemical modification consists of subtractive and additive techniques. Physical modifications mainly affect the wood's macro- and microstructure, improving properties such as mechanical strength through densification. Chemical modifications offer a more precise control on a molecular level. Subtractive chemical modification allows for the removal of certain wood components which will result in new chemical- or pore structures. For example the removal of cellulose, hemicellulose, and lignin. In the cells of a wood structure, lignin is the binder that holds cellulose nanofibrils together in the cell wall. Removing this component through delignification will result in a wood structure with a higher porosity, lower stiffness and lower strength.

Thermal modification is a wood treatment method in which chemical and structural changes affect the wood through high temperatures, affecting the lignin and hemicellulose. Lignin is a thermoplastic polymer, meaning it softens when heated. **Thermal modification** of wood is normally carried out at temperatures from 150 °C to 240 °C, as the lignin glass transition temperature (Tg) in a dry state is approximately 170 °C. At high temperatures, the bonds between lignin and hemicellulose can break causing irreversible changes to the wood structure. This degradation can have permanent effects on the wood's mechanical properties and hygroscopic behaviour (Jančíková and Jablonský, 2025; Ross, 2010).

Hygrothermal modification is a form of thermal modification with moisture. The presence of moisture significantly lowers the temperature at which the lignin softens because the water acts as a plasticizer (Börcsök & Pásztory, 2021; Ross, 2010). The glass transition temperature of lignin under water-saturated conditions is between 60 °C and 90 °C (Munier et al., 2020). Much lower than the Tg of wood in a dry state. As a result, hot water treatments exceeding 90 °C can lead to irreversible damage to the material. The difference between thermal and hygrothermal modification highlights the importance of controlling the temperature when using hot-water treatments on wood, as the effects of the same temperature significantly differ.

2.4 Environmental influences

Environmental conditions such as temperature and relative humidity (RH) significantly influence the interaction of wood with moisture. The hygroscopic nature of wood causes the material to continuously interact with the moisture in the surrounding environment, trying to reach its equilibrium moisture content (EMC). Meaning that when the RH is high, the wood will absorb moisture and swell and when the RH is low, the wood will release moisture and shrink. Pournou (2020) discusses the phenomenon called **hysteresis**, where the rate of absorption and desorption to and from EMC are not equal in the same environmental circumstances. The ratio of adsorption EMC to desorption EMC is around 0.8 at room temperature. Meaning that wood holds more moisture when it is releasing moisture than when it is absorbing moisture at the same humidity level (figure 4). This value is not only dependent on RH and temperature but also on wood species. EMC for European species at 25 °C and 60% RH is around 5-6%. Whereas EMC for U.S. species under the exact same conditions is around 10-11%.

Hysteresis shows that external influences such as environmental moisture and temperature affect wood in a complex way. The response of wood with moisture is history-dependent. This means that the wood's moisture content at any RH can vary depending on if the wood is releasing or absorbing moisture. As a result, sudden changes in humidity or temperature do not lead to a predictable moisture content. This phenomenon is important to consider when trying to predict wood behaviour in any environment, especially in natural environments where conditions such as temperature and humidity continuously fluctuate.

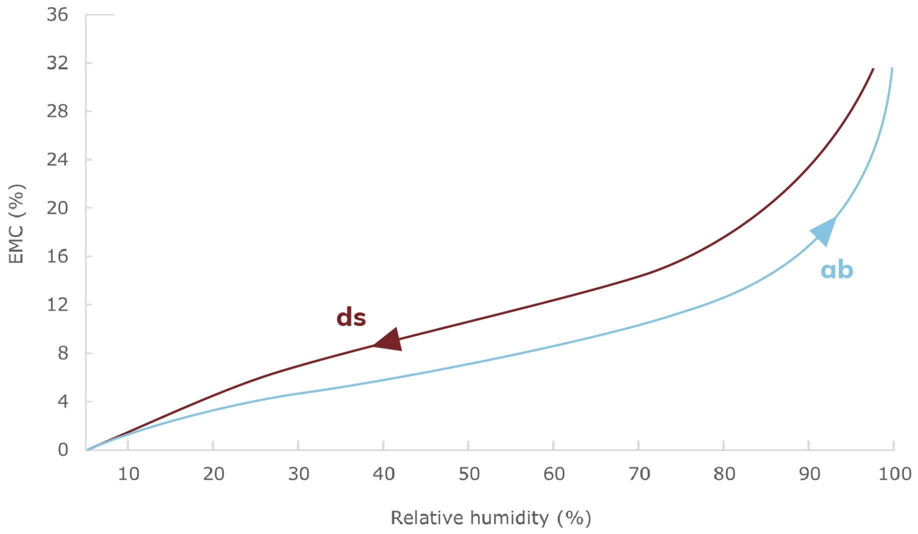


Fig 4. Wood desorption (ds) and absorption (ab) measured on relative humidity and EMC Pournou (2020).

2.5 Discussion

The literature findings discussed in this chapter are explained as separate influencing properties. However in reality, these principles are intertwined in multiple ways.

The swelling directions with different magnitudes in each direction, the anisotropic swelling, affect the natural curvature response as stated. This in turn affects the bilayer principle, which is built on the difference in moisture interaction of each layer. With bilayers, materials that swell and shrink isotropically can result in curvatures. When anisotropic swelling is introduced to this principle, an interesting dynamic could be created where the natural curvature can be enhanced through bilayers.

Between different wood species, there is variation in density and porosity as well as the EMC, which influences the hysteresis response. These variations between wood species could affect the natural curvature response, resulting in differences of curvature amount, curvature amplitudes, actuation speed, and stability of the material.

The influence of the thickness ratio between bilayers as explained by Rüggeberg and Burgert (2015), demonstrates that the curvature result is not only influenced by the material structure. The geometry and design of structure can also impact the resulting curvature.

The existing research on wood veneer is often focused on specific design applications. In these directional studies, general knowledge about the material and findings not directly related to the application are usually not mentioned. For designers, this broader understanding is essential when trying to design with the material. The existing literature can only be used as a starting point and extensive material research would be necessary to understand the basic principles of the material and influencing variables. The current application-focused research therefore limits the accessibility of the material for designers wanting to explore working with a material such as wood veneer.

In most studies on bilayer structures made from wood veneer, the bilayer is formed by combining two pieces of veneer, usually differing in species or fiber direction. These layers are connected with an adhesive, which effectively creates a three-layer system, since the adhesive itself has properties that can influence the structure's behavior. What is mainly missing from the literature are bilayer systems made with a true two-layer approach, such as using a coating directly to the veneer acting as the second layer. This creates an interesting research direction, exploring the performance of true two-layer structures.

In research on shape-changing wood veneer, the natural curvature of the material is rarely mentioned as a property that can enhance movement. The moisture response of the material is seen as a property to compensate for instead of a possible design feature. This again allows for an interesting research direction. How can the natural curvature response of the material be intentionally enhanced and support the veneer curvature?

2.6 Conclusion

In the discussion various research gaps and resulting research directions are defined.

- Developing a method of providing designers with fundamental material research on wood veneer outside of an application-specific study.
- Exploring the performance of true two-layer bilayer structures.
- Investigating how the natural moisture-induced curvature of wood veneer can intentionally be enhanced and used as a design feature.

To approach these research directions, the first step is understanding the material. Through experimental testing the influence of a range of variables can be tested, determining how the natural curvature can positively be influenced.

Based on the findings of anisotropic swelling, multiple veneer cutting orientations as well as fiber directions are tested in the following experimental testing chapter. Various wood species are tested on species-dependent properties. From the literature on bilayers, multiple coatings are tested, including thickness ratios through the amount of coating layers. Hygrothermal modification is also tested with variations in soaking temperatures and times.

3

EXPERIMENTAL TESTING

3.1 Introduction

The research process in this project consists mostly of experimental tests with wood veneer samples. Each round has its own focus where a range of variables is tested in changing combinations, with the results of each round shaping the plan of the next round, making this a very iterative process. Some tests were explorative in nature, starting without a clear hypothesis of the result. Others were more systematic, aiming to isolate the influence of specific variables to later eliminate or continue with these variables.

The main goal of the experimental testing was to create a sample with a repeating dynamic curvature response activated by moisture. Starting with a sample in a curved reference state, it becomes flat with increasing moisture and curves back to the reference state when dry. To achieve this goal, the first step was to create the curved reference state. An increased curvature in the reference state leads to a greater observable movement. Therefore a selection of variables were tested on the amount of resulting curvature. The samples with the best results are then tested on their dynamic response by being exposed to moisture in various methods.

3.2 Exploring curvature response through wood programming

The main focus of this chapter is to explore how to create the most extreme curvature of the wood veneer samples through hot water treatment, referred to as wood programming. This is done through testing a wide variety of variables in different combinations and their resulting effect on the curvature (figure 5).

As explained in the literature review, wood has a natural curvature response when it comes in contact with moisture, the samples consistently bent in the same direction. The aim of these tests is to try and enhance this natural curvature response by testing the effect of different variables. Figure 6 shows samples that are bent in their natural curvature direction. Each side of the sample is named to simplify future explanations about curvature directions. NIC refers to the natural inside curve and NOC to the natural outside curve. This natural direction can be found by soaking test pieces in water and letting them dry. By marking one side of the veneer (NIC in this case), it is possible to keep track of the natural curvature sides. The testing phase has an iterative approach with a total of six test rounds, where the results of each round shape the next. In appendix B a heat map can be found, showing all the variable combinations tested. Appendix C shows a table with all the samples tested, their properties and measurement results.

Wood species

Each wood species has its own unique properties as described in the previous chapter, resulting in varying moisture responses. Therefore a range of different wood species were tested to explore how different species respond to the effects of changing variables. The wood species tested were oak, rosewood, ash, beech, maple and teak. In the first few test rounds mainly oak and rosewood were used to test the influence of different variables with. Later on a test was conducted with the other wood species, set up as an explorative test without clear expectations of the response.

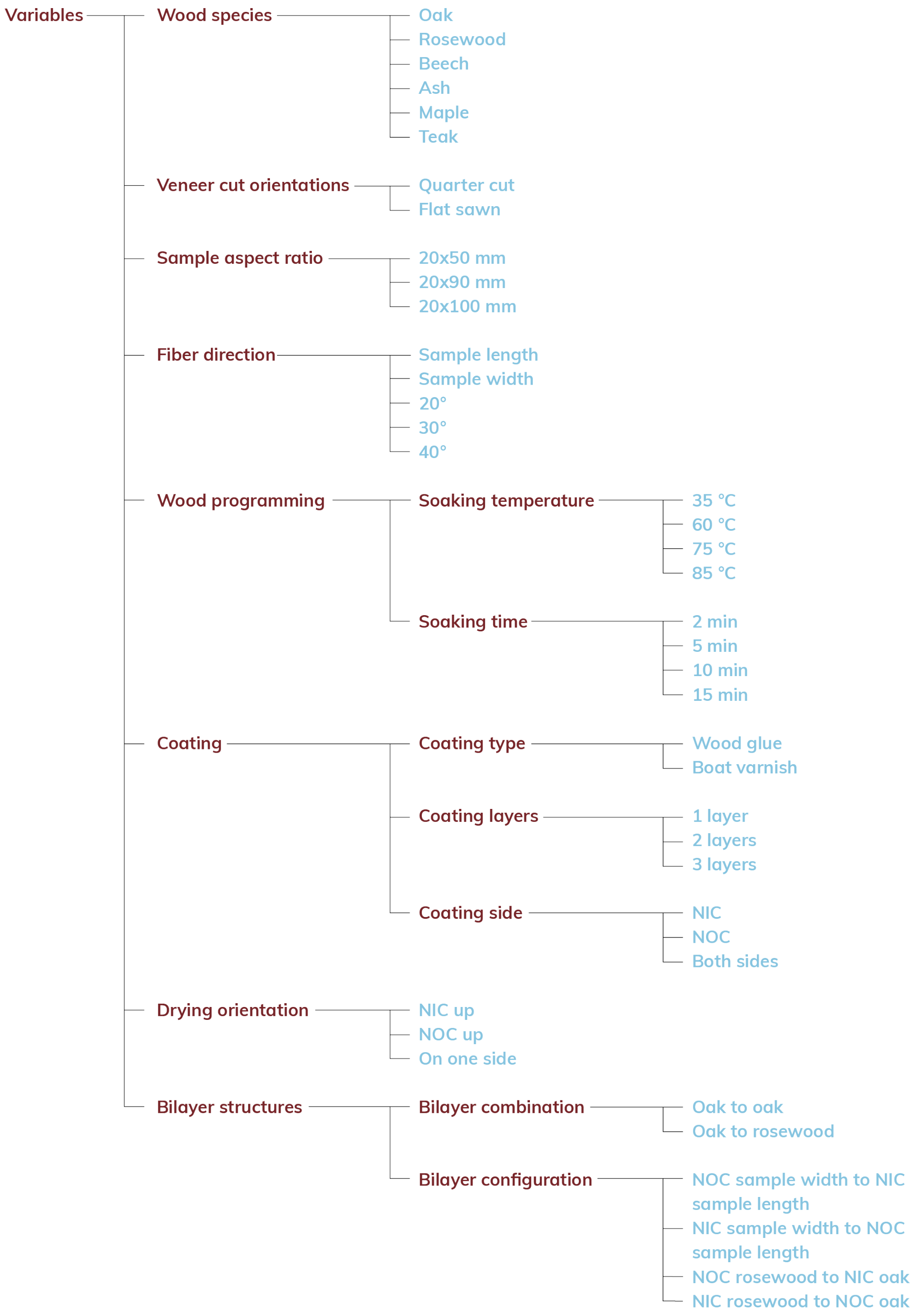


Fig 5. Variables tested during experimental testing

Veneer cutting orientation

As explored through the literature review, the veneer cutting orientations impact the natural curvature direction. The aim of the explorative tests is to investigate how the natural curvature can be enhanced, therefore both quarter cut and flat sawn veneer were tested. The goal of testing this variable was to determine which veneer cutting direction provided the best curvature response in terms of amount of curvature and stability. The expectation for the flat sawn veneer was to result in more extreme natural curvature based on the literature. Based on handling the material, the flat sawn veneer felt very fragile. Combining that with the more uniform and stable structure of the quarter cut veneer, it was expected that the quarter cut veneer might lead to less extreme natural curvature but a more reliable veneer cut to work with.

Fiber direction

Varying fiber direction orientations were tested to explore which orientation of the fibers relative to the sample shape would result in the most extreme curvature. These results were used for the continuation of following test rounds. Next to testing fiber directions parallel and perpendicular to the sample length, varying angles were also tested to broaden the understanding of possibilities for future design applications. The expectation was that changing fiber directions would impact the curvature direction. Initially, there were no clear expectations on the resulting amount of curvature, as this test was mainly explorative. In later test rounds, when the results of curvature amount and direction were known, the expectations became more specific. With testing different angles of fiber direction, it was expected that a 45° angle would result in the most extreme twisting.

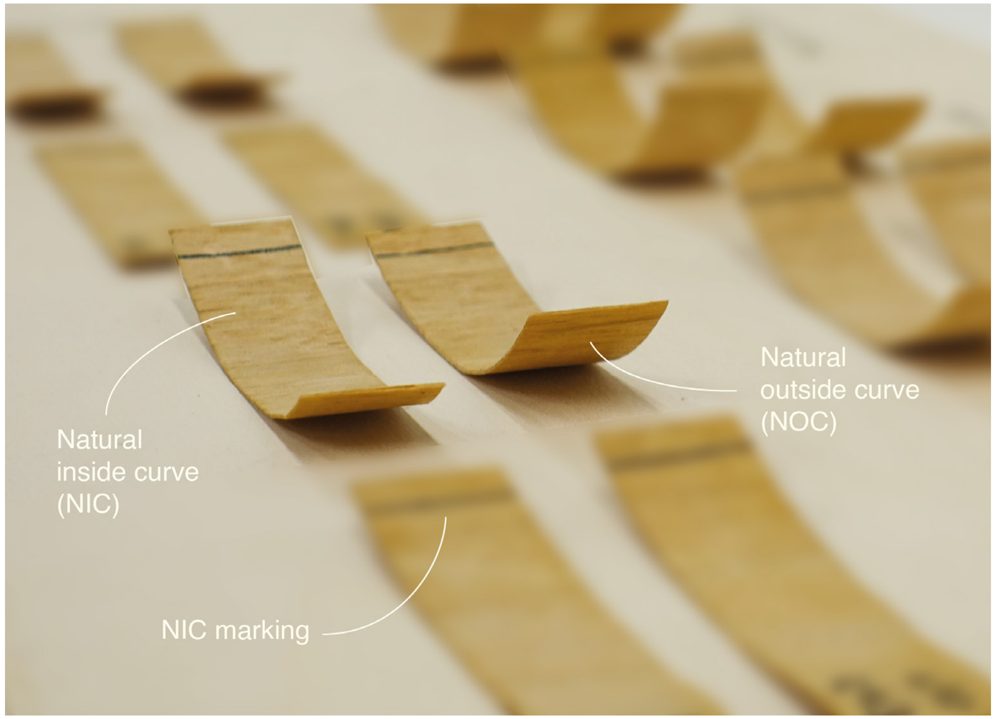


Fig 6. Indication of curvature sides. Natural inside curvature (NIC) and natural outside curvature (NOC).

Wood programming

Through wood programming, the moisture response was tested. Wood programming is defined as a process of soaking the wood samples in a water bath, with **soaking time** and **soaking temperature** as the main variables. According to Munier et al. (2020), the glass transition temperature of lignin in water is between 60 °C and 90 °C. Therefore soaking temperatures of 35 °C, 60 °C, 75 °C and 85 °C were tested. Most temperatures fall within the range of the glass transition temperature. However to explore the effect of the response outside of this range, 35 °C was also tested.

In the first test rounds, all samples were left to dry in the same orientation, with the NOC side down. The variable **drying orientation** was introduced to examine its effect on the resulting curvature. The samples were tested drying on the NOC side, NIC side and on one edge.

The goal of testing these three variables was to define their effect on the resulting curvature of the dry samples after the wood programming. The soaking times and temperatures were tested exploratively, without clear expectations of the resulting curvature. It was expected that drying the samples with the NIC side down could limit the resulting curvature, as the samples curve toward the NIC side.

Coating

The idea of testing coatings in general originated from the research found on bilayer structures. The literature on bilayer structures from wood veneer all created a bilayer from two layers of wood with different properties, for example Rüggeberg and Burgert (2015) tested a layer of beech with spruce. However all these bilayer structures also included an adhesive combining the two wood layers, in reality creating a structure with three layers. To simplify interpreting the results, bilayer structures were created where the adhesive or coating acts as the second layer. For the coating, different variables were tested: **the coating type, amount of coating layers** and **the coating side.**

The selected coating types to test were chosen based on several criteria.

- The coating is expected to act as a second layer and should therefore barely soak into the material.
- The coating should remain flexible after drying. The veneer is meant to curve and the coating should be able to curve with the veneer without cracking or breaking.
- The coating should be waterproof. The wood is programmed by soaking it in water for an extended period of time. The coating should stay on the veneer and not dissolve in water.

From these criteria waterproof woodglue and boat varnish were selected to be tested.

The coating was tested with 1, 2 and 3 layers on the veneer. Where one coating layer corresponds to a coating weight of 55 g/m². The coating side was tested to explore how it affects the natural curvature direction. This was tested with applying the coating on the NIC side, NOC side and on both sides of the same sample.

It was expected that boat varnish would soak into the wood more than woodglue because of the low viscosity and oil base. Therefore it was assumed that the woodglue would create a more distinctive bilayer structure that could possibly lead to better curvature results.

As for many variables, the coatings were tested in multiple rounds. Earlier test rounds resulted in expectations about the coating side. Assuming coating layers on the NOC side would support the curvature and coating on the NIC side would block the natural curvature.

Fig 7. Samples from the experimental testing phase

Method

The method of testing all the variables listed above happens in three stages. First creating the samples, testing them with wood programming and evaluating the results.

Materials & equipment

To prepare the samples for testing, the wood veneer was cut into pieces with a laser cutter. The equipment needed during the wood programming stage can be seen in figure 8. It includes a circulating water bath, probe thermometer, timer, thermo-hygrometer, scale, sample sheet with the samples and a custom measurement setup to evaluate the resulting curvature of the samples.

The measurement setup was made to measure the chord and sagitta of the samples once they were dry (figure 9). The chord is the straight-line distance between the two ends of a curved sample. The sagitta is the height of the arc measured from the midpoint of the chord. From these measured values the radius could be calculated.

In total six test rounds were conducted where 144 samples were tested. Every sample was made by cutting 0.6 mm thick wood veneer in the desired aspect ratio (figure 7 gives an impression of the samples tested).

Procedure

1. Sample making & preparation
2. Wood programming
3. Sample evaluation

Step 1
The samples are made by laser cutting the veneer considering the variables wood species, veneer cut orientation, aspect ratio and fiber direction. Coating the samples is done in this stage if this is required, letting the coating dry in between each layer. Lastly all samples are weighed when dry.

Step 2
During the wood programming the samples are submerged in a circulating water bath for a specific amount of time at a specified temperature. After being taken out of the water, the samples are immediately weighed

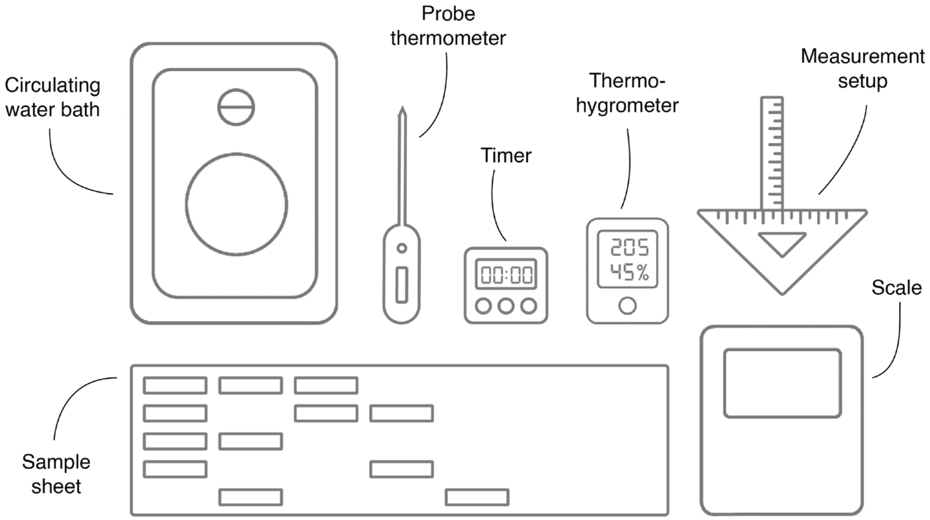


Fig 8. Experimental test setup with equipment.

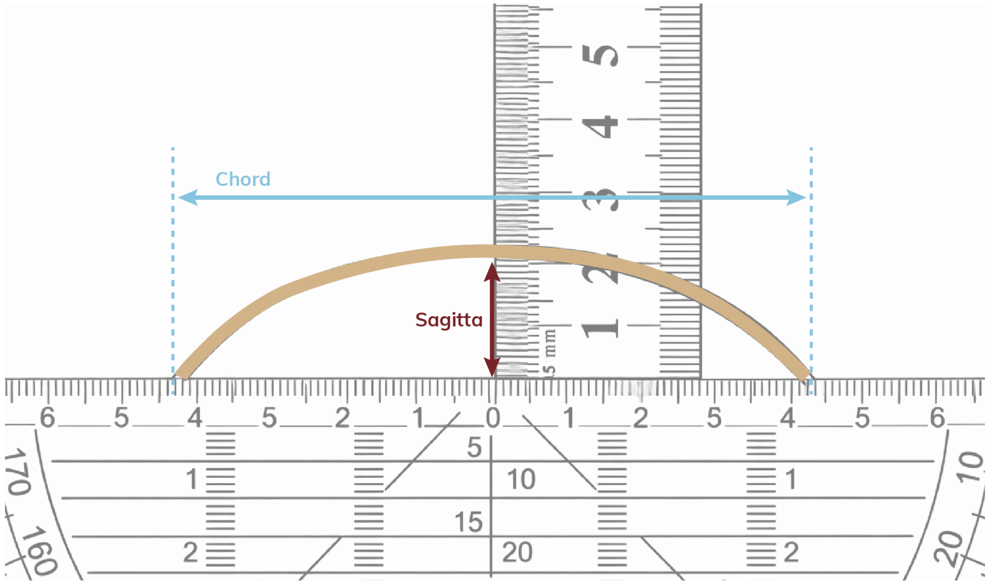


Fig 9. Measurement setup to measure the sagitta and chord

again to record the wet weight of each sample. The environmental temperature and humidity are recorded for the duration of the wood programming stage. When the wood programming is completed, the samples are placed to dry.

Step 3
After all the samples have dried, their resulting curvature is evaluated by measuring the sagitta and chord. These measurements are used to calculate the radius of each sample.

Results

The tests in this chapter have been conducted in multiple test rounds where each round tested different variable combinations. This results section explains the most important findings per variable. The full table with all samples and their measurement results per test round can be found in appendix C.

As explained in the method, to express the curvature of samples both the sagitta and chord were measured to calculate the radius. In this results section, only the sagitta has been used to express the sample curvature. During the analysis of the results, it became clear that the sagitta is a more reliable measure of curvature than the radius. Since the radius is calculated from both the sagitta and chord, any minimal fluctuation in either measurement causes disproportionately large deviations in the radius value. With the possibility of reading errors and wood samples with fluctuating curvatures with humidity changes, the sagitta expresses the curvature more reliably than the radius. A more detailed explanation and calculated example can be found in appendix D.

Wood species

With each test round, the dry weight of the samples was measured in addition to the wet weight when the samples were saturated from the wood programming. Figure 10 shows the difference in dry weight and wet weight of both oak and rosewood. As can be seen from the figure, for both wood species the wet weight has increased compared to the dry weight. Oak presents a larger increase of weight with 0.38 grams compared to rosewood with 0.27 grams.

To test the effect of water absorption on the resulting sagitta, a linear regression analysis was performed including both oak and rosewood as wood species. The variable water absorption was defined by the weight difference between the material in a dry and saturated state. The overall model was significant ($p = 0.001$), and a significant interaction was observed. This indicated that the relationship between

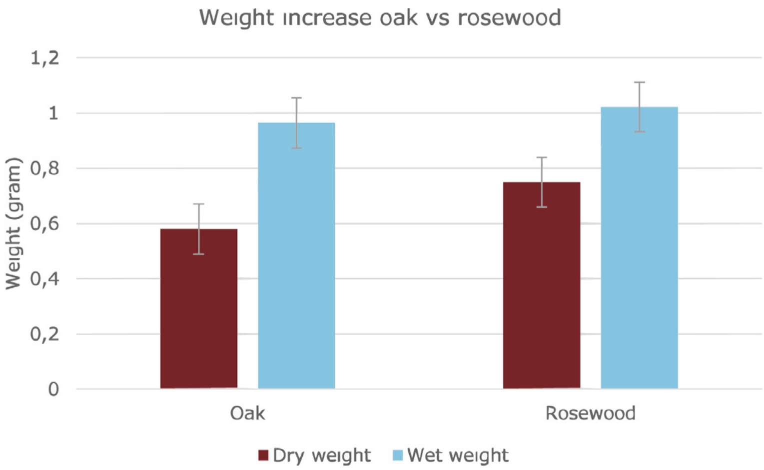


Fig 10. Bar chart with weight increase of wood veneer samples from dry state to saturated state. Comparison between oak and rosewood.

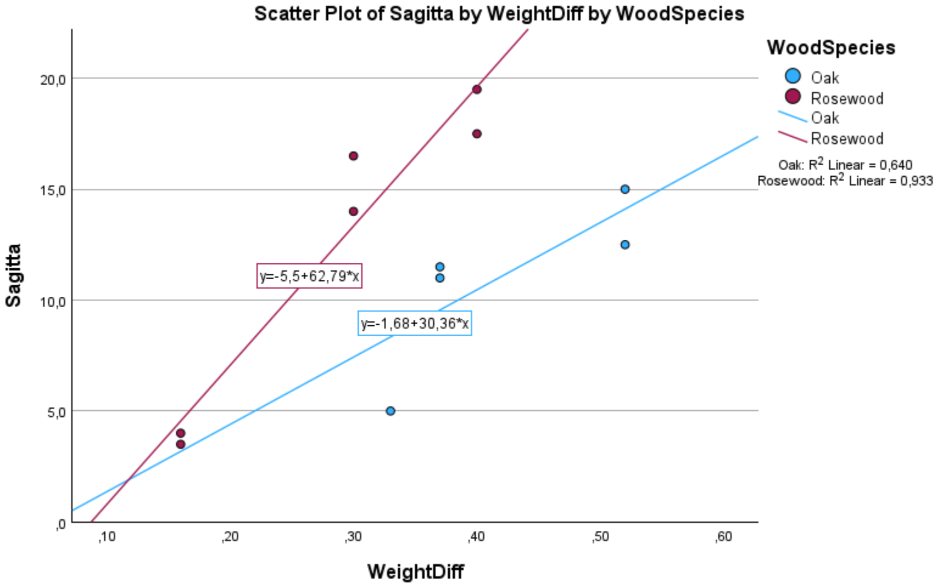


Fig 11. Scatterplot of sagitta versus weight difference for oak and rosewood, including linear regression lines per wood species.

the water absorption and sagitta differed between the two wood species.

Simple slope analysis revealed that water absorption was a strong and significant predictor for the sagitta of rosewood (B = 62.79, p = 0.002). Oak showed a positive but non-significant trend (B = 30.36, p = 0.056). Figure 11 shows the regression slopes of both rosewood and oak.

In figure 12 the effect of coating types on the resulting curvature can be seen for both oak and rosewood. The resulting curvature is expressed with the sagitta in millimeters.

With oak veneer, no coating results in the lowest sagitta value. The curvature increases with boat varnish and the highest sagitta value can be seen with wood glue as a coating. For the rosewood the same order of coatings results in the opposite response. Where the highest sagitta value is without any coating, and the lowest sagitta is with wood glue. Overall the strongest curvature, with the highest sagitta value, can be seen for oak veneer with a wood glue coating.

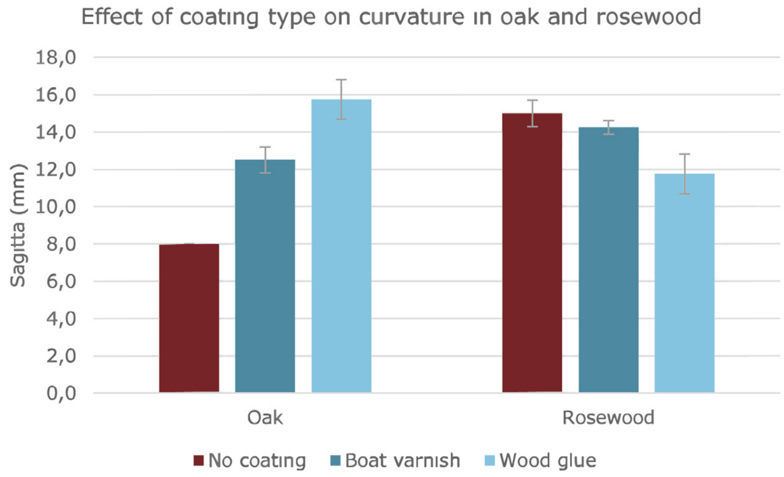


Fig 12. Bar chart of the effect of coating types on sagitta, for oak and rosewood.

Veneer cut orientations

To test veneer cut orientations, flat sawn and quarter cut veneers from different wood species were programmed and their resulting curvature evaluated. Figure 13 compares flat sawn and quarter cut samples with fiber directions along the sample width. The flat sawn veneers (beech and ash) show large variations in curvature, both between species and within the same species. Beech shows irregular curvature along the sample length, with substantial differences between the two samples, while both ash samples display similar curvature with a slight twist. The quarter cut veneers (oak and teak) show consistent curvature direction with different magnitudes, teak has a more extreme curvature than oak.

Sample aspect ratio

Table 2 displays the results of testing the influence of the sample aspect ratio of oak veneer samples on the resulting curvature in sagitta. All measurements showed identical sagitta values (SD = 0) regardless of the aspect ratio.

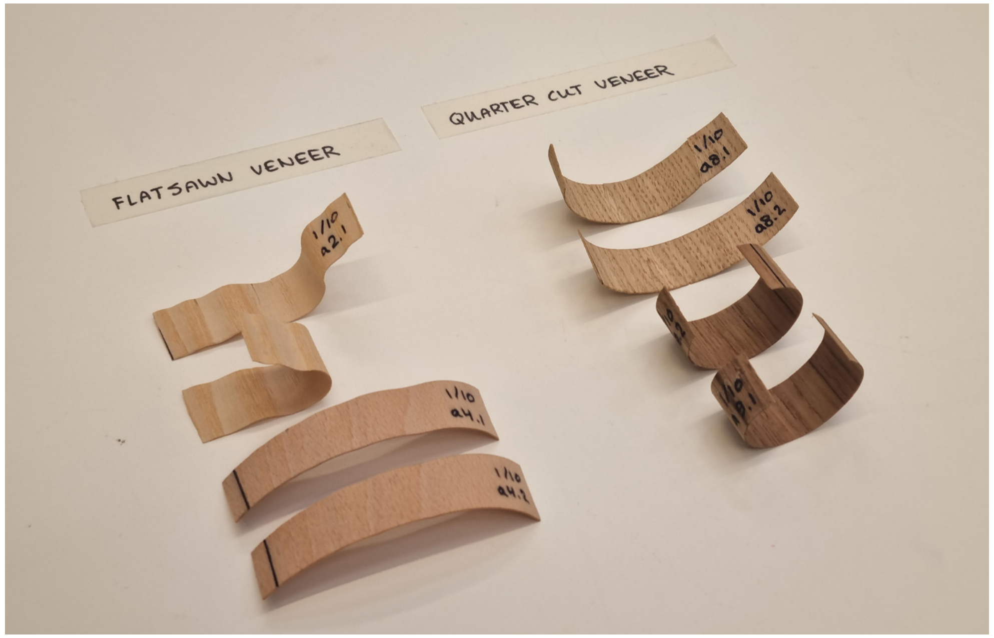


Fig 13. Selection of samples tested of flatsawn veneer (beech and ash wood) and quarter cut veneer (oak and teak wood).

Sample aspect ratio (mm)	Number of samples (n)	Sagitta (mm)
20 x 50	2	1.2
20 x 100	2	1.2

Table 2. Resulting sagitta values of samples tested with varying aspect ratio's.

Fiber direction

The influence of the fiber directions on the resulting curvature can be seen in figure 14. The veneer always bends perpendicular to the fiber direction. Cutting the veneer in different orientations relative to the fiber direction results in samples that seem to bend in different directions or even twist when the fibers are placed on an angle relative to one of the sample edges.

Wood programming

Figure 15 displays the difference in resulting curvature of different soaking times (2 and 15 minutes) grouped by the programming temperature. As can be seen from the graph, for each soaking temperature an increase in soaking time results in an increased sagitta.

Figure 16 shows the influence of the tested soaking temperatures (35, 60 and 85 °C) on the resulting sagitta for 15 minutes of soaking. With an increase of temperature, an increase of the sagitta can be seen.

Fig 14. Samples tested with varying fiber orientations and their curvature result.

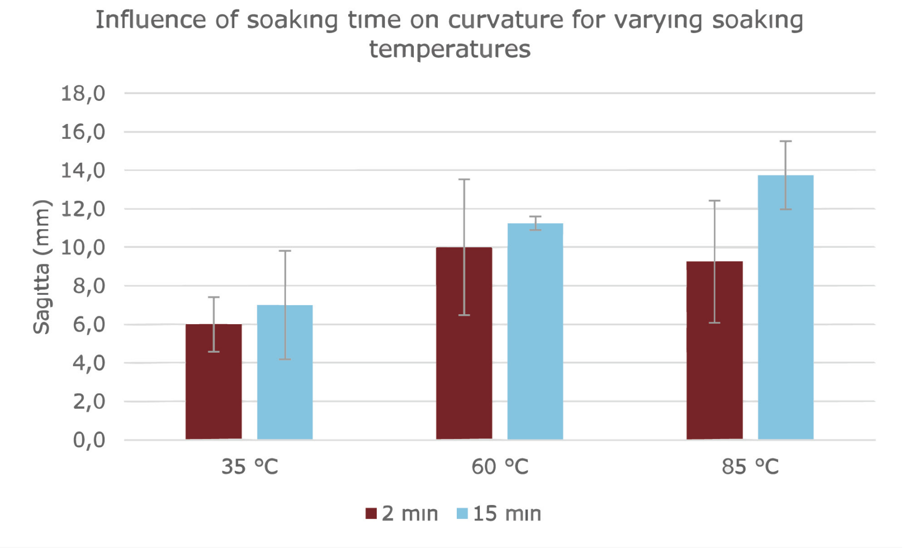


Fig 15. Bar chart of the influence of soaking time on the sagitta, for three different temperatures.

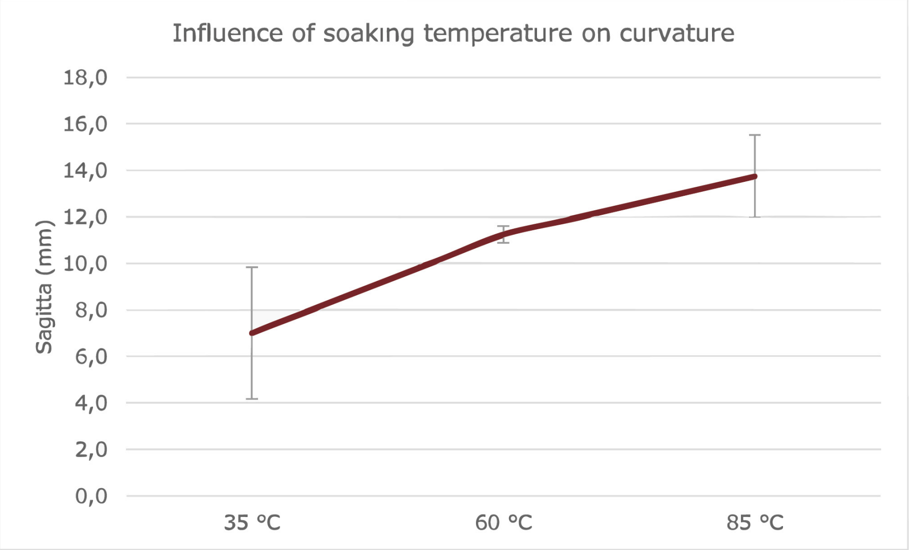


Fig 16. Line chart of the influence of soaking temperatures on the sagitta.

Coating

The influence of coating types on the resulting curvature in sagitta has been tested. Figure 17 shows the results. The lowest sagitta value can be seen for the veneer sample without any coating. The sagitta value increases with the use of boat varnish and the highest sagitta value can be seen for a wood glue coating.

Additionally, the coating side and amount of coating layers were tested. In figure 18 it can be seen that coating the NIC side of the material results in a sample without any curvature (sagitta=0). A coating on both the NIC and NOC sides results in some curvature with one layer of wood glue coating. However with increasing the coating layers, this curvature disappears. Coating the samples on the NOC side results in the highest sagitta value and most amount of curvature. With this coating side, it can also be seen that with the increase of coating layers, the sagitta value also increases.

Drying Orientation

In order to know whether the drying orientation of the samples after the wood programming had any effect on the resulting curvature, this variable has also been tested. Multiple samples with identical pre-treatment were let to dry in varying orientations. As can be seen from figure 19, drying the samples on the NIC side or the NOC side has resulted in the exact same sagitta value of 11 mm. Drying the sample on its side resulted in a slightly lower sagitta value of 10.5 mm.

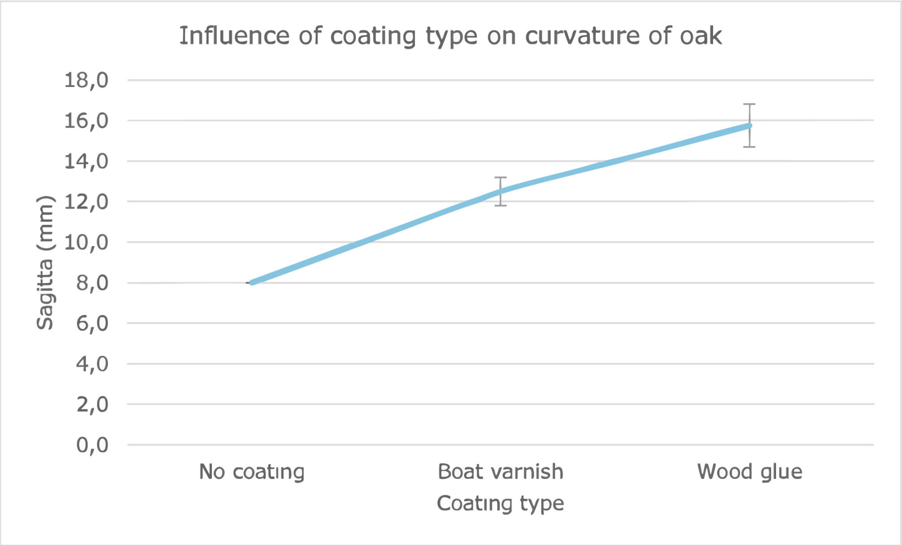


Fig 17. Line chart of the influence of coating types on the sagitta.

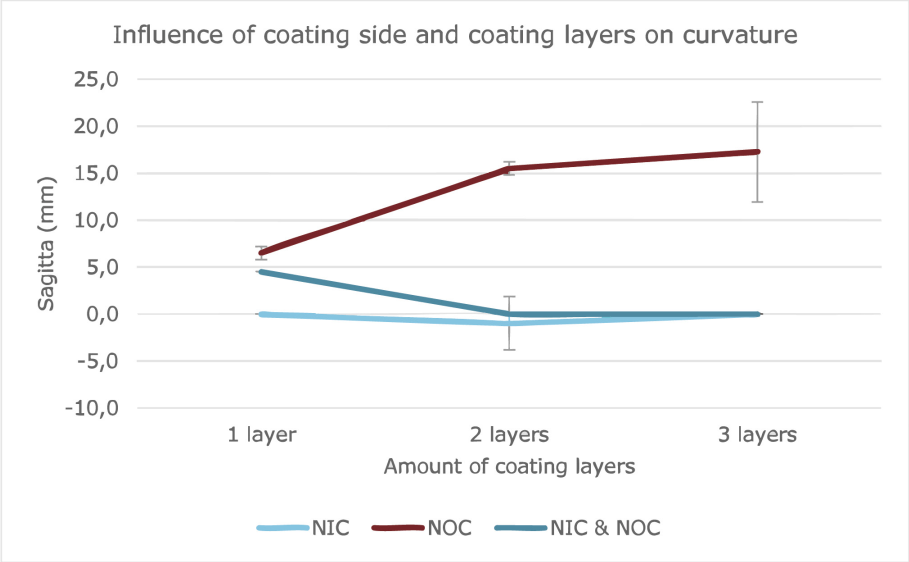


Fig 18. Line chart of the influence of amount of coating layers on the sagitta, per coating side.

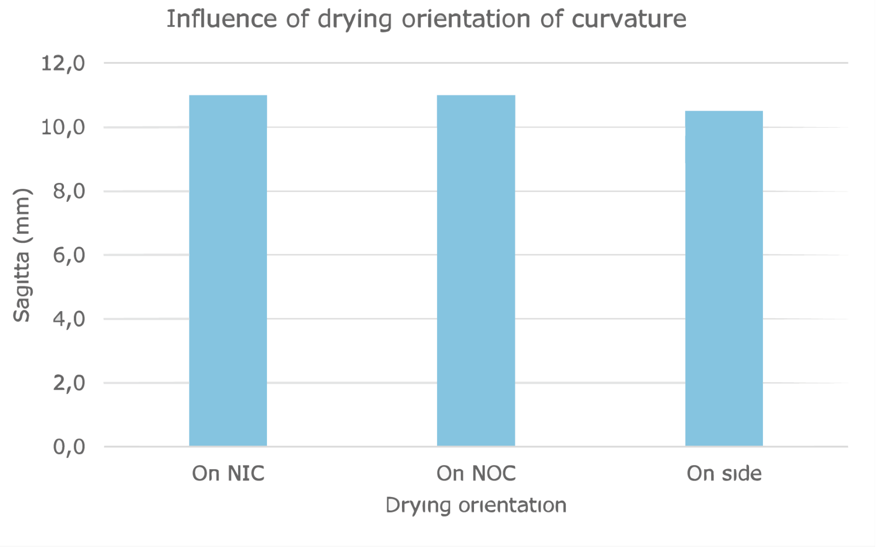


Fig 19. Bar chart of the influence of drying orientations on the sagitta.

Discussion

Wood species

The results show that oak presents a larger increase in weight compared to rosewood from a dry to a saturated state after the same amount of time, meaning the oak veneer absorbs a larger amount of moisture than the rosewood veneer. The results of the linear regression analysis show that there is a positive relationship between the amount of water absorbed during the wood programming and the resulting sagitta after drying. Combining these findings indicates that oak veneer should result in more extreme curvature results than rosewood because of its ability to absorb greater amounts of moisture within the same amount of time. Connecting this to the density values of wood species mentioned in the literature. Rosewood has a density of about 830 kg/m2, while oak has a density of 720 kg/m2 which is much lower. This lower density value of oak could potentially be the cause of the possibility to absorb greater amounts of moisture.

Additionally, comparing oak and rosewood on their response to various coatings results in an unexpected finding. The curvature of the oak veneer increases with the application of coatings, while the curvature of rosewood decreases. The oak veneer presents the expected results, with coating the veneer on one side a bilayer structure is created. As mentioned in the literature study, and based on studies such as Rüggeberg and Burgert (2015), the creation of a bilayer should result in a curvature response. A possible explanation for the unexpected performance of the rosewood veneer can be related to the properties of this specific wood species. Rosewood naturally contains high levels of oils and waxes, limiting the wood's ability to absorb moisture (Ross, 2010). By coating the material on one side, the surface area that is able to absorb moisture is limited even more. Since more water absorption leads to a more extreme resulting sagitta, the introduction of coating to the rosewood decreases its resulting curvature.

Veneer cut orientations

The results of the veneer cut orientation test show that quarter cut veneer presents a more reliable result than flaw sawn veneer. Similarly as explained in the literature, quarter cut veneer results in a uniform fiber structure while flaw sawn veneer does not.

Sample aspect ratio

The results of the aspect ratio test reveal that the size of the sample has no influence on the resulting curvature. Both samples with varying sizes result in the exact same sagitta value.

Fiber direction

From the results it became clear that the curvature direction of the veneer is always perpendicular to the fiber direction, as is supported by the literature (Ross, 2010; Rüggeberg and Burgert, 2015; Wagenführ et al., 2023). Comparing samples with the same size, placing the fibers along the length will visually result in the most extreme amount of curvature.

Wood programming

From the results it becomes clear that soaking the samples for 15 minutes instead of 2 minutes leads to higher sagitta values. Soaking the samples for a longer period of time allows the wood to absorb more moisture, leading to more extreme curvature. The soaking temperature positively influences the resulting sagitta. With the highest sagitta value for 85 °C. As explained in the literature, the glass transition temperature of wood lowers significantly when saturated and is between 60 °C and 90 °C. The literature also explains how the wood could be damaged with temperatures too high, affecting the material structure and thereby the natural curvature response of the material. Although the test revealed 85 °C resulted in the most extreme curvatures after the wood programming, a temperature this high might not be beneficial to the intended goal of the material: to create a sample with a repeating dynamic curvature response.

Coating

The results suggest that a coating can result in more extreme curvature results than without a coating. Indicating that a bilayer structure can improve the curvature response as is mentioned in the literature.

Coating the NIC and NOC side resulted in limited curvature results. A possible explanation for this result is the ability of the material to absorb water. Since the coating is waterproof woodglue, it likely prevents moisture absorption through the coating. By coating both sides of the material, the surface area through which moisture could be absorbed is extremely limited. Since the amount of water absorption is related to the resulting curvature, coating the wood on both sides results in a lack of curvature.

Coating the material on the NOC side resulted in the most promising curvature results. This can be related to the natural curvature direction of the material. Coating the material on the NIC side could result in resistance against the natural curvature direction, while coating the NOC side can support the natural curvature direction and positively influences the amount of curvature.

The results also show the amount of coating layers positively influencing the resulting curvature for a NOC side coating. This finding is in line with the findings of Rüggeberg and Burgert (2015), where it is stated that the thickness ratio between the layers of a bilayer structure has a significant influence on the resulting curvature.

Drying Orientation

The drying orientation was tested to determine whether this would influence the curvature response. The results show there is no difference in resulting curvature between drying the samples on the NIC side or NOC side. The samples that were dried on their side have resulted in a sagitta value that is 0.5 mm lower. Since the veneer is a natural material where every piece has a slightly different structure, it can not be expected that every curvature result is the same. It is therefore not clear that the drying orientation is what caused this minor difference in curvature result.

Although a wide variety of variables has been tested in this phase, a lot of values remain not tested. For example the soaking time variable. From the tested values, a 15 minute soaking time has resulted in most promising results. However it remains unknown whether even longer soaking times would result in better results. For each variable there is still much more to learn but due to the time constraints of this project, not everything could be tested.

Conclusion

This chapter explored the curvature response of wood veneer through wood programming. By testing different variables and combinations of variables, the results provide insights in the curvature response of the material.

From the findings, the resulting material with which further testing will be done is a quarter cut oak wood veneer with the fiber direction along the width of the sample. Coated with wood glue on the NOC side, programmed at 60 °C for 15 minutes (figure 20 & 21).

The oak was chosen as the wood species to continue with for several reasons. In comparison to rosewood, oak is able to absorb more moisture and therefore result in more curvature. Additionally, oak presented much more predictable results compared to the other wood species.

For the veneer cutting orientation, quarter cut presented most reliable results because of the uniformity of fibers.

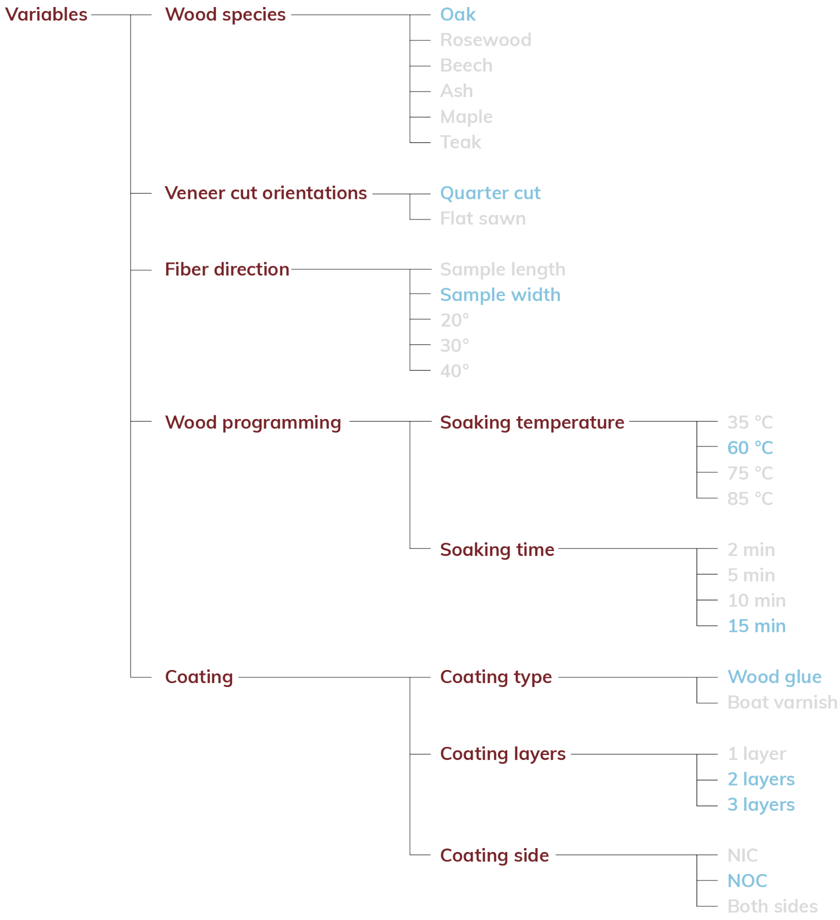


Fig 20. Chosen variable values to continue researching.

The fiber direction was chosen to be placed along the width of the samples for the following test phases. This direction provides most curvature visually and therefore simplifies measurements.

The soaking time of the wood programming stage was chosen to be 15 minutes because it resulted in most extreme curvature results. The soaking temperature to continue with was chosen to be 60 °C. The results showed the highest sagitta values to be at 85 °C. However, considering the goal of the material is to have a repeating dynamic curvature response, lower temperatures are preferred to limit damaging the material structure and its natural curvature response.

The coating was chosen to be wood glue coating on the NOC side of the material because this resulted in the highest sagitta values. A consideration for the following tests is the positive influence of the amount of coating layers on the curvature.

Lastly the sample aspect ratio and drying orientation are considered non-influencing variables and will not be considered in following tests.

The insights gathered in this chapter are essential for the creation of the guidelines. These findings define the material, moisture-responsive wood veneer, and will therefore be central in the design phase.

In the next phase, the dynamic performance of the material will be tested by reintroducing moisture to the dry curved samples. During these tests, there will be a focus on the bilayer configuration. Testing thickness ratios through the amount of coating layers.

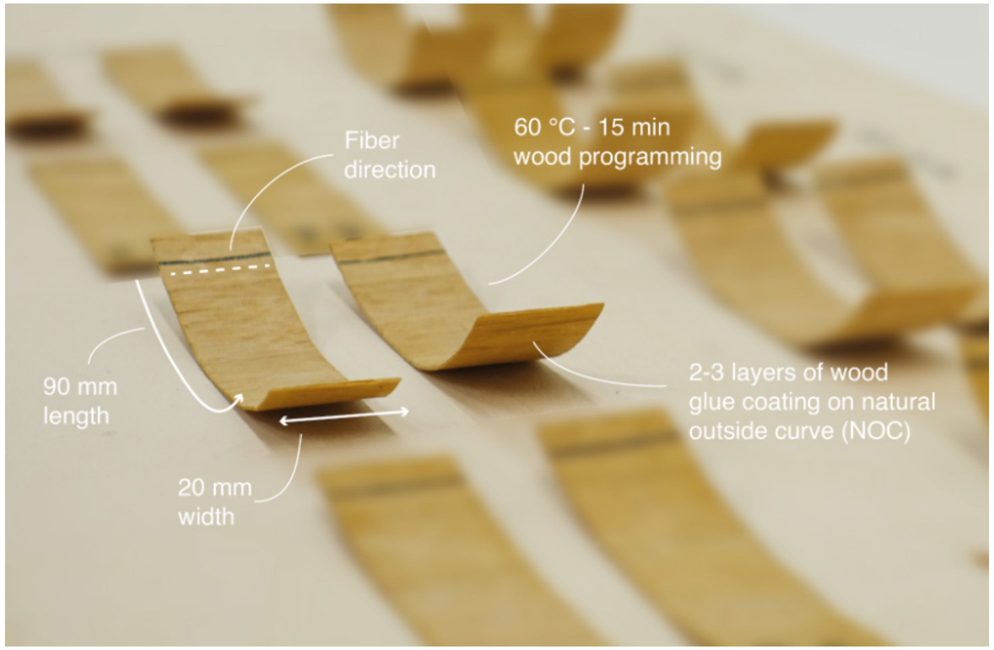


Fig 21. Visual representation of the chosen material with its variables for future tests.

3.3 Dynamic performance evaluation of programmed wood veneer

This chapter tests the dynamic performance of the material when subjected to moisture. The samples tested in this phase have been made according to the method explained previously, starting with a programmed curvature. The goal is for the samples to change their curvature when subjected to moisture and return to their programmed curvature when dry again.

With these tests, the influence of the coating strategies on the dynamic performance is explored. By testing the difference in performance with samples with and without coating and later testing the influence of the amount of coating layers.

Method

With this test the wood samples are submerged in a water bath of 22 °C for varying periods of time. After being taken out of the water, the samples are weighed and the sagitta and chord are measured. The samples are then set to dry and the sagitta and chord are measured again after drying.

The goal in the end is for the dynamic performance of the wood to be activated by changes in humidity, environmental moisture. By submerging the samples in water, the response of the samples is not a very accurate representation of the response that would occur with relative humidity changes. This is because the moisture content in the wood changes at completely different rates, influencing the amount of curvature and the speed at which the samples change curvature. It does however predict the type of performance very quickly, such as the direction of curvature. The test setup with the equipment used can be seen in figure 22.

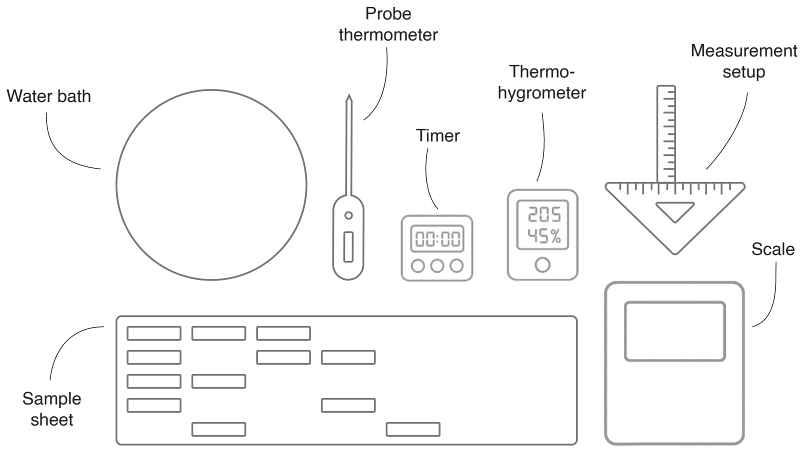


Fig 22. Test setup of water submersion. The test setup contains a water bath, probe thermometer, timer, thermo-hygrometer, sample measurement setup, the sheet with samples and a scale.

Results

The results show a difference in dynamic performance of samples with and without a wood glue coating. The samples without the coating start with a programmed curvature (to the NIC side), flatten as they are submerged and bend back to their starting curvature after drying.

The samples with wood glue have presented very interesting behaviour. They start with a programmed curvature to the NIC side and become flat while being submerged. However, when these samples are drying, they first curve to the NOC side, then become flat again, and finally return to their initial programmed curvature to the NIC side.

The samples with a wood glue coating thus have a bidirectional dynamic curvature performance. The amount of coating layers has shown to influence the amount of curvature. In figure X these results can be seen. Different amounts of coating layers are compared from one to three. With an increase in coating layers, the curvature towards the NOC side becomes stronger, as is reflected in lower negative sagitta values. Resulting in a larger total amplitude of movement. The table with all samples with their properties and measurement results can be found in appendix C.

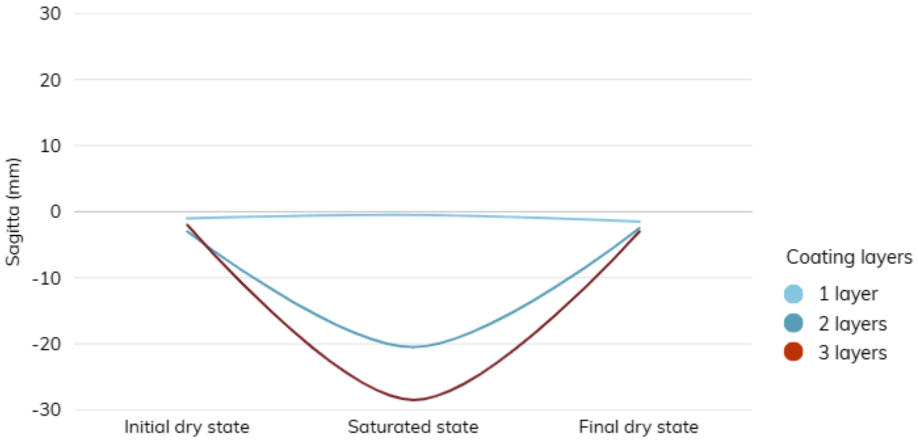


Fig 23. The influence of amount of coating layers on the change in amount of curvature, expressed as the sagitta in mm. The curvature is measured at three points over time: before the test with dry samples (initial dry state), right after the samples have soaked in water (saturated state) and after the test when the samples have completely dried again (final dry state). A positive sagitta represents a curvature to the NIC side and a negative sagitta represents a curvature to the NOC side.

Discussion

The samples coated with wood glue showed a bidirectional dynamic performance while drying. Starting from a flat sample when saturated, they first bend opposite to the natural curvature direction to the NOC side when drying and then return to the natural curvature direction (NIC side). This behaviour can be related to bilayer structure of wood and glue, which differ a lot in moisture absorption and desorption rates. After soaking, the glue layer, which contains less water, dries and shrinks faster than the wood. As this layer is shrinking, the wood is stretched over the glue, causing the bending to the NOC side. As the drying continues, the wood starts to release moisture, shrinks, and the sample gradually returns to its original curvature.

The effect that more coating layers result in a larger total curvature amplitude can be related to the influence of the bilayer thickness ratio as discussed in the literature. Changing the amount of coating layers subsequently changes this bilayer thickness ratio.

Conclusion

To conclude the main findings of this phase, a wood glue coating on oak samples results in a bidirectional movement of the samples. With more glue layers, more curvature is seen, making the range of movement more extreme. This finding has implications for the content of the guidelines. In possible design applications, the amount of movement could be controlled. For example by alternating the placement and thickness of the coating, a specific type of curve can be created.

Connecting these findings with the previously defined material, the performance connected to the material is now determined. A responsive wood veneer that curves bidirectionally under the influence of changes in moisture.

In the following chapter, the performance of the material will be investigated further in a more controlled environment to see the effects of humidity changes on the material.

4

CLIMATE CHAMBER TESTING

From the experimental testing phase, the response of the material to moisture has been tested by soaking the samples in water. To learn more about the material performance based on humidity changes, the samples are tested in a climate chamber with a controlled environment.

This chapter combines all climate chamber tests that have been conducted. First the overarching method is explained along with the data processing and analysis. Then each test is described iteratively with its unique method, results and discussion. Afterwards an overall conclusion ties all the findings together.

4.1 Method

The climate chamber tests evaluate the response of wood veneer samples to fluctuating humidities. The samples are placed in the climate chamber where the temperature and humidity can be controlled. The climate chamber is programmed in advance of the test with a constant temperature of 20 °C and varying humidity cycles based on the test. As the program runs, a camera records a timelapse for later analysis of the curvature changes in relation to the program.

Materials & equipment

For these tests, an ESPEC SH-661 climate chamber was used. In order to record the results, a camera on a tripod was placed in front of the climate chamber. Inside of the chamber, a white backdrop was made by bending a piece of acrylic. 3D printed clips are taped on this backdrop to hold the samples in place. The setup can be seen in figure 24.

The samples used in the climate chamber tests were 20x90 mm pieces of 0.6mm thick quarter cut oak veneer with fiber directions along the width of the samples. A 3 layer woodglue coating was applied to the NOC side of the samples. Lastly the samples were programmed in a hot water bath of 60 °C for 15 minutes. These specific sample specifications were chosen based on the results of the previous experimental tests.

For all climate chamber tests, the samples were placed in the same orientation with the NIC side of the sample to the right. This ensured the results between the different tests were comparable in response to low or high humidities.

Although the climate chamber provides a controlled environment to test in, there was also a limit to the humidities that could be tested. At 20 °C the lowest humidity the climate chamber could reach was 30% and the highest 95%. Only at higher temperatures could a drying environment exist, resulting in the limits of the climate chamber determining part of the testing range.

Procedure

Each test was conducted based on a unique program. For all tests the temperature remained constant at 20 °C and the humidity pattern varies per test. The climate chamber could be programmed in steps, where each humidity value is related to a time interval and either stays constant or changes linearly.

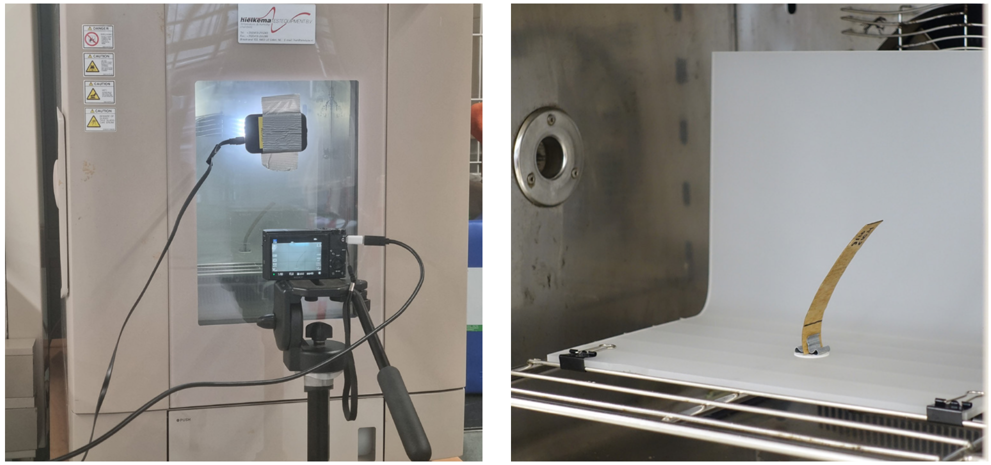


Fig 24. Test setup of climate chamber tests. The outside of the climate chamber (left image) including a light and camera setup. And the inside (right image) with a bent acrylic backdrop with the sample secured on the backdrop with a clip.

4.2 Data processing & analysis

Linking the recorded images to the program (figure 25) allows for analysis of the sample performance at every stage of the program. The images are combined into a timelapse using Adobe Premiere Pro and synchronized to a timecode representing the actual elapsed test time. The graph displaying the program is animated to the timecode, linking the timelapse of the sample to the exact stages of the program, allowing the sample's performance to be evaluated.

To visualise the amplitude of the sample at every cycle, reference markers were edited in the video at the end of every holding time. This is when the sample is supposed to reach its maximum curvature to each side. The markers are placed at the end point of the sample, visualizing the different amplitudes of the sample each cycle.

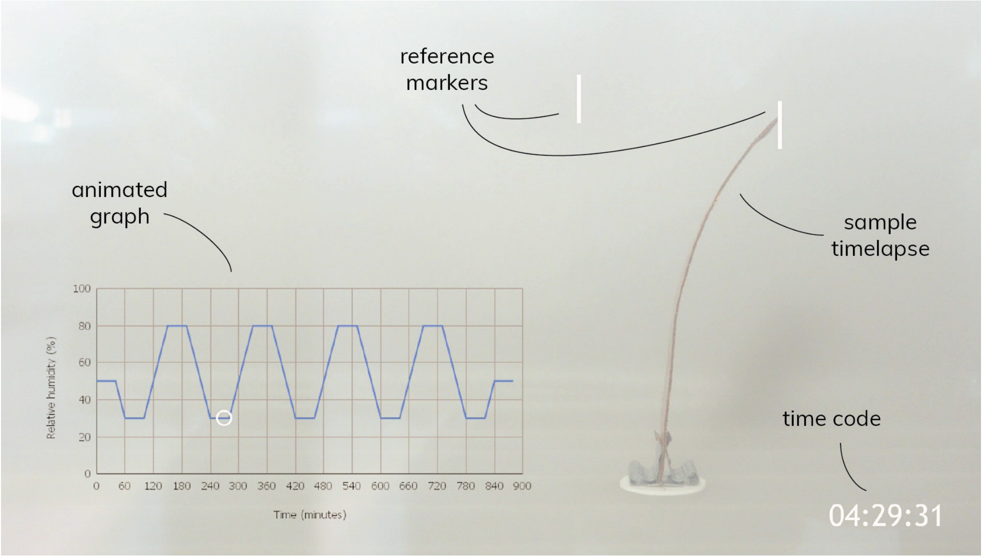


Fig 25. Data analysis method using recorded timelapse. The videos are edited to include a timecode, reference markers, the sample timelapse and an animated graph to connect to the timelapse.

4.3 Sample response to humidity changes

This first climate chamber test aimed at testing how the material responds to humidity changes from 30% to 95%. Based on the experimental tests, it was known that with induced moisture, the sample bends towards the NOC side. Therefore it was expected that this behaviour would be replicated when the RH in the climate chamber increased.

Climate chamber program

Figure 26 shows the program followed by the climate chamber in this test round. It follows one cycle, with constant holding times of 30 minutes and a 1% RH change per minute. The program shifts from 50% RH to 30% RH to 95% RH and ends at 50% RH. The total duration of the test was 4 hours and 20 minutes.

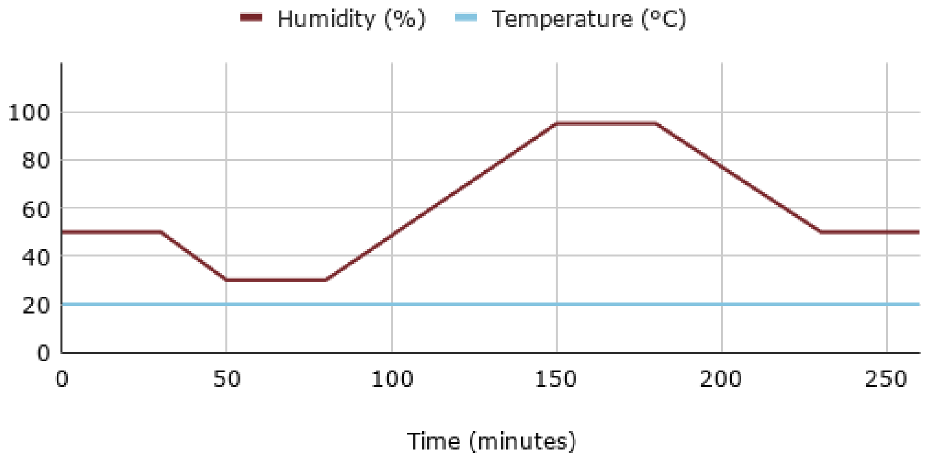


Fig 26. Climate chamber program

Results

The tests in the climate chamber have shown that the samples move towards the NIC direction when the RH is low and they curve to the NOC with a high RH. Figure 27 shows four measurement points connected to the program of the climate chamber.

Comparing the second and the last measurement point at 80 and 260 minutes, the curvature at 260 minutes where the RH is 50% is more extreme than the curvature at 80 minutes where the RH is 30%. The RH at minute 30 and 260 is the same but the amount of curvature is very different.

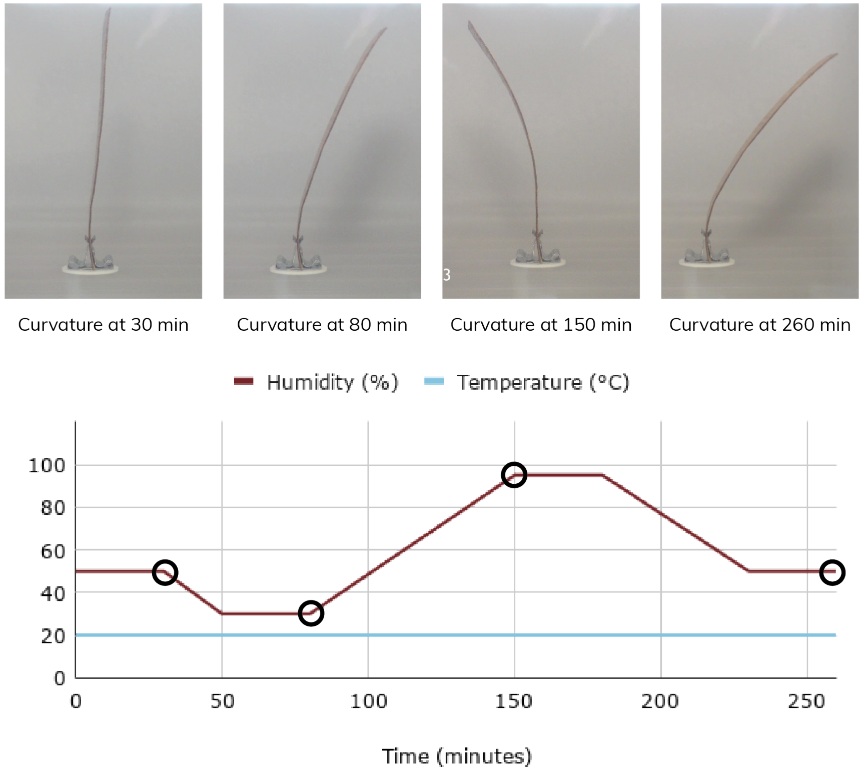

Curvature at 30 min
Curvature at 80 min
Curvature at 150 min
Curvature at 260 min

Fig 27. Sample curvature related to the climate chamber program. The graph shows the constant temperature of the climate chamber and changing relative humidity over time. The dots correspond with the times at which the photos are taken.

Discussion

The results from the test in the climate chamber show the change in curvature with changing RH, where a low RH results in curvature to the NIC side and a high RH in curvature to the NOC side, confirming the initial expectations.

Interestingly, the curvature to the NIC side at 260 minutes and 50% RH is more extreme than at 80 minutes and 30% RH, even though it would be expected that a lower RH would result in more extreme curvature. Additionally, at 30 minutes there is almost no curvature visible but at 260 minutes the curvature is at its most extreme point and at both of these moments the RH was 50%. These results can be explained by the history dependency of wood moisture response as explained in the literature by Pournou (2020). The curvature is dependent on the state prior. At 30 minutes and 50% RH, the sample was just placed in the climate chamber and a limited amount of moisture had entered the wood. At 260 minutes and 50% RH, the sample was exposed to 95% RH prior. Meaning there was a lot of moisture in the wood to release when moving back to 50% RH, creating the extreme curvature.

This test revealed the bidirectional curvature response of the material to changing humidity cycles. The following test will explore the influence of multiple of the cycles on the material, testing the fatigue.

4.4 Exploratory cyclic fatigue testing

The longevity and durability are fundamental components of material performance. To test these, the following cyclic test was performed in the climate chamber. Through testing multiple humidity cycles, the aim was to define the moisture fatigue resistance of the material. Observing whether a loss of performance occurs over time and the span of multiple humidity cycles.

Climate chamber program

To determine the fatigue of the material, the test exposes the sample to a program that follows multiple identical cycles of RH changes over time. Figure 28 shows the program that the climate chamber followed. In order to let the sample acclimatize to the environment in the climate chamber, the program begins and ends at 50% RH, similar to the approximate RH in the lab. In between the program follows four identical cycles where the RH shifts from 30% to 80% with a 1% RH change per minute. At both extremes there is a holding time of 40 minutes before the program continues to the following humidity ramp. The total duration of this test was 14 hours and 40 minutes. Throughout the entire program, a constant temperature of 20 °C was maintained.

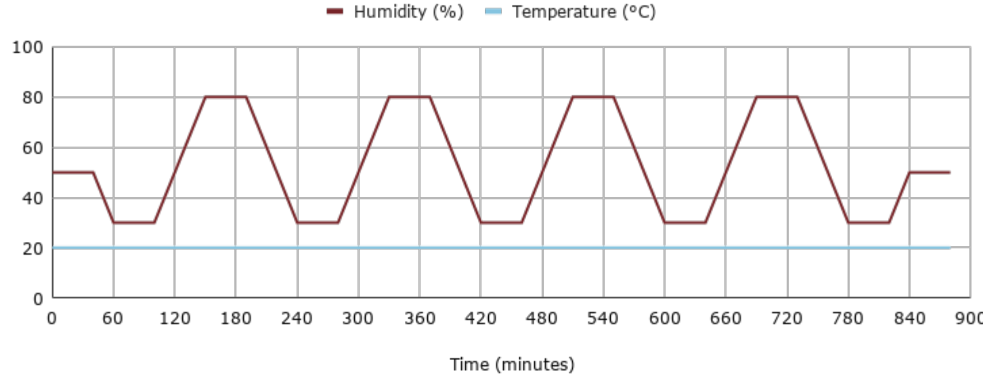


Fig 28. Climate chamber program

Results

Throughout the program, the sample showed a repeated bending response. With curvature towards the NIC side at low RH values and curvature towards the NOC side with high RH values. When the program reached the holding times at 30% RH and 80% RH, the sample continued the curvature until the end of the holding time.

Figure 29 shows a videoframe of the last cycle of the program. The white reference markers indicate the amplitude of the sample during the first cycle, while the blue reference markers indicate the amplitude at the subsequent three cycles. Although the deformation amplitude remains comparable across all cycles, a displacement of the reference markers can be observed between the first and later cycles.

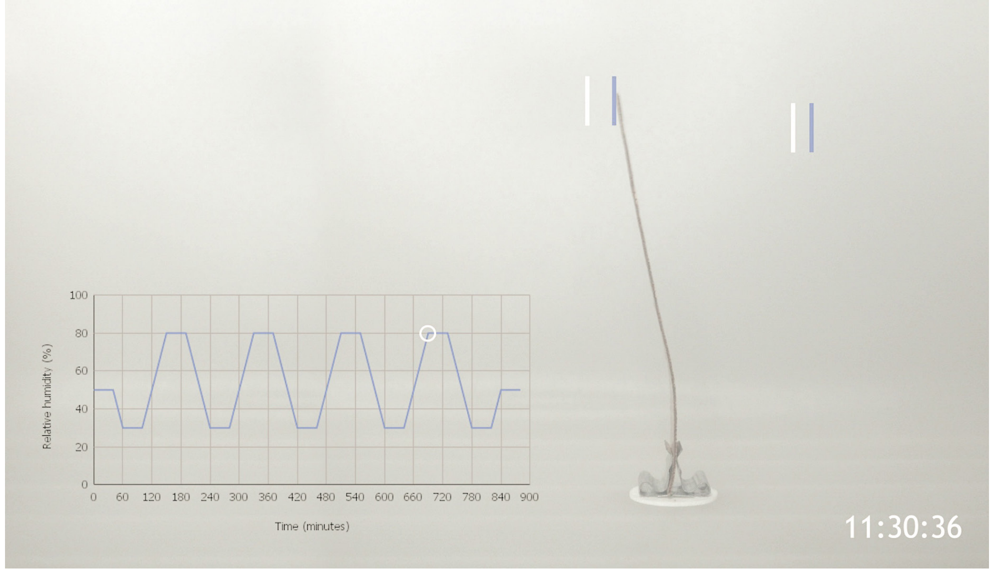


Fig 29. Videoframe of data analysis. White reference markers next to the sample indicate the sample amplitude during the first cycle and the blue refernce markers indivate the sample amplitude of the remaining three cycles.

Discussion

The observed displacement in the results indicates a cumulative drift in the sample position after the first cycle. This suggests that the first cycle represents a calibration phase in which the sample is adjusting to the environmental conditions in the climate chamber. This calibration effect is likely caused by the difference between the internal moisture content of the material and the RH in the climate chamber imposed by the test program.

After the first full cycle, the sample has been exposed to all RH levels tested in the program, which appears to influence the response to the following cycles. From the second cycle onward, the deformation amplitudes remain comparable, indicating stable performance. This suggests no clear fatigue effects develop during the duration of this test.

However when identifying the first cycle as a calibration cycle, only three cycles remain for the assessment of the fatigue behaviour. Although the lack of observable fatigue is promising, the amount and quality of the data are insufficient to draw strong conclusions about the long-term durability of the material. To obtain more data, this test should be repeated with a greater number of cycles. Additionally, quantifying the deformation amplitude would improve the quality of comparison between cycles. These findings have implications for the continuation of the testing phase. For future climate chamber tests, the first cycle should be considered a calibration cycle and excluded from the performance analysis.

4.5 Holding time optimization

In the previous climate chamber test, it was observed that the movement of the sample continues during the holding periods at constant RH during the program. To improve the understanding of the material response and optimize the test program, the influence of holding time on the deformation amplitude is tested. Based on observations from previous tests, a holding time of 30 minutes resulted in continued movement of the sample until the end of the holding period. It is however unclear whether extending the holding time would lead to an increased deformation amplitude, or how shortening the holding time would affect the sample's response.

The aim is to determine the optimal holding time that allows the sample to reach its maximum curvature. This is tested by varying the duration of the holding time at 30% and 80% RH. Based on earlier observations, it is expected that the ideal holding time is at least 30 minutes. Holding times that are too short are expected to disrupt the sample's movement, as they would interrupt the continuous movement.

Climate chamber program

In order to determine the ideal holding time, a climate chamber program was designed with multiple cycles, each varying the duration of the holding time. Although the expectancy is that the ideal holding time is at least 30 minutes, this test exposes the sample to both shorter and longer holding time in order to identify an optimal balance.

Figure 30 shows the climate chamber program of this test. It follows three cycles where the RH shifts from 30% to 80% with a 1% RH change per minute. The program starts and ends at 50% RH to let the sample acclimatize. The first cycle is considered to be the calibration cycle with a holding time of 30 minutes. The second cycle tests the longer holding time of 60 minutes and cycle 3 has a shorter holding time of 5 minutes. The total duration of this test was 10 hours and 30 minutes. Throughout the entire program, a constant temperature of 20 °C was maintained.

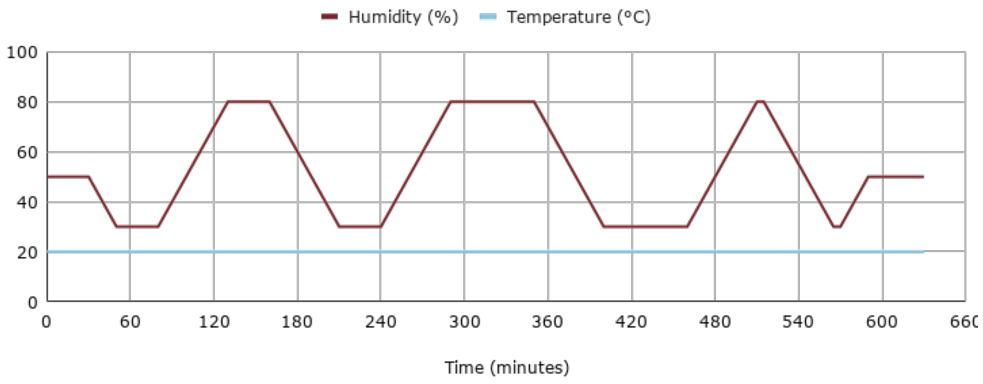


Fig 30. Climate chamber program

Results

During the first phase of cycle 2, as the RH increases to 80%, the sample bends towards the NOC side. At 290 minutes, when the RH enters the holding phase at 80%, the sample loses curvature in the NOC direction and begins to bend back towards the NIC side (figure 31). In the second phase of cycle 2, as the RH decreases to 30%, bending towards the NIC side continues. The maximum curvature is reached approximately 30 minutes into the holding period at 30% RH. The sample remains at this maximum curvature for an additional 30 minutes, to the end of the holding time.

In contrast to the varying responses at 30% and 80% RH observed in cycle 2, the response during both holding periods in cycle 3 is similar. The sample does not complete its movement within the 5-minute holding times and continues bending beyond the holding phases as the program progresses. During the initial increase to 80% RH, the sample bends towards the NOC side and continues as the RH begins to decrease. The sample changes bending direction and begins to bend towards the NIC side after approximately 20 minutes of the decreasing RH ramp, at around 60% RH.

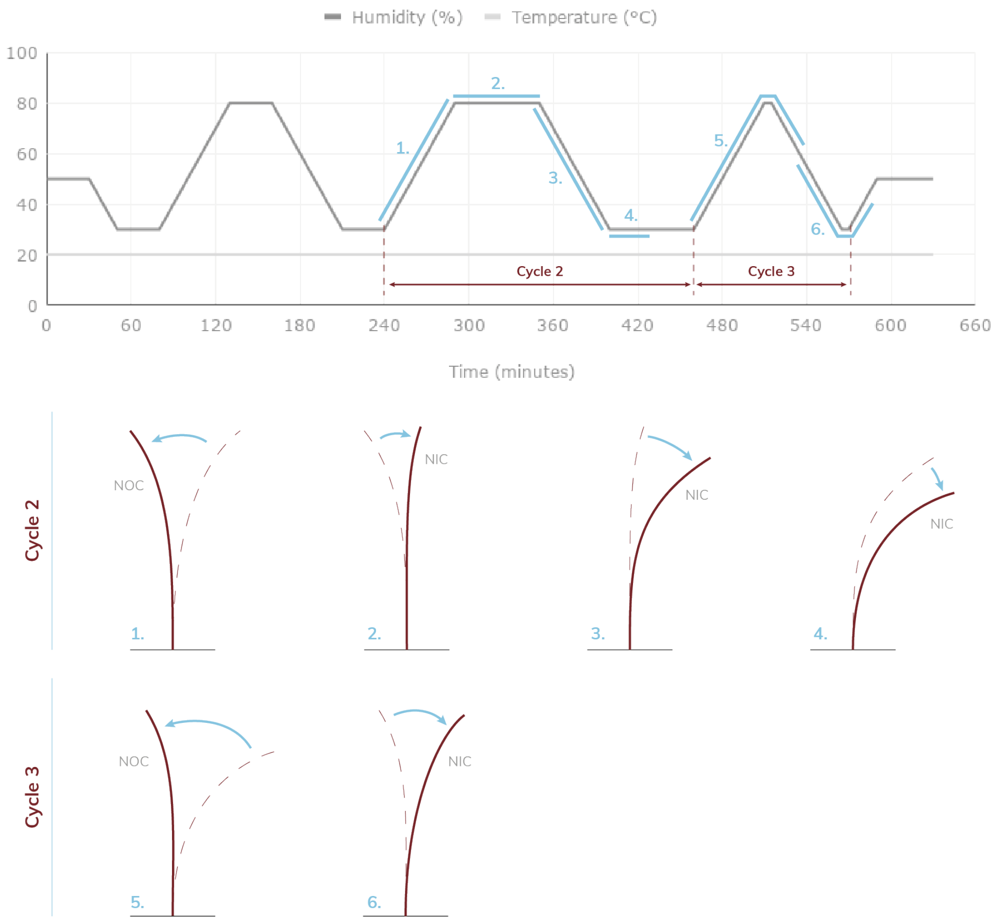


Fig 31. Sample movement directions during cycle 2 and 3 of the climat chamber program.

Discussion

The loss of curvature is an unexpected performance that only occurs at a constant high RH but not at a low RH. The limitation of this test is the lack of repeated cycles. Each holding time is only tested in one cycle, therefore it is unclear if this unexpected performance is an experimental error or reflects the true response of the material.

The result of the continuation of movement after 5 minutes confirms the importance of the holding time. The sample has not completed its movement before the end of the holding time. Therefore instead of moving in the opposite direction when the RH ramp begins, the sample continues the current movement. A sufficient holding time is necessary for the sample to slow down its movement before the RH ramp begins and curvature in the opposite direction is expected, confirming the initial expectations on the effect of short holding times.

The ideal holding time can be derived from the results by comparing the curvature responses of 5 minutes vs 60 minutes. Because the movement continues after the holding time in cycle 3, the duration of the holding time should be longer than 5 minutes. Considering the 30% holding time of cycle 2, the curvature movement ends after 30 minutes. The remaining 30 minutes of the holding time, the sample remains at a constant curvature. Therefore 30 minutes of holding time is long enough for the sample to finish its movement before the program continues and curvature in the opposite direction is expected, again confirming the initial expectations.

A required 30 minute holding time indicates the material needs time to adjust to the changes of the climate chamber program, meaning there is a delay in response of the material with rapid humidity changes as mentioned in the literature about history dependency.

The following test will retest the fatigue of the material for an increased amount of cycles, including the established ideal holding time.

4.6 Extended cyclic fatigue testing

Building on the findings from the previous two tests, this third climate chamber test evaluates the fatigue behavior of the material over an extended number of cycles. Integrating the results of the holding time optimization test to improve the climate chamber program. The aim is to assess the material's long-term performance under repeated cycles and to generate more robust data for evaluating fatigue and cumulative drift. Based on the exploratory cyclic fatigue test, any potential fatigue effect is expected to be limited.

Climate chamber program

Similar to the program of the exploratory cyclic fatigue test, figure 32 shows the climate chamber program of this test. It follows seven identical cycles where the RH ranges from 30-80%, with a 30 minute holding time and a 1% RH change per minute in every cycle. The program starts and ends at 50% to let the three samples tested acclimatize. The first cycle is considered the calibration cycle, therefore six cycles contribute to the analysis of the fatigue.

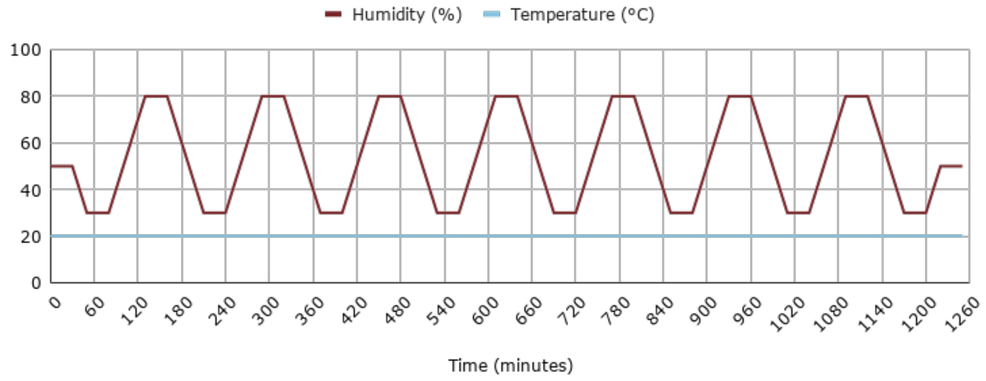


Fig 32. Climate chamber program

Data processing & analysis

The results for this test were processed in a more detailed manner than the previous climate chamber tests. Combining the reference markers with quantitative values, pixels were used as a unit of distance. By calculating the distance between reference markers in pixels, the deformation amplitude of the sample movement could be expressed. Pixels can be used as a unit in this analysis because the results of the samples are only compared relative to each other, resulting in a percentual difference of deformation amplitude between the first and last cycle of the program.

Since three samples were tested at the same time, the amplitudes (pixel distance) are calculated for each cycle per sample. The retention of the deformation amplitude is then calculated per sample by dividing the amplitude of the last cycle by the amplitude of the first cycle. The average of these values then results in a percentage of **deformation amplitude retention** of these samples.

Cycle	**Amplitude of samples (mm)**		
	Sample 1	Sample 2	Sample 3
1	36.19	44.38	38.97
2	35.88	43.61	39.74
3	35.26	42.99	39.59
4	34.79	42.84	39.59
5	35.41	42.06	38.97
6	34.95	41.75	38.81

Table 3. Amplitude values per sample per program cycle. All amplitude values are expressed in mm and reoresent the horizontal difference between the sample end points.

To make the results easier to interpret, the pixel measurements are converted to millimeters. The length of the samples in these tests was 90 mm. In the timelapse video, this corresponds with a distance of 582 pixels. Meaning that 1 pixel is equal to 0.155 mm.

Results

Table 3 shows the values of every sample amplitude per cycle. The deformation amplitude retention of sample 1 is 96.6%, 94.1% for sample 2 and 99.6% for sample 3. Resulting in an average amplitude retention of 96.8%

Identical to the results of the holding time climate chamber test, the samples showed a loss of curvature at the 80% holding time. At the 30% holding times the sample continued their movement until the end of the holding time.

Discussion

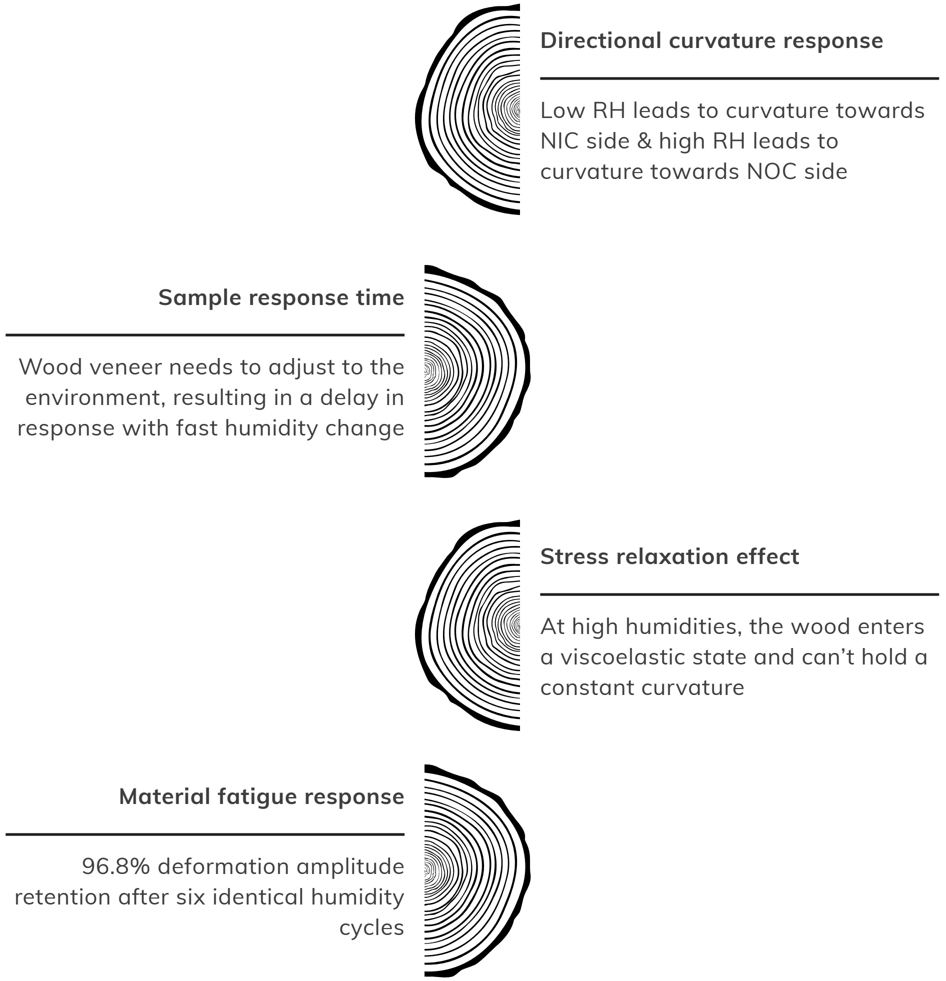
The results show a deformation amplitude retention of 96.8% based on all three samples over six humidity cycles. Indicating that a limited amount of fatigue occurs as was expected.

The loss of curvature at high humidities as seen in the results of the holding time climate chamber test, is also seen in this climate chamber test repeated over all cycles. Therefore this effect can be described as a systematic material characteristic rather than an experimental error. This behaviour is consistent with the plasticizing effect of moisture on wood as mentioned in the background, where the glass transition temperature of lignin is significantly lower with the introduction of water. Although the temperature in the climate chamber was too low for the glass transition temperature to be reached, the increased humidity likely brought the material closer to a softened viscoelastic state. This would allow stress relaxation and deformation to occur, resulting in the material response with a loss of curvature.

4.7 Conclusion & implications

The climate chamber tests in this chapter have evaluated the response of wood veneer to controlled moisture changes. The findings describe the material's responsiveness to moisture, the change in response over time, and its limits in maintaining curvature at high humidities. These main findings are listed in figure 33.

Together, these findings define the material performance in fluctuating environmental humidity conditions. In order to design applications with this material, this information is crucial because it defines both the performance and limitations of the material. Findings like these, which expand the knowledge about the material performance are essential to include in the guidelines. By making the material's behaviour explicit, the guidelines support informed design decisions and help ensure that applications are suited to the material's capabilities.



Directional curvature response

Low RH leads to curvature towards NIC side & high RH leads to curvature towards NOC side

Sample response time

Wood veneer needs to adjust to the environment, resulting in a delay in response with fast humidity change

Stress relaxation effect

At high humidities, the wood enters a viscoelastic state and can't hold a constant curvature

Material fatigue response

96.8% deformation amplitude retention after six identical humidity cycles

Fig 33. Main findings of experimental testing

5

GUIDELINES DESIGN PROCESS

5.1 Design goal

This chapter presents the design guidelines developed from the experimental exploration of the moisture-responsive wood veneer. The main goal of these guidelines is to inform and inspire designers with the developed material by making its performance accessible and usable within a design context. The findings from the extensive testing phases are translated into knowledge relevant to design with, allowing designers to understand how the material works and how to work with it. The guidelines function as a design tool that connects material research to design practice.

5.2 Approach

The design process leading to the guidelines follows the double diamond method (figure 34).

Discover
Gathering information and insight through interviews and research in order to understand the user, their needs and the context in which the guidelines would be used. With ideation in the forms of mind mapping and sketching the possibilities for the guideline content, structure and form were explored.

Define
By narrowing down all the insights of the discover phase, decisions were made on what information the guidelines should convey and how.

Develop
Developing the content of the guidelines was done through material testing and sample prototyping. Resulting in an extensive amount of findings about the material performance and possibilities for sample concepts.

Deliver
The guidelines were finalised by testing the sample concepts, refining the test findings, combining everything to the design and testing the final guidelines.

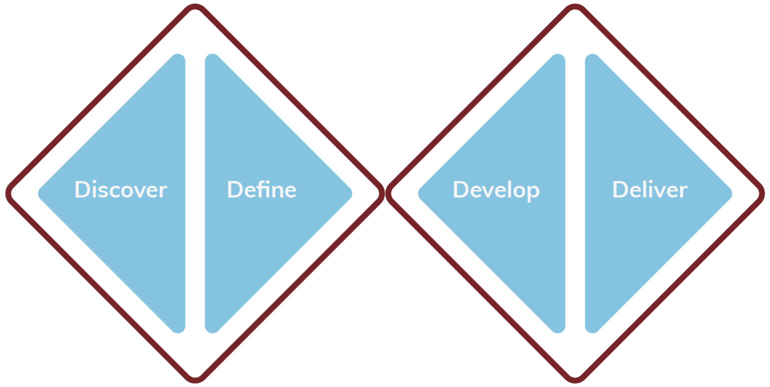


Fig 34. Double diamond method

5.3 Discover

Designer interviews

To gain more insight to the possible content and form of the guidelines, several interviews were conducted with design students. In total 4 design students were interviewed. The interviews were semi-structured with prepared questions but leaving space for follow-up questions. Each interview lasted approximately 30 to 45 minutes, they were conducted individually and took place both in person and online. The design students were asked about what kind of information they would need and want to know in order to design an application with the material. Additionally, they were asked about the potential form of the guidelines, the influence of including examples of what you can make with the material, the structure of the guidelines, what they would like to see and not want to see. These are the main insights from these interviews:

Content
- The guidelines should contain technical information about the material. Which variables influence the material performance, material specifications, how the material can be actuated, what the environmental conditions must be, etc.
- Explaining the material through system examples instead of just one sample would make the material explanation much clearer for designers. Instead of explaining the performance of the material based on one strip, combined structures can show the possibilities of movement, for example from flat to dome.
- Including failures as learning points can help users of the guidelines recognize when their own tests will not result in the expected outcome.
- Include a method on how to make the material to allow readers to recreate the samples presented in the guidelines.

Form
- The guidelines could be presented in many different forms: a booklet (similar to a recipe book or instruction manual), a digital tool such as a website or app, or a toolkit.

Structure
- With the examples starting from an overview of the possibilities and then detailing the approach on how to make it would improve the clarity of the guidelines.

Inspiration

In addition to the input from the interviews, inspiration was also found through existing works. For example the Chemarts cookbook by Kääriäinen et al. (2020). Which describes a wide variety of recipes using wood- and plant-based materials. And the paper 'Biomaterial Recipes for 3D printing: a cookbook of sustainable and extrudable bio-pastes' by Bell et al. (2025).

Content and form ideation

With ideation through mindmapping, these interview findings were combined with new ideas about the possible content and form of the guidelines (figure 35).

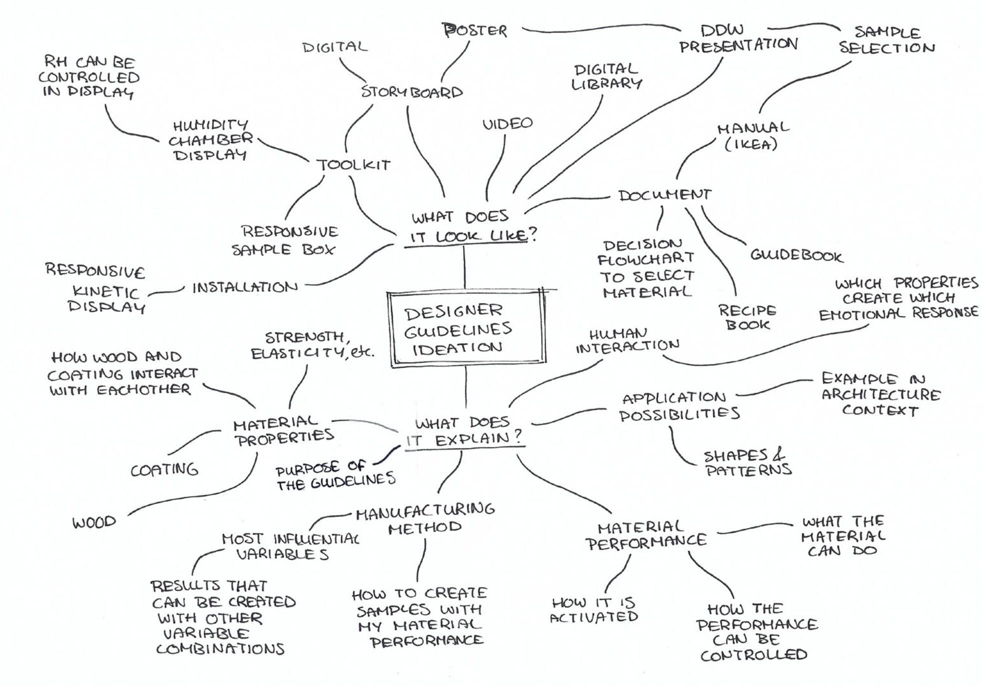


Fig 35. Mindmap of guideline content and form ideation.

5.4 Define

From the content generated in the discover phase, the main structure and content of the guidelines was determined. The guidelines should include:

- General information about the material, describing specifications and performance
- Various examples of sample structures, visualising the material performance through shapes
- Examples of possible material applications in an indoor context to show the possibilities of the material for future applications

List of requirements

Based on the insights from the interviews and ideation, combined with the defined content for the guidelines, the following requirements for the design of the guidelines were determined (table 4).

The main goal of the guidelines is to inform and inspire designers to work with the moisture-responsive wood veneer and possibly apply it to an application. The requirements are addressed in three categories: material explanation, designer guidance and design inspiration. Together the requirements in these categories address the goal of the guidelines.

The requirements for material explanation describe part of the content that the guidelines should contain. Since designers need to be able to work with the guidelines, the designer guidance requirements determine the accessibility of the information to the designers. Lastly, the guidelines also aim at inspiring designers, expressed through the requirements in the design inspiration category.

Design inspiration	
	The guidelines should inspire designers to **consider wood veneer as a design material.**
	The guidelines should **spark creativity** and broaden designers' understanding of design possibilities.
	The guidelines should enable the translation of **experiential material qualities**
	The guidelines should include **design application examples** that demonstrate experiential qualities and design potential.
Designer guidance	
	The guidelines should be **clear, easy to understand, and easy to navigate.**
	The guidelines should allow designers to work with the material **without external instructions**
	The guidelines should allow designers to **achieve the expected material performance.**
	The guidelines should specify the **required materials and equipment.**
	The guidelines should use **visuals** to support understanding.
	The guidelines should include **sample structure examples** that visually explain how structure leads to performance.
Material explanation	
	The guidelines should explain the **material performance and observable behavior**.
	The guidelines should explain **how and why the material works**
	The guidelines should identify how **key variables** influence material performance to allow designers to control performance outcomes
	The guidelines should clearly describe the **limitations** of the material.
	The guidelines should explain **how the material is made**.

Table 4. Guidelines design requirements

5.5 Develop

About the material

A large part of the content for the guidelines is the explanation about the material performance. The results from the experimental testing and climate chamber tests have resulted in the main content of the guidelines.

The experimental testing resulted in the following designed material

- 0.6 mm quarter cut oak veneer with waterproof woodglue coating on the NOC side, programmed at 60 °C for 15 min.

From the climate chamber tests, the follow performance findings were found:

- low RH towards NIC side, high RH towards NOC side
- slow response time of the veneer, cannot keep up with rapid RH changes
- At high RH, curvature can be lost
- 96.8% deformation amplitude retention after six identical humidity cycles from 30-80%

Sample structure examples

The second part of the guidelines consists of sample structure examples. The importance of the examples is to provide a visual representation of the material performance. Showing examples of sample structures make the material movement, response and characteristics more understandable. They also show a range of design possibilities, helping designers see how the material performs in a structure instead of an isolated form, making the examples an educational tool and source of inspiration.

- Designing the sample structures was done through several iterations, each time optimizing the designs based on the previous results. The main findings collected through these iterations were the following:
- With patterned structures, a tolerance is necessary between the cut-outs. With the swelling interactions of the material, without tolerance the active segments could get stuck limiting their movement.
- Assembling structures should be done after the wood programming. Mainly for structures that are assembled with glue, the wood programming softens the glue and could loosen the connected sections.

In appendix E ideation sketches of this design phase can be found.

Additionally by combining the findings from the the experimental tests and the sample structure design process the following variables were found that can be adjusted to influence the material performance:

- **Fiber directions**: visually changes curvature direction
- **Coating layers amount:** changes how extreme the curvature is
- **Coating placement**: can impact where the curvature happens
- **Aspect ratio:** visually changes how much curvature is seen

With these learnings implemented, the final sample structures for the guidelines were created. In total five structures are presented (figure 36), each with slight variations of variables to show how these impact the material in a structure.

The examples can be divided in two categories: assembled structures and patterned structures. The flower, wave and twist are assembled structures, meaning the veneer is initially cut into multiple separate segments which are connected and combined into one structure. The frame and diamond are patterned structures. These are made from a singular piece of veneer from which shapes are cut out, creating a pattern.

As mentioned previously, strategically placing the coating determines the curvature location. In the assembled structures, all sample pieces are fully coated on one side and therefore function entirely as active parts. In the patterned structures, only selected areas of the veneer are coated. This results in a division within the structure between active areas and the remaining non-active area.

Flower structure

The flower structure is the first of the assembled structures. This structure is a construction made from several individual petals which form a flower. Each petal is made from wood veneer and is glued onto a plywood base, creating a layered structure. The arrangement of the veneer petals defines the overall flower shape and fixes the sample in its final configuration. When this sample is activated by moisture, the petals appear to be opening and closing, bending towards the center of the structure (figure 37).

Wave structure

The wave structure is another assembled structure consisting of a combination of petals and a plywood base. The petals all vary in size and are ordered according to their size. They are placed on slightly varying angles relative to each other as well as slight displacements parallel to the petals to create more interest in the overall form (figure 38).

Twist structure

The twist structure is the last assembled structure. Similar to the wave structure, it is made by gluing veneer pieces in engraved lines of a base. However this structure differs from the previous because it utilizes the possibility of changing the visual curvature direction. The fibers in this

Fig 36. Figure of all final sample structures of the guidelines

structure are angled resulting in a twisting motion. The structure is made from multiple mirrored pieces of veneer combined in pairs. Each pair is glued together and the bottom edges are glued in the base. This structure demonstrates the possibility of limiting curvature through the assembly design. Without gluing the veneer pieces together, the bottom edge would twist. However, through the method of assembly, this twisting motion on one end of each veneer piece is restricted (figure 39).

Frame structure

The frame structure is the first of the patterned structures. It is one piece of veneer from which lines are cut, creating various frames. The frames in this structure are considered the active areas, while the surrounding material is expected to remain flat. The fiber direction is placed vertically on the structure. In combination with the direction of the cut-outs, this results in frames moving back and forth. An important aspect of a patterned structure like this is the required tolerance spacing. Since the frames are expected to move through the surrounding material, a slight spacing is required to prevent the surrounding material from blocking the movement of the frames (figure 40).

Diamond pattern

The diamond pattern is the last patterned structure. It is made similarly to the frame structure where certain areas of one veneer piece are cut out. However, this structure is made from two layers of veneer. In comparison to the frame structure, the diamond pattern relies on the second veneer layer to limit the movement of the non-active area of the sample. The fiber directions of this second layer are placed horizontally, perpendicular to the vertical fiber of the first layer. Layer 1 includes the active parts of the structure. To prevent restriction of the movement, layer 2 has cut-outs in the exact place of the active parts (figure 41).

Inspiration

The last chapter of the guidelines shows visual examples of possible applications. These images were generated with AI to clearly communicate the design ideas with a high degree of visual realism. The ideas behind the images are based on an indoor architectural design context. Through interviews with designers, additional ideas for applications were discussed. These are also implemented in the inspiration chapter.

Fig 37. Flower structure

Fig 38. Wave structure

Fig 39. Twist structure

Fig 40. Frame structure

Fig 41. Diamond pattern

5.6 Deliver

In this last design phase, the final guidelines were created and written. However in this phase many iterations occurred. The guidelines were tested in three parts: Sample structure functional tests, guidelines testing through workshop and guideline evaluation through interviews with professional designers. Each of these test phases resulted in new content for the guidelines or improvement of the already existing content.

The functional sample structure tests mainly provided new insights in the performance of the material based on these specific sample structures. This was useful information to include in the guidelines, being able to say something about the curvature response of these specific structures over time. The full method of these tests and subsequent results and conclusions are written in the following chapter 6, sample structure tests.

The guidelines themselves were also tested with design students. Here the goal was to test how well the information of the guidelines is transferred and how well the guidelines inform designers. Based on reading the guidelines, the participants were asked to make their own sample structures, allowing for analysis of the clarity, effectiveness and creativity of the guidelines. Additionally a material experiential characterization was conducted. This test resulted in a lot of insights about the guidelines in the current format and improvements to be made on the guidelines. Chapter 7 explains this full testing phase, with the results and conclusions for the guidelines.

Lastly, the guidelines were evaluated through an interview with a professional designer. The goal was to gain insight into how the guidelines would function in a professional design context. The interview focussed on exploring the potential of the responsive wood veneer and the role that the guidelines could have in a design process. The interview was conducted in person and lasted approximately one hour. Audio recordings were taken during the interview to capture the responses.

During the interview, several sample structures were shown to the expert. The designer showed interest in the material and immediately started generating ideas for possible applications. This included ideas to use the material for acoustic panels for office environments. This way the tactile and visual qualities of the wood veneer would add value. Additionally, the designer showed interest in the aesthetic possibilities of the material through coloring techniques. These ideas and discussions indicated that the material and its qualities were perceived as promising for design contexts.

When asked about the value of the guidelines in a design process, the expert indicated that this would be highly dependent on the type of designer or professional engaging with them. For product designers, the guidelines could function as a form of consultancy. Where they could be used to support the design process and as a resource of information about the material properties and performance. For interior designers, additional information about the material such as fire safety performance or acoustic properties would likely be more relevant. Lastly, he mentioned that designers with a more artistic approach might rely less on the guidelines and would prefer to do their own experimentation with the material.

During the interview, as the designer was interacting with the samples, he brought up several questions about the material and its performance out of interest to work with it. Interestingly, the answers to his questions were already explained in the guidelines before he had seen them. This validated that the information in the guidelines corresponds with the questions a designer might have and would want answered before working with the material.

To conclude this evaluation, the interview highlighted the inspirational value of the material itself, leading to ideas for possible design applications. Additionally, the discussion indicated that the guidelines could be useful as a source of information for designers working with the material.

All of these tests contributed to the finalisation of the guidelines, improving and adding on to the content. The full and final guidelines are presented in chapter 8, Guidelines design.

6

SAMPLE STRUCTURE TESTS

In order to provide an extensive overview of the sample structures in the guidelines, it is important to define the performance of the samples. In previous tests, it was observed that there is some relation between the amount of moisture subjected to the samples and the speed of movement. The goal of this test is to find how this relation can be defined.

Based on the observations, it is expected that with more moisture applied to the sample, the speed of curvature change increases. And subsequently, less moisture will result in a lower speed of movement. Next to this, it is also expected that most of the movement will be immediately after activation and the speed of the movement slows down over time.

6.1 Method

Test design

To test the influence of the amount of moisture on the speed of curvature change, the first step is to test the speed of curvature change over time. Then relate it to the amount of water uptake in the sample. This is done by spraying the samples with water and measuring the curvature of each segment of the sample in time intervals of 60 seconds. Additionally, the weight of the sample is measured before and after applying moisture to the sample.

With this method, the samples are sprayed with water trying to distribute it as evenly as possible. For further calculations it is assumed that the water is equally distributed over the surface area it is sprayed on.

There are some limitations to this method. First of all, the samples are changing curvature over time. With this method the curvature is measured every 60 seconds, however not every sample segment can be measured at the same time. This allows for some possible errors in the accuracy of the measured values. Not every segment is measured at the exact time interval. This error tried to be avoided as much as possible by splitting the measurement of one sample into groups of segments. Thereby limiting the time necessary to take the measurements at each time interval.
Every measurement of curvature is done by hand with a diameter gauge. This allows for additional room for error due inaccuracy of measuring and reading the values.

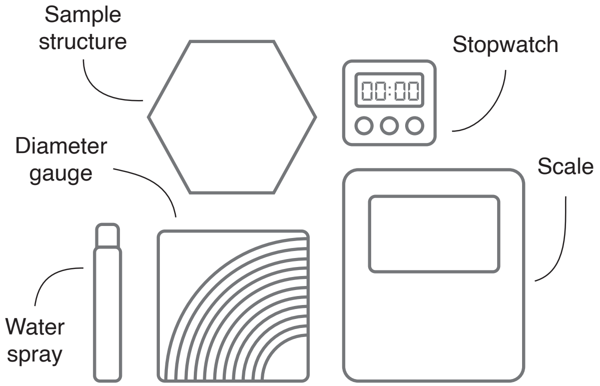


Fig 42. Materials & equipment used in the sample structure tests

Fig 43. Sample structures being tested

Materials and equipment

The test setup with equipment can be seen in figure 42. It includes the sample to be tested, a scale, a spray bottle of water, a diameter gauge set and a stopwatch.

The diameter gauge was made specifically for this test. Quarters of circles were laser-cut from 4 mm plywood, with a diameter range from 30 mm to 175 mm in steps of 5 mm. Diameters were chosen as a unit instead of radii because it provides more rounded values, improving the efficiency of measurements during the test.

Figure 43 shows the total of five sample structures that were tested. Two of which are patterned structures where the different segments are formed by cutting the pattern from a single piece of veneer. The remaining structures are created by cutting out loose segments of veneer and combining them afterwards in a structure. This method allows for manipulation of the bending direction of the segments relative to each other. These structures vary in how the segments are cut from the veneer. In the twisting structure, the fiber direction of the veneer is at a 45° angle relative to the segment length, creating a visual twisting effect.

Test procedure

The method used includes measuring the curvature diameter at time intervals of 60 seconds. The sample structures all consist of multiple segments that need individual measurements. To ensure accuracy of the measurements, the sample structures are split in segment groups. The size of the groups is determined by how fast each segment can be measured. Aiming for every measurement to be done as close to the time interval as possible. Resulting in groups of 2-4 segments being measured at once.

Fig 44. Method of measuring the curvature diameter. The figure shows the custom diameter gauge being held against a segment of the sample structure, measuring the exact curvature diameter.

The following steps explain the test procedure:

1. Weigh the entire sample structure and measure the curvature diameter of the segments being tested in the direction that they bend (figure 44)
2. Spray the selected segments with water, aiming to evenly cover the entire segments.
3. Start the stopwatch and weigh the entire sample structure again after spraying it with water.
4. Measure the curvature diameter of the segments at 60, 120, 180 and 240 seconds.
5. Repeat steps 1 through 4 until all segments of one sample have been measured.

Data processing

To process the measurement data, curvature rate and water uptake were calculated. A step-by-step explanation of each calculation is described below. Each sample was measured in two separate measurement rounds, resulting in two sets of calculations per sample.

Curvature rate calculations

In order to quantify how fast the curvature of the samples changed over time, the curvature rate was calculated. The curvature of each sample segment was measured at time intervals of 60 seconds. The samples had varying initial and final curvature values. Calculating the curvature rate over the entire measurement period would lead to results based on different curvature amplitudes. Calculating rates over an **identical common curvature amplitude** is a vital step for ensuring samples with different starting points are comparable.

Overview of Steps

1. Convert measured diameters of each sample to curvature values.
2. Calculate the average curvature at each time interval.
3. Make a scatterplot of the average curvature values at each time interval per sample measurement and fit a 2nd-order polynomial trendline to the scatterplot for each sample measurement
4. Take the derivative of each polynomial trendline equation
5. Calculate the curvature rate for each sample for t=0

Step 1
The first step was to convert the diameter measurements of each segment at all time intervals to curvature values. Curvature *k* is defined as the inverse of the radius *R*:

$$k = \frac{1}{R}$$

The radius was calculated from the measured diameter $D_{t,i}$ in millimeters, converted to centimeters, and then inverted. Resulting in the curvature for each segment *i* at a given time *t*:

$$k_{t,i} = \frac{20}{D_{t,i}}$$

Step 2
Next, the **average curvature** of all segments at each time interval *t* was calculated where *n* is the total number of samples:

$$k_{avg,t} = \frac{1}{n}\sum_{i=1}^{n} k_{t,i}$$

Step 3
A scatterplot was made with the calculated average curvature values on the y-axis and the time intervals on the x-axis. A polynomial trendline of the second-order was fitted over the five data points of each sample measurement.

Step 4
Each polynomial trendline has a fitting equation in the following form:

$$k_i(t) = at^2 + bt + c$$

Calculating the derivative resulted in equations for each sample:

$$k_i(t) = 2at + b$$

Step 5
Finally, the **curvature rate** for each sample was calculated at t=0, resulting in the curvature rates at activation.

Water uptake calculations

The water uptake was calculated to determine the mass fraction of water in a sample. The method of calculation is based on the surface areas of every sample segment and segment groups. The measurements for one sample are performed in segment groups, making the water weight increase dependent on the segment groups that were measured. Specifically the samples with varying surface areas per segment. Additionally, there are samples that contain active and non-active segments. The water uptake should only be calculated for the active segments of these samples. Normalizing the weight increase by the active surface area ensures that the results are comparable across samples with varying geometries.

Overview of steps

1. Determine the active surface area and the total surface area of each sample.
2. Calculate the material density using reference test samples.
3. Calculate the mass of each active segment.
4. Calculating the total active mass and total sample mass.
5. Determine the fraction of active material in each sample.
6. Calculate the weight increase per measurement step and the total weight increase per sample.
7. Calculate the active weight increase and active water uptake.

Step 1
The first step was to find the surface area per sample. Each sample consists of multiple segments. The patterned sample structures are singular pieces of veneer

where a specific segment of that piece is active and the surrounding area is non-active. The other sample structures are a combined system of loose segments that are all active. The **active surface area** A_i (in mm^2) refers to the surface area of a single active segment. Extracting exact surface area values from Illustrator files provides a high level of precision for calculating water uptake mass fractions. For the patterned sample structures both the active surface area and the **total surface area** A_{total} (in mm^2) were extracted from the Illustrator file. For the combined sample structures, the total surface area was calculated as the sum of all active surface areas:

$$A_{total} = \sum_{i=1}^{n} A_i$$

Step 2
To calculate the mass from the surface area, the material density is required. All samples are made from the same material and coated identically, the material density was calculated once and used as a constant in the following calculations.

The density was calculated using reference test samples with known dimensions and mass. Each test sample had dimensions of 2×9 cm, a thickness t of 0.06 cm, a surface area of 18 cm², and an average mass of 0.78 g. The density ρ was calculated with:

$$\rho = \frac{m}{V} = \frac{m}{A \cdot t}$$

With a resulting material density of
$\rho = 0.72$ g/cm^3

Step 3
Using the values for the active surface area and the obtained density, the mass of each active segment was calculated:

$$m_i = \rho \cdot t \cdot A_i \left(\frac{1}{100}\right)$$

where A_i is converted to cm^2 and t= 0.06 cm.

Step 4
The **total active mass** of the sample was calculated by summing the masses of all active segments:

$$m_{active,total} = \sum_{i=1}^{n} m_i$$

The **total sample mass** was calculated using the total surface area, where A_{total} is converted to cm^2:

$$n_{sample,total} = \rho \cdot t \cdot A_{total} \left(\frac{1}{100}\right)$$

Step 5
From these values, the **fraction of active material** of a sample was determined as:

$$f_{active} = \frac{m_{active,total}}{m_{sample,total}}$$

Step 6
In order to calculate the increase of moisture in the samples, the weight has been measured before and after applying moisture to the samples. In some samples, not all segments could be measured for their curvature simultaneously, therefore the measurements were done with groups of segments. These samples were weighed multiple times before and after applying moisture to specified groups of segments.

For each measurement step *j*, the sample mass was measured before moisture application, $m_{before,\ j}$ and after moisture application, $m_{after,\ j}$. The **weight increase** was calculated as:

$$\Delta m_j = m_{after,j} - m_{before,j}$$

Each value Δm_j related to the water uptake of a specific group of segments.

The **total weight increase of the sample** was then calculated by taking the sum of the mass increases of all measurement steps:

$$\Delta m_{total} = \sum \Delta m_j$$

Step 7
Now knowing the total weight increase of each sample, the weight increase of only the active segments of a sample can be determined. The **active weight increase** is calculated by multiplying the total weight increase by the active mass fraction:

$$\Delta m_{active} = f_{active} \cdot \Delta m_{total}$$

Finally, the **active water uptake**, WU_{active}, was calculated as the ratio between the active weight increase and total active mass:

$$WU_{active} = \frac{\Delta m_{active}}{m_{active,total}} \cdot 100\%$$

6.2 Results

The calculations above have resulted in the values shown in table 5. This table displays the calculated average curvature values per sample at every measured time interval. The negative values represent curvature when the sample is bent towards the natural inside curvature (NIC). The positive values represent curvature towards the natural outside curvature (NOC).

The values shown in table 5 are plotted in the following scatterplot with fitted polynomial trendlines per sample structure (figure 45). As an overall trend it can be seen that the samples have a similar pattern of curvature change over time. All starting at a negative curvature value (bending towards NIC) and ending in a positive curvature value (bending towards NOC). The majority of curvature change happens in the first 120 seconds. From 120 to 240 seconds, the slope of the lines flatten.

Comparing the average total curvature amplitude per sample, the flower system has the largest total average amplitude of 0.350 cm^{-1}. The smallest is the diamond pattern, with an amplitude of 0.187 cm^{-1}. Resulting in a difference between largest and smallest amplitude of 0.163 cm^{-1}.

Table 6 shows the values of the calculated curvature rate per sample and measurement round. Additionally it also shows the values for the water uptake per sample.

The values of table 6 are translated to the graph in figure 46, where linear trendlines are fitted to the data points per sample structure. For the frame and wave structure, the curvature rate increases as the water uptake increases. With the remaining structures, the curvature rate decreases as the water uptake increases.

The measurement data of all samples including the calculated values can be found in appendix F.

Measurement round	Sample	Time intervals (sec)				
		0	60	120	180	240
1	Diamond	-0,120	-0,033	0,033	0,038	0,075
2	Diamond	-0,033	0,038	0,101	0,131	0,145
1	Frame	-0,187	-0,053	0,050	0,106	0,115
2	Frame	-0,179	-0,025	0,108	0,130	0,158
1	Wave	-0,164	-0,037	0,036	0,088	0,120
2	Wave	-0,193	-0,032	0,019	0,071	0,106
1	Flower	-0,234	-0,104	0,013	0,073	0,109
2	Flower	-0,226	-0,068	0,006	0,064	0,132
1	Twist	-0,248	-0,124	-0,064	-0,016	0,014
2	Twist	-0,265	-0,155	-0,068	-0,037	0,027

Table 5. The average curvature values per sample at every time interval in cm^{-1}. These values are calculated from the measured curvature diameters. Every sample structure was measured twice, shown by the measurement round.

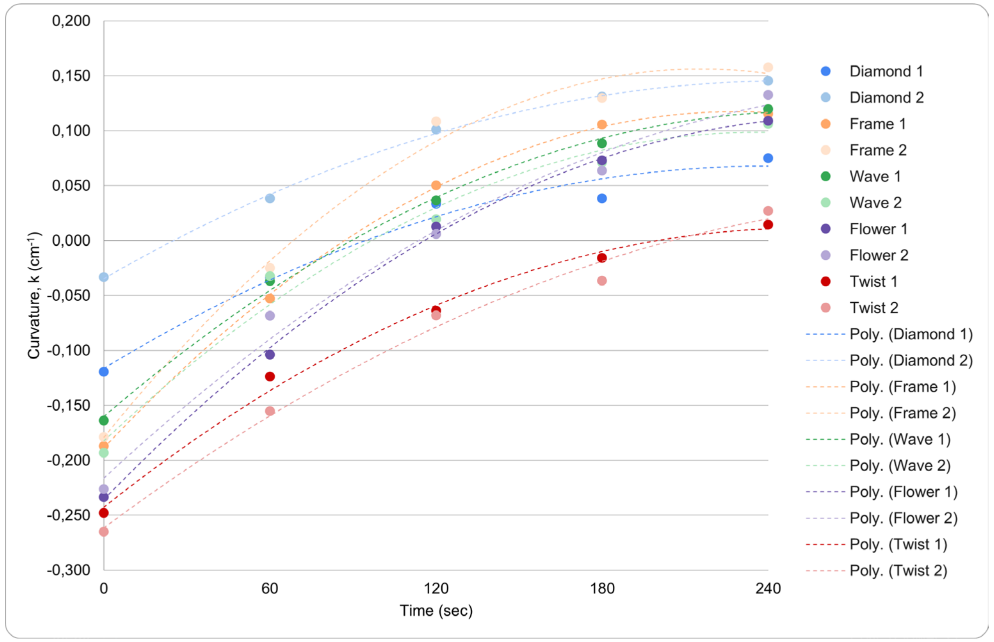


Fig 45. Graph showing the curvature values at time intervals for both measurement rounds per sample structure. With the polynomial trendlines an approximation of the uniform behavior of the samples is demonstrated with a transition from negative values (curvature towards the NIC side) to positive values (curvature towards the NOC side).

Measurement round	Sample	Curvature rate ($cm^{-1}s^{-1}$)	Water uptake (%)
1	Diamond	0,0015	9,77
2	Diamond	0,0015	9,00
1	Frame	0,0027	15,99
2	Frame	0,0031	14,87
1	Wave	0,0022	11,71
2	Wave	0,0024	17,18
1	Flower	0,0026	16,42
2	Flower	0,0023	21,72
1	Twist	0,0020	26,91
2	Twist	0,0019	21,11

Table 6. The calculated curvature rates and water uptake of every sample structure per measurement round.

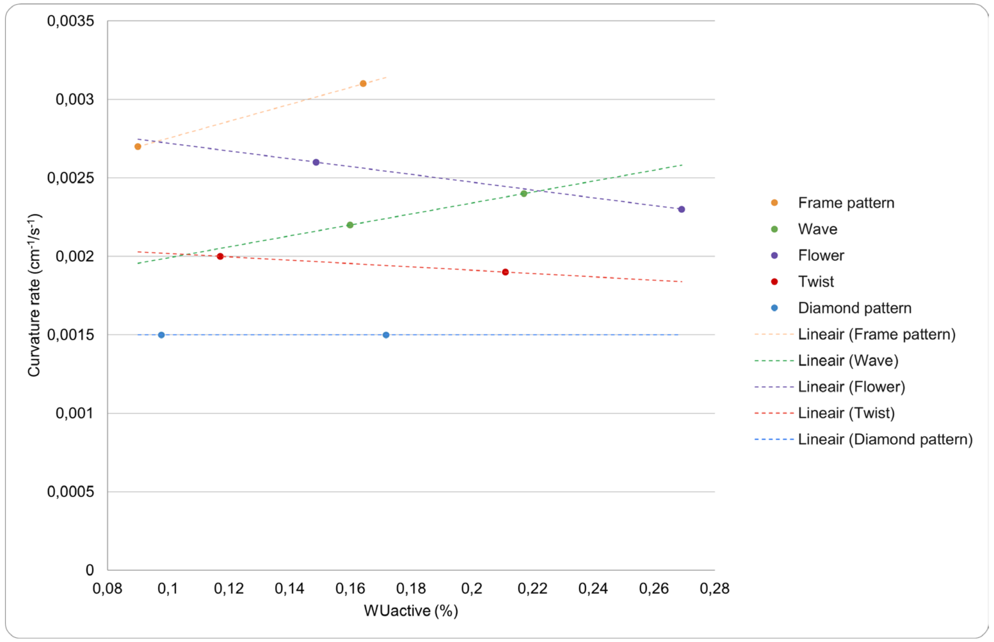


Fig 46. Graph showing the curvature rate per sample structure in relation to values for water uptake of the active sample segments. Linear trend lines are fitted to connect the calculated data points.

6.3 Discussion

Similar results can be seen for all sample structures in terms of curvature behaviour regardless of their initial curvature. All samples follow the same path of movement, starting from a negative curvature value and moving towards a positive curvature value. This can be related to the experimental testing and climate chamber testing findings where the directional curvature response of the material was described. With an increase of moisture, the material bends towards the NOC side. While the samples are drying, the curvature returns to the NIC side. The samples tested in this chapter were all programmed and had a resulting reference curvature towards the NIC side (a negative curvature value). As moisture was introduced, the samples began changing curvature towards the NOC side. Therefore the curvature of all samples starts negative and changes towards positive.
All the sample structures tested were made with the same type and amount of coating and were programmed the same way. It was therefore expected that the samples would perform similarly in their response to moisture. Since the differentiating factor between samples was the geometry, the similar resulting behaviour suggests that geometry does not significantly influence the speed of curvature change.

However, while the geometry does not appear to affect the temporal dynamics, it does influence the spatial distribution and direction of actuation. Each geometry produces a unique movement pattern, such as a wave-like motion, or twisting. This indicates that the temporal response is mainly the result of material behaviour in response to moisture, while geometry influences the spatial outcome of the movement.

Most of the curvature change occurs immediately after the activation of the sample with water. This behaviour can be related to the history dependent response of the material as described in the literature. When the samples are sprayed with water, their internal moisture content rapidly changes from dry to saturated. The extreme difference in internal moisture content explains the speed of curvature change. At the same time the shrinking and swelling interaction of the bilayer structure is activated. The wood veneer absorbs the moisture and swells much faster than the coating layer, causing the sample to bend towards the NOC. Because the environmental humidity is significantly lower than the humidity within the veneer, the wood begins to dry as soon as no more moisture is applied. The drying process is what is slowing down the movement after approximately 120 seconds.

The data on curvature rate against water uptake shows varying results between samples. The linear trend lines show a variety in directions for different samples. Where the frame and wave structure show an increasing trendline, indicating an increase of curvature rate with greater water uptake. In contrast, the flower and twist structure show negative trendlines, suggesting a decrease in curvature rate as the water uptake increases. There is no clear explanation why this difference in results exists. However, the data is based on two measurements per sample, all measured by hand. This leaves room for error in the measurements.

The initial expectation an increase in curvature rate with the increase of water uptake for all samples. However, the results do not consistently support this hypothesis. Given that each sample has only been tested twice, this test on the curvature rate vs water uptake should be defined as exploratory. Therefore no clear conclusions can be drawn on the relationship between the two variables.

6.4 Conclusion

While the initial hypothesis suggested that geometry might influence the speed of movement, the results indicated that geometry does not significantly affect the temporal speed of curvature change. Instead, the history dependency of the material causes the most rapid movement to occur immediately after activation, when the difference in internal moisture content is the greatest.

The influence of the amount of moisture on the speed of curvature change was also tested. It was expected that with an increasing amount of moisture, the speed of curvature change also increases. However the results do not support this expectation. Since the limited number of measurements per sample have led to defining the analysis as explorative, no definitive conclusion can be drawn about the relationship between the curvature rate and the water uptake.

Although geometry does not appear to influence the speed of response, it does influence the spatial distribution, direction and character of the movement. Each geometry results in a unique deformation pattern, which is critical for possible design applications of the material.

The results of the curvature measurements over time have implications for the guideline design. The graphs resulting from the data provide clear information on the performance of each individual sample structure. This information is valuable to include in the guidelines because it provides designers with insight to the type of performance they can expect from the material.

7

GUIDELINE TESTING

The guidelines are tested to evaluate their effectiveness in conveying information to designers to support their design process. Specifically, the test examines whether designers are able to apply the knowledge they gained from the guidelines in a design task.

A workshop is chosen as the evaluation method because it tests how well designers receive, interpret and apply the guideline information in a design context. Thereby testing the quality of the information delivered.

The goals of the guideline test are the following:

Clarity
The test aims to evaluate whether the guideline information is clear and understandable for designers. Allowing them to correctly interpret the information required to apply in a design context.

Effectiveness
The test aims to assess whether participants are able to make a design in line with their intentions and expectations. This indicates an understanding of the influence of different variables on the material performance.

Creativity
The test aims to evaluate whether the sample structure examples support or limit the participants' creativity in generating new ideas, thereby providing insight in the relevance of the sample structure examples in the guidelines.

Experiential connection
The test aims to examine how the experiential characterization of the material is reflected in the participants' design outcomes, revealing whether experiential qualities of the material can be transferred through the guidelines.

The overall expectation is that the guidelines provide enough detailed information that the designers are able to complete the design tasks without additional assistance other than the guidelines they receive. However, some concepts might be complicated to grasp the first time. So it is therefore expected that participants will possibly have some trouble with making a sample that will perform the way they expect.

7.1 Method

To test the different design goals, this test consisted of several steps each with a different purpose. The workshop test started with an introduction to the material and an experiential characterization. Followed by two design rounds where the participants had to read part of the design guidelines and then work on an exercise to make a sample from paper, testing the clarity and effectiveness of the guidelines. The setup of the two design rounds tested the contribution of the sample structure examples to the participants' creativity. The first design round explicitly excluded the examples from the guidelines, only in the second design round were the examples revealed. Allowing for the possibility to test the participants' response to the design tasks with and without examples. Afterwards a reflection on the experiential characterization was done by comparing the characterization of the initial material to the participants' designed samples. This reflection tested the experiential connection of the guidelines.

Participants

The workshop was conducted in multiple rounds with a maximum of 4 participants at a time. In total 7 design students participated in the test. All participants had some experience with material driven design, including the Ma2E4 experiential characterization method. None of the participants had any experience working with wood veneer.

Materials

The workshop test required several materials. Two separate booklets of the guidelines were made for each participant. The first booklet contained general information about the wood veneer material and the identified performance. Additionally, it explained the manufacturing method and which variables can be adjusted to control the performance. The second booklet described three separate sample structure examples. Including explanations and visuals on the performance and manufacturing method of each sample structure.

An additional booklet was made for participants to fill in (figure 47). It included a consent form, introductory questions, experiential characterization questions and evaluation questions of both design rounds. The design rounds of the workshop required striped paper, marker, scissors, tape and glue for the participants to make samples (figure 48). For the experiential characterization, wood veneer samples were shown to the participants. Presentation slides were used in addition to verbal instructions to explain the assignments and show a video of the material performance. The full booklets can be found in appendix G.

Experiential Characterization

Affective level

Choose 3 emotions that you think fit the best with the material and performance. Place them in the graph

frustration
boredom
disappointment
reluctance
confusion
rejection
disgust
melancholy
distrust
doubt

love
amusement
surprise
confidence
enchantment
respect
attraction
curiosity
fascination
confort

Interpretive level

Choose meanings that you think fit the best with the material and performance. Associate 2 pictures with every chosen meaning without considering the material (only the meaning of the word). Write down the number of the picture (1-5).

aggressive
cozy
elegant
frivolous
futuristic
masculine
ordinary
sexy
toy-like
natural
hand-crafted

calm
aloof
vulgar
sober
nostalgic
feminine
strange
not sexy
professional
innatural
manufactured

Meaning 1:
Meaning 2:

Picture 1
Picture 2

Fig 47. Workshop booklet pages.

Procedure

The procedure of the test is described in the following steps:

1. Introduction to the workshop test
2. Material introduction & experiential characterization
3. Design round 1
4. Design round 2
5. Design round evaluation questions
6. Experiential characterization reflection
7. Overall reflection & discussion

Step 1

The test started with a short introduction to the procedure of the test to follow, encouraging the participants to think aloud and ask any question that comes to mind. The participants were asked to fill in introductory questions asking about their experience with material driven design and working with wood veneer.

Step 2

The participants received some wood veneer samples to see and feel. At the same time I showed them a video of the bidirectional movement of the sample in the climate chamber to demonstrate the material performance. They were then asked to answer the experiential characterization questions about the material with its performance. These questions were from the affective and interpretive level of the Ma2E4 toolkit. For both levels a selected number of words needed to be chosen from a list of emotions and meanings fitting their interpretation of the material.

Step 3

The first design round started with the participants reading the chapter ‘About the material’ of the guidelines. They were then asked to make any shape they wanted from paper, considering the fiber directions and coating side and bend the paper how they expected the wood veneer to curve. (figure 48). The paper they received had stripes representing the fiber directions and they could indicate the coating side with markers. Their second assignment in this design round was to sketch or think of a sample structure, explained as a combination of multiple shapes working together to create a structure.

Step 4

The second design round started again with the participants reading a section of the guidelines, this time the chapter ‘Sample structures’. After this followed another design exercise where they were asked to make a sample structure from the paper, again considering the fiber directions and coating side. They could make the structure they came up with in the first design round or make something new. The created samples of the design rounds can be found in appendix G.

Step 5

After both design rounds I asked them to fill out the evaluation questions for both design rounds. Evaluating the clarity of the task, difficulty to get started and their confidence in designing something that performs to their expectation.

Step 6

The participants were asked to reflect on their initial experiential characterization. Considering how their initial answers would change if they would perform the same characterization again based on their own created samples.

Step 7

Lastly, a short overall discussion was conducted where participants were encouraged to ask any remaining questions and provide feedback on the guidelines or the workshop test in general. Specifically how they perceived the workshop test, what went well or where they were struggling.

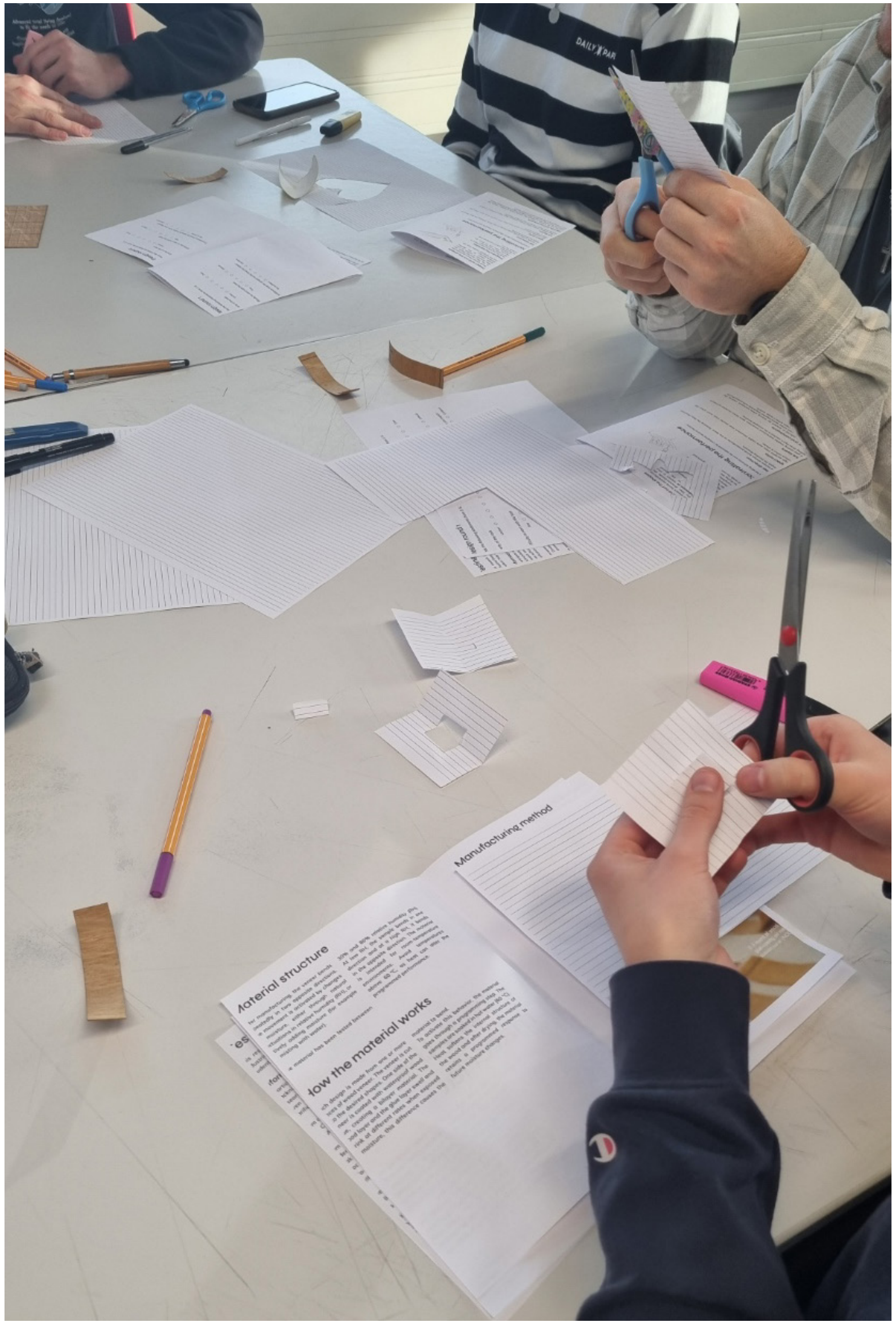


Fig 48. Workshop test design round.

7.2 Results

The results of this test can be divided into two categories. The self-reported data by the participants is supported through the booklets and the observational data about the participants' behaviour during the test, such as their approach to the design exercises and their concerns and questions.

Experiential characterization
From the self-reported participant data figure 49 shows the responses of the experiential characterization. It shows the words used to describe the material performance for both the affective and the interpretive level. From the affective level the words curiosity, fascination and surprise were mentioned the most. From the interpretive level the words are natural and calm.

At the end of the test during a reflection, the answers from the beginning were evaluated and compared to how the participants would answer the same questions for their own designed sample. The results from this discussion were that overall participants mostly did not change their answers. A few participants mentioned the emotions they used to describe change in intensity:

- Less surprise because they learned how the material worked through the workshop.
- Increased curiosity because working with the material increased their curiosity of the material possibilities.

At the interpretive level, again not many changes in the participants' answers. The main result was that the count for 'hand-crafted' increased from 1 to 4.

Design rounds
After the design rounds the participants answered three questions to evaluate the clarity, difficulty and their confidence of the sample responding to their expectations. The average scores for each question at both design rounds can be found in table 7. For each average score, the standard deviation (SD) was calculated. Together these results are plotted in the graph of figure 50.

The results of the observational data revealed that there was some confusion in the first design round. Participants were unsure if their assumptions about the fiber direction in relation to their expected curvature was correct. In the second design round this confusion was no longer observed.

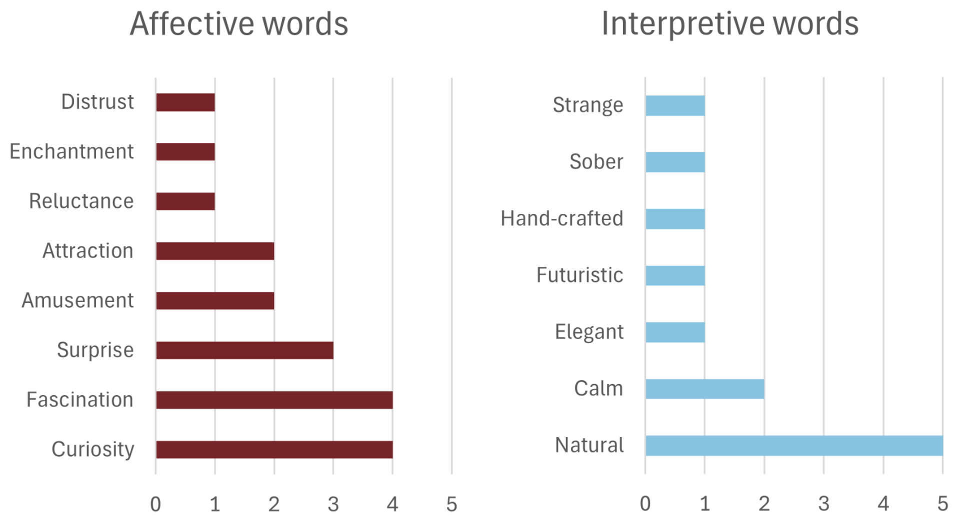


Fig 49. Graphs showing the result of the wordcount from the affective and interpretive level of the initial experiential characterization before the design rounds.

	Design round 1		**Design round 2**	
	Score	SD	Score	SD
Clarity of the task (unclear = 1 - clear = 5)	4,17	0,75	4,67	0,52
Difficulty of task (easy = 1 - difficult = 5)	2,33	1,51	2,17	0,98
Confidence (not confident = 1 - confident = 5	3,67	1,21	3,67	0,52

Table 7. Averages of evaluation scores from both design rounds. For each score the standard deviation (SD) is calculated.

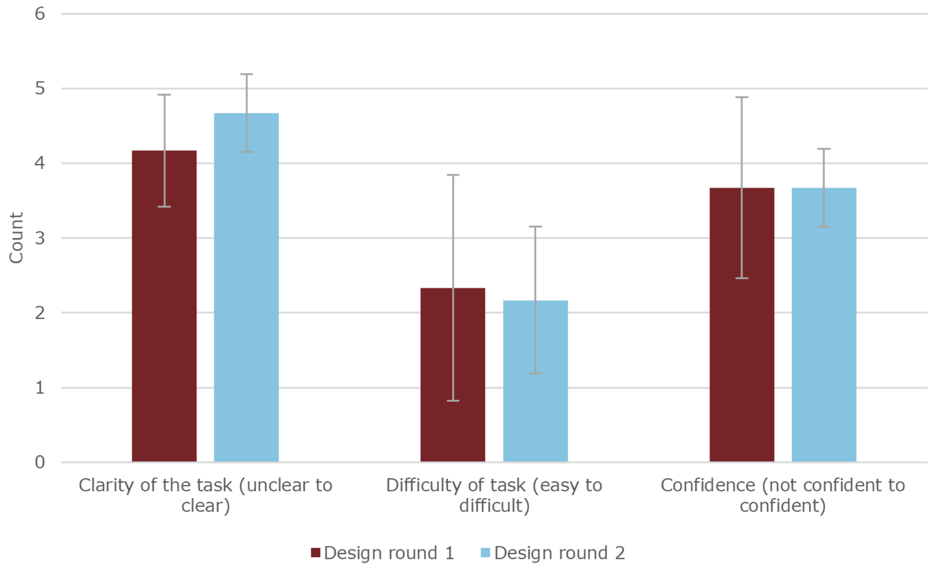


Fig 50. Result of the average scores of clarity, difficulty and confidence plotted including their standard deviation.

7.3 Discussion

Experiential characterization

The results of the experiential characterization show the words mostly used to describe the material were curiosity, fascination, surprise and amusement. Indicating a positive response to the material. Additionally the material provokes exploratory behaviour, the participants are curious to work with the material. At the interpretive level, the word 'natural' was chosen to describe the material far more than any other word. This could be explained by the fact that the designed material is not much different than wood in its natural form. Only one side of the veneer is coated, while the other has the natural look and feel of wood.

The reflection at the end of the workshop, comparing the initial material characterization to the characterization of the participants' own sample designs, resulted in limited differences in answers. The participants incorporated the experiential qualities of the wood veneer in their sample designs. Indicating the experiential qualities of the material are translated through the guidelines.

Design rounds

The scores given of the design round evaluations show the difference between perceived clarity, difficulty and confidence that their designs work to their expectation. The results show the clarity increasing with 0.5 towards the second design round. Through a participant discussion, this increase could be related to the additional information provided by the guidelines in the second design round. The main point of unclarity in the first design round was the exercise where participants were asked to make a sample structure. After reading the second chapter of the guidelines about sample structure examples, the concept of a sample structure became much clearer.

The difficulty increased slightly with a score of 0.16 with a relatively large standard deviation meaning very diverse scores between participants, especially in design round 1. The variation and scores could be explained by the interpretation of the question per participant. The first design round consisted of two exercises. The evaluation question of difficulty does not specify how it should be answered. Therefore some participants might have evaluated the difficulty of either one of the exercises while other participants have given a score combining the difficulty of both exercises. Additionally, the large variety of scores is in line with the observational results. Some participants were visually struggling more with making the samples than others.

The results show the average confidence score is exactly the same for both design rounds with a much higher variability in answers in the first design round than the second design round. Meaning the change in confidence varies widely between participants, where for some the confidence increased towards the second design round and for others their confidence decreased.

Observational results

The results of the observations mention confusion being seen during the first design round. Most confusion was around the impact of the fiber direction on the bending direction. This could be related to the unfamiliarity of the participants with the material, as none of the participants had any experience working with wood veneer. Participants were also seen checking the guidelines again while making their samples and in the end were able to create samples that implemented the variables correctly. Indicating the confusion was partly related to the lack of retaining the information than the clarity of the information. Additionally, one participant mentioned she was unfamiliar with the term ‘perpendicular’, used to describe the bending response related to the fiber orientation.

Participant questions & reflection

At the end of the workshop there was room for questions and reflections about the workshop and guidelines. This resulted in a few questions related to the concepts explaining the material performance. Participants were curious about the principles behind the performance, for example how the coating causes the veneer to bend bidirectionally. These questions indicate there is an interest in this aspect of the material that had not yet been explained in the guidelines.

The feedback on the guidelines was overall very positive. Participants thought the information was presented clearly and understandable, especially through the visuals. They mentioned some images that show the movement stages of the sample structure examples could be improved to see more extreme changes in movement. Additionally, a visual explaining the relation between the fiber direction and bending orientation would be helpful.

Limitations

This workshop test came with a number of limitations and uncertainties. First of all, in total 7 design students with all a similar background and experience participated in the test. This limited sample size and the similarity in background limits the representativeness of the results and makes it difficult to draw strong conclusions, making the results exploratory.

A second limitation is that participants worked with a paper-based representation of material during the design exercises rather than the actual wood veneer. This might have impacted the way the participants interacted with the material and completed the design tasks.

Lastly, the data collected from this test is mostly self-reported participant data. This data reflects perceived experience rather than objective data. It also allows for differences in interpretation of the questions and exercises.

7.4 Conclusion

Through the workshop test explained in this chapter the guidelines were tested to evaluate their effectiveness in conveying information to designers. This was done through four test goals: the clarity, effectiveness, creativity and experiential connection of the guidelines. The conclusions of these goals can be seen in figure 51.

Clarity

The test has proven the guidelines present the information clearly and understandable for designers to apply in a design task. All participants were able to create a sample design with the variables implemented in the correct way without any additional help other than the guidelines they were presented with. In addition, participant feedback confirmed that the information in the guidelines was easy to follow and clear. Especially the supporting visuals in the guidelines improved the understanding of the explained concepts.

Effectiveness

Although there were some uncertainties and doubts with participants in the beginning, at the end of the workshop all participants were able to create a sample design that would function in line with their expectation. Indicating the guidelines were effective in translating the information.

Creativity

By testing the ability of the participant to create a sample structure before and after having seen the examples in the guidelines, it was observed and supported by participant feedback that the guideline examples support the ability to create more complex designs. The participants also mentioned these examples helping them to visualise the possibilities of the material, and thereby improving their creative thinking.

Experiential connection

Because of the similar experiential characterization results at the beginning and end of the test, it can be concluded that the experiential qualities of the material are translated through the guidelines.

Overall based on the evaluation of these goals, the guidelines work as expected. They provide clear information and allow designers to create sample designs without any additional information required.

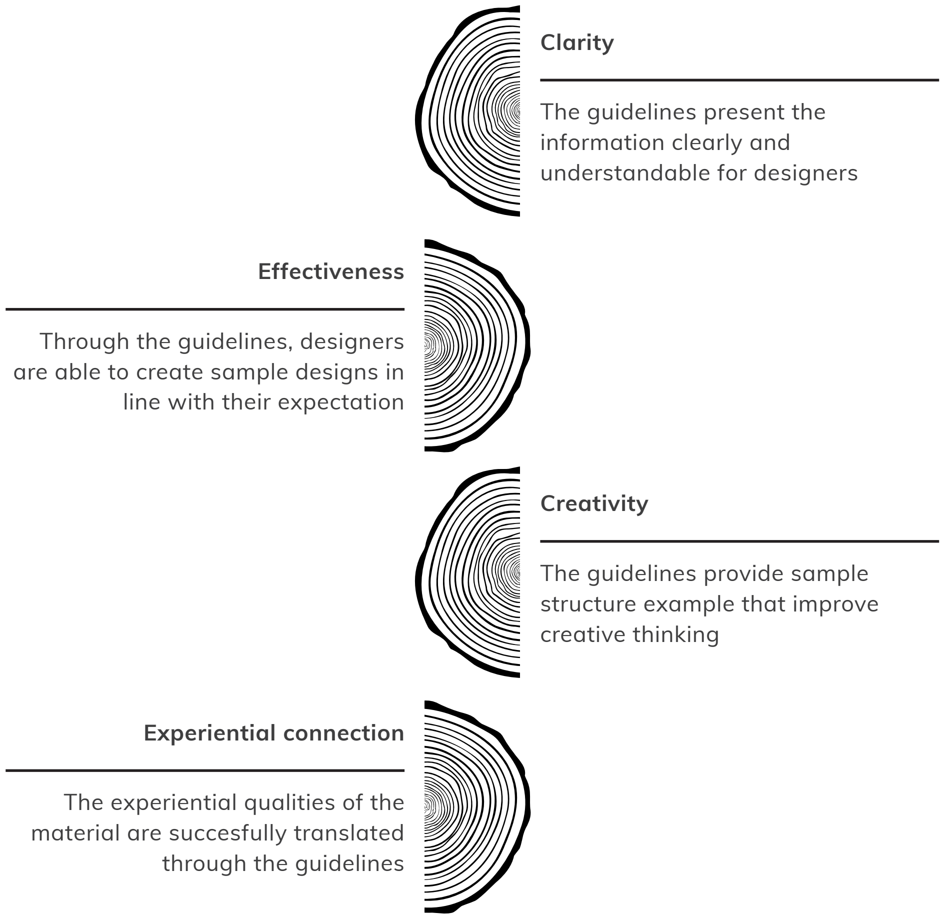


Fig 51. Main conclusions of guideline workshop test goals

8

FINAL GUIDELINES DESIGN

8.1 Guidelines design

The finalised guidelines design combines the findings of the material performance from the experimental testing and climate chamber testing. In addition it includes designed sample structure examples visualising possibilities of material use. Each explained through their material properties, manufacturing method and resulting performance. To provide inspiration, several images are used to show the material in potential design applications. Figures 52 and 53 show mockups of the guidelines.

The guidelines are presented in this chapter through images of the pages. With every chapter of the guidelines, a short description will outline the structure and content of the guidelines. Starting with figure 54, where the cover of the guidelines booklet can be seen. Figure 55 shows the table of contents.

Fig 52. Design guidelines mockup

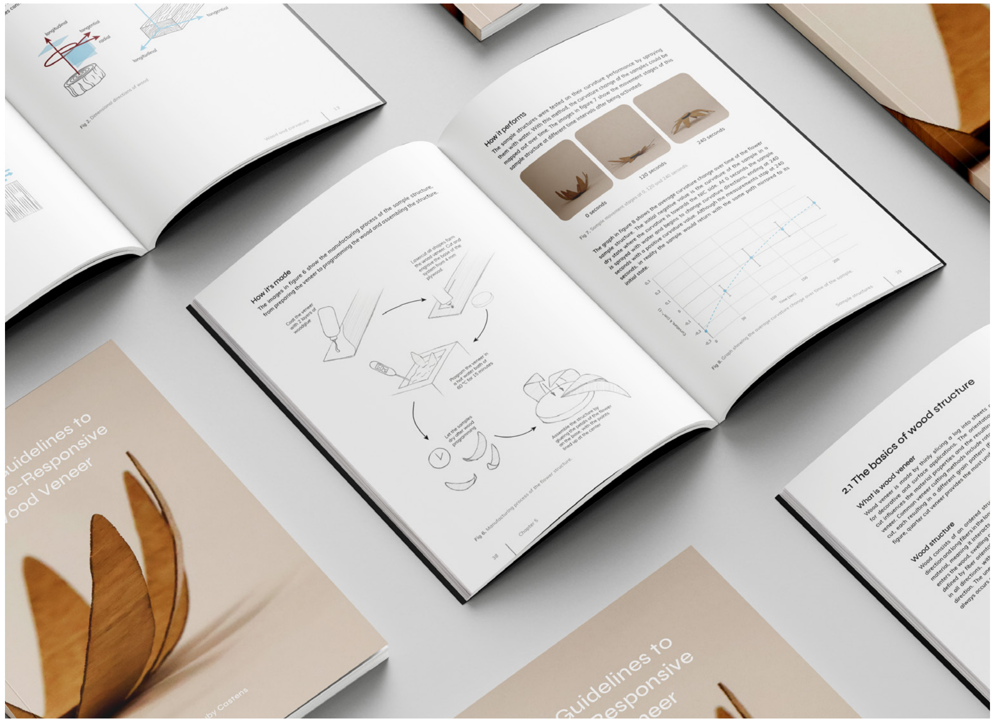


Fig 53. Design guidelines mockup

Design Guidelines to
Moisture-Responsive
Wood Veneer

Ruby Castens

Designer guidelines - moisture responsive wood veneer
March 17th 2026
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Fig 54. Guidelines cover and opening page.

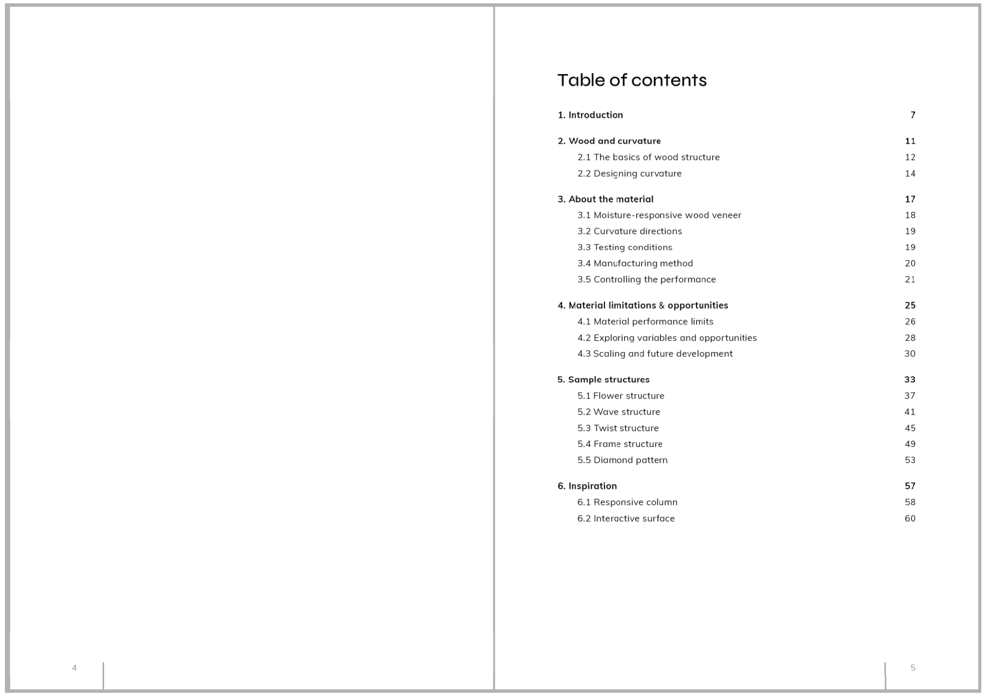


Table of contents

Fig 55. Guidelines table of contents.

Figure 56 shows the first chapter of the guidelines, *the introduction*. This chapter introduces the reader to the guidelines: the material and performance that forms the base of the guidelines, what the guidelines are intended for, the content that has formed the creation of the guidelines, and an overview of the structure.

In figure 57 chapter 2 of the guidelines can be seen, *wood and curvature*. This chapter explains the relevant background information on the basics of wood structure, wood veneer and wood species. It then explains how curvature in wood can be designed through the creation of bilayer structures and the application of hot water treatments.

Chapter 3 of the guidelines, *about the material*, introduces the moisture-responsive wood veneer that forms the basis of these guidelines. It describes in detail what the material is, how it performs, how the curvature directions are defined supported by an annotated image, and the testing conditions under which the material was tested (figure 59). It then also explains the general manufacturing method of the material supported by illustrations, and several aspects of the material performance that can be controlled. It is explained how changing specific variables can affect the performance, for example changing the fiber direction changes the visual curvature direction, as supported by an image of multiple samples (figure 60).

1

INTRODUCTION

These guidelines introduce a shape-morphing wood veneer developed for responsive design applications. The material is an oak veneer that bends back and forth in response to environmental moisture changes. The bending response is created by using the wood's natural response to moisture and enhancing it through a specific manufacturing process.

The guidelines are intended as a design tool, making this material performance accessible and usable for designers. By translating experimental findings into design-oriented knowledge about the material, the guidelines act as a bridge between material research and design practice.

The guidelines are written based on the outcomes of a material research leading to a singular performance of oak wood veneer. Different variables are described that can be adjusted to influence the performance, primarily in terms of design outcomes. Although the scope of the guidelines is relatively focused, the underlying principles are relevant for understanding how wood veneer in general reacts to moisture and can be used as a starting point for further research with other wood species or applications.

Chapter 2, *Wood and curvature*, explains the relevant background information on the basics of wood structure, wood veneer and wood species. It then explains how curvature in wood can be designed through the creation of bilayer structures and the application of hot water treatments. Chapter 3, *About the material*, introduces the moisture-responsive wood veneer that forms the basis of these guidelines. It describes in detail what the material is, how it performs, how it is manufactured and how its performance can be controlled. Chapter 4, *Material limitations & opportunities*, outlines the constraints of the material that should be considered when working with it, possible material exploration opportunities, and scaling of the material and manufacturing stages. Chapter 5, *Sample structures*, applies the described material in several examples of sample structures. Each example has its own unique design and manufacturing method. Finally, Chapter 6, *Inspiration*, presents possible applications of the moisture-responsive wood veneer in an indoor architectural context, providing an impression of its potential possibilities.

8 | Chapter 1

Fig 56. Guidelines chapter 1, Introduction.

2

2.1 The basics of wood structure

2.2 Designing curvature

WOOD AND CURVATURE

2.1 The basics of wood structure

What is wood veneer

Wood veneer is made by thinly slicing a log into sheets and is commonly used for decorative and surface applications. The orientation in which the wood is cut influences the material properties and the resulting visual appearance of the veneer. Common veneer cutting methods include rotary cut, flat sawn, and quarter cut, each resulting in a different grain pattern (figure 1). As can be seen in the figure, quarter cut veneer provides the most uniform appearance and fiber pattern.

Wood structure

Wood consists of an ordered structure, with annual growth rings in the radial direction and long fibers in the longitudinal direction (figure 2). Wood is a hygroscopic material, meaning it interacts with moisture from its environment. When moisture enters the wood, swelling occurs in multiple directions due to the material structure defined by fiber orientation and growth ring direction. This swelling is not equal in all directions, with the largest amount of swelling occurring in the tangential direction. The uneven swelling causes the wood to bend. This bending response always occurs perpendicular to the fiber direction.

Fig 1. Wood veneer cutting directions.

Wood species

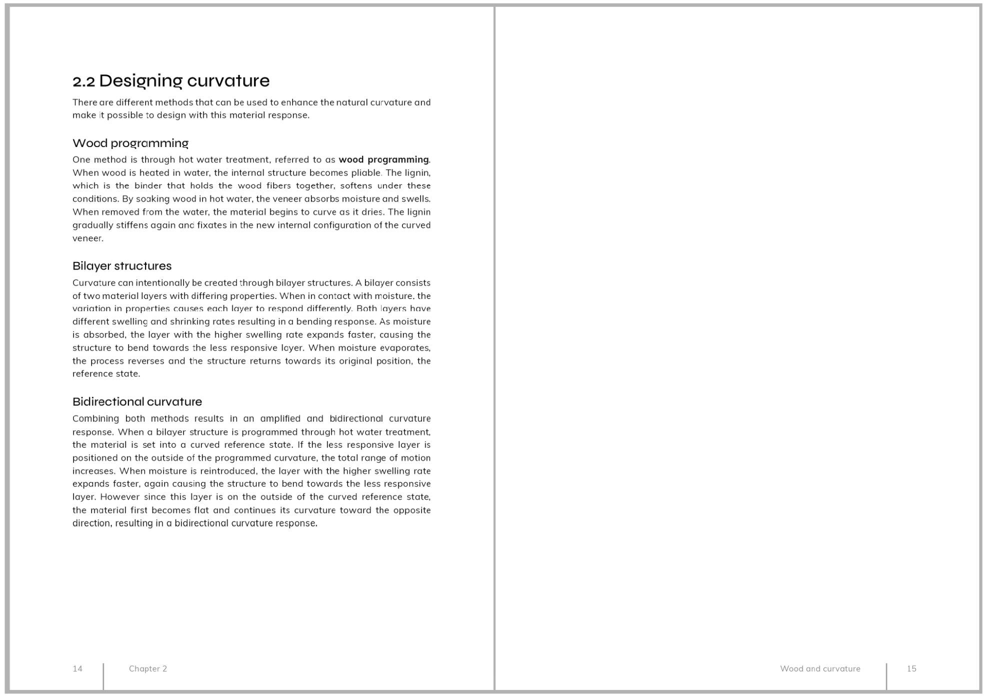
There are many different species of wood. While all wood species respond to moisture in the same way in principle, the specific properties of each species influence how strong and how fast this response is. Zooming in on the structure of wood, each annual growth ring consists of a matrix of cells oriented in the longitudinal direction. Each cell contains a central open space, called the lumen, surrounded by the cell walls. The ratio between cell wall thickness and lumen size varies significantly between wood species. This variation affects properties such as density and porosity, which influence the amount of water absorption and the rate. These factors directly affect the natural bending response of wood when exposed to moisture. Because of these variations between wood species, the response of one species cannot be generalized to other wood species.

Fig 2. Dimensional directions of wood

12 | Chapter 2

Wood and curvature | 13

Fig 57. Guidelines chapter 2, Wood and curvature.



2.2 Designing curvature

There are different methods that can be used to enhance the natural curvature and make it possible to design with this material response.

Wood programming

One method is through hot water treatment, referred to as **wood programming**. When wood is heated in water, the internal structure becomes pliable. The lignin, which is the binder that holds the wood fibers together, softens under these conditions. By soaking wood in hot water, the veneer absorbs moisture and swells. When removed from the water, the material begins to curve as it dries. The lignin gradually stiffens again and fixates in the new internal configuration of the curved veneer.

Bilayer structures

Curvature can intentionally be created through bilayer structures. A bilayer consists of two material layers with differing properties. When in contact with moisture, the variation in properties causes each layer to respond differently. Both layers have different swelling and shrinking rates resulting in a bending response. As moisture is absorbed, the layer with the higher swelling rate expands faster, causing the structure to bend towards the less responsive layer. When moisture evaporates, the process reverses and the structure returns towards its original position, the reference state.

Bidirectional curvature

Combining both methods results in an amplified and bidirectional curvature response. When a bilayer structure is programmed through hot water treatment, the material is set into a curved reference state. If the less responsive layer is positioned on the outside of the programmed curvature, the total range of motion increases. When moisture is reintroduced, the layer with the higher swelling rate expands faster, again causing the structure to bend towards the less responsive layer. However since this layer is on the outside of the curved reference state, the material first becomes flat and continues its curvature toward the opposite direction, resulting in a bidirectional curvature response.

14 | Chapter 2

Wood and curvature | 15

Fig 58. Guidelines chapter 2, Wood and curvature

3

3.1 Moisture-responsive wood veneer

3.2 Curvature directions

3.3 Testing conditions

3.4 Manufacturing method

3.5 Controlling the performance

ABOUT THE MATERIAL

3.1 Moisture-responsive wood veneer

The moisture-responsive wood veneer designed and explained in these guidelines is a **quarter cut oak wood veneer with a one sided coating acting as a bilayer.** At around 50% relative humidity (RH), the veneer is in a programmed 'reference curvature'. As the RH lowers, this curvature becomes stronger. When moisture is introduced and the RH rises, the material bends to a curvature in the opposite direction to the reference curvature.

The quarter cut oak veneer is the base material. The combination of oak as a wood species and the quarter cut veneer result in a very uniform material structure, ensuring more reliable results. The veneer is coated on one side with waterproof woodglue, creating a bilayer structure. Waterproof woodglue works well as a coating because it does not soak through the material, thereby creating a second layer. It remains flexible after drying, allowing the coating to bend with the wood. The coating is waterproof and stays on the material with the introduction of moisture.

To achieve the reference curvature, the veneer goes through a hot water treatment, the wood programming stage. The veneer is soaked in a hot water bath of 60 °C for 15 minutes.

3.2 Curvature directions

When wood veneer in its natural form has come into contact with moisture it dries towards one side of the veneer, its natural curvature direction. To simplify further explanations, each side of the veneer has been named based on this natural curvature direction. Figure 3 shows a curved sample with annotated the natural inside curve (NIC) and the natural outside curve (NOC). The woodglue coating of the material is applied to the NOC side of the veneer.

3.3 Testing conditions

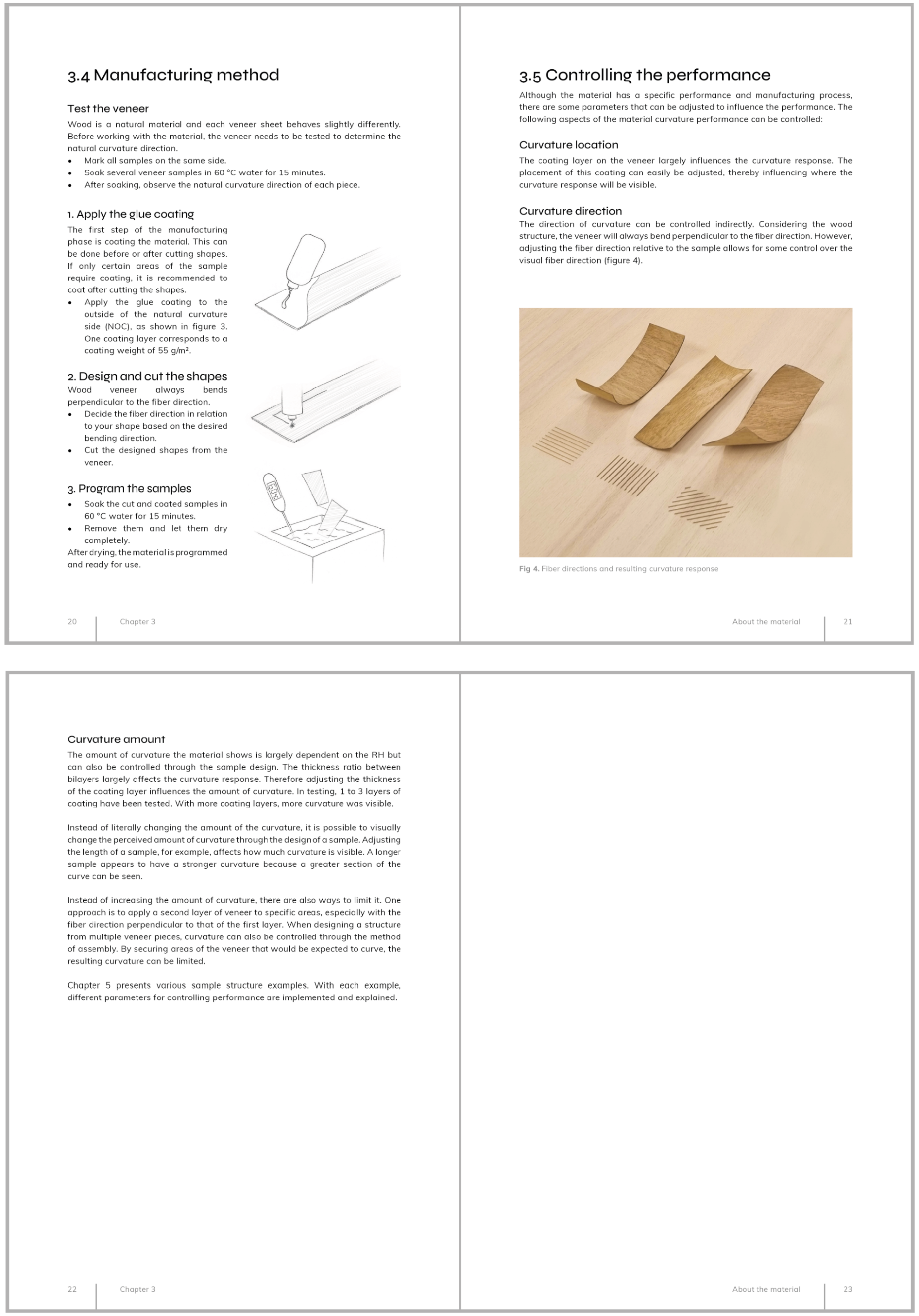
The material response has been tested in a controlled environment. In a climate chamber various programs of changing humidity have been tested with a range of 30% to 80% RH at a constant temperature of 20 °C. The fatigue of the material has been tested through multiple cyclic tests in the climate chamber. A change in amplitude between the curvature extremes at 30% and 80% would indicate whether fatigue was occurring. After testing six complete cycles, 96.8% of the initial amplitude remained.

Fig 3. Curvature directions: Natural inside curvature (NIC) and natural outside curvature (NOC).

18 | Chapter 3

About the material | 19

Fig 59. Guidelines chapter 3, About the material.



3.4 Manufacturing method

Test the veneer

Wood is a natural material and each veneer sheet behaves slightly differently. Before working with the material, the veneer needs to be tested to determine the natural curvature direction.

- Mark all samples on the same side.
- Soak several veneer samples in 60 °C water for 15 minutes.
- After soaking, observe the natural curvature direction of each piece.

1. Apply the glue coating

The first step of the manufacturing phase is coating the material. This can be done before or after cutting shapes. If only certain areas of the sample require coating, it is recommended to coat after cutting the shapes.

- Apply the glue coating to the outside of the natural curvature side (NOC), as shown in figure 3. One coating layer corresponds to a coating weight of 55 g/m².

2. Design and cut the shapes

Wood veneer always bends perpendicular to the fiber direction.

- Decide the fiber direction in relation to your shape based on the desired bending direction.
- Cut the designed shapes from the veneer.

3. Program the samples

- Soak the cut and coated samples in 60 °C water for 15 minutes.
- Remove them and let them dry completely.

After drying, the material is programmed and ready for use.

20 Chapter 3

3.5 Controlling the performance

Although the material has a specific performance and manufacturing process, there are some parameters that can be adjusted to influence the performance. The following aspects of the material curvature performance can be controlled:

Curvature location

The coating layer on the veneer largely influences the curvature response. The placement of this coating can easily be adjusted, thereby influencing where the curvature response will be visible.

Curvature direction

The direction of curvature can be controlled indirectly. Considering the wood structure, the veneer will always bend perpendicular to the fiber direction. However, adjusting the fiber direction relative to the sample allows for some control over the visual fiber direction (figure 4).

Fig 4. Fiber directions and resulting curvature response

About the material 21

Curvature amount

The amount of curvature the material shows is largely dependent on the RH but can also be controlled through the sample design. The thickness ratio between bilayers largely affects the curvature response. Therefore adjusting the thickness of the coating layer influences the amount of curvature. In testing, 1 to 3 layers of coating have been tested. With more coating layers, more curvature was visible.

Instead of literally changing the amount of the curvature, it is possible to visually change the perceived amount of curvature through the design of a sample. Adjusting the length of a sample, for example, affects how much curvature is visible. A longer sample appears to have a stronger curvature because a greater section of the curve can be seen.

Instead of increasing the amount of curvature, there are also ways to limit it. One approach is to apply a second layer of veneer to specific areas, especially with the fiber direction perpendicular to that of the first layer. When designing a structure from multiple veneer pieces, curvature can also be controlled through the method of assembly. By securing areas of the veneer that would be expected to curve, the resulting curvature can be limited.

Chapter 5 presents various sample structure examples. With each example, different parameters for controlling performance are implemented and explained.

22 Chapter 3

About the material 23

Fig 60. Guidelines chapter 3, About the material.

Figures 61 and 62 show chapter 4, *material limitations & opportunities*. This chapter explains certain findings from the material research phase that outline the constraints of the material that should be considered when working with it, possible material exploration opportunities, and scaling of the material and manufacturing stages.

Figures 63 through 68 show chapter 5 of the guidelines, *sample structures*. This chapter applies the described material in several examples of sample structures. Each example has its own unique design and manufacturing method.

Figure 63 shows the chapter page and the introduction to this chapter. This introduction explains why these sample structures are included in the guidelines. It also introduces the structures through categories: assembled and patterned structures, and active and non-active parts.

All sample structures are outlined in the same format. The first two pages introduce the sample through an explanation of the structure including the materials and specifications needed to create this sample. On the third page the manufacturing method of each specific sample is shown through an illustrated process. On the last page of each sample structure, the performance is explained. Starting with three images of the sample in different movement stages to show the performance of the sample structure. Then followed by an explanation about the curvature response time of the sample, supported by a graph.

The first sample, the flower structure, can be seen in figure 64. Figure 65 shows the wave structure, figure 66 the twist structure. Followed by the frame structure in figure 67 and lastly the diamond pattern in figure 68.

Chapter 6, *inspiration*, is the last chapter of the guidelines (figures 69 & 70). As the title suggests, this chapter is meant to serve as inspiration for the reader of the material possibilities. It presents possible applications of the moisture-responsive wood veneer in an indoor architectural context.

4

4.1 Material performance limits

4.2 Exploring variables and opportunities

4.3 Scaling and future development

MATERIAL LIMITATIONS & OPPORTUNITIES

4.1 Material performance limits

The material explained in these guidelines comes with a few limitations to consider when working with it. These findings were acquired through experimental testing and climate chamber testing.

Sample response time

The speed of movement of the material is a complicated characteristic to define. With natural RH fluctuations, the material follows the environmental humidity through constant exchange of moisture between the wood veneer and the environment. During climate chamber testing it was discovered that with fast RH changes, the material needed time to respond. During this test the RH went from 30% to 80% with 1% RH change per minute, stayed constant at 80% for 5 minutes and then returned to 30% RH again with 1% RH change per minute. The veneer needs to adjust to the environment, which therefore creates a delay in response time, in this tested scenario of roughly 10 minutes.

Within the climate chamber tests, this response time was optimized for the test. Resulting in a minimal constant holding time of 30 minutes when the humidity switches from going up to 80% to going down to 30%. In this specific scenario, the fastest response time of the material to keep up with the surrounding environment was 30 minutes.

Connecting this finding to possible design applications, means a delay should be expected with very sudden moisture changes. However if the material is used in an application where it responds to the natural environmental humidity changes, it is expected that these natural changes are slow enough for the material to follow.

Stress relaxation effect

Through the testing phase of the material it was also tested how the material performs at constant humidities. It was found that at high humidities, tested at 80% RH, the material could not retain a constant curvature. While at low humidities the curvature of the material remained the same with a constant RH, with approaching high humidities the material would curve to its most extreme point and almost immediately return while the RH stayed constant. This is likely caused by the high moisture content in the veneer, making the material flexible and limiting its strength.

26 Chapter 4

When using this material for an application, this limitation becomes a design constraint. In high-humidity environments, the material is not suited to remain in an extreme curvature state and might fail or drift from its extreme curvature. A high humidity can initiate strong curvature but the curvature cannot remain like that.

To work with this limitation, there could be possibilities in for example mechanically restraining the material at high humidities. This has however not been tested and would require further exploration.

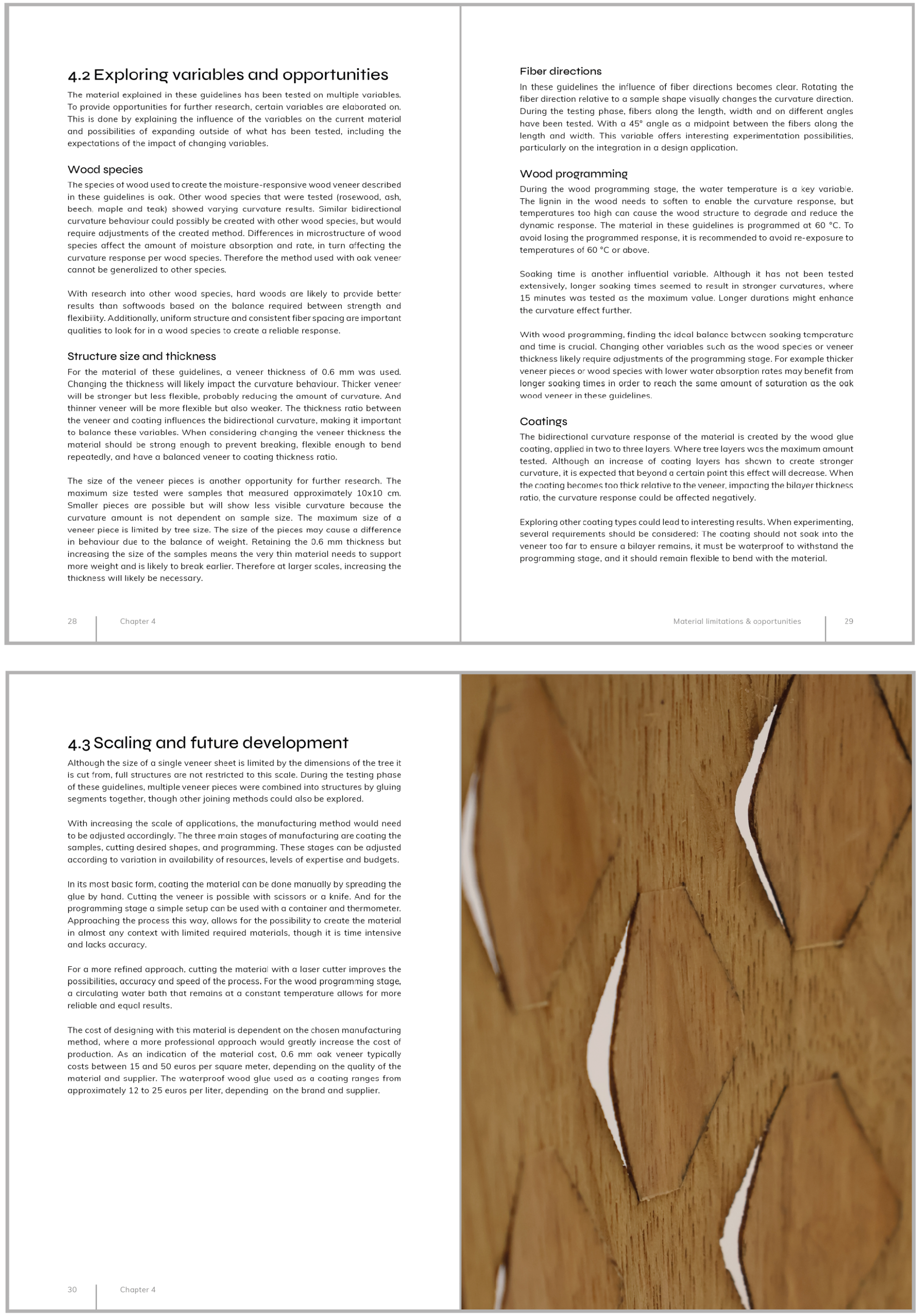
Natural material variations

Another observed limitation or consideration of the material is the reliability of curvature response. The programmed material makes use of the natural curvature response of wood and enhances this. Therefore most of the natural materials qualities remain. Every piece of wood is different in structure, and no two pieces are identical. Therefore the response of the material is also not always identical, even if treated exactly the same. Where some pieces may have a stronger curvature than others where it would be expected they would show the same response

These natural variations within the material could be viewed as a limitation if the goal is a perfectly predictable performance, but it can also be seen as a beauty of the material. After all, wood is a natural material and this slight difference in performance shows that. It is not a completely engineered material and it still has some of its natural remaining qualities.

Material limitations & opportunities 27

Fig 61. Guidelines chapter 4, Material limitations & opportunities



4.2 Exploring variables and opportunities

The material explained in these guidelines has been tested on multiple variables. To provide opportunities for further research, certain variables are elaborated on. This is done by explaining the influence of the variables on the current material and possibilities of expanding outside of what has been tested, including the expectations of the impact of changing variables.

Wood species

The species of wood used to create the moisture-responsive wood veneer described in these guidelines is oak. Other wood species that were tested (rosewood, ash, beech, maple and teak) showed varying curvature results. Similar bidirectional curvature behaviour could possibly be created with other wood species, but would require adjustments of the created method. Differences in microstructure of wood species affect the amount of moisture absorption and rate, in turn affecting the curvature response per wood species. Therefore the method used with oak veneer cannot be generalized to other species.

With research into other wood species, hard woods are likely to provide better results than softwoods based on the balance required between strength and flexibility. Additionally, uniform structure and consistent fiber spacing are important qualities to look for in a wood species to create a reliable response.

Structure size and thickness

For the material of these guidelines, a veneer thickness of 0.6 mm was used. Changing the thickness will likely impact the curvature behaviour. Thicker veneer will be stronger but less flexible, probably reducing the amount of curvature. And thinner veneer will be more flexible but also weaker. The thickness ratio between the veneer and coating influences the bidirectional curvature, making it important to balance these variables. When considering changing the veneer thickness the material should be strong enough to prevent breaking, flexible enough to bend repeatedly, and have a balanced veneer to coating thickness ratio.

The size of the veneer pieces is another opportunity for further research. The maximum size tested were samples that measured approximately 10x10 cm. Smaller pieces are possible but will show less visible curvature because the curvature amount is not dependent on sample size. The maximum size of a veneer piece is limited by tree size. The size of the pieces may cause a difference in behaviour due to the balance of weight. Retaining the 0.6 mm thickness but increasing the size of the samples means the very thin material needs to support more weight and is likely to break earlier. Therefore at larger scales, increasing the thickness will likely be necessary.

28 Chapter 4

Fiber directions

In these guidelines the influence of fiber directions becomes clear. Rotating the fiber direction relative to a sample shape visually changes the curvature direction. During the testing phase, fibers along the length, width and on different angles have been tested. With a 45° angle as a midpoint between the fibers along the length and width. This variable offers interesting experimentation possibilities, particularly on the integration in a design application.

Wood programming

During the wood programming stage, the water temperature is a key variable. The lignin in the wood needs to soften to enable the curvature response, but temperatures too high can cause the wood structure to degrade and reduce the dynamic response. The material in these guidelines is programmed at 60 °C. To avoid losing the programmed response, it is recommended to avoid re-exposure to temperatures of 60 °C or above.

Soaking time is another influential variable. Although it has not been tested extensively, longer soaking times seemed to result in stronger curvatures, where 15 minutes was tested as the maximum value. Longer durations might enhance the curvature effect further.

With wood programming, finding the ideal balance between soaking temperature and time is crucial. Changing other variables such as the wood species or veneer thickness likely require adjustments of the programming stage. For example thicker veneer pieces or wood species with lower water absorption rates may benefit from longer soaking times in order to reach the same amount of saturation as the oak wood veneer in these guidelines.

Coatings

The bidirectional curvature response of the material is created by the wood glue coating, applied in two to three layers. Where tree layers was the maximum amount tested. Although an increase of coating layers has shown to create stronger curvature, it is expected that beyond a certain point this effect will decrease. When the coating becomes too thick relative to the veneer, impacting the bilayer thickness ratio, the curvature response could be affected negatively.

Exploring other coating types could lead to interesting results. When experimenting, several requirements should be considered: The coating should not soak into the veneer too far to ensure a bilayer remains, it must be waterproof to withstand the programming stage, and it should remain flexible to bend with the material.

Material limitations & opportunities 29

4.3 Scaling and future development

Although the size of a single veneer sheet is limited by the dimensions of the tree it is cut from, full structures are not restricted to this scale. During the testing phase of these guidelines, multiple veneer pieces were combined into structures by gluing segments together, though other joining methods could also be explored.

With increasing the scale of applications, the manufacturing method would need to be adjusted accordingly. The three main stages of manufacturing are coating the samples, cutting desired shapes, and programming. These stages can be adjusted according to variation in availability of resources, levels of expertise and budgets.

In its most basic form, coating the material can be done manually by spreading the glue by hand. Cutting the veneer is possible with scissors or a knife. And for the programming stage a simple setup can be used with a container and thermometer. Approaching the process this way, allows for the possibility to create the material in almost any context with limited required materials, though it is time intensive and lacks accuracy.

For a more refined approach, cutting the material with a laser cutter improves the possibilities, accuracy and speed of the process. For the wood programming stage, a circulating water bath that remains at a constant temperature allows for more reliable and equal results.

The cost of designing with this material is dependent on the chosen manufacturing method, where a more professional approach would greatly increase the cost of production. As an indication of the material cost, 0.6 mm oak veneer typically costs between 15 and 50 euros per square meter, depending on the quality of the material and supplier. The waterproof wood glue used as a coating ranges from approximately 12 to 25 euros per liter, depending on the brand and supplier.

30 Chapter 4

Fig 62. Guidelines chapter 4, Material limitations & opportunities


5

5.1 Flower structure
5.2 Wave structure
5.3 Twist structure
5.4 Frame structure
5.5 Diamond pattern

SAMPLE STRUCTURES

This chapter introduces five sample structures made from moisture-responsive wood veneer. These examples are meant to serve as a source of inspiration by demonstrating the potential of the material. They represent an intermediate step between the underlying material principle and a functional application of the material.

Chapter 3 explained several parameters that can be adjusted to influence the resulting performance. The effect of modifying these parameters becomes visible in the following examples, not only on the performance result of the samples but also in the way the manufacturing process is affected.

Assembled and patterned structures

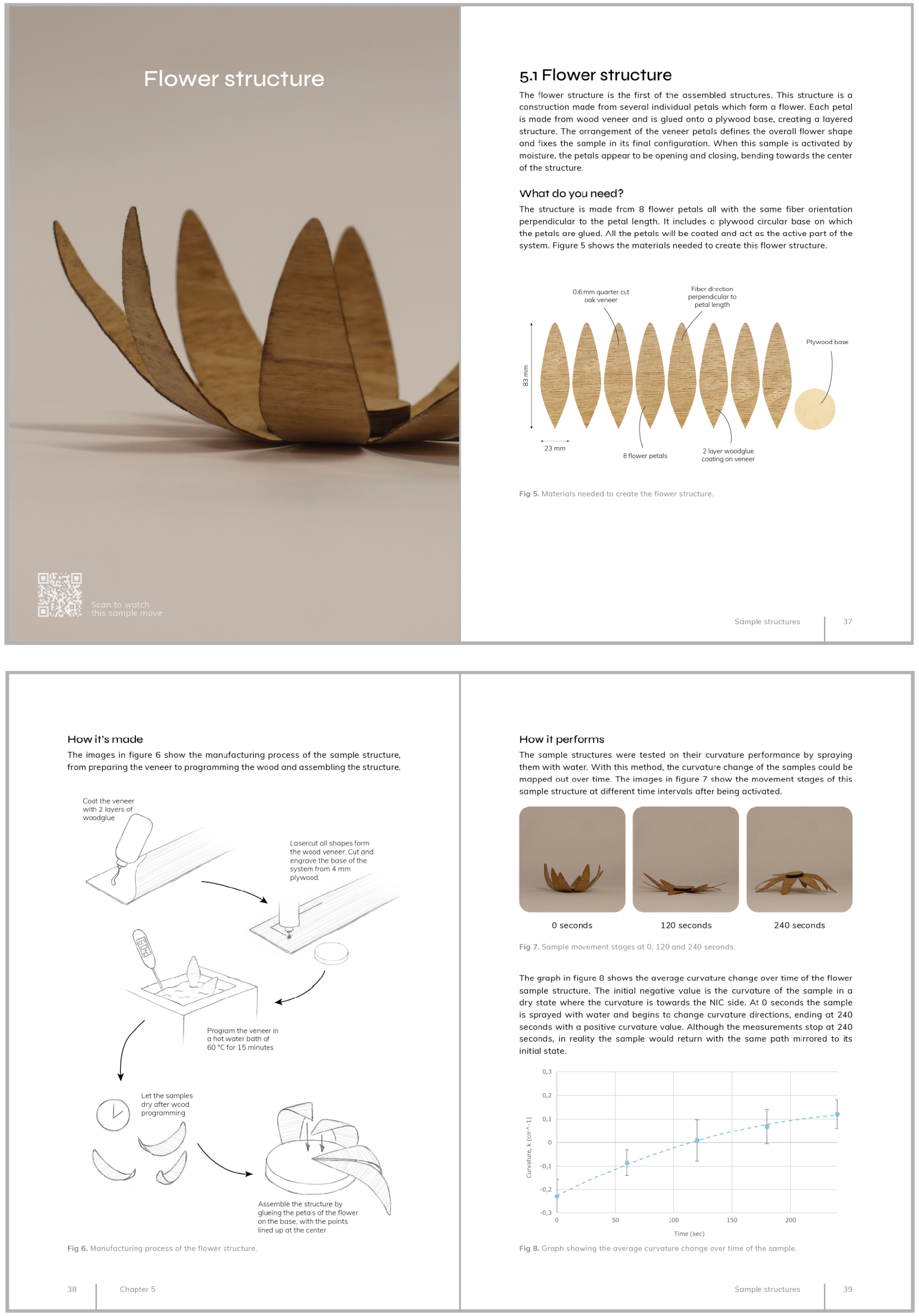
The examples can be divided in two categories: assembled structures and patterned structures. The first three examples are assembled structures, meaning the veneer is initially cut into multiple separate segments which are connected and combined into one structure. The last two examples are patterned structures. These are made from a singular piece of veneer from which shapes are cut out, creating a pattern.

Active and non-active parts

As mentioned previously, strategically placing the coating determines the curvature location. In the assembled structures, all sample pieces are fully coated on one side and therefore function entirely as active parts. In the patterned structures, only selected areas of the veneer are coated. This results in a division within the structure between active areas and the remaining non-active area.

34 Chapter 5

Fig 63. Guidelines chapter 5, Sample structures.


Flower structure

Scan to watch this sample move

5.1 Flower structure

The flower structure is the first of the assembled structures. This structure is a construction made from several individual petals which form a flower. Each petal is made from wood veneer and is glued onto a plywood base, creating a layered structure. The arrangement of the veneer petals defines the overall flower shape and fixes the sample in its final configuration. When this sample is activated by moisture, the petals appear to be opening and closing, bending towards the center of the structure.

What do you need?

The structure is made from 8 flower petals all with the same fiber orientation perpendicular to the petal length. It includes a plywood circular base on which the petals are glued. All the petals will be coated and act as the active part of the system. Figure 5 shows the materials needed to create this flower structure.

Fig 5. Materials needed to create the flower structure.

Sample structures 37

How it's made

The images in figure 6 show the manufacturing process of the sample structure, from preparing the veneer to programming the wood and assembling the structure.

Coat the veneer with 2 layers of woodglue

Lasercut all shapes form the wood veneer. Cut and engrave the base of the system from 4 mm plywood.

Program the veneer in a hot water bath of 60 °C for 15 minutes

Let the samples dry after wood programming

Assemble the structure by glueing the petals of the flower on the base, with the points lined up at the center

Fig 6. Manufacturing process of the flower structure.

38 Chapter 5

How it performs

The sample structures were tested on their curvature performance by spraying them with water. With this method, the curvature change of the samples could be mapped out over time. The images in figure 7 show the movement stages of this sample structure at different time intervals after being activated.

0 seconds
120 seconds
240 seconds

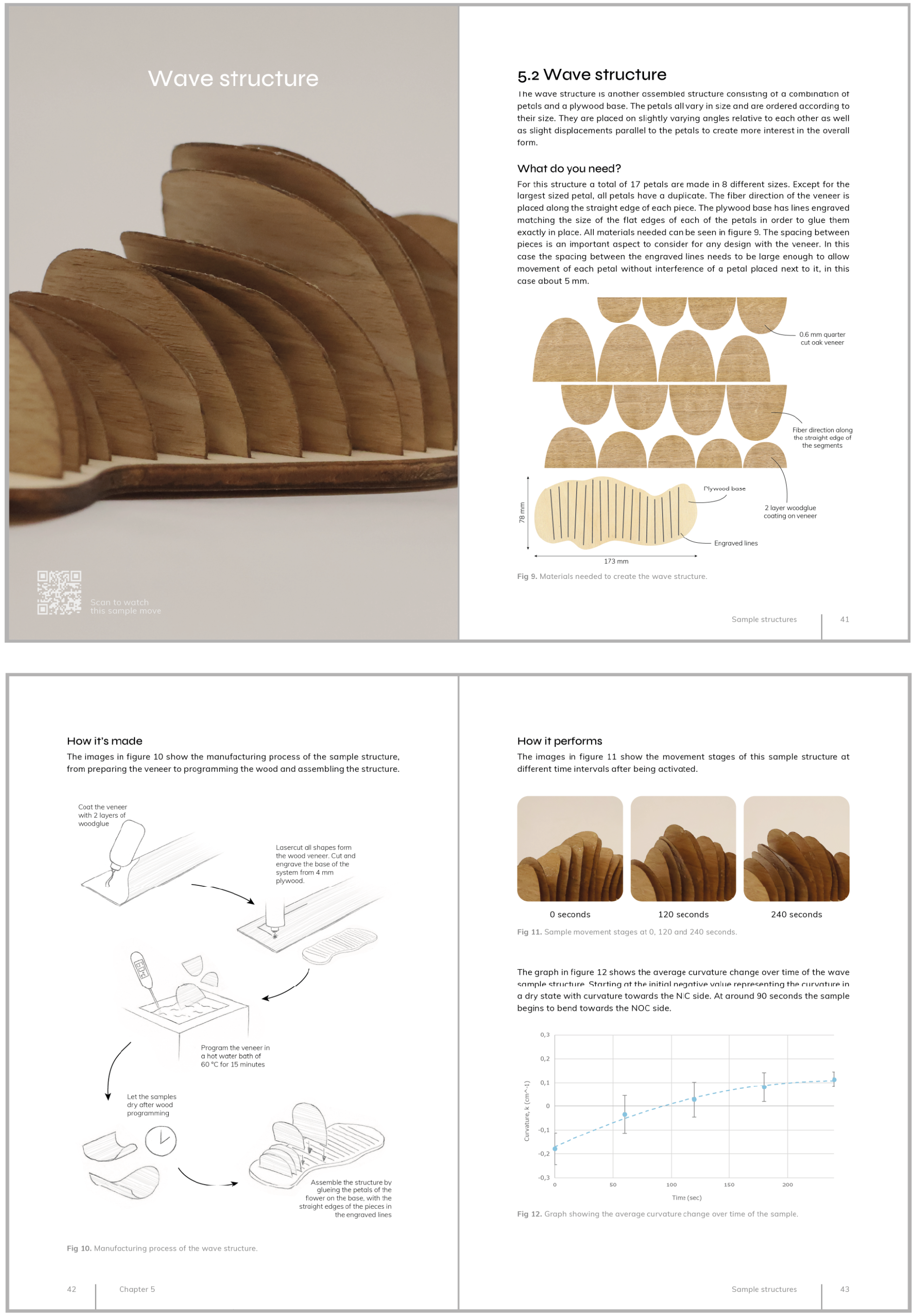
Fig 7. Sample movement stages at 0, 120 and 240 seconds.

The graph in figure 8 shows the average curvature change over time of the flower sample structure. The initial negative value is the curvature of the sample in a dry state where the curvature is towards the NIC side. At 0 seconds the sample is sprayed with water and begins to change curvature directions, ending at 240 seconds with a positive curvature value. Although the measurements stop at 240 seconds, in reality the sample would return with the same path mirrored to its initial state.

Fig 8. Graph showing the average curvature change over time of the sample.

Sample structures 39

Fig 64. Guidelines chapter 5, flower structure.



Wave structure

Scan to watch this sample move

5.2 Wave structure

The wave structure is another assembled structure consisting of a combination of petals and a plywood base. The petals all vary in size and are ordered according to their size. They are placed on slightly varying angles relative to each other as well as slight displacements parallel to the petals to create more interest in the overall form.

What do you need?

For this structure a total of 17 petals are made in 8 different sizes. Except for the largest sized petal, all petals have a duplicate. The fiber direction of the veneer is placed along the straight edge of each piece. The plywood base has lines engraved matching the size of the flat edges of each of the petals in order to glue them exactly in place. All materials needed can be seen in figure 9. The spacing between pieces is an important aspect to consider for any design with the veneer. In this case the spacing between the engraved lines needs to be large enough to allow movement of each petal without interference of a petal placed next to it, in this case about 5 mm.

Fig 9. Materials needed to create the wave structure.

Sample structures | 41

How it's made

The images in figure 10 show the manufacturing process of the sample structure, from preparing the veneer to programming the wood and assembling the structure.

Fig 10. Manufacturing process of the wave structure.

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How it performs

The images in figure 11 show the movement stages of this sample structure at different time intervals after being activated.

0 seconds | 120 seconds | 240 seconds

Fig 11. Sample movement stages at 0, 120 and 240 seconds.

The graph in figure 12 shows the average curvature change over time of the wave sample structure. Starting at the initial negative value representing the curvature in a dry state with curvature towards the NIC side. At around 90 seconds the sample begins to bend towards the NOC side.

Fig 12. Graph showing the average curvature change over time of the sample.

Sample structures | 43

Fig 65. Guidelines chapter 5, wave structure.

Twist structure

Scan to watch this sample move

5.3 Twist structure

The twist structure is the last assembled structure. Similar to the wave structure, it is made by gluing veneer pieces in engraved lines of a base. However this structure differs from the previous because it utilizes the possibility of changing the visual curvature direction. The fibers in this structure are angled resulting in a twisting motion. The structure is made from multiple mirrored pieces of veneer combined in pairs. Each pair is glued together and the bottom edges are glued in the base. This structure demonstrates the possibility of limiting curvature through the assembly design. Without gluing the veneer pieces together, the bottom edge would twist. However, through the method of assembly, this twisting motion on one end of each veneer piece is restricted.

What do you need?

This system is made with pairs of two samples. The system consists of 5 pairs glued in engraved lines on the plywood base. Each pair is made from two mirrored pieces of veneer that are glued together at the seam, creating a twisting motion where only the corners of the pairs move. The direction of the fibers is placed at a 45° angle relative to the sample length. All materials are listed in figure 13.

Fig 13. Materials needed to create the twist structure.

Sample structures | 45

How it's made

The images in figure 14 show the manufacturing process of the sample structure, from preparing the veneer to programming the wood and assembling the structure.

Fig 14. Manufacturing process of the twist structure.

46 | Chapter 5

How it performs

The images in figure 15 show the movement stages of this sample structure at different time intervals after being activated.

0 seconds | 120 seconds | 240 seconds

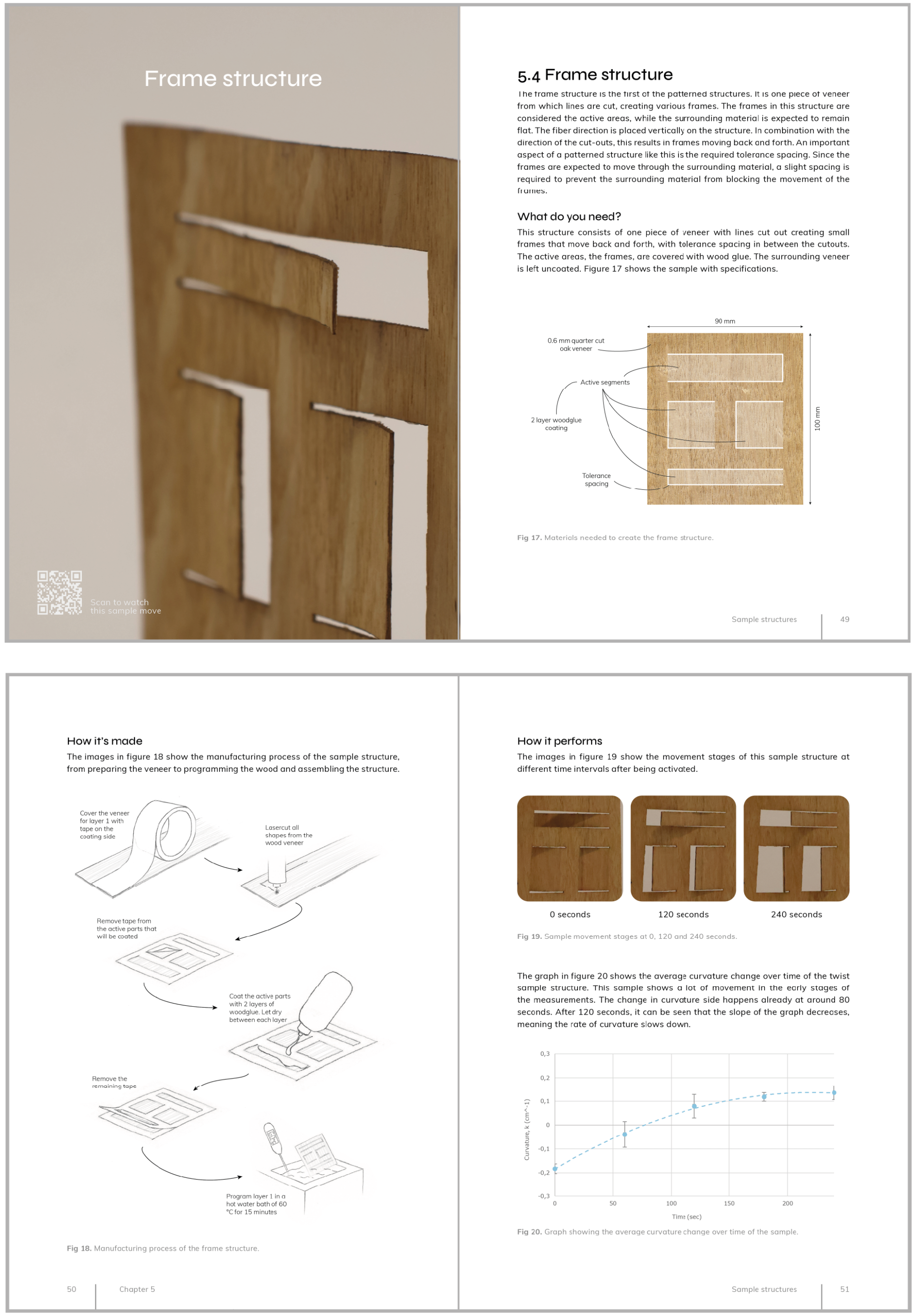
Fig 15. Sample movement stages at 0, 120 and 240 seconds.

The graph in figure 16 shows the average curvature change over time of the twist sample structure. The initial negative curvature value of this sample is quite strong. This results in a relatively late change of curvature direction from the NIC side to the NOC side, at around 220 seconds.

Fig 16. Graph showing the average curvature change over time of the sample.

Sample structures | 47

Fig 66. Guidelines chapter 5, twist structure.



Frame structure

Scan to watch this sample move

5.4 Frame structure

The frame structure is the first of the patterned structures. It is one piece of veneer from which lines are cut, creating various frames. The frames in this structure are considered the active areas, while the surrounding material is expected to remain flat. The fiber direction is placed vertically on the structure. In combination with the direction of the cut-outs, this results in frames moving back and forth. An important aspect of a patterned structure like this is the required tolerance spacing. Since the frames are expected to move through the surrounding material, a slight spacing is required to prevent the surrounding material from blocking the movement of the frames.

What do you need?

This structure consists of one piece of veneer with lines cut out creating small frames that move back and forth, with tolerance spacing in between the cutouts. The active areas, the frames, are covered with wood glue. The surrounding veneer is left uncoated. Figure 17 shows the sample with specifications.

Fig 17. Materials needed to create the frame structure.

Sample structures 49

How it's made

The images in figure 18 show the manufacturing process of the sample structure, from preparing the veneer to programming the wood and assembling the structure.

Fig 18. Manufacturing process of the frame structure.

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How it performs

The images in figure 19 show the movement stages of this sample structure at different time intervals after being activated.

0 seconds 120 seconds 240 seconds

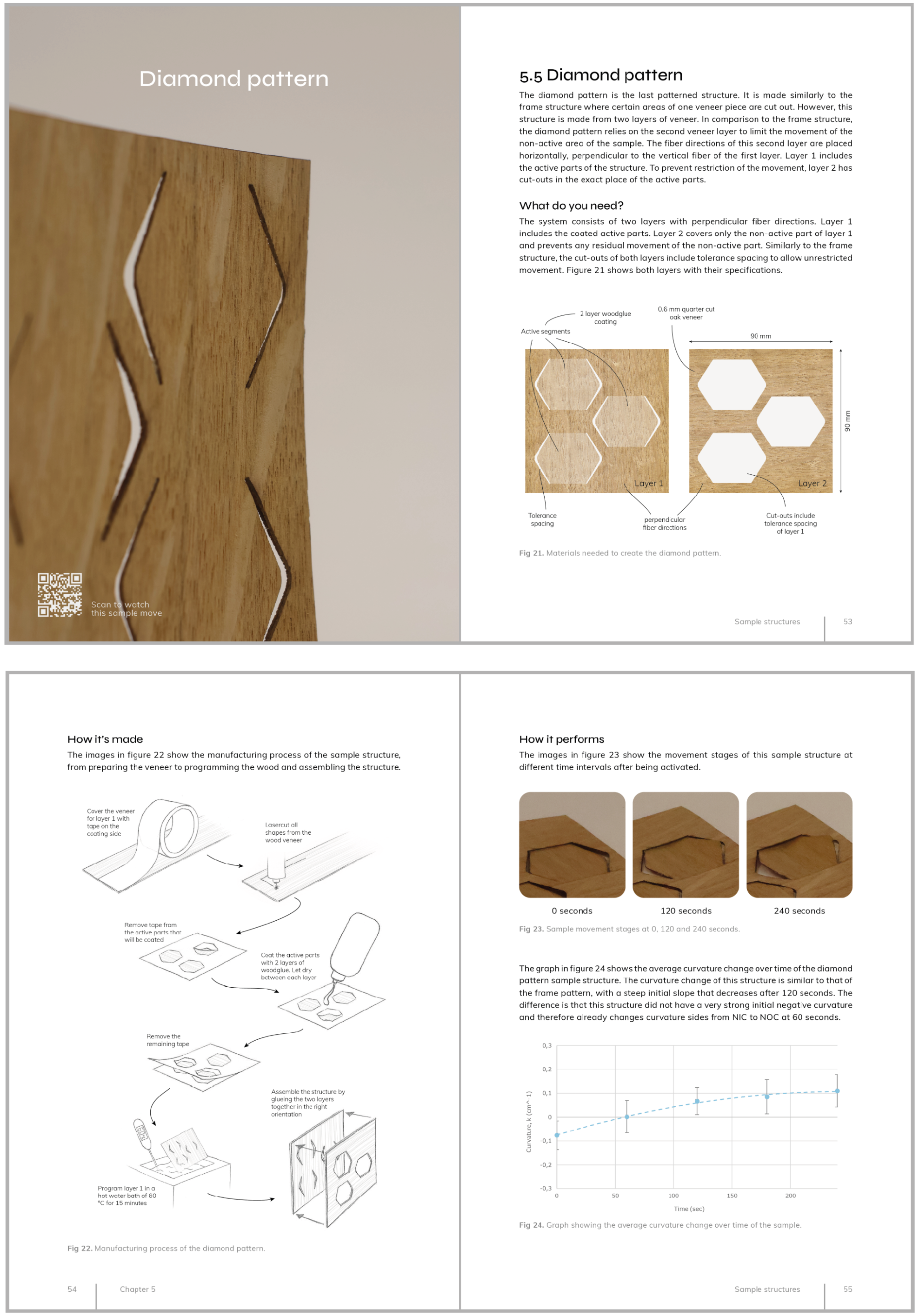
Fig 19. Sample movement stages at 0, 120 and 240 seconds.

The graph in figure 20 shows the average curvature change over time of the twist sample structure. This sample shows a lot of movement in the early stages of the measurements. The change in curvature side happens already at around 80 seconds. After 120 seconds, it can be seen that the slope of the graph decreases, meaning the rate of curvature slows down.

Fig 20. Graph showing the average curvature change over time of the sample.

Sample structures 51

Fig 67. Guidelines chapter 5, frame structure.



Diamond pattern

Scan to watch this sample move

5.5 Diamond pattern

The diamond pattern is the last patterned structure. It is made similarly to the frame structure where certain areas of one veneer piece are cut out. However, this structure is made from two layers of veneer. In comparison to the frame structure, the diamond pattern relies on the second veneer layer to limit the movement of the non-active area of the sample. The fiber directions of this second layer are placed horizontally, perpendicular to the vertical fiber of the first layer. Layer 1 includes the active parts of the structure. To prevent restriction of the movement, layer 2 has cut-outs in the exact place of the active parts.

What do you need?

The system consists of two layers with perpendicular fiber directions. Layer 1 includes the coated active parts. Layer 2 covers only the non-active part of layer 1 and prevents any residual movement of the non-active part. Similarly to the frame structure, the cut-outs of both layers include tolerance spacing to allow unrestricted movement. Figure 21 shows both layers with their specifications.

Fig 21. Materials needed to create the diamond pattern.

Sample structures 53

How it's made

The images in figure 22 show the manufacturing process of the sample structure, from preparing the veneer to programming the wood and assembling the structure.

Fig 22. Manufacturing process of the diamond pattern.

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How it performs

The images in figure 23 show the movement stages of this sample structure at different time intervals after being activated.

0 seconds 120 seconds 240 seconds

Fig 23. Sample movement stages at 0, 120 and 240 seconds.

The graph in figure 24 shows the average curvature change over time of the diamond pattern sample structure. The curvature change of this structure is similar to that of the frame pattern, with a steep initial slope that decreases after 120 seconds. The difference is that this structure did not have a very strong initial negative curvature and therefore already changes curvature sides from NIC to NOC at 60 seconds.

Fig 24. Graph showing the average curvature change over time of the sample.

Sample structures 55

Fig 68. Guidelines chapter 5, diamond pattern.

6

6.1 Responsive column

6.2 Interactive surface

INSPIRATION

This chapter presents a series of generated images that illustrate possible applications of the material as inspiration for its potential use. The examples focus on indoor architectural contexts, highlighting the aesthetic value of the wood veneer and demonstrating how it can be implemented at a larger scale. In these examples, the material contributes to the atmosphere and character of a space.

As a biobased and renewable material, wood is a lower-impact material to apply in large scale applications. In addition to the sustainable qualities of the material itself, the exhibited movement functions as a form of passive actuation. No mechanical systems or external energy sources are required. Instead, the material responds directly to environmental conditions, resulting in subtle movements that reflect changes in the surrounding climate. Together, the examples in this chapter demonstrate how the material can be applied in architectural contexts as a responsive structure that expresses environmental interaction.

6.1 Responsive column

The first example presents a centrally placed column within a large interior space, expanding outward into a structure that connects to the roof. The wood veneer is integrated by covering the main column with multiple smaller veneer segments. This example demonstrates how a large-scale architectural element can be made from many smaller pieces. By integrating the veneer in segments, the column gains a layered texture. The fiber direction of the pieces is oriented horizontally, allowing them to bend upward or downward in response to changes in relative humidity, as illustrated in Figure 25. This results in a subtle opening and closing movement caused by the natural curvature of the material. Through this gentle motion, the column becomes a responsive element within the space. Rather than functioning as a static structure, it translates invisible environmental fluctuations into visible and tactile changes, allowing the material to communicate its interaction with the surrounding climate and contributing to a more dynamic interior experience.

Fig 25. Illustrated movement of the responsive column design.

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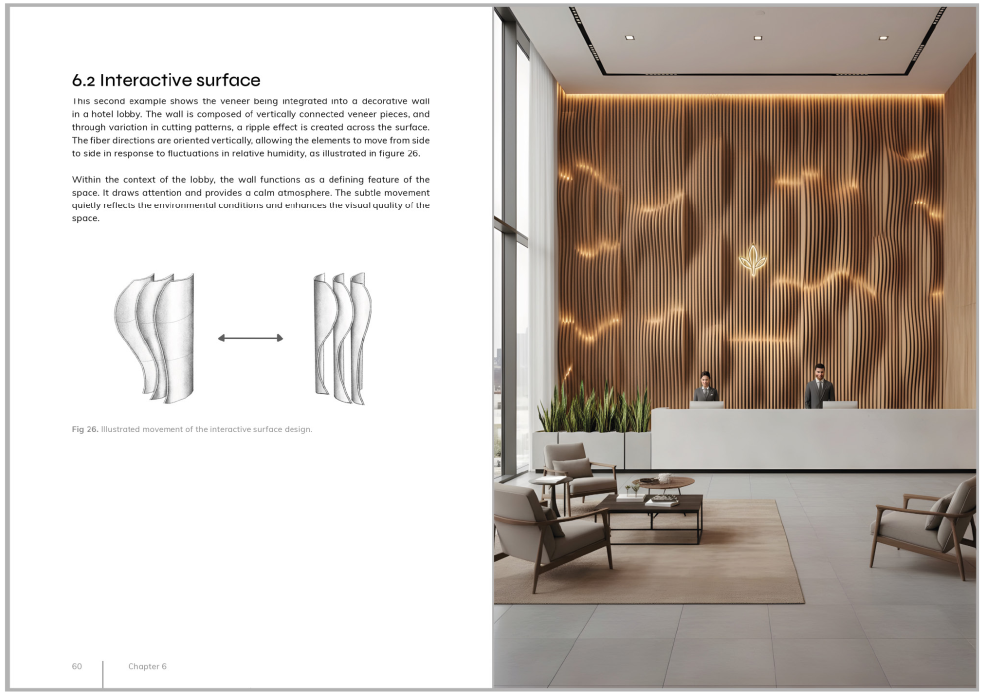
Fig 69. Guidelines chapter 6, Inspiration.



6.2 Interactive surface

This second example shows the veneer being integrated into a decorative wall in a hotel lobby. The wall is composed of vertically connected veneer pieces, and through variation in cutting patterns, a ripple effect is created across the surface. The fiber directions are oriented vertically, allowing the elements to move from side to side in response to fluctuations in relative humidity, as illustrated in figure 26.

Within the context of the lobby, the wall functions as a defining feature of the space. It draws attention and provides a calm atmosphere. The subtle movement quietly reflects the environmental conditions and enhances the visual quality of the space.

Fig 26. Illustrated movement of the interactive surface design.

60 Chapter 6

Fig 70. Guidelines chapter 6, Inspiration.

8.2 Guidelines presenter

To display the guidelines as one of the final deliverables, the following presenter was made (figures 71 and 72). On a wooden piece, a short description of the material and the guidelines is engraved. Additionally, the presenter integrates some veneer samples and a shelf with a printed book of the guidelines.

Fig 71. Guidelines presenter.

Fig 72. Guidelines presenter.

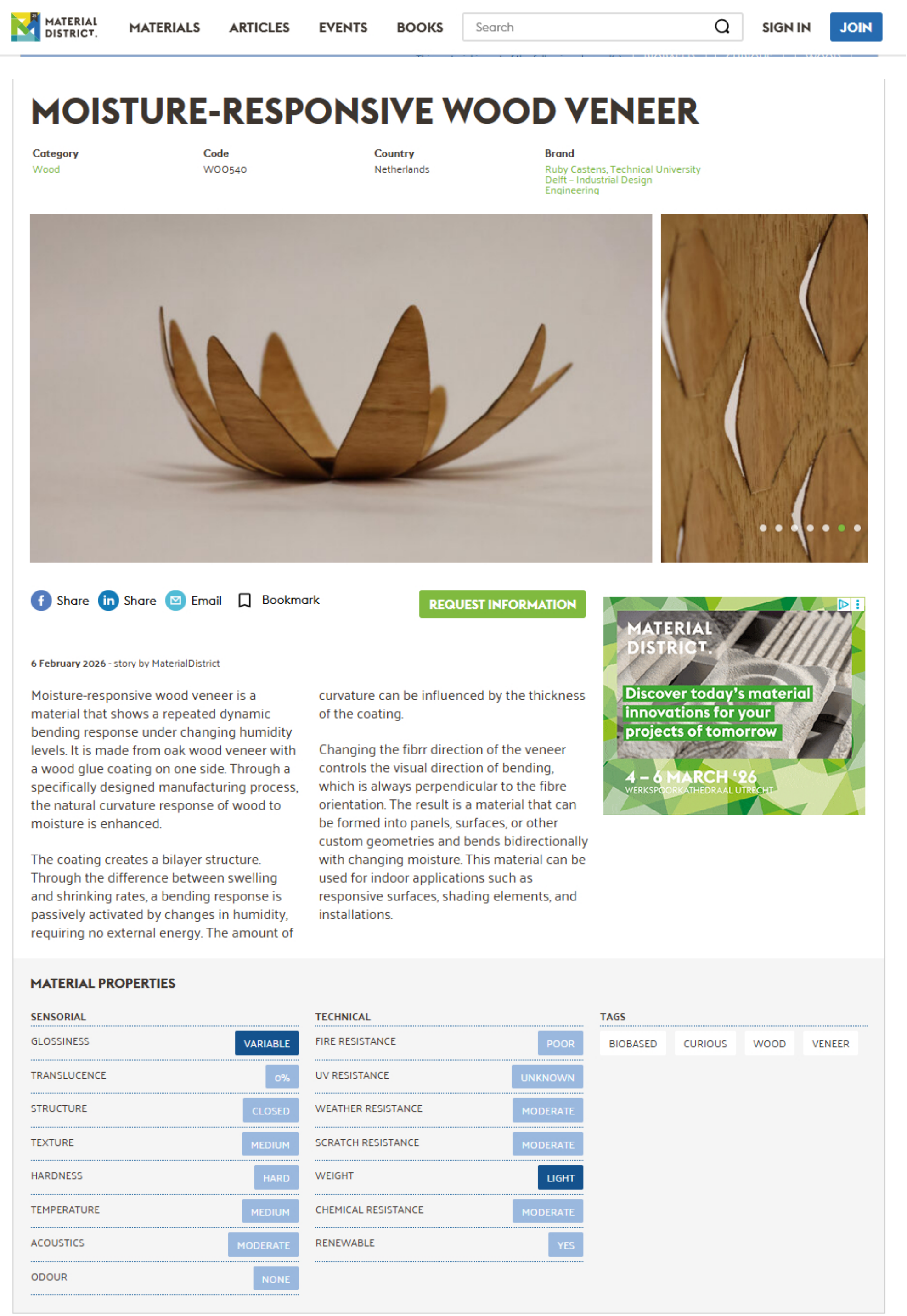
8.3 MaterialDistrict

The moisture-responsive wood veneer developed in this project was exhibited at MaterialDistrict 2026, providing the opportunity to present these material research outcomes to a wider audience of designers, architects, and material experts.

The exhibition showed two of the sample structures developed for the guidelines, the wave structure and the flower structure. In addition it showed some of the principles of the material. The amount of coating layers was shown with three round veneer pieces. Each with a different amount of coating layers, enabling visitors to feel the difference in texture between each sample, highlighting this influential variable. Lastly, three rectangular samples were exhibited with changing fiber directions. These samples were programmed, showing the effect of changing fiber directions on the visual bending direction. The exhibition can be seen in figure 73. In appendix E ideation sketches for this exhibition can be found.

In addition to the physical exhibition, the material is part of the material library on the website of MaterialDistrict. This page can be seen in figure 74.

Fig 73. MaterialDistrict exhibition board.



MOISTURE-RESPONSIVE WOOD VENEER

Category	Code	Country	Brand
Wood	WOO540	Netherlands	Ruby Castens, Technical University Delft – Industrial Design Engineering

6 February 2026 - story by MaterialDistrict

Moisture-responsive wood veneer is a material that shows a repeated dynamic bending response under changing humidity levels. It is made from oak wood veneer with a wood glue coating on one side. Through a specifically designed manufacturing process, the natural curvature response of wood to moisture is enhanced.

The coating creates a bilayer structure. Through the difference between swelling and shrinking rates, a bending response is passively activated by changes in humidity, requiring no external energy. The amount of curvature can be influenced by the thickness of the coating.

Changing the fibrr direction of the veneer controls the visual direction of bending, which is always perpendicular to the fibre orientation. The result is a material that can be formed into panels, surfaces, or other custom geometries and bends bidirectionally with changing moisture. This material can be used for indoor applications such as responsive surfaces, shading elements, and installations.

MATERIAL PROPERTIES

SENSORIAL		TECHNICAL		TAGS
GLOSSINESS	VARIABLE	FIRE RESISTANCE	POOR	BIOBASED CURIOUS WOOD VENEER
TRANSLUCENCE	0%	UV RESISTANCE	UNKNOWN	
STRUCTURE	CLOSED	WEATHER RESISTANCE	MODERATE	
TEXTURE	MEDIUM	SCRATCH RESISTANCE	MODERATE	
HARDNESS	HARD	WEIGHT	LIGHT	
TEMPERATURE	MEDIUM	CHEMICAL RESISTANCE	MODERATE	
ACOUSTICS	MODERATE	RENEWABLE	YES	
ODOUR	NONE			

Fig 74. MaterialDistrict website page.

9

DISCUSSION

9.1 Design evaluation

This chapter evaluates the guidelines by first assessing the design requirements, evaluating if and how they were met. Then evaluating the guidelines through three lenses: desirability, feasibility and viability.

The evaluations are based on several aspects of the design process. The interviews with design students in the discover phase, providing insight in the needs and wants of designers from the guidelines. The guidelines were also tested and evaluated with several methods. First through a workshop test with design students and then also through interviews with professional designers. The results from these different activities contribute to this final evaluation of the guidelines

Design requirements

The design requirements formulated for the guidelines were structured in three categories: design inspiration, designer guidance and material explanation. The requirements are evaluated in the same structure.

Design inspiration
The requirements in this category mention that the guidelines should:

- inspire designers to work with the material;
- spark creativity;
- translate experiential material qualities;
- and include design application examples that demonstrate design potential.

From the results of the workshop test, it was seen that the ability of the participants to design and create sample structures improved after reviewing the sample structures chapter of the guidelines. Indicating the guidelines do spark creativity, as was confirmed by the feedback of the participants.

During the same workshop test, an experiential characterization of the material was conducted of the material at the beginning of the workshop, and of the designed samples at the end of the workshop. The results confirmed that the guidelines translate experiential material qualities.

Additionally, the final design of the guideline also includes design application examples that show multiple possibilities of the material in a design context. Concluding that these three requirements were all met.

The requirement that the guidelines should inspire designers to work with the material is more complicated to evaluate. 'Inspiration' is complex to measure and very subjective. Therefore this requirement is assessed through observations and expressed intentions of participants from the workshop test and the expert interviews. From both evaluations, it became clear that the guidelines and the material sparked curiosity and fascination, triggered new design ideas, and stimulated interest in working with the material. Indicating that the guidelines have inspirational potential.

Designer guidance
The requirements in this category mention that the guidelines should:
be clear, understandable and easy to navigate;

- allow designers to work with the material and achieve the expected material performance without additional external instructions;
- include specifications of the material and equipment needed;
- include visuals and sample structure examples.

The results from the workshop test confirm that participants were able to create designs with the material by reading the guidelines. Confirming the guidelines were clear and understandable, and allowed for designs to be made with just the information in the guidelines.

The final guidelines include a detailed description of the material and multiple visuals supporting the written information on fiber directions, coating sides, manufacturing processes and performance descriptions. Thereby meeting all requirements in this category.

Material explanation
The requirements in this category mention that the guidelines should:

- explain the material and its performance including how and why it works;
- explain how the material is made;
- identify how designers can control the material performance through key variables;
- and describe the limitations of the material.

In chapter 3 of the guidelines, About the material, the moisture-responsive wood veneer is introduced. This chapter explains what the material is, the performance of the material, the manufacturing method and how the performance can be influenced through changing multiple variables.
The reasoning behind the performance of the material is partially explained in chapter 3. However chapter 2, wood and curvature, explains relevant background information to understanding the material. Most of the explanation behind how the material works is related back to the concepts explained in chapter 2.

Chapter 4, limitations and opportunities, describes design constraints of the material in addition to possibilities of the material outside of the already described.

In these described chapters, all requirements of this category are addressed.

Desirability

Are the guidelines attractive and valuable as a design tool?

Value for designers
The guidelines provide new value compared to existing research publications on wood veneer. As mentioned in the literature review, most research on veneer focuses on highly specific applications, lacking broader and general insights about the material required to apply the material in different contexts. The guidelines translate research findings into actionable, design-oriented steps. Instead of focusing on a single application, they present the material with the necessary background knowledge to apply the material to various design contexts.

In addition, the guidelines present various opportunities for design. The examples of sample structures in chapter 5 demonstrate a proof of concept of the material for different variations of structures. The final chapter of the guidelines integrates the material into large scale indoor architectural designs. This layered method of presentation, from the material behaviour to functional structures to architectural applications, makes the potential of the material tangible. The visualization of the possibilities is meant to support and inspire designers in applying this material to their own designs.

The guidelines also show potential beyond the specific moisture-responsive veneer on which they are based. Chapter 4 describes the boundaries of the material but also additional opportunities, enabling not only replication of the material but further exploration outside the existing knowledge. Designers are not only given instructions on how to create a specific outcome, they are also encouraged to experiment beyond it.

The guidelines bridge material science and design practice by translating literature research findings and experimental testing findings into clear, applicable information for designers. This way, lowering the threshold for designers to engage with the material.

Clarity & engagement
Based on the interviews with design students and the guideline evaluation workshop, the guidelines are perceived as useful, clear, and accessible. The information is structured logically, supported by visuals, and written to be actionable for designers.

Additionally, the evaluations imply that designers interact with the guidelines in a curious way, inspiring design exploration. During the workshop evaluation, participants were actively engaging with the written content of the guidelines by discussing the content and asking questions about the material's potential. Indicating that the guidelines stimulate engagement and exploration.

Design freedom
The guidelines are written to describe the material in a way that enables replication without focussing on a specific design application. This creates room for interpretation of the reader, supporting the creative freedom in the design possibilities of the material. This makes the guidelines function as a design tool rather than a manual for recreation.

Feasibility

Can the guidelines realistically be understood and applied?

The results of the workshop test have shown that the guidelines provide information clearly enough for designers to create samples without the need for external information. Additionally, comparing the results between participants revealed consistency in their interpretation of the guidelines. Indicating that the guidelines are understandable and provide sufficient information in order to design with the material.

The content of the guidelines is written to add to the understandability and applicability of the guidelines.

The background knowledge ensures no prior knowledge is needed to work with the guidelines. The background knowledge has been kept limited to prevent an overload of technical information, but still enough information to understand the material and allow the reader to work with it. The results from the workshop test confirmed this. None of the participants had any previous experience working with wood veneer and all were able to work with the material after reading the guidelines.

The chapter, About the material, explains the material and its performance and describes the general manufacturing process. This ensures the applicability of the guidelines. The clearly described and illustrated manufacturing method makes the material reproducible for the reader. This chapter also translates material findings into actionable design decisions by highlighting the possibilities of changes to the performance through adapting specific variables.

The limits and opportunities of the material described in the guidelines provide designers with the boundaries of the material and thereby the design space. The opportunities provide possible new material research and design directions, providing designers with a starting point for further exploration.

The sample structures chapter provides the reader with direct examples of the material being applied to a structure and the subsequent results. This adds to the understandability of the material by providing a visual example, making the explanation of the material much more concrete and clear.

Finally the inspiration chapter provides possibilities of the material in a designed structure in an architectural context. This chapter ensures the reader is provided with an example of a real application, adding to the applicability of the material.

Viability

Can the guidelines be effectively implemented and sustained in real-world practice?

Integration in practice
Designing with new materials often requires extensive testing and research. For moisture-responsive wood veneer, the guidelines provide designers with a baseline understanding and possibility to test further with a starting point. The guidelines offer information limitations and unexplored opportunities to expand on the current material research, making them transferable beyond the described material.

From the expert interview, one of the key insights was the need for consultants or experts often in design processes to provide knowledge and possibilities about a material. The guidelines can fulfill a similar role, with the material knowledge documented supporting designers in making decisions. Additionally, the interview validated that the information in the guidelines corresponds with the questions a designer might have and wants answered before working with the material.

Scalability
Although the material described in the guidelines was made and tested on a small scale, the guidelines explain possibilities for implementing the material across different production scales and budgets. With descriptions of various manufacturing methods, ranging from small scale low budget experiments to professional and semi-automated production. The focus on scalability makes the guidelines relevant for a range of contexts, from educational to professional. It also offers designers the flexibility in choosing manufacturing methods based on available resources, levels of expertise and budgets.

Long term relevance
The guidelines identify limitations and opportunities, encouraging further exploration of the material. New insights about the described material or exploration to other wood species for example, could be incorporated. Meaning the guidelines could evolve and be expanded on over time. Making the guidelines not only a tool for design practice but also a foundation for continued research.

Conclusion

This evaluation has shown that the guidelines successfully meet the design requirements. They provide inspiration, thorough explanation about the material, and support creative freedom and experimentation. Based on the results of the workshop test and the expert interview, the guidelines have been shown to be understandable, actionable, informative and engaging. Not only do the guidelines allow designers to create with the material, it also functions as a tool helping with decision making in continued material research. In addition, the guidelines are scalable across different production methods and budgets. Overall, the guidelines transfer material research to actionable design knowledge, acting as a design tool that supports immediate material application and continued exploration.

9.2 Limitations

This project was conducted within a limited time frame, which influenced the scope and depth of the research. During the initial experimental testing phase, a large number of variables and samples were explored. However, the number of sample replications was limited. Per test, usually only two identical samples were tested. Since wood is a natural material that exhibits variability in performance even with identical manufacturing, this limitation may influence the repeatability of the results.

Additionally, the scope of the research was narrowed down early in the research process because of the large number of possible variables. Therefore, the guidelines focus on a single wood species veneer with a specific performance.

All material testing was conducted at a small scale in a laboratory environment under controlled conditions. Due to the scope of this project, the material was not tested in naturally occurring environmental conditions or in larger-scale applications and manufacturing processes. Resulting in uncertainties about large-scale fabrication and long-term durability.

Because a significant part of this project focused on material research, the design process of the guidelines was not very extensive. The rapid development of the guidelines in parallel to material testing resulted in a relatively short design process. One of the aspects affected by this was the evaluation of the guidelines. Through the workshop test, the informative aspect of the guidelines was evaluated. Further evaluation was done through interviewing a professional designer. Both evaluations provided relevant and valuable insights. However, the number of participants was relatively small, especially in the expert evaluation where only one professional designer was interviewed. With more participants, the evaluation of the guidelines could have been much stronger.

Although these limitations have affected the outcomes of this project, they also highlight opportunities for future research. Especially regarding the exploration of the material, with a wider scope and more in depth results this can lead to expansion and refinement of the guidelines.

9.3 Recommendations

The recommendations for this project can be structured on different levels, related to the design guidelines and the material research on which they are based.

First, it is recommended to further evaluate the functionality of the guidelines themselves. As mentioned in the limitations, the evaluation of the guidelines was not supported by a large number of participants. With future research, they could be tested on a larger scale. For example by allowing designers to use the guidelines within real design projects and thereby evaluating how well the design process is supported by the guidelines.

Secondly, future research is recommended on the material in real-world conditions. At this stage the material performance has been tested in a climate chamber with programmed humidity cycles. Although in this project, the material performance has been observed with natural humidity fluctuations, it was not systematically measured. To provide a more realistic understanding of the material's behaviour in real applications, the material should be tested under naturally occurring humidity fluctuations.

The long-term durability of the material is another important recommendation for further research. In this project, the material fatigue was tested in a climate chamber with multiple humidity cycles. However, the long-term performance under repeated fluctuations in moisture is unknown. In future research, the effect of a large number of humidity cycles should be investigated. Providing more accurate insights into the material fatigue and possibilities for design applications.

The guidelines explain various sample structures with different geometries. These structures have been tested on their performance, and this report shortly discusses the effect of geometry on the curvature response. However, this relationship was explored to a limited extent and the measurement results showed considerable variations. An interesting future research direction could be how geometries influence the material performance.

The guidelines present examples of large scale design applications. However, the material has only been tested on a small scale. It is therefore recommended that the material behaviour is investigated in larger-scale applications.

Finally, the guidelines explain other opportunities outside of the researched material, for example expanding to other wood species. As mentioned in the literature and discovered during the testing phase, wood species respond differently to changes in moisture. Before expanding the research to other species, it is recommended that the material behaviour of oak veneer as described in the guidelines is further defined. More detailed measurements of the material properties, such as strength and flexibility at various stages, could improve the understanding of the material related to species-specific properties. This deeper understanding could then be translated to other wood species.

10

CONCLUSION

10.1 Final conclusion

This project used a material-driven design approach to investigate the behaviour of moisture-responsive wood veneer. The goal was to explore the moisture-responsive bending behaviors of wood veneer and to combine these findings into actionable guidelines that inform and inspire designers in working with the material.

In this research the knowledge transfer gap between material research and design practice is addressed. Existing studies on responsive wood veneer are often application-specific and therefore limited in providing knowledge about the relationship between variables and resulting material behaviour. Resulting in a lack of applicable and accessible material information for designers who wish to design with the material. The aim of this project was to bridge that gap by presenting material research insight into actionable design guidelines. To achieve this, the project has been structured in three domains.

The focus of the first domain was to explore the influence of variables on the resulting curvature of programmed wood veneer. Through testing wood species, veneer cutting orientations, fiber directions, programming conditions and coating strategies, the results showed that the material's curvature response is extremely dependent on the material structure. With variations of cell wall thickness, lumen ratios and material composition, the moisture absorption and bending response differ per species. Meaning that the responsive performance found for oak veneer does not directly apply for other wood species. Additionally fiber direction was shown to determine the visual curvature direction, while the thickness ratio of bilayers and the number of coating layers influenced the amount of bending.

The second domain continued on these insights. Through testing the dynamic curvature responsive by re-exposing the material to high moisture levels, a bidirectional curvature response was revealed. This response was then tested by exposing the material to humidity cycles ranging from 30% to 80%. Resulting in curvature towards the NIC side at low humidities and curvature to the NOC side with high humidities. Additionally, climate chamber tests revealed a delayed response to rapid humidity changes, a stress relaxation effect preventing a constant curvature at high humidities, and 96.8% deformation amplitude retention after six identical humidity cycles.

The results from these first two domains indicate that through adapting and changing variables, the bidirectional curvature can intentionally be controlled. Changing the natural curvature response of the material from a side effect to a controllable design parameter.

The first domains define the material performance, however the primary contribution of this project is in the third domain, where these findings are translated into design guidelines. The findings of the material research were combined into structured guidelines that make the moisture-responsive wood veneer an accessible material to designers. The guidelines describe the relationship between the variables and resulting material performance.

The guidelines include general information about the material, explanations about the performance, a manufacturing method for replication, examples of sample structure demonstrating the effect of influential variables, and an inspiration chapter with impressions of possible design applications. The evaluation of the guidelines through a workshop test and expert interview validated the potential as a design tool that supports designers in working with responsive wood veneer.

Together, the findings in these three domains answer the main research question: How can the moisture-responsive behaviour of wood veneer be translated into actionable design guidelines for designers?

By documenting the relationship between material variables and the resulting material performance, and structuring these findings into design-oriented knowledge, the guidelines bridge experimental material research and design practice.

10.2 Personal reflection

This graduation project has challenged me in many different ways and taught me so much. Looking back, the material research phase was probably my favorite part of the entire project. It allowed me to work hands-on with the material, exploring its possibilities through a very structured and systematic approach. At the same time it was also one of the most challenging phases. Tests had to be repeated due to equipment failures and unpredictability in results. I struggled mostly with the interpretation of the results, where I quickly noticed my limited knowledge about material research. This made it very complicated to understand the material behaviour and identify the right research directions.

When working on a project, I often want to figure everything out independently. However, the challenges of this phase made that difficult and reminded me that asking for help can be very valuable. The help I received from the people in the lab, my supervisors and fellow students have only made this project so much better.

This project also taught me how to deal with uncertainties. The MDD approach meant this project started without a clear idea of what the final outcome would be. As the project went on, every step, result or finding changed the direction the project was going in. Meaning I constantly had to redefine my expectations. I learned that not knowing the outcome does not have to influence the process negatively. On the contrary, the uncertainty of the outcome allowed me to move through the project freely.

I also realised how high my expectations for myself can be. Although these expectations often motivate me and result in higher quality outcomes, it also means I am often disappointed when my expectations are not met. With this project, I struggled with this aspect a lot. The time limitations and unexpected directions of the project meant some of my expectations could not be met. Even though this was the case, I am still very proud of the final outcome. This project showed me that a valuable result can be achieved even though not all expectations were met.

Finally, through this project I gained a lot of confidence in my own abilities and judgement. As the project progressed, I learned that I am quite aware of the quality of my work. Before meetings with my supervisors, I often already knew what I would improve or what my next steps were going to be. Many times, the feedback I received aligned very closely with my expectations. Reminding me that I can trust my instincts more.

Overall, I look back on this project with a strong sense of accomplishment. Not everything was easy, but the challenges made the success so much more meaningful. I got to execute this project in a way that really suits me, a lot of practical work, and working hands-on with the material. And in the end I delivered a result that I am truly proud of.

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APPENDICES

Appendix A: Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Ruby Castens

Student number 5250463

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Exploring the influence of wood structure on dynamic rotational performance in nature-inspired systems

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Biomimicry is a well known and used method in design. It aims to solve design challenges by studying and transferring nature's mechanisms and principles. An interesting field within this, is the study of plant seeds and their complex dynamic motion created purely through their material properties and structural geometry. One example is the Erodium seed, which uses hygroscopic actuation to rotate and self-bury in the soil. Inspired by this, Luo et al. (2023) have developed seed carriers from wood veneer that mimic the seed's coiling behavior (figure 1).

This research builds upon this work by investigating how wood, a hygroscopic and structurally complex natural material, can be shaped to replicate the dynamic rotational movement found in plant seeds. Starting with researching the hierarchical structure levels of wood (Chen et al., 2020) to build an understanding of the material and its properties (figure 2), following with the hygroscopic behaviour of the material and how this affects the material curvature. The goal is to understand in what way the material properties influence the curvature movement in order to translate this into a designed application for potential domains such as agriculture, healthcare, consumer products, etc.

While wood offers opportunities due to its inherent structure and sustainable nature, there are limitations that exist with the material. Because it's a natural material, no piece of wood will be the same, making controllable tests quite challenging.

Chen, C., Kuang, Y., Zhu, S., Burgert, I., Keplinger, T., Gong, A., Li, T., Berglund, L., Eichhorn, S. J., & Hu, L. (2020). Structure–property–function relationships of natural and engineered wood. Nature Reviews Materials, 5(9), 642–666. https://doi.org/10.1038/s41578-020-0195-z

Luo, D., Maheshwari, A., Danielescu, A., Li, J., Yang, Y., Tao, Y., Sun, L., Patel, D. K., Wang, G., Yang, S., Zhang, T., & Yao, L. (2023). Autonomous self-burying seed carriers for aerial seeding. Nature, 614(7948), 463–470. https://doi.org/10.1038/s41586-022-05656-3

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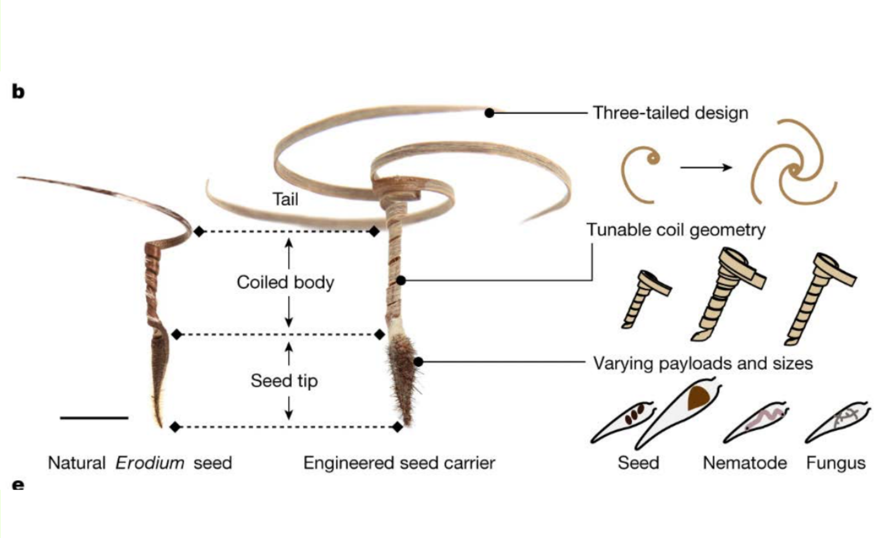


image / figure 1 Seed carrier design by Luo et al., 2023

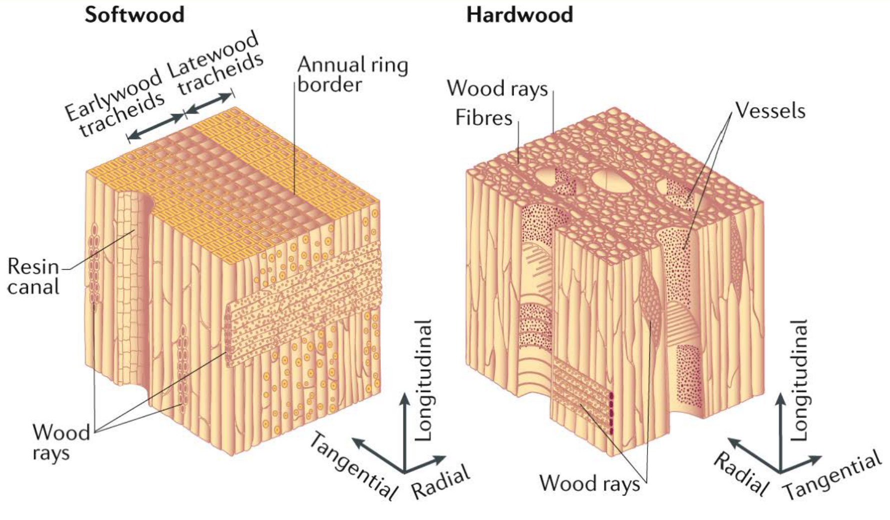


image / figure 2 Microstructure of wood classified by softwood and hardwood (Chen et al., 2020)

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

This graduation project will build on the research done by Luo et al. (2023) by creating coil shapes made from wood veneer, and activating their dynamic rotational movement with moisture. The design of the wood coil in this research was highly tailored to their specific application, seed dispersal. The material selection, processing methods, and final shape were optimized for that singular function. As a result, their approach is can not be easily reproduced and applied for other or more general applications.

Understanding the material and how its structural and hygroscopic properties can be tuned to create dynamic coiling behaviour for possible applications in different contexts is what this graduation project aims to address. The goal is to gain insight into the material through hands-on exploration, in order to develop a design with reliable and consistent behavior that can be adapted for use in a range of contexts.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Develop a predictable, moisture-activated rotating wood coil through material exploration and prototyping, apply it in a functional proof-of-concept, and provide guidelines to help other designers adapt the material across diverse contexts.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This project will start with the research & exploration phase. This includes mainly the tinkering phase, learning about the material through the creation and testing of samples. Based on my literature research, I will create different samples including variables such as the earlywood to latewood ratio, the fiber direction and environmental influences. And test the influence of the variables on the dynamic rotational behaviour. In this phase there experiential characterization will also take place. This feedback will be used to improve this exploration and will provide insights for the design phase. Following this research & exploration phase, is the design phase. Here I will be using my results and conclusions from the first phase to design a fitting application for the material. This will be done through ideation, concept development and concept prototyping. The third phase will be focussed on evaluating the prototype and implementing these results to perfect the design. Lastly there will be a documentation phase, where all the results will be documented for the report and finalised for the graduation presentation.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting***, ***mid-term evaluation meeting***, ***green light meeting*** *and* ***graduation ceremony***. *Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting 8 sep 2025

Mid-term evaluation 27 okt 2026

Green light meeting 12 jan 2026

Graduation ceremony 13 feb 2026

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

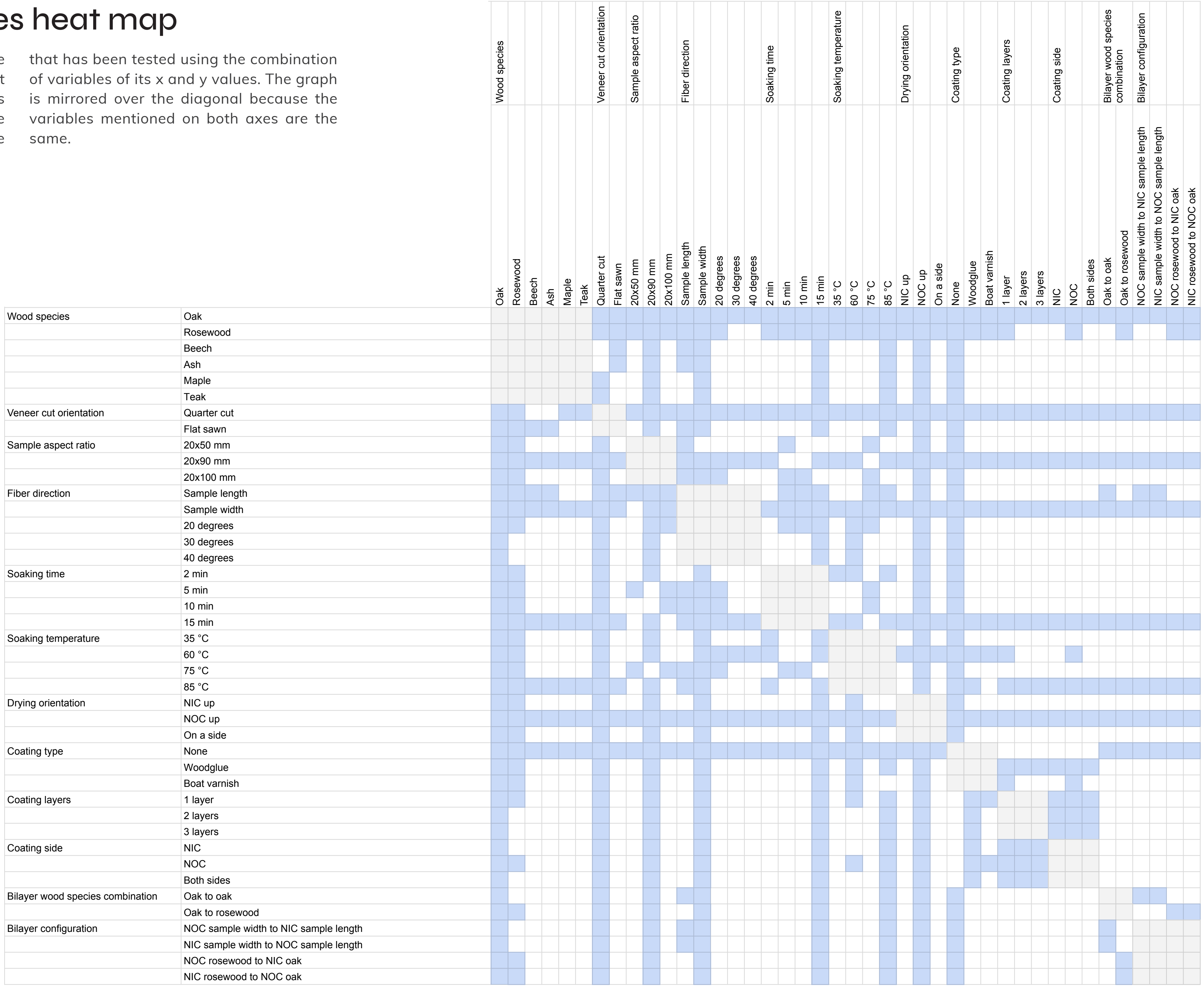
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My favourite part of any design project is the prototyping stage. I have always enjoyed the hands-on process, experimenting, testing and learning through making. And I wanted to create the opportunity to do this a lot in my graduation project. At the same time material-driven design is very intruiging to me because it is so different from any other design approach. Instead of starting with a defined problem or need, starting with the material itself, exploring, tinkering and optimizing it and figuring out later what it could become. Working with the material is something I really look forward to, discovering the possibilities of a material and using this to inspire a design.

This graduation project will also be a way to challenge myself in a field that I don't have a lot experience in or feel very comfortable in but still find very interesting. I want to test my own abilities in navigating this project.
One of my goals is to improve my time management. I'm good at making plans and managing a project but I struggle sometimes to stay on track of my own plan. I also want to build more confidence and trust in my own skills to experience this project with less stress and enjoy the process.

Appendix B: Variables heat map

The heat map on this page shows all the variables that have been tested against eachother. The variables with their values are listed on both the x- and y-axis. The blue filled boxes represent at least one sample that has been tested using the combination of variables of its x and y values. The graph is mirrored over the diagonal because the variables mentioned on both axes are the same.



Appendix C: Samples experimental testing

3.2 Exploring curvature response through wood programming:

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
6.1	24/9 a1.1	Oak	20	100	sample length			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	2.0		
6.1	24/9 a1.2	Oak	20	100	sample length			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	2.0		
6.1	24/9 a2.1	Rosewood	20	100	sample length			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	1.8		
6.1	24/9 a2.2	Rosewood	20	100	sample length			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	1.8		
6.1	24/9 a3.1	Oak	20	100	sample width			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	7.0		
6.1	24/9 a3.2	Oak	20	100	sample width			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	11.0		
6.1	24/9 a4.1	Rosewood	20	100	sample width			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	15.0		
6.1	24/9 a4.2	Rosewood	20	100	sample width			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	21.0		
6.1	24/9 a5.1	Oak	20	100	18 degree angle			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	-		
6.1	24/9 a5.2	Oak	20	100	18 degree angle			10 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	-		
6.1	24/9 a6.1	Rosewood	20	100	18 degree angle			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	-		
6.1	24/9 a6.2	Rosewood	20	100	18 degree angle			10 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	-		
6.1	24/9 a7.1	Oak	20	100	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	1.2		
6.1	24/9 a7.2	Oak	20	100	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	2.0		
6.1	24/9 a8.1	Rosewood	20	100	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	1.2		
6.1	24/9 a8.2	Rosewood	20	100	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	1.2		
6.1	24/9 a9.1	Oak	20	100	sample width			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	9.0		
6.1	24/9 a9.2	Oak	20	100	sample width			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	9.0		
6.1	24/9 a10.1	Rosewood	20	100	sample width			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	15.0		
6.1	24/9 a10.2	Rosewood	20	100	sample width			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	20.0		
6.1	24/9 a11.1	Oak	20	100	18 degree angle			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	-		
6.1	24/9 a11.2	Oak	20	100	18 degree angle			5 min - 75 °C	39%, 21.4-21.8 °C	0.6	1.2	-		
6.1	24/9 a12.1	Rosewood	20	100	18 degree angle			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	-		
6.1	24/9 a12.2	Rosewood	20	100	18 degree angle			5 min - 75 °C	39%, 21.4-21.8 °C	0.8	1.2	-		

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
6.1	24/9 b1.1	Oak	20	50	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.3	0.6	1.2		
6.1	24/9 b1.2	Oak	20	50	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.3	0.6	1.2		
6.1	24/9 b2.1	Rosewood	20	50	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.4	0.6	1.8		
6.1	24/9 b2.2	Rosewood	20	50	sample length			5 min - 75 °C	39%, 21.4-21.8 °C	0.4	0.6	1.8		
6.2	25/9 a1.1	Oak	20	90	sample width			2 min - 35 °C	37%, 22.1-22-.2 °C	0.58		5.0	88.0	196.1
6.2	25/9 a1.2	Oak	20	90	sample width			2 min - 35 °C	37%, 22.1-22-.2 °C	0.58		7.0	87.0	138.7
6.2	25/9 a2.1	Rosewood	20	90	sample width			2 min - 35 °C	37%, 22.1-22-.2 °C	0.75		2.0	89.0	496.1
6.2	25/9 a2.2	Rosewood	20	90	sample width			2 min - 35 °C	37%, 22.1-22-.2 °C	0.75		3.0	89.0	331.5
6.2	25/9 a3.1	Oak	20	90	sample width			15 min - 35 °C	37%, 22.1-22-.2 °C	0.58	0.91	5.0	88.0	196.1
6.2	25/9 a3.2	Oak	20	90	sample width			15 min - 35 °C	37%, 22.1-22-.2 °C	0.58	0.91	9.0	87.0	109.6
6.2	25/9 a4.1	Rosewood	20	90	sample width			15 min - 35 °C	37%, 22.1-22-.2 °C	0.75	0.91	4.0	89.0	249.5
6.2	25/9 a4.2	Rosewood	20	90	sample width			15 min - 35 °C	37%, 22.1-22-.2 °C	0.75	0.91	3.5	88.5	281.5
6.2	25/9 a5.1	Oak	20	90	sample width			2 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.86	7.5	87.5	131.4
6.2	25/9 a5.2	Oak	20	90	sample width			2 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.86	12.5	85.0	78.5
6.2	25/9 a6.1	Rosewood	20	90	sample width			2 min - 60 °C	37%, 22.1-22-.2 °C	0.75	0.95	9.0	86.0	107.2
6.2	25/9 a6.2	Rosewood	20	90	sample width			2 min - 60 °C	37%, 22.1-22-.2 °C	0.75	0.95	11.0	86.0	89.5
6.2	25/9 a7.1	Oak	20	90	sample width			15 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.95	11.5	86.0	86.1
6.2	25/9 a7.2	Oak	20	90	sample width			15 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.95	11.0	86.0	89.5
6.2	25/9 a8.1	Rosewood	20	90	sample width			15 min - 60 °C	37%, 22.1-22-.2 °C	0.75	1.05	16.5	81.0	58.0
6.2	25/9 a8.2	Rosewood	20	90	sample width			15 min - 60 °C	37%, 22.1-22-.2 °C	0.75	1.05	14.0	84.0	70.0
6.2	25/9 a9.1	Oak	20	90	sample width			2 min - 85 °C	37%, 22.1-22-.2 °C	0.58	1.0	11.5	85.0	84.3
6.2	25/9 a9.2	Oak	20	90	sample width			2 min - 85 °C	37%, 22.1-22-.2 °C	0.58	1.0	7.0	88.0	141.8
6.2	25/9 a10.1	Rosewood	20	90	sample width			2 min - 85 °C	37%, 22.1-22-.2 °C	0.75	1.05	7.0	88.0	141.8
6.2	25/9 a10.2	Rosewood	20	90	sample width			2 min - 85 °C	37%, 22.1-22-.2 °C	0.75	1.05	16.0	81.0	59.3
6.2	25/9 a11.1	Oak	20	90	sample width			15 min - 85 °C	37%, 22.1-22-.2 °C	0.58	1.10	15.0	81.0	62.2
6.2	25/9 a11.2	Oak	20	90	sample width			15 min - 85 °C	37%, 22.1-22-.2 °C	0.58	1.10	12.5	84.5	77.7
6.2	25/9 a12.1	Rosewood	20	90	sample width			15 min - 85 °C	37%, 22.1-22-.2 °C	0.75	1.15	17.5	81.0	55.6
6.2	25/9 a12.2	Rosewood	20	90	sample width			15 min - 85 °C	37%, 22.1-22-.2 °C	0.75	1.15	19.5	77.0	47.8
6.2	25/9 b1	Oak	20	90	sample width		drying on top side	15 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.95	11.0	85.5	88.6
6.2	25/9 b2	Rosewood	20	90	sample width		drying on top side	15 min - 60 °C	37%, 22.1-22-.2 °C	0.58	1.05	13.0	84.0	74.3
6.2	25/9 b3	Oak	20	90	sample width		drying on side	15 min - 60 °C	37%, 22.1-22-.2 °C	0.58	0.95	10.5	86.0	93.3

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
6.2	25/9 b4	Rosewood	20	90	sample width		drying on side	15 min - 60 °C	37%, 22.1-22-.2 °C	0.75	1.05	12.5	85.0	78.5
6.2	25/9 c1.1	Oak	20	90	20 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.2	25/9 c1.2	Oak	20	90	20 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.2	25/9 c2.1	Oak	20	90	30 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.2	25/9 c2.2	Oak	20	90	30 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.2	25/9 c3.1	Oak	20	90	40 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.2	25/9 c3.2	Oak	20	90	40 degrees, angle			15 min - 60 °C	37%, 22.1-22-.2 °C					
6.3	25/9 d1.1	Oak	20	90	sample width	None		15 min - 60 °C	35%, 22 °C			8.0	87.0	122.3
6.3	25/9 d1.2	Oak	20	90	sample width	None		15 min - 60 °C	35%, 22 °C			8.0	88.0	125.0
6.3	25/9 d2.1	Oak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	35%, 22 °C			16.5	80.5	57.3
6.3	25/9 d2.2	Oak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	35%, 22 °C			15.0	82.0	63.5
6.3	25/9 d3.1	Oak	20	90	sample width	Boat varnish	1 coating layer	15 min - 60 °C	35%, 22 °C			13.0	85.0	76.0
6.3	25/9 d3.2	Oak	20	90	sample width	Boat varnish	1 coating layer	15 min - 60 °C	35%, 22 °C			12.0	87.0	84.8
6.3	25/9 d6.1	Rosewood	20	90	sample width	None		15 min - 60 °C	35%, 22 °C			14.5	83.0	66.6
6.3	25/9 d6.2	Rosewood	20	90	sample width	None		15 min - 60 °C	35%, 22 °C			15.5	82.5	62.6
6.3	25/9 d7.1	Rosewood	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	35%, 22 °C			12.5	86.0	80.2
6.3	25/9 d7.2	Rosewood	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	35%, 22 °C			11.0	86.0	89.5
6.3	25/9 d8.1	Rosewood	20	90	sample width	Boat varnish	1 coating layer	15 min - 60 °C	35%, 22 °C			14.5	85.0	69.5
6.3	25/9 d8.2	Rosewood	20	90	sample width	Boat varnish	1 coating layer	15 min - 60 °C	35%, 22 °C			14.0	85.0	71.5
7.1	1/10 a1.1	Beech flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.58	1.09			
7.1	1/10 a1.2	Beech flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.58	1.09			

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
7.1	1/10 a10.1	Rosewood flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	1.28	0.68			
7.1	1/10 a10.2	Rosewood flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	1.28	0.68			
7.1	1/10 a11.1	Rosewood flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	1.28	0.68			
7.1	1/10 a11.2	Rosewood flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	1.28	0.68			
7.1	1/10 a2.1	Beech flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.58	1.09			
7.1	1/10 a2.2	Beech flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.58	1.09			
7.1	1/10 a3.1	Ash flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.65	1.13			
7.1	1/10 a3.2	Ash flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.65	1.13			
7.1	1/10 a4.1	Ash flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.65	1.13	15.0	83.5	65.6
7.1	1/10 a4.2	Ash flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.65	1.13	18.0	80.0	53.4
7.1	1/10 a5.1	Maple quarter cut	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.63	1.15	8.0	88.0	125.0
7.1	1/10 a5.2	Maple quarter cut	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.63	1.15	5.0	88.0	196.1
7.1	1/10 a6.1	Oak flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.65	1.24	4.0	89.0	249.5
7.1	1/10 a6.2	Oak flat sawn	20	90	sample length			15 min - 85 °C	43%, 22 °C	0.65	1.24	5.0	89.0	200.5
7.1	1/10 a7.1	Oak flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.65	1.24	31.0	51.0	26.0
7.1	1/10 a7.2	Oak flat sawn	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.65	1.24	21.0	75.0	44.0
7.1	1/10 a8.1	Oak quarter cut 2.0	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.56	1.10			
7.1	1/10 a8.2	Oak quarter cut 2.0	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.56	1.10	16.0	81.0	59.3
7.1	1/10 a9.1	Teak quarter cut	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.50	0.88	29.0	41.0	21.7

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
7.1	1/10 a9.2	Teak quarter cut	20	90	sample width			15 min - 85 °C	43%, 22 °C	0.50	0.88	31.0	37.0	21.0
7.2	1/10 b1.1	Oak	20	90	sample width	1 layer, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.68	1.17	0.0	90.0	0.0
7.2	1/10 b1.2	Oak	20	90	sample width	1 layer, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.68	1.17	0.0	90.0	0.0
7.2	1/10 b10.1	Oak	20	90	sample width	2 layers, Woodglue	Half/half both side coating	15 min - 85 °C	43%, 22 °C	0.84	1.35			
7.2	1/10 b10.2	Oak	20	90	sample width	2 layers, Woodglue	Half/half both side coating	15 min - 85 °C	43%, 22 °C	0.78	1.35			
7.2	1/10 b2.1	Oak	20	90	sample width	1 layer, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.68	1.17	6.0	88.0	164.3
7.2	1/10 b2.2	Oak	20	90	sample width	1 layer, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.68	1.17	7.0	88.0	141.8
7.2	1/10 b3.1	Oak	20	90	sample width	1 layer, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	0.8	1.30	4.5	89.0	222.3
7.2	1/10 b3.2	Oak	20	90	sample width	1 layer, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	0.8	1.30	4.5	89.0	222.3
7.2	1/10 b4.1	Oak	20	90	sample width	2 layers, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.8	1.30	20.0	78.0	48.0
7.2	1/10 b4.2	Oak	20	90	sample width	2 layers, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.8	1.30	21.0	78.0	46.7
7.2	1/10 b5.1	Oak	20	90	sample width	2 layers, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.78	1.26	15.0	83.0	64.9
7.2	1/10 b5.2	Oak	20	90	sample width	2 layers, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.78	1.26	16.5	82.0	59.2
7.2	1/10 b6.1	Oak	20	90	sample width	2 layers, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	1.04	1.41	0.0	90.0	0.0
7.2	1/10 b6.2	Oak	20	90	sample width	2 layers, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	1.04	1.41	0.0	90.0	0.0
7.2	1/10 b7.1	Oak	20	90	sample width	3 layers, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.92	1.42	0.0	90.0	0.0
7.2	1/10 b7.2	Oak	20	90	sample width	3 layers, Woodglue	Inside coating	15 min - 85 °C	43%, 22 °C	0.92	1.42	0.0	90.0	0.0
7.2	1/10 b8.1	Oak	20	90	sample width	3 layers, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.88	1.37	21.0	75.0	44.0

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
7.2	1/10 b8.2	Oak	20	90	sample width	3 layers, Woodglue	Outside coating	15 min - 85 °C	43%, 22 °C	0.88	1.37	13.5	85.0	73.6
7.2	1/10 b9.1	Oak	20	90	sample width	3 layers, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	1.24	1.66	0.0	90.0	0.0
7.2	1/10 b9.2	Oak	20	90	sample width	3 layers, Woodglue	Both side coating	15 min - 85 °C	43%, 22 °C	1.24	1.66	0.0	90.0	0.0
7.4	1/10 d1.1	Oak	20	90	sample length, sample width		Outside width to inside length	15 min - 85 °C	43%, 22 °C	1.44	2.20	10.0	87.0	99.6
7.4	1/10 d1.2	Oak	20	90	sample length, sample width		Outside width to inside length	15 min - 85 °C	43%, 22 °C	1.44	2.20	8.0	88.0	125.0
7.4	1/10 d2.1	Oak	20	90	sample length, sample width		Outside width to inside length, Fiber length - half sample	15 min - 85 °C	43%, 22 °C	0.95	1.63	9.0	88.0	112.1
7.4	1/10 d2.2	Oak	20	90	sample length, sample width		Outside width to inside length, Fiber length - half sample	15 min - 85 °C	43%, 22 °C	0.95	1.63	10.0	88.5	102.9
7.4	1/10 d3.1	Oak	20	90	sample length, sample width		Outside width to inside length, Fiber length - two ends	15 min - 85 °C	43%, 22 °C	0.98	1.61	10.5	87.0	95.4
7.4	1/10 d3.2	Oak	20	90	sample length, sample width		Outside width to inside length, Fiber length - two ends	15 min - 85 °C	43%, 22 °C	0.98	1.61	8.0	88.0	125.0
7.4	1/10 d4.1	Oak	20	90	sample length, sample width		Inside width to outside length, Fiber length - two ends	15 min - 85 °C	43%, 22 °C	0.98	1.61	0.0	90.0	0.0
7.4	1/10 d4.2	Oak	20	90	sample length, sample width		Inside width to outside length, Fiber length - two ends	15 min - 85 °C	43%, 22 °C	0.98	1.61	0.0	90.0	0.0

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Environmental values	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
7.4	1/10 d5.1	Oak, Rosewood	20	90	sample width		Inside rosewood to outside oak	15 min - 85 °C	43%, 22 °C	1.5	2.10	4.0	89.0	249.5
7.4	1/10 d5.2	Oak, Rosewood	20	90	sample width		Inside rosewood to outside oak	15 min - 85 °C	43%, 22 °C	1.58	2.23	3.0	89.0	331.5
7.4	1/10 d6.1	Oak, Rosewood	20	90	sample width		Inside oak to outside rosewood	15 min - 85 °C	43%, 22 °C	1.55	2.24	5.0	89.0	200.5
7.4	1/10 d6.2	Oak, Rosewood	20	90	sample width		Inside oak to outside rosewood	15 min - 85 °C	43%, 22 °C	1.55	2.24	6.0	89.0	168.0

3.3 Dynamic performance of programmed wood veneer:

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
7.3	1/10 c1.1	Oak	20	90	sample width			15 min - 60 °C	0,58	0,96	13,0	84,0	74,3
7.3	1/10 c1.2	Oak	20	90	sample width			15 min - 60 °C	0,58	0,96	15,0	83,0	64,9
7.3	1/10 c1.3	Oak	20	90	sample width			15 min - 60 °C	0,58	0,96	14,5	84,0	68,1
7.3	1/10 c1.4	Oak	20	90	sample width			15 min - 60 °C	0,58	0,96	15,0	83,5	65,6
7.3	1/10 c2.1	Oak	20	90	sample width	1 layer, Woodglue		15 min - 60 °C	0,58	1,03	13,0	84,0	74,3
7.3	1/10 c2.2	Oak	20	90	sample width	1 layer, Woodglue		15 min - 60 °C	0,68	1,03	14,0	83,0	68,5
7.3	1/10 c2.3	Oak	20	90	sample width	1 layer, Woodglue		15 min - 60 °C	0,68	1,03	17,0	79,0	54,4
7.3	1/10 c2.4	Oak	20	90	sample width	1 layer, Woodglue		15 min - 60 °C	0,68	1,03	13,0	83,0	72,7
7.3	1/10 c3.1	Oak	20	90	sample width	None		15 min - 85 °C	0,58	1,08	11,0	85,0	87,6
7.3	1/10 c3.2	Oak	20	90	sample width	None		15 min - 85 °C	0,58	1,08	13,0	85,0	76,0
7.3	1/10 c3.3	Oak	20	90	sample width	None		15 min - 85 °C	0,58	1,08	11,0	86,0	89,5
7.3	1/10 c3.4	Oak	20	90	sample width	None		15 min - 85 °C	0,58	1,08	14,0	84,0	70,0
7.3	1/10 c4.1	Oak	20	90	sample width	1 layer, Woodglue		15 min - 85 °C	0,68	1,14	9,0	87,0	109,6
7.3	1/10 c4.2	Oak	20	90	sample width	1 layer, Woodglue		15 min - 85 °C	0,68	1,14	11,0	87,0	91,5
7.3	1/10 c4.3	Oak	20	90	sample width	1 layer, Woodglue		15 min - 85 °C	0,68	1,14	7,0	88,0	141,8
7.3	1/10 c4.4	Oak	20	90	sample width	1 layer, Woodglue		15 min - 85 °C	0,68	1,14	11,0	87,0	91,5
9.1	9/10 c1.1	Teak	20	90	sample width	None		15 min - 60 °C	0,50	0,77	18,0	76,0	49,1
9.1	9/10 c1.2	Teak	20	90	sample width	None		15 min - 60 °C	0,50	0,77	13,0	84,0	74,3
9.1	9/10 c2.1	Oak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	0,65	0,97	-2,0	90,0	-507,3

Round	Name	Wood type	Sample width (mm)	Sample length (mm)	Fiber direction	Coating	Notes	Wood programming	Weight dry (grams)	Weight wet (grams)	Sagitta (mm)	Chord (mm)	Radius (mm)
9.1	9/10 c2.2	Oak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	0,65	0,97	0,0	90,0	0,0
9.1	9/10 c3.1	Teak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	0,58	0,80	4,0	89,0	249,5
9.1	9/10 c3.2	Teak	20	90	sample width	Woodglue	1 coating layer	15 min - 60 °C	0,58	0,80	4,0	89,0	249,5
9.1	9/10 c4.1	Oak	20	90	sample width	Woodglue	2 coating layers	15 min - 60 °C	0,76	1,12	0,0	90,0	0,0
9.1	9/10 c4.2	Oak	20	90	sample width	Woodglue	2 coating layers	15 min - 60 °C	0,76	1,12	-6,0	89,0	-168,0
9.1	9/10 c5.1	Teak	20	90	sample width	Woodglue	2 coating layers	15 min - 60 °C	0,67	0,85	5,0	89,0	200,5
9.1	9/10 c5.2	Teak	20	90	sample width	Woodglue	2 coating layers	15 min - 60 °C	0,67	0,85	4,5	89,0	222,3
9.1	9/10 c6.1	Oak	20	90	sample width	Woodglue	3 coating layers	15 min - 60 °C	0,89	1,25	-4,0	90,0	-255,1
9.1	9/10 c6.2	Oak	20	90	sample width	Woodglue	3 coating layers	15 min - 60 °C	0,89	1,25	0,0	90,0	0,0
9.1	9/10 c7.1	Teak	20	90	sample width	Woodglue	3 coating layers	15 min - 60 °C	0,70	0,94	5,0	89,0	200,5
9.1	9/10 c7.2	Teak	20	90	sample width	Woodglue	3 coating layers	15 min - 60 °C	0,75	1,02	4,0	88,0	244,0
9.1	9/10 c8.1	Oak	20	90	sample width	Woodglue	1 coating layer, timelapse	15 min - 60 °C	0,67	0,99	0,0	90,0	0,0
9.1	9/10 c12.1	Oak	20	90	sample width	Woodglue	2 coating layers, no pre-treatment	-			-4,0	89,5	-252,3
9.1	9/10 c12.2	Oak	20	90	sample width	Woodglue	2 coating layers, no pre-treatment	-			-2,5	89,5	-401,8
9.1	9/10 c13.1	Oak	20	90	sample width	Woodglue	2 coating layers, no pre-treatment	-			-3,0	89,0	-331,5
9.1	9/10 c13.2	Oak	20	90	sample width	Woodglue	2 coating layers, no pre-treatment	-			-3,0	89,0	-331,5
9.2	9/10 c10.1	Oak	20	90	sample width	2 layers, Woodglue	Outside coating	15 min - 60 °C	0,76	1,10	2,5	90,0	406,3
9.2	9/20 c10.4	Oak	20	90	sample width	2 layers, Woodglue	Outside coating	15 min - 60 °C	0,76	1,10	4,0	89,0	249,5

Appendix D: Custom measurement setups

Sagitta calculation

Initially during the experimental testing, the chord and sagitta of the samples was measured to eventually calculate the radius. During the analysis of the results based on the radii values, it was observed that the difference in values was quite extreme even though the difference in sagitta and chord measurements only differed a few millimeters.

Considering the method the radius is calculated, any minimal fluctuations in either the chord or sagitta resulted in disproportionately large deviations in the radius value. Since the sagitta and chord are measured by hand, these small fluctuations in measurements are not uncommon. The following calculation shows with an example what the impact is of such a small fluctuation on the radius value:

The radius, *R*, is calculated with the following equation where c is the chord and s is the sagitta:

$$\mathrm{R} = \frac{\mathrm{c}^2}{8\mathrm{s}}$$

Assume c=100 mm and s=1 mm, then:

$$\mathrm{R} = \frac{100^2}{81} = 1250 \text{ mm}$$

Now with a tiny measurement error, the sagitta is 0.5 mm, then:

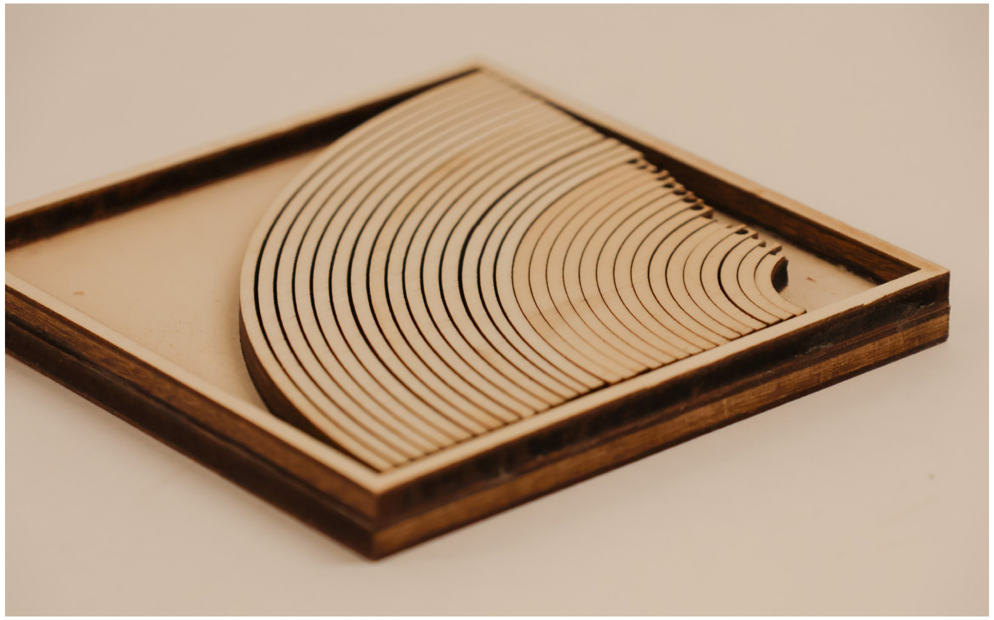
$$\mathrm{R} = \frac{100^2}{80.5} = 2500 \text{ mm}$$

So a 0.5 mm reading error in the sagitta leads to a 1250 mm difference in radius.

Therefore comparing curvature using only the sagitta measurements is more accurate compared to comparing curvature using the radius, where small errors are amplified in the calculated values.

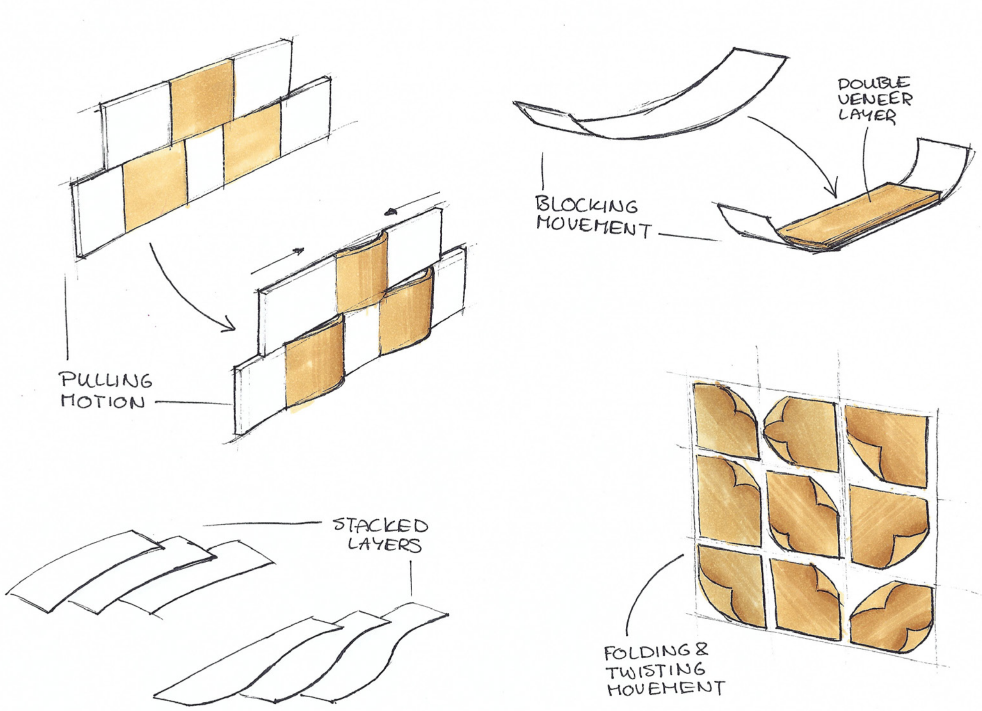
Sample diameter measurement setup

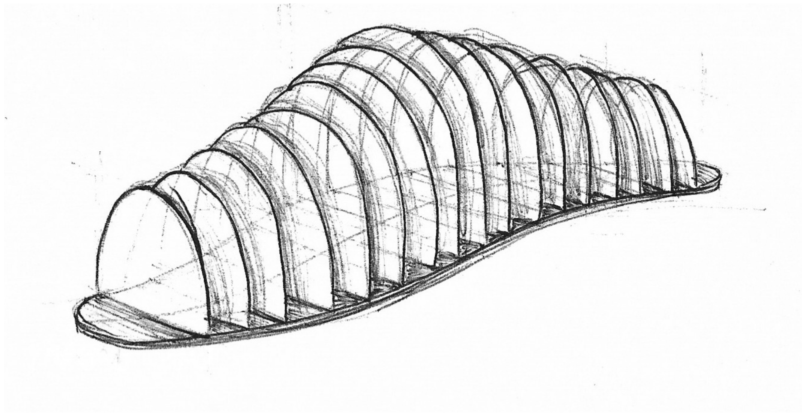
The samples structured of the guidelines were measured on their curvature at different time intervals. In order to easily measure curvature of various shapes, a diameter gauge set was made. By laser cutting quarters of circles with a difference of 5 mm in diameter, a gauge set was created that could measure diameter values from 30 to 175 mm as can be seen in the figures below.

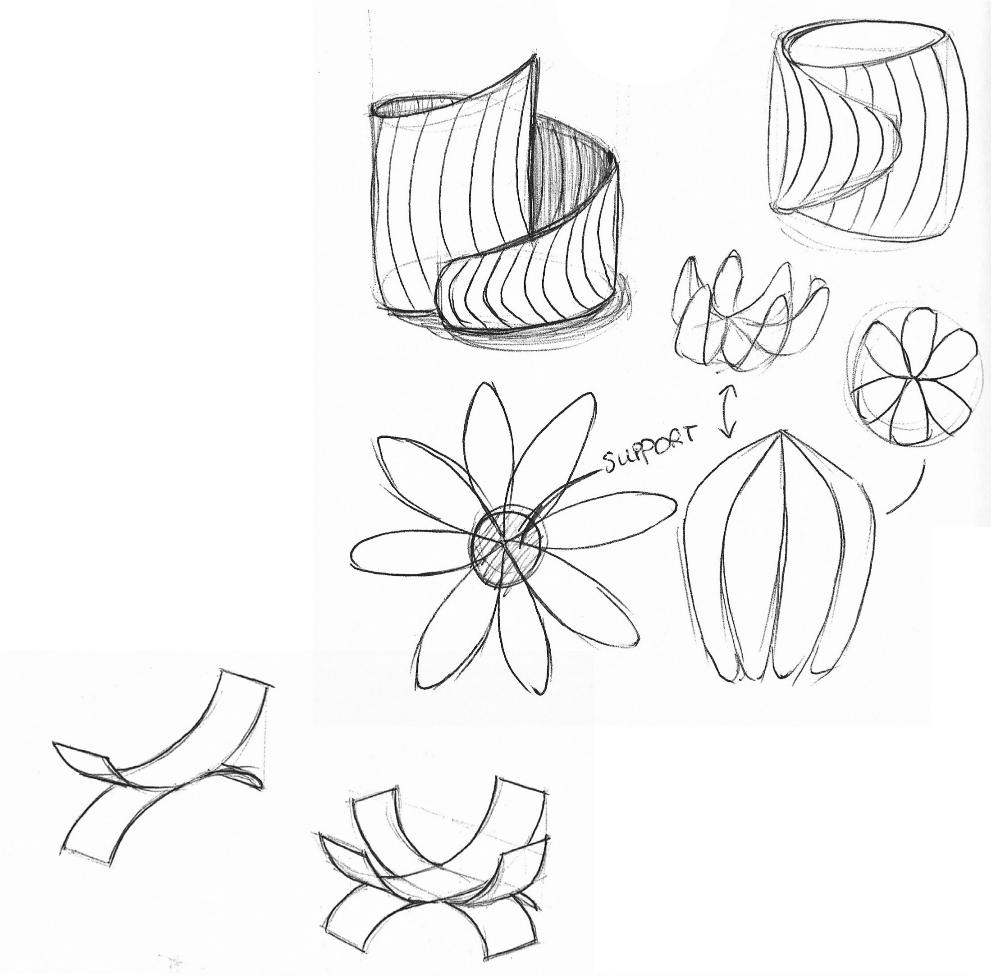


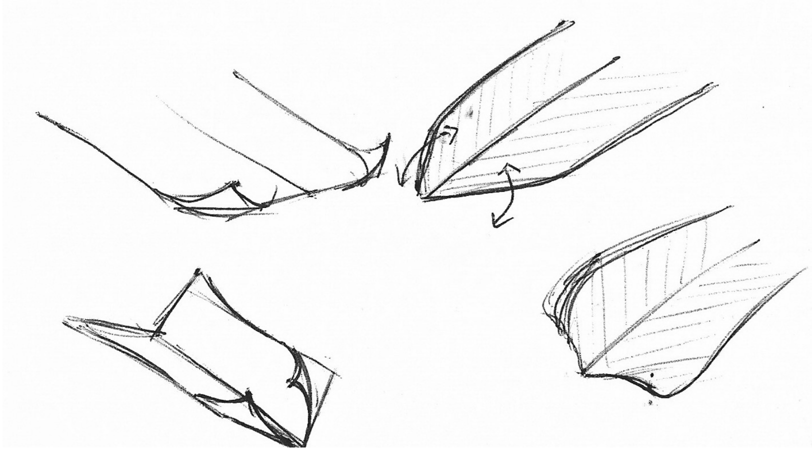
Appendix E: Design process sketches

Sample structure ideation

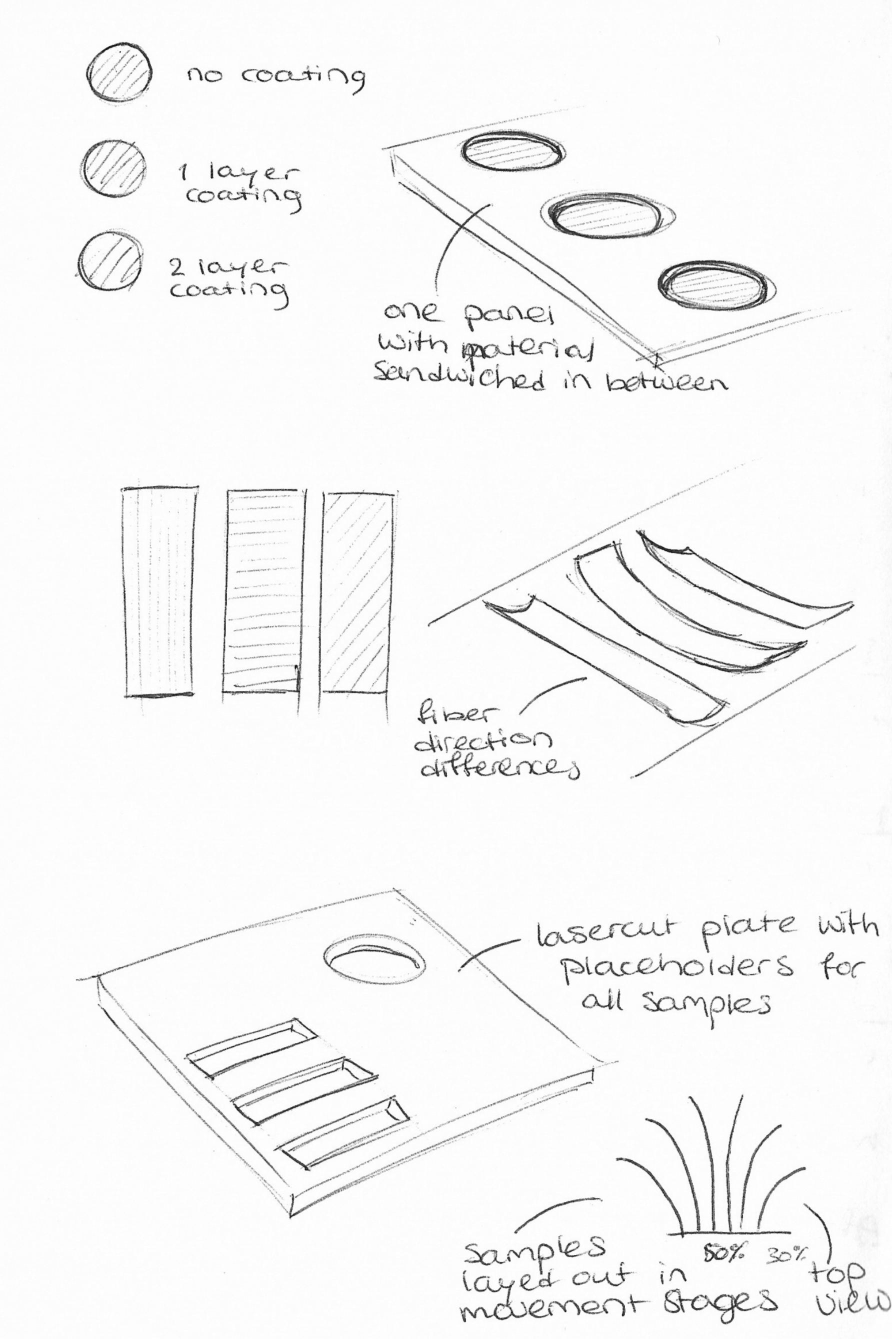


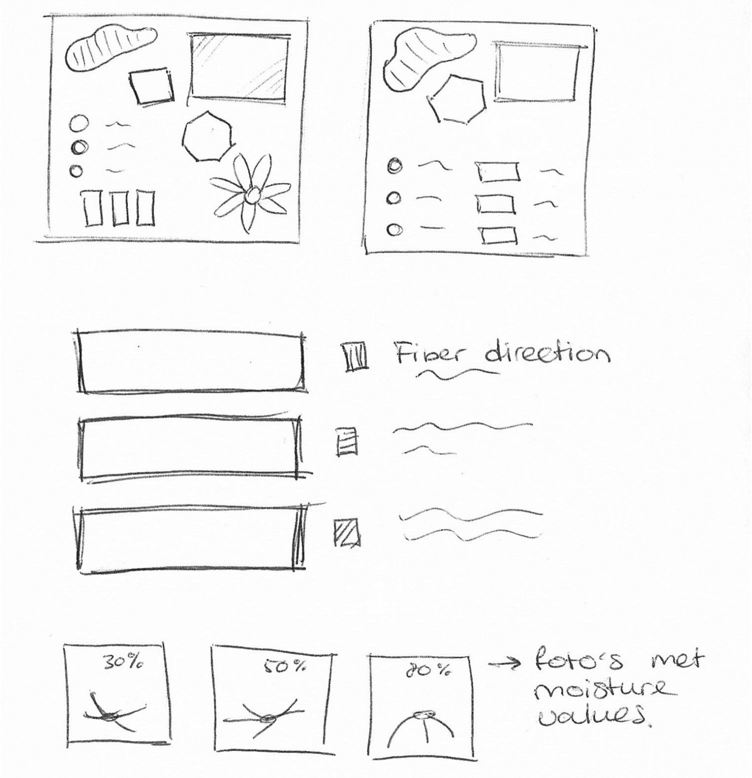


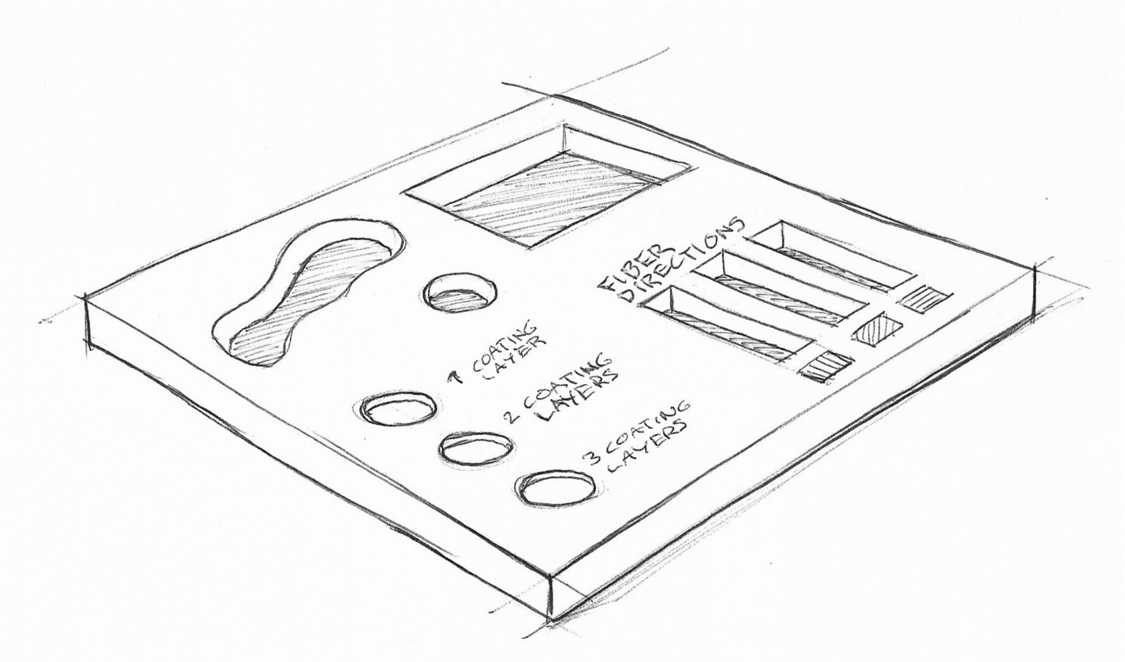




MaterialDistrict ideation







Appendix F: Sample structure measurements

Curvature rate calculations

The table below shows the results of curvature rate calculations of the sample structure testing phase. Where five sample structures were measured for their curvature at different time intervals. From these measurements, the curvature was calculated per sample per time interval, followed by the calculation of the curvature rate through the equation of the polynomial trendlines. In the table below, the measured values per sample structure can be seen in addition to the calculated values from these measurements in the grey columns. The samples bend in two directions. The negative values represent curvature towards the NIC side.

Flower structure

Name	Round	Sample segment	D0 (mm)	D60 (mm)	D120 (mm)	D180 (mm)	D240 (mm)	k0 (cm)	k60 (cm)	k120 (cm)	k180 (cm)	k240 (cm)
6.1	1	1	-55	-115	-175	0	0	-0,364	-0,174	-0,114	0,000	0,000
6.1	1	2	-90	-200	0	0	200	-0,222	-0,100	0,000	0,000	0,100
6.1	1	3	-140	0	200	110	95	-0,143	0,000	0,100	0,182	0,211
6.1	1	4	-80	-200	0	155	180	-0,250	-0,100	0,000	0,129	0,111
6.1	1	5	-80	-175	0	0	200	-0,250	-0,114	0,000	0,000	0,100
6.1	1	6	-100	-200	175	145	110	-0,200	-0,100	0,114	0,138	0,182
6.1	1	7	-130	-200	200	150	120	-0,154	-0,100	0,100	0,133	0,167
6.1	1	8	-70	-140	-200	0	0	-0,286	-0,143	-0,100	0,000	0,000
6.1	2	1	-55	-180	-200	250	200	-0,364	-0,111	-0,100	0,080	0,100
6.1	2	2	-80	-180	-200	0	175	-0,250	-0,111	-0,100	0,000	0,114
6.1	2	3	-175	0	180	150	120	-0,114	0,000	0,111	0,133	0,167
6.1	2	4	-80	-180	-250	0	200	-0,250	-0,111	-0,080	0,000	0,100
6.1	2	5	-95	-200	0	0	175	-0,211	-0,100	0,000	0,000	0,114
6.1	2	6	-110	0	175	130	110	-0,182	0,000	0,114	0,154	0,182
6.1	2	7	-130	0	200	140	110	-0,154	0,000	0,100	0,143	0,182
6.1	2	8	-70	-175	0	0	200	-0,286	-0,114	0,000	0,000	0,100

Time interval	Average curvature round 1	Average curvature round 2
0	-0,234	-0,226
60	-0,104	-0,068
120	0,013	0,006
180	0,073	0,064
240	0,109	0,132

Wave structure

Name	Round	Sample segment	D0 (mm)	D60 (mm)	D120 (mm)	D180 (mm)	D240 (mm)	k0 (cm)	k60 (cm)	k120 (cm)	k180 (cm)	k240 (cm)
5.1	1	1	-110	-175	-250	200	175	-0,182	-0,114	-0,080	0,100	0,114
5.1	1	2	-140	0	200	180	160	-0,143	0,000	0,100	0,111	0,125
5.1	1	3	-140	0	200	175	140	-0,143	0,000	0,100	0,114	0,143
5.1	1	4	-100	0	0	0	200	-0,200	0,000	0,000	0,000	0,100
5.1	1	5	-100	0	200	180	160	-0,200	0,000	0,100	0,111	0,125
5.1	1	6	-80	-200	0	0	200	-0,250	-0,100	0,000	0,000	0,100
5.1	1	7	-135	0	200	175	140	-0,148	0,000	0,100	0,114	0,143
5.1	1	8	-90	-200	0	190	175	-0,222	-0,100	0,000	0,105	0,114
5.1	1	9	-90	-175	0	180	175	-0,222	-0,114	0,000	0,111	0,114
5.1	1	10	-130	0	200	175	130	-0,154	0,000	0,100	0,114	0,154
5.1	1	11	-115	-200	0	0	200	-0,174	-0,100	0,000	0,000	0,100
5.1	1	12	-140	0	0	200	180	-0,143	0,000	0,000	0,100	0,111
5.1	1	13	-175	0	0	200	175	-0,114	0,000	0,000	0,100	0,114
5.1	1	14	-175	0	0	200	180	-0,114	0,000	0,000	0,100	0,111
5.1	1	15	-135	-200	0	200	175	-0,148	-0,100	0,000	0,100	0,114
5.1	1	16	-175	0	200	180	160	-0,114	0,000	0,100	0,111	0,125
5.1	1	17	-175	0	200	180	160	-0,114	0,000	0,100	0,111	0,125
5.1	2	1	-80	180	0	200	180	-0,250	0,111	0,000	0,100	0,111
5.1	2	2	-110	0	0	200	175	-0,182	0,000	0,000	0,100	0,114
5.1	2	3	-110	0	0	200	175	-0,182	0,000	0,000	0,100	0,114
5.1	2	4	-130	-175	0	200	170	-0,154	-0,114	0,000	0,100	0,118
5.1	2	5	-70	-170	-200	0	180	-0,286	-0,118	-0,100	0,000	0,111
5.1	2	6	-50	-130	-175	-180	0	-0,400	-0,154	-0,114	-0,111	0,000
5.1	2	7	-150	-200	175	160	150	-0,133	-0,100	0,114	0,125	0,133
5.1	2	8	-70	-150	-180	0	200	-0,286	-0,133	-0,111	0,000	0,100
5.1	2	9	-70	-140	-175	-200	0	-0,286	-0,143	-0,114	-0,100	0,000
5.1	2	10	-100	-200	200	180	170	-0,200	-0,100	0,100	0,111	0,118
5.1	2	11	-120	-200	0	200	180	-0,167	-0,100	0,000	0,100	0,111
5.1	2	12	-140	0	0	200	180	-0,143	0,000	0,000	0,100	0,111
5.1	2	13	-170	200	180	170	150	-0,118	0,100	0,111	0,118	0,133
5.1	2	14	-170	200	180	170	150	-0,118	0,100	0,111	0,118	0,133
5.1	2	15	-125	-200	200	200	180	-0,160	-0,100	0,100	0,100	0,111
5.1	2	16	-175	200	180	175	170	-0,114	0,100	0,111	0,114	0,118
5.1	2	17	-180	200	170	150	120	-0,111	0,100	0,118	0,133	0,167

Time interval	Average curvature round 1	Average curvature round 2
0	-0,164	-0,193
60	-0,037	-0,032
120	0,036	0,019
180	0,088	0,071
240	0,12	0,106

Twist structure

Name	Round	Sample segment	D0 (mm)	D60 (mm)	D120 (mm)	D180 (mm)	D240 (mm)	k0 (cm)	k60 (cm)	k120 (cm)	k180 (cm)	k240 (cm)
8.1	1	1	-115	0	300	300	200	-0,174	0,000	0,067	0,067	0,100
8.1	1	2	-105	0	300	180	170	-0,190	0,000	0,067	0,111	0,118
8.1	1	3	-45	-75	-100	-135	-160	-0,444	-0,267	-0,200	-0,148	-0,125
8.1	1	4	-65	-85	-115	-125	-145	-0,308	-0,235	-0,174	-0,160	-0,138
8.1	1	5	-145	0	0	200	180	-0,138	0,000	0,000	0,100	0,111
8.1	1	6	-60	-80	-100	-155	-165	-0,333	-0,250	-0,200	-0,129	-0,121
8.1	1	7	-110	-180	0	0	200	-0,182	-0,111	0,000	0,000	0,100
8.1	1	8	-110	-175	0	0	200	-0,182	-0,114	0,000	0,000	0,100
8.1	1	9	-90	-175	-200	0	0	-0,222	-0,114	-0,100	0,000	0,000
8.1	1	10	-65	-135	-200	0	0	-0,308	-0,148	-0,100	0,000	0,000
8.1	2	1	-130	-180	0	0	200	-0,154	-0,111	0,000	0,000	0,100
8.1	2	2	-90	-180	0	0	200	-0,222	-0,111	0,000	0,000	0,100
8.1	2	3	-45	-65	-80	-100	-125	-0,444	-0,308	-0,250	-0,200	-0,160
8.1	2	4	-50	-80	-95	-120	-160	-0,400	-0,250	-0,211	-0,167	-0,125
8.1	2	5	-125	0	0	0	200	-0,160	0,000	0,000	0,000	0,100
8.1	2	6	-50	-70	-90	-100	-120	-0,400	-0,286	-0,222	-0,200	-0,167
8.1	2	7	-80	-180	0	200	180	-0,250	-0,111	0,000	0,100	0,111
8.1	2	8	-100	-180	0	200	180	-0,200	-0,111	0,000	0,100	0,111
8.1	2	9	-90	-150	0	0	200	-0,222	-0,133	0,000	0,000	0,100
8.1	2	10	-100	-150	0	0	200	-0,200	-0,133	0,000	0,000	0,100

Time interval	Average curvature round 1	Average curvature round 2
0	-0,248	-0,265
60	-0,124	-0,155
120	-0,064	-0,068
180	-0,016	-0,037
240	0,014	0,027

Frame structure

Name	Round	Sample segment	D0 (mm)	D60 (mm)	D120 (mm)	D180 (mm)	D240 (mm)	k0 (cm)	k60 (cm)	k120 (cm)	k180 (cm)	k240 (cm)
2.2	2	1	-135	0	200	180	175	-0,148	0,000	0,100	0,111	0,114
2.2	2	2	-100	0	200	200	180	-0,200	0,000	0,100	0,100	0,111
2.2	2	3	-100	-200	0	200	180	-0,200	-0,100	0,000	0,100	0,111
2.2	2	4	-100	-180	0	180	160	-0,200	-0,111	0,000	0,111	0,125
2.2	3	1	-120	0	180	150	110	-0,167	0,000	0,111	0,133	0,182
2.2	3	2	-110	0	180	170	150	-0,182	0,000	0,111	0,118	0,133
2.2	3	3	-100	-200	180	175	150	-0,200	-0,100	0,111	0,114	0,133
2.2	3	4	-120	0	200	130	110	-0,167	0,000	0,100	0,154	0,182

Time interval	Average curvature round 1	Average curvature round 2
0	-0,187	-0,179
60	-0,053	-0,025
120	0,05	0,108
180	0,106	0,13
240	0,115	0,158

Diamond pattern

Name	Round	Sample segment	D0 (mm)	D60 (mm)	D120 (mm)	D180 (mm)	D240 (mm)	k0 (cm)	k60 (cm)	k120 (cm)	k180 (cm)	k240 (cm)
1.2	2	1	-150	-200	0	0	0	-0,133	-0,100	0,000	0,000	0,000
1.2	2	2	-180	0	200	175	160	-0,111	0,000	0,100	0,114	0,125
1.2	2	3	-175	0	0	0	200	-0,114	0,000	0,000	0,000	0,100
1.2	3	1	-200	0	250	200	180	-0,100	0,000	0,080	0,100	0,111
1.2	3	2	0	175	140	110	95	0,000	0,114	0,143	0,182	0,211
1.2	3	3	0	0	250	180	175	0,000	0,000	0,080	0,111	0,114

Time interval	Average curvature round 1	Average curvature round 2
0	-0,12	-0,033
60	-0,033	0,038
120	0,033	0,101
180	0,038	0,131
240	0,075	0,145

In this table below, the translation of curvature calculations to curvature rate can be seen for each measurement of each sample structure. Beginning with the equation that resulted from the polynomial trendlines for each sample.

Sample structure (round)	Polynomial function	Derivative function	Curvature rate at t=0
Flower structure 1	k= -0,000005t^2 + 0,0026t -0,2357	k' =-0,00001t + 0,0026	0,0026
Flower structure 2	k= -0,000004t^2 + 0,0023t -0,2162	k' =-0,000008t + 0,0023	0,0023
Wave structure 1	k= -0,000004t^2 + 0,0022t -0,1602	k' =-0,000008t + 0,0022	0,0022
Wave structure 2	k= -0,000005t^2 + 0,0024t -0,1823	k' =-0,00001t + 0,0024	0,0024
Twist structure 1	k= -0,000004t^2 + 0,002t -0,2426	k' =-0,000008t + 0,002	0,0020
Twist structure 2	k= -0,000003t^2 + 0,0019t -0,2615	k' =-0,000006t + 0,0019	0,0019
Frame structure 1	k= -0,000006t^2 + 0,0027t -0,1887	k' =-0,000012t + 0,0027	0,0027
Frame structure 2	k= -0,000007t^2 + 0,0031t -0,1791	k' =-0,000014t + 0,0031	0,0031
Diamond pattern 1	k= -0,000003t^2 + 0,0015t -0,1164	k' =-0,000006t + 0,0015	0,0015
Diamond pattern 2	k= -0,000003t^2 + 0,0015t -0,0346	k' =-0,000006t + 0,0015	0,0015

Water uptake calculations

The tables below show the measurements and calculations of the samples to calculate the water uptake. The grey columns show the calculated values compared to the white columns with the measured values.

Flower structure

Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Mass per segment (g)
6.1	1	1	5,63	5,96	0,33	1125,44	0,488
6.1	1	2				1125,44	0,488
6.1	1	3				1125,44	0,488
6.1	1	4				1125,44	0,488
6.1	1	5	5,78	5,85	0,07	1125,44	0,488
6.1	1	6				1125,44	0,488
6.1	1	7	5,77	5,95	0,18	1125,44	0,488
6.1	1	8				1125,44	0,488
6.1	2	1	6,11	6,39	0,28	1125,44	0,488
6.1	2	2				1125,44	0,488
6.1	2	3	6,25	6,52	0,27	1125,44	0,488
6.1	2	4				1125,44	0,488
6.1	2	5	6,46	6,71	0,25	1125,44	0,488
6.1	2	6				1125,44	0,488
6.1	2	7	6,51	6,76	0,25	1125,44	0,488
6.1	2	8				1125,44	0,488

	WUactive round 1	WUactive round 2
Total weight increase, Δmtotal (g)	0,58	1,05
Total active mass, mactivetotal (g)	3,9	3,9
Water Uptake, WUactive (%)	14,87%	26,91%

Wave structure

Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Mass per segment (g)
5.1	1	1	36,27	36,53	0,26	1396,12	0,605
5.1	1	2				1176,58	0,510
5.1	1	3				996,47	0,432
5.1	1	4	36,07	36,56	0,49	996,47	0,432
5.1	1	5				1176,58	0,510
5.1	1	6				1396,12	0,605
5.1	1	7				1626,03	0,705
5.1	1	8	35,85	36,34	0,49	1877,73	0,814
5.1	1	9				2215,77	0,960
5.1	1	10				2606,45	1,129
5.1	1	11	35,57	36,11	0,54	3049,07	1,321
5.1	1	12				3584,95	1,553
5.1	1	13				3049,07	1,321
5.1	1	14				2606,45	1,129
5.1	1	15	35,26	35,8	0,54	2215,77	0,960
5.1	1	16				1877,73	0,814
5.1	1	17				1626,03	0,705
5.1	2	1	35,62	36,06	0,44	1396,12	0,605
5.1	2	2				1176,58	0,510
5.1	2	3				996,47	0,432
5.1	2	4	37,67	38,3	0,63	996,47	0,432
5.1	2	5				1176,58	0,510
5.1	2	6				1396,12	0,605
5.1	2	7	37,24	38,21	0,97	1626,03	0,705
5.1	2	8				1877,73	0,814
5.1	2	9				2215,77	0,960
5.1	2	10				2606,45	1,129

Wave structure

Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Mass per segment (g)
5.1	2	11	37,18	37,63	0,45	3049,07	1,321
5.1	2	12				3584,95	1,553
5.1	2	13				3049,07	1,321
5.1	2	14				2606,45	1,129
5.1	2	15	35,92	36,58	0,66	2215,77	0,960
5.1	2	16				1877,73	0,814
5.1	2	17				1626,03	0,705

	WUactive round 1	WUactive round 2
Total weight increase, Δmtotal (g)	2,32	3,15
Total active mass, mactivetotal (g)	14,51	14,51
Water Uptake, WUactive (%)	15,99%	21,72%

Twist structure

Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Mass per segment (g)
8.1	1	1	21,83	22,04	0,21	2088,19	0,905
8.1	1	2				2088,19	0,905
8.1	1	3	21,93	22,15	0,22	2088,19	0,905
8.1	1	4				2088,19	0,905
8.1	1	5	22,02	22,19	0,17	2088,19	0,905
8.1	1	6				2088,19	0,905
8.1	1	7	22	22,24	0,24	2088,19	0,905
8.1	1	8				2088,19	0,905
8.1	1	9	22,04	22,26	0,22	2088,19	0,905
8.1	1	10				2088,19	0,905
8.1	2	1	22,07	22,76	0,69	2088,19	0,905
8.1	2	2				2088,19	0,905
8.1	2	3				2088,19	0,905
8.1	2	4				2088,19	0,905
8.1	2	5	22,54	23,38	0,84	2088,19	0,905
8.1	2	6				2088,19	0,905
8.1	2	7				2088,19	0,905
8.1	2	8				2088,19	0,905
8.1	2	9	23,01	23,39	0,38	2088,19	0,905
8.1	2	10				2088,19	0,905

	WUactive round 1	WUactive round 2
Total weight increase, Δmtotal (g)	1,06	1,91
Total active mass, mactivetotal (g)	9,05	9,05
Water Uptake, WUactive (%)	11,71%	21,11%

Frame structure

Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Total surface area, a (mm²)	Mass per segment (g)
2.2	2	1	3	3,34	0,34	598,72	8714,74	0,259
2.2	2	2				723,48		0,314
2.2	2	3				723,48		0,314
2.2	2	4				1048,33		0,454
2.2	3	1	3,05	3,67	0,62	598,72	8714,74	0,259
2.2	3	2				723,48		0,314
2.2	3	3				723,48		0,314
2.2	3	4				1048,33		0,454

	WUactive round 1	WUactive round 2
Total weight increase, Δmtotal (g)	0,34	0,62
Total active mass, mactivetotal (g)	1,34	1,34
Total sample mass, mtot (g)	3,776	3,776
Mass percentage active (%)	35,50%	35,50%
Weight increase active, Δmactive (g)	0,12	0,22
Water Uptake, WUactive (%)	9,00%	16,42%

Diamond pattern

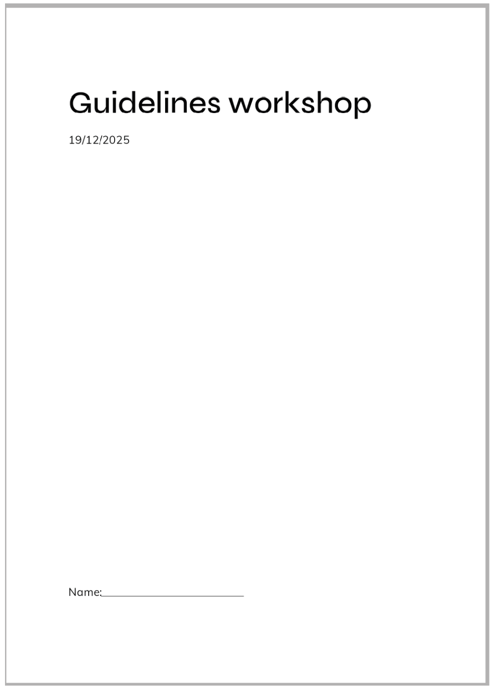
Name	Round	Sample segment	Dry weight (g)	Wet weight (g)	Weight increase (g)	Active surface area, A (mm²)	Total surface area, a (mm²)	Mass per segment (g)
1.2	2	1	4,63	4,96	0,33	1012,44	7791,1	0,439
1.2	2	2				1012,44		0,439
1.2	2	3				1012,44		0,439
1.2	3	1	4,74	5,32	0,58	1012,44	7791,1	0,439
1.2	3	2				1012,44		0,439
1.2	3	3				1012,44		0,439

	WUactive round 1	WUactive round 2
Total weight increase, Δmtotal (g)	0,33	0,58
Total active mass, mactivetotal (g)	1,32	1,32
Total sample mass, mtot (g)	3,376	3,376
Mass percentage active (%)	38,98%	38,98%
Weight increase active, Δmactive (g)	0,13	0,23
Water Uptake, WUactive (%)	9,77%	17,18%

Appendix G: Guidelines workshop test

Workshop booklet

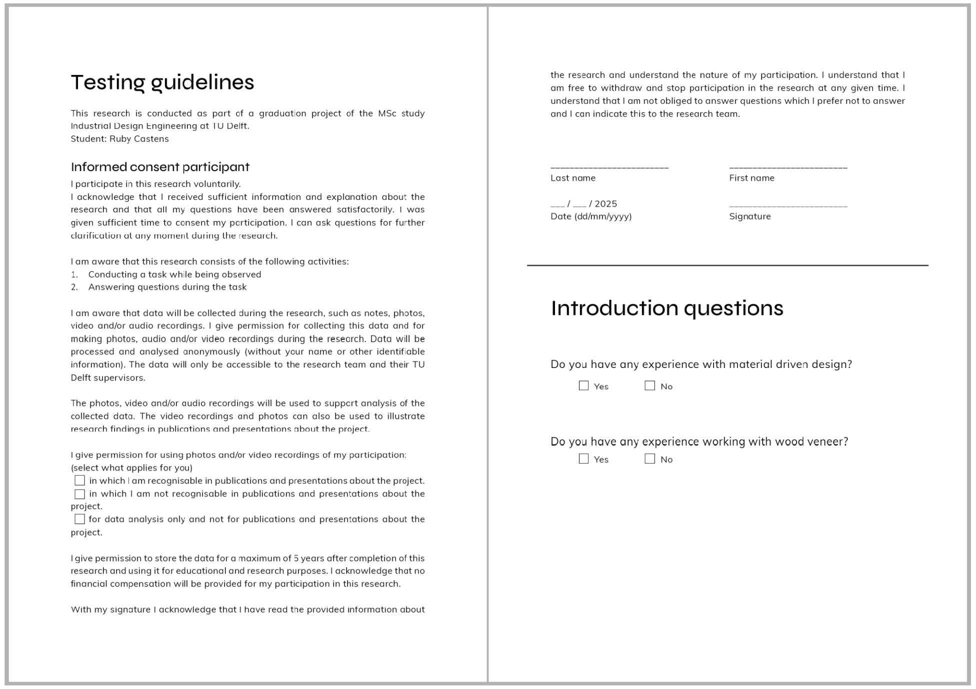
During the workshop test, every participant received a workshop booklet to organize the collected insights. This booklet included an informed consent, introduction question, experiential characterization questions and design evaluation questions. The full booklet pages can be seen in the following images.



Guidelines workshop

19/12/2025

Name:________________________



Testing guidelines

This research is conducted as part of a graduation project of the MSc study Industrial Design Engineering at TU Delft.
Student: Ruby Castens

Informed consent participant

I participate in this research voluntarily.
I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:
1. Conducting a task while being observed
2. Answering questions during the task

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the research team and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)
☐ in which I am recognisable in publications and presentations about the project.
☐ in which I am not recognisable in publications and presentations about the project.
☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes. I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

____
Last name

____
First name

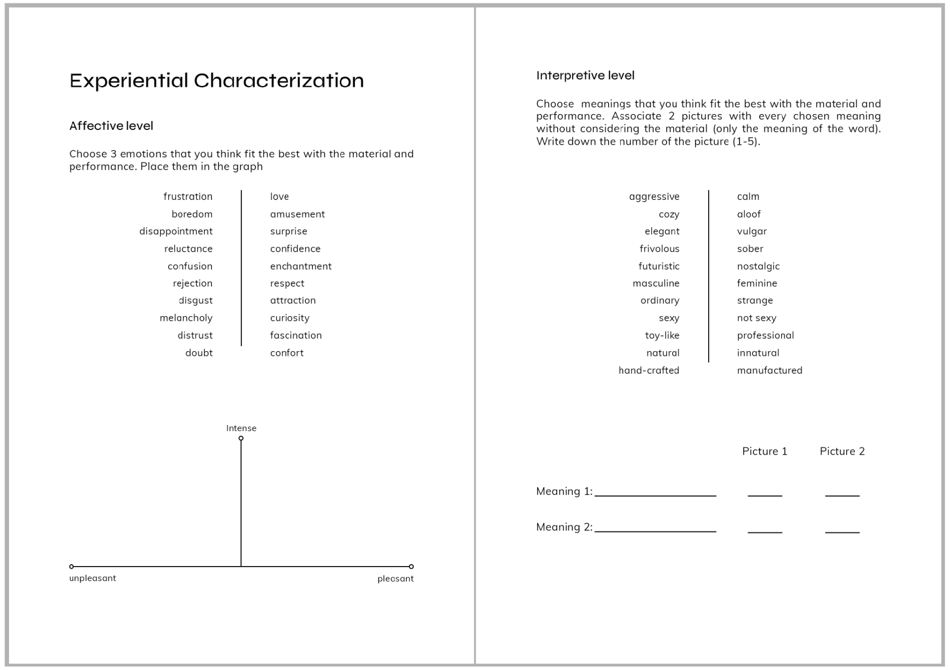
___ / ___ / 2025
Date (dd/mm/yyyy)

____
Signature

Introduction questions

Do you have any experience with material driven design?
☐ Yes ☐ No

Do you have any experience working with wood veneer?
☐ Yes ☐ No



Experiential Characterization

Affective level

Choose 3 emotions that you think fit the best with the material and performance. Place them in the graph

frustration	love
boredom	amusement
disappointment	surprise
reluctance	confidence
confusion	enchantment
rejection	respect
disgust	attraction
melancholy	curiosity
distrust	fascination
doubt	confort

Interpretive level

Choose meanings that you think fit the best with the material and performance. Associate 2 pictures with every chosen meaning without considering the material (only the meaning of the word). Write down the number of the picture (1-5).

aggressive	calm
cozy	aloof
elegant	vulgar
frivolous	sober
futuristic	nostalgic
masculine	feminine
ordinary	strange
sexy	not sexy
toy-like	professional
natural	innatural
hand-crafted	manufactured

	Picture 1	Picture 2
Meaning 1: ________________	_____	_____
Meaning 2: ________________	_____	_____

Design round 1

Rate the following statements from 1-5.

Clarity of the task

Unclear ○ ○ ○ ○ ○ Clear

Difficulty to start with the task

Easy ○ ○ ○ ○ ○ Difficult

Confidence that the sample works how you expect

Not confident ○ ○ ○ ○ ○ Conficent

Design round 2

Rate the following statements from 1-5.

Clarity of the task

Unclear ○ ○ ○ ○ ○ Clear

Difficulty to start with the task

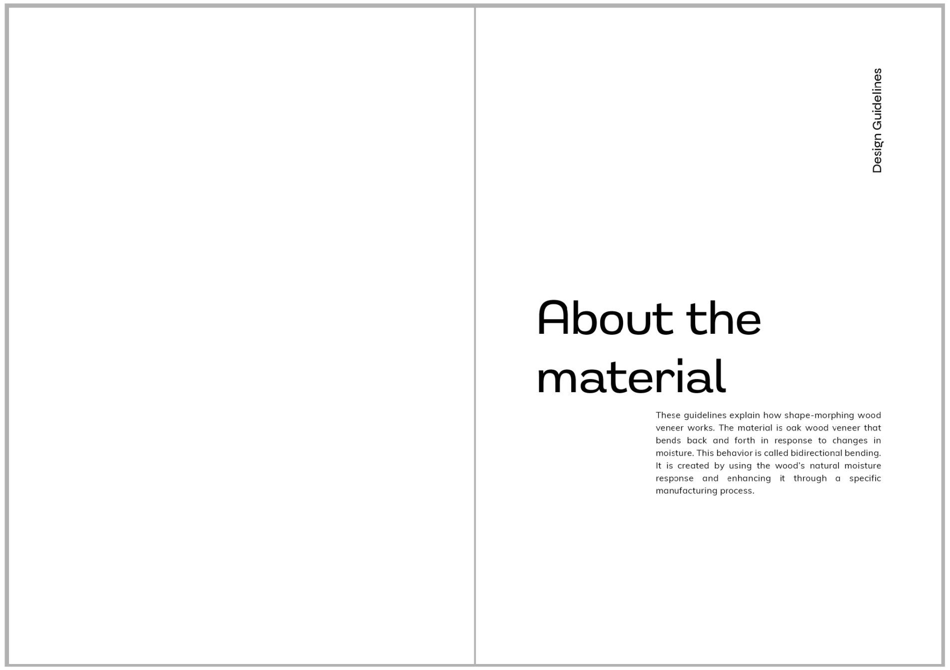
Easy ○ ○ ○ ○ ○ Difficult

Confidence that the sample works how you expect

Not confident ○ ○ ○ ○ ○ Confident

Guidelines workshop

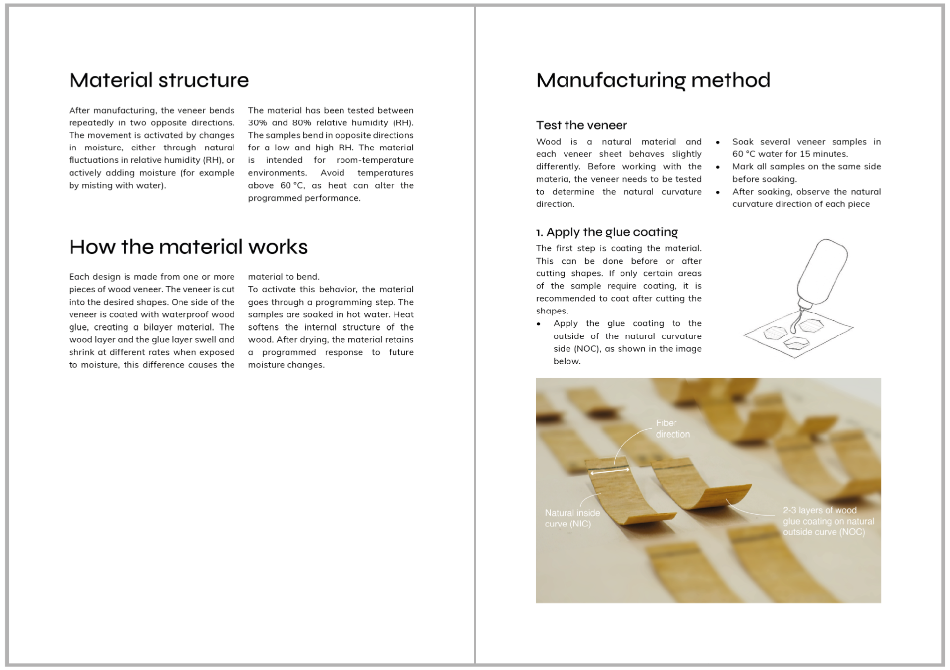
The guidelines that participants received during the workshop can be seen in the following images.



Design Guidelines

About the material

These guidelines explain how shape-morphing wood veneer works. The material is oak wood veneer that bends back and forth in response to changes in moisture. This behavior is called bidirectional bending. It is created by using the wood's natural moisture response and enhancing it through a specific manufacturing process.



Material structure

After manufacturing, the veneer bends repeatedly in two opposite directions. The movement is activated by changes in moisture, either through natural fluctuations in relative humidity (RH), or actively adding moisture (for example by misting with water).

The material has been tested between 30% and 80% relative humidity (RH). The samples bend in opposite directions for a low and high RH. The material is intended for room-temperature environments. Avoid temperatures above 60 °C, as heat can alter the programmed performance.

How the material works

Each design is made from one or more pieces of wood veneer. The veneer is cut into the desired shapes. One side of the veneer is coated with waterproof wood glue, creating a bilayer material. The wood layer and the glue layer swell and shrink at different rates when exposed to moisture, this difference causes the material to bend.

To activate this behavior, the material goes through a programming step. The samples are soaked in hot water. Heat softens the internal structure of the wood. After drying, the material retains a programmed response to future moisture changes.

Manufacturing method

Test the veneer

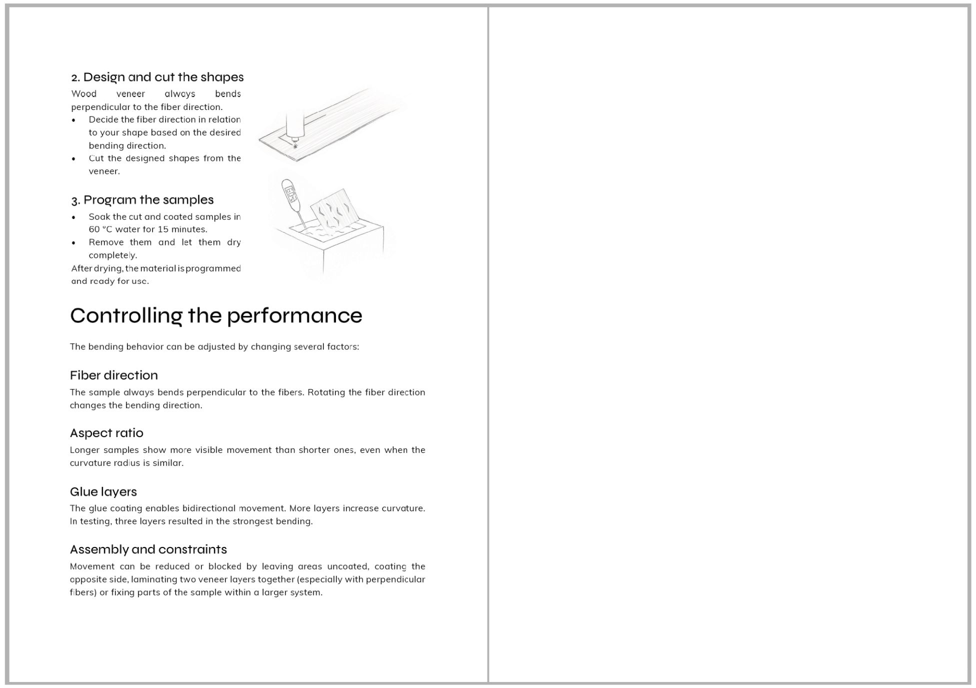
Wood is a natural material and each veneer sheet behaves slightly differently. Before working with the materia, the veneer needs to be tested to determine the natural curvature direction.

- Soak several veneer samples in 60 °C water for 15 minutes.
- Mark all samples on the same side before soaking.
- After soaking, observe the natural curvature direction of each piece

1. Apply the glue coating

The first step is coating the material. This can be done before or after cutting shapes. If only certain areas of the sample require coating, it is recommended to coat after cutting the shapes.

- Apply the glue coating to the outside of the natural curvature side (NOC), as shown in the image below.



2. Design and cut the shapes

Wood veneer always bends perpendicular to the fiber direction.

- Decide the fiber direction in relation to your shape based on the desired bending direction.
- Cut the designed shapes from the veneer.

3. Program the samples

- Soak the cut and coated samples in 60 °C water for 15 minutes.
- Remove them and let them dry completely.

After drying, the material is programmed and ready for use.

Controlling the performance

The bending behavior can be adjusted by changing several factors:

Fiber direction

The sample always bends perpendicular to the fibers. Rotating the fiber direction changes the bending direction.

Aspect ratio

Longer samples show more visible movement than shorter ones, even when the curvature radius is similar.

Glue layers

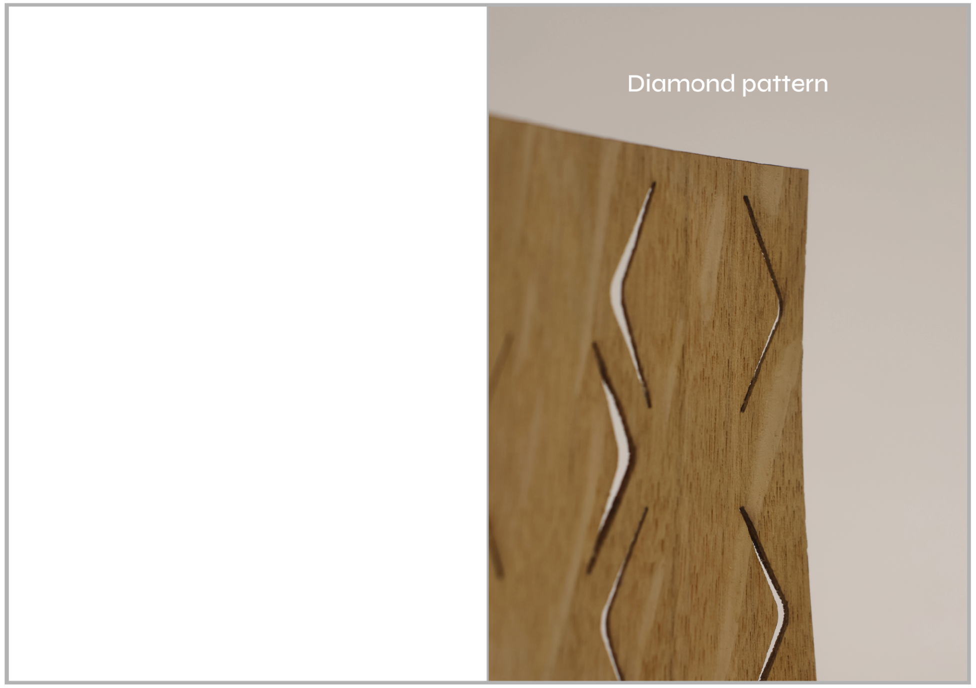
The glue coating enables bidirectional movement. More layers increase curvature. In testing, three layers resulted in the strongest bending.

Assembly and constraints

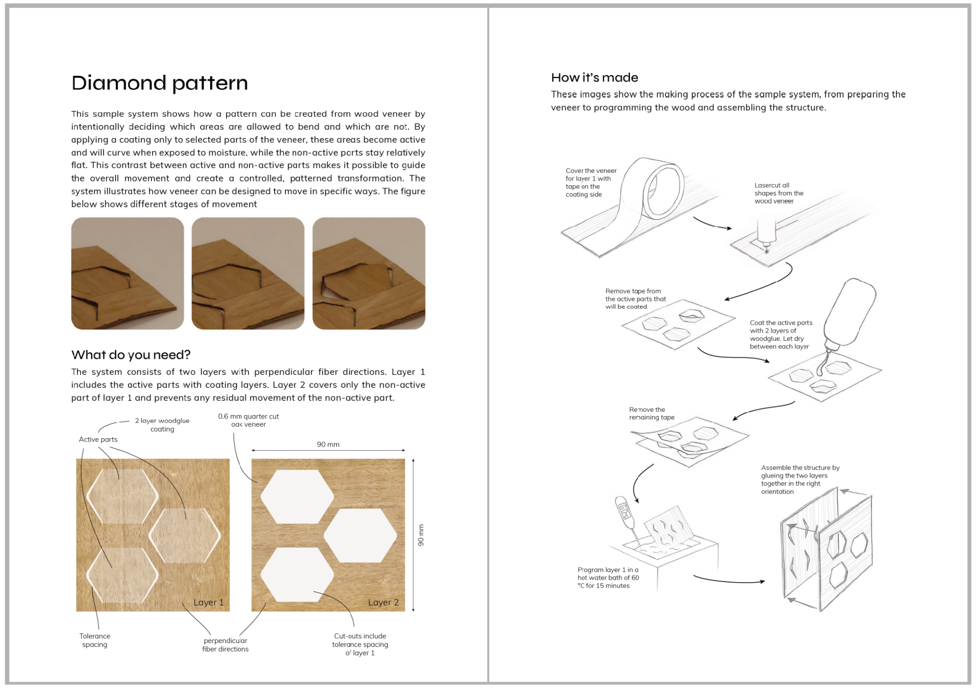
Movement can be reduced or blocked by leaving areas uncoated, coating the opposite side, laminating two veneer layers together (especially with perpendicular fibers) or fixing parts of the sample within a larger system.

Design Guidelines

Sample systems



Diamond pattern



Diamond pattern

This sample system shows how a pattern can be created from wood veneer by intentionally deciding which areas are allowed to bend and which are not. By applying a coating only to selected parts of the veneer, these areas become active and will curve when exposed to moisture, while the non-active parts stay relatively flat. This contrast between active and non-active parts makes it possible to guide the overall movement and create a controlled, patterned transformation. The system illustrates how veneer can be designed to move in specific ways. The figure below shows different stages of movement

What do you need?

The system consists of two layers with perpendicular fiber directions. Layer 1 includes the active parts with coating layers. Layer 2 covers only the non-active part of layer 1 and prevents any residual movement of the non-active part.

How it's made

These images show the making process of the sample system, from preparing the veneer to programming the wood and assembling the structure.

Cover the veneer for layer 1 with tape on the coating side

Lasercut all shapes from the wood veneer

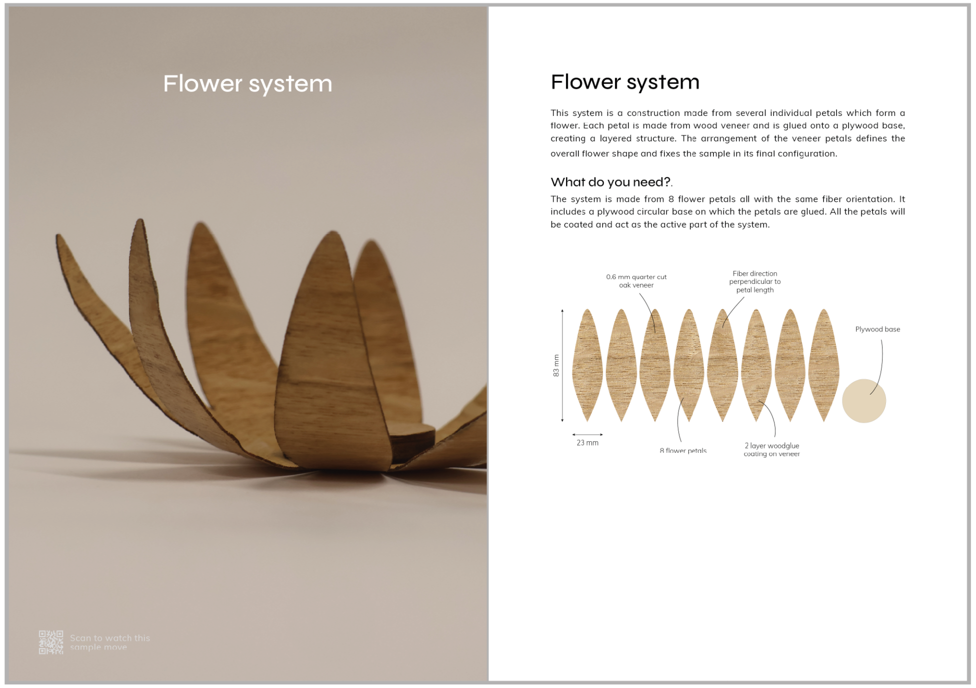
Remove tape from the active parts that will be coated

Coat the active parts with 2 layers of woodglue. Let dry between each layer

Remove the remaining tape

Assemble the structure by glueing the two layers together in the right orientation

Program layer 1 in a hot water bath of 60 °C for 15 minutes



Flower system

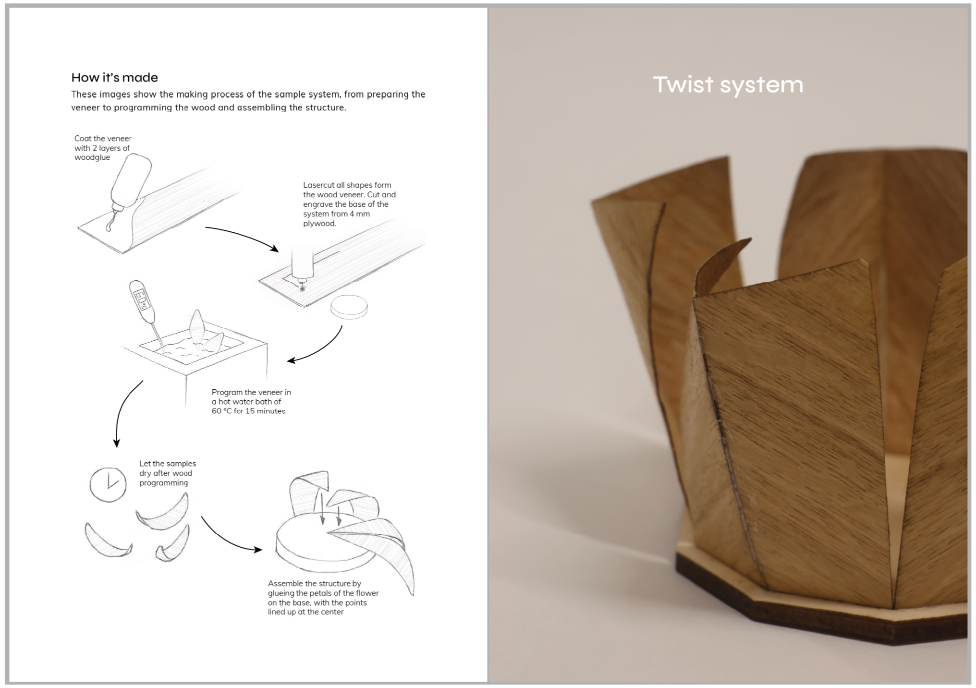
Scan to watch this sample move

Flower system

This system is a construction made from several individual petals which form a flower. Each petal is made from wood veneer and is glued onto a plywood base, creating a layered structure. The arrangement of the veneer petals defines the overall flower shape and fixes the sample in its final configuration.

What do you need?.

The system is made from 8 flower petals all with the same fiber orientation. It includes a plywood circular base on which the petals are glued. All the petals will be coated and act as the active part of the system.



How it's made

These images show the making process of the sample system, from preparing the veneer to programming the wood and assembling the structure.

Coat the veneer with 2 layers of woodglue

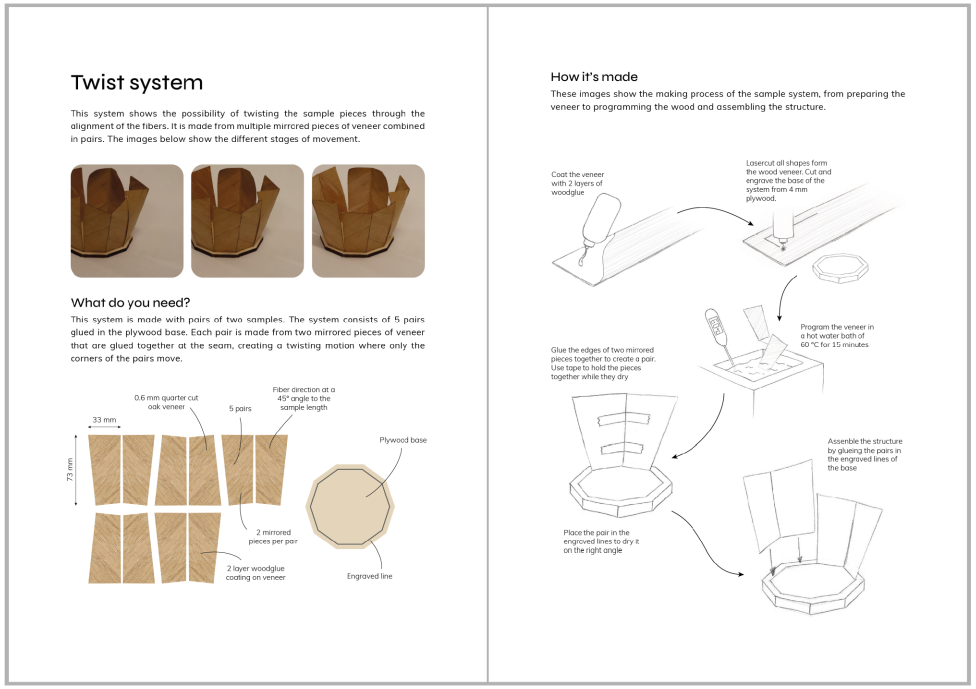
Lasercut all shapes form the wood veneer. Cut and engrave the base of the system from 4 mm plywood.

Program the veneer in a hot water bath of 60 °C for 15 minutes

Let the samples dry after wood programming

Assemble the structure by glueing the petals of the flower on the base, with the points lined up at the center

Twist system



Twist system

This system shows the possibility of twisting the sample pieces through the alignment of the fibers. It is made from multiple mirrored pieces of veneer combined in pairs. The images below show the different stages of movement.

What do you need?

This system is made with pairs of two samples. The system consists of 5 pairs glued in the plywood base. Each pair is made from two mirrored pieces of veneer that are glued together at the seam, creating a twisting motion where only the corners of the pairs move.

How it's made

These images show the making process of the sample system, from preparing the veneer to programming the wood and assembling the structure.

Coat the veneer with 2 layers of woodglue

Lasercut all shapes form the wood veneer. Cut and engrave the base of the system from 4 mm plywood.

Program the veneer in a hot water bath of 60 °C for 15 minutes

Glue the edges of two mirrored pieces together to create a pair. Use tape to hold the pieces together while they dry

Assenble the structure by glueing the pairs in the engraved lines of the base

Place the pair in the engraved lines to dry it on the right angle

Materials workshop

Participant sample results