WOOD TECHNOLOGY

GRADUATION THESIS

INTERLOCKING WOOD-TO-WOOD JOINERY CONNECTIONS

WITH MOISTURE INDUCE PROCESS

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MSc Architecture Urbanism and Building Technology
Master track – Building Technology

OCT. 2023

TU Delft

MASTER THESIS

Title: Interlocking wood to wood joinery connections with moisture induce process.

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INTERLOCKING OPTIMIZATION OF DIGITAL MANUFACTURED HOUSEHOLDS: AN ALTERNATIVE CONSTRUCTION SYSTEM AS SOLUTION FOR AFFORDABLE HOUSING IN COLOMBIA.

KEY WORDS

DfMA, IATP, Digital Fabrication, Wood to Wood connections, novel joints, Social Housing, Social Construction.

ABSTRACT

From a global perspective, the building industry is one of the significant factors of environmental impact on the planet. Related activities in this industry refer to 40% of total carbon emissions; 28% of this value accounts for building operations, while the remaining 12% represents the manufacturing of new construction materials. Studies have revealed that 90% of construction waste comes from demolition (Ahn et al., 2022). Wood as a construction material is an uprising in the building practice due to its carbon storage capabilities and prefabricated possibilities (Gong, 2021). Prefabricated timber constructions can benefit rural Colombia's social reconstruction with the help of digital fabrication technologies. Likewise, this method could bring better performance of materials and its End of Life (EOL) (Ahn et al., 2022). Nevertheless, research has identified wood-to-wood timber connections as a gap in the academia to tackle better design, manufacture, assembly, and deconstruction (DfMA + D) in the field (Mehra et al., 2021). The following study aims to investigate the application of CNC technologies to fabricate novel and affordable wood joinery connection solutions for the construction of rural housing in Colombia. This research emphasizes the cooperation of the wood material to moisture fluctuation, with the aim of introducing a more sustainable and efficient assembly method.

DOCUMENT STRUCTURE

This research document embarks on an exploration of the potential integration of climatic conditions, particularly humidity variations, in the context of developing an alternative prefabricated housing system tailored to the unique geographical, climatological, and socio-economic conditions prevailing in Colombia. The research unfolds through several key phases, each of which contributes to a holistic understanding of this multifaceted work.

Literature Research: The research commences with an extensive examination of Colombia's geographical and climatic characteristics. By delving into the diverse climatic conditions present in the country, this phase aims to identify opportunities and challenges associated with harnessing climatic variables, notably humidity, in the construction of housing solutions.

Social and Economic Context: This document then pivots towards an exploration of Colombia's social and economic landscape. It seeks to establish the socio-economic requirements that underscore the need for innovative housing solutions, particularly those designed to supply to low-income populations. By understanding the unique challenges faced by these communities, the research aims to position itself as a response to pressing societal needs.

Project Reference Study: The research extends into a comprehensive study of prefabricated wooden systems that are user-centric, emphasizing the concept's evolution over time. This phase provides valuable insights into the evolution of user-built, prefabricated housing solutions and their relevance in contemporary construction paradigms.

Wood Industry Evaluation: An appraisal of the current state of the wood industry in Colombia ensues. This assessment takes into account advancements and available materials, offering a nuanced understanding of the financial and technical facets that should inform the thesis's development trajectory.

Material Study: A detailed exploration of material dynamics, particularly in response to humidity levels, is then undertaken. This study serves to enrich our comprehension of working with wood in construction and the strategies required to effectively integrate humidity-related considerations into the design and production processes.

Experimental Methodology: An experimental methodology is developed to empirically validate theoretical constructs related to material reactions and specific characteristics pertinent to wood construction. This phase bridges the gap between theory and practice, serving as a conduit for translating knowledge into actionable insights.

Digital Manufacturing Strategy: The research proceeds to devise a manufacturing strategy grounded in digital fabrication techniques. This strategy is tailor-made to suit Colombia's unique environmental conditions, paving the way for an alternative production approach that aligns with the country's specific context.

Wooden Connections Assessment: An in-depth examination of wooden connections is undertaken as a pivotal aspect of enabling user-driven construction. This assessment encompasses the manufacturing, assembly, and structural performance characteristics of various connection options, ultimately guiding the selection of the most suitable choice.

Experimentation Methodology: The research culminates in a rigorous experimentation methodology that synthesizes knowledge gleaned from material characteristics, novel wood joint manufacturing, and assembly method performance. This final phase aims to substantiate the hypothesis positing a symbiotic relationship between humidity, digital manufacturing, and user-driven assembly.

Through these meticulously structured phases, this research document aspires to shed light on the potential of integrating climatic variables, especially humidity, in the development of prefabricated housing solutions tailored to Colombia's unique needs and conditions. By addressing the intersection of climate, digital manufacturing, and user participation, this research endeavors to make a meaningful contribution to the field of construction in Colombia and the scientific community.

Taking in consideration the boundary conditions of digital manufacturing technology, as well as the current state of the art in relation to connections in timber structures and sustainability the main research question emerges:

Main Research Question:

To what extent can 3-axis CNC milling, a digital manufacturing technology, be utilized to fabricate wood-to-wood connections in sawn timber structures for low-cost housing in Colombia while adhering to Design for Manufacture and Assembly (DfMA) principles?

This report delves into the unique constraints faced in Colombia, taking into consideration factors like temperature variations, relative humidity levels, and societal challenges, thus providing an principal context for the research framework. Additionally, an examination of prefabrication systems utilizing wood-based materials insights on both historical and contemporary developments, thus laying the groundwork for exploring the potential applicability of these construction methodologies within the country. This research section leads to the emergence of the initial sub-question concerning manufacturing and climate conditions, which is as follows:

Boundary conditions:

1. Average relative Humidity 80%-85% as great part of the country.
2. Climate ranges 23 to 27 degrees Celsius, as 86% is restrain to these conditions.

I. SUB-QUESTION

Is it feasible to develop a construction system that creates an Off-site production of prefab housing elements and an On-site assembly method that responds to the high humidity variables affecting moisture stability and, ultimately, assembly effectiveness of wood construction in Colombia's rural areas?

As a result, the study has pinpointed the existing forestry industry and available wood products within the national market. The findings of this survey have highlighted the absence of Engineered Wood Products (EWPs) in the market, opening up an opportunity to utilize low-tech materials like sawn timber in digital production. This leads to the second sub-question concerning material precision.

Boundary conditions:

1. The relevance of **scale** in structural components minimizes the number of people in the construction process.
2. Urgency to simplify and typify **interlocking details** to speed up the building process.
3. Development of **modules** that facilitated unit transportation, handling, and assembly.
4. Implementation of **Local materials** provided by the industry and the site.

2. SUB-QUESTION

How can the advantages of assembly efficiency achieved through digital manufacturing be extended to materials of lower precision, such as locally sawn timber available in the Colombian forestry industry?

Furthermore, material classification, mechanical properties, and moisture behavior are examined. Several kinds of wood have been identified in the commercial industry. Considering the variety of wood and its properties, the repercussion of manufacturing wood-to-wood joints must explore the following parameters. The third question is formulated:

Boundary conditions:

1. Wood types – hardness relation with milling performance.
2. Wood shrinkage due to moisture stabilization process.
3. Milling accuracy of wood connections.
4. Interlocking precision – tolerances in connection points.
5. Material performance / weight

3. SUB-QUESTION

The third question emerges as follows: What are the implications of manufacturing wood-to-wood joints considering the variety of wood species, their mechanical properties, and moisture behavior?

THE RESULT:

Lastly, the identification of structural parameter in relation to the final objective are set:

Striving to develop a lightweight prefabricated joinery system, working conditions and structural characterizations are selected to further analysis the structural mechanic of individual parts. As a boundary condition the study focuses on one section of the structure to create typification details that can be replicated across the structure. In relation to façade specifications and envelope detailing, the investigation will briefly mention possible applications. Nevertheless, this is not the main focused of the research

RESEARCH METHODOLOGY:

This research has proposed a bottleneck structure program, following the approach of Buchanan (2001) & Friedman (2000) in research through design (Frankel & Racine, 2010). The methodology is broken down into three main categories: Clinical examination, Applied Research, and Basic research, which can be seen in the report.

Clinical Research P1 – P2:

This chapter and sub-methodology are focused on specific functional scenarios. As the graduation project concentrates on the Colombia context:

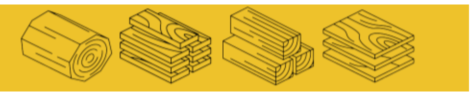
For Literature Research, a browser metadata search using Elsevier, Google scholar engines, governmental and national databases, public reports from the ministry of environment, and public affairs are used.

Keywords like: “Colombian bio-mass”, “humidity study in south American territories”, “post-conflict situation in Colombia”, “sub-soil characterizations of Colombia”, “national forestry industry”, and “EWP projection in Colombia” were used. It is relevant to highlight the most updated information is in Spanish, as previous studies refer to 2016 or older periods. Nevertheless, various English citations which studied current conditions were used.

The insight can be found in the Colombian environmental and social conditions from the report section.

Applied Research P2 – P3:

This subcategory focuses on identifying techniques, materials, and technologies of the digital manufacturing industry for wood-to-wood connections housing. First, an approximation of the definition and first historical examples are brought to attention; for this section, a hardcopy of Prefabrication is used, and a database for TU Delft University. a framework and conditions are identify for the prototyping stage.



Basic Research – Prototype P4 – P5:

This section focuses on the empirical examination of fundamental principles previously demonstrated in the methodologies for P1- to P4 to establish the rules and experimentation of proposed prototypes.

The exploration, and development of these parameters can be found on each big chapter:

First, an evaluation of the industry and material conditions is identified for structural applications; This is a fundamental study factor as it will define manufacturing conditions, design, and further structural implementations.

The compilation of information analyzing national forestry reports performed by the government and identifying stakeholders involved in the process is mentioned in section 5. Then, further enquiry into the references that tackle similar project objectives are discussed in section 6; this information is compared to the Colombian scenarios in section 7; lastly, the evaluation of structural constraints in term of specific design goals are established in sections 8 and 9.

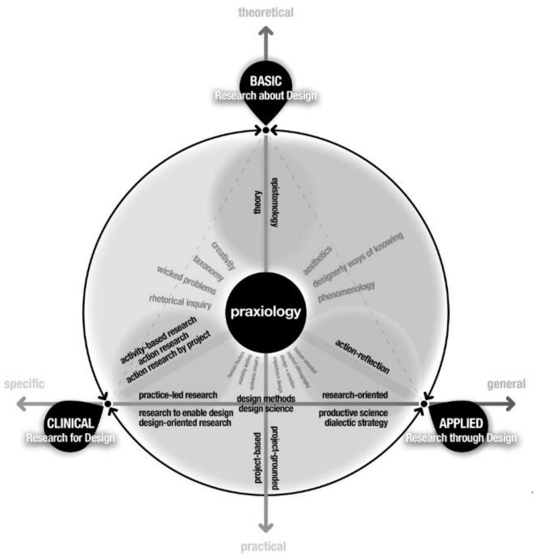
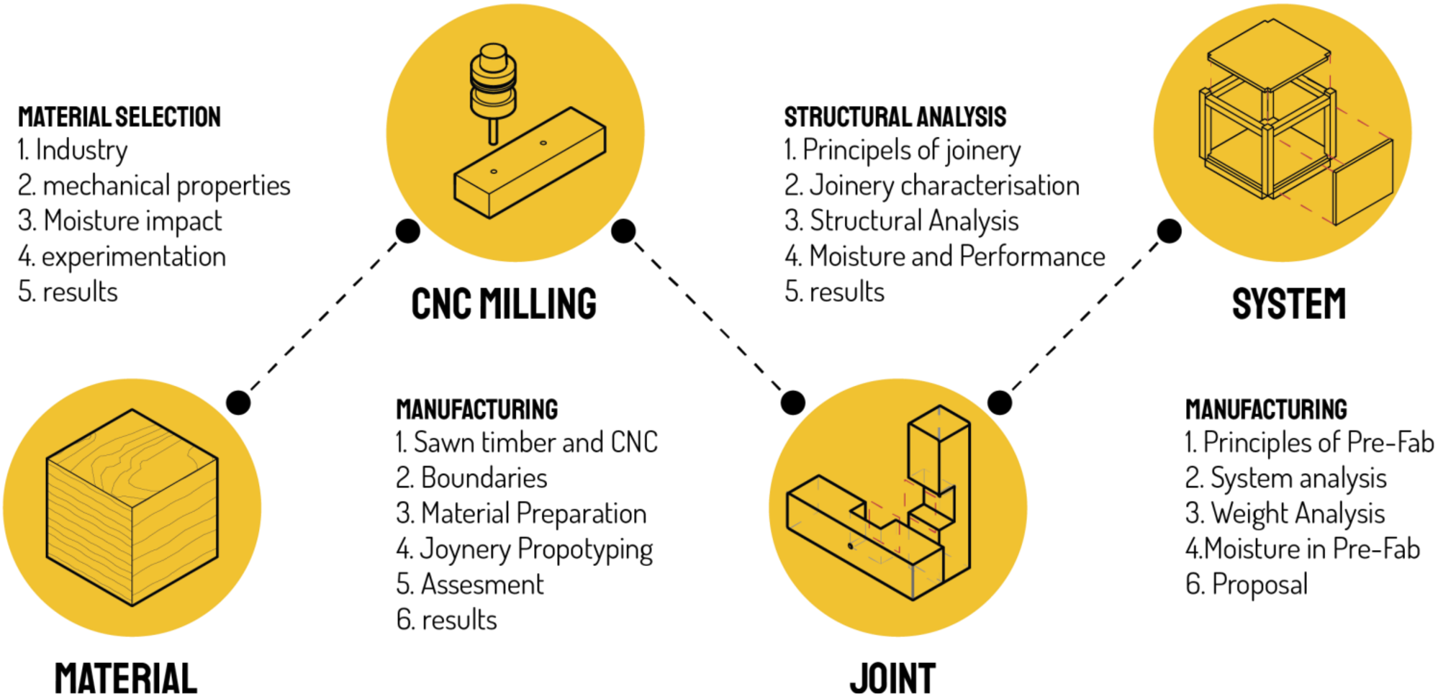


Fig 1. Map of Design Research Categories

Figure 2 diagram, research methodlogy source:



MATERIAL SELECTION
1. Industry
2. mechanical properties
3. Moisture impact
4. experimentation
5. results

CNC MILLING

STRUCTURAL ANALYSIS
1. Principels of joinery
2. Joinery characterisation
3. Structural Analysis
4. Moisture and Performance
5. results

SYSTEM

MANUFACTURING
1. Sawn timber and CNC
2. Boundaries
3. Material Preparation
4. Joynery Propotyping
5. Assesment
6. results

MANUFACTURING
1. Principles of Pre-Fab
2. System analysis
3. Weight Analysis
4.Moisture in Pre-Fab
6. Proposal

MATERIAL

JOINT

Figure 1 research workFlow structure

I. INTRODUCTION

The potential of industrialized building manufacturing systems is an option for affordable housing when the residential shortage and environmental and social crises have become more prominent. For example, in the Netherlands, 1 million additional households are projected to be needed by 2035 (ABF Research, 2019). These statistics predict that two hundred and fifty thousand homes will replace old dwellings, while the remaining 75% will need refurbishment due to this overgrown worldwide population (Jonkman et al., 2022). However, this is not just a matter of demand; in countries like Switzerland, the effects of rapid densification in urban areas have caused an increase in house pricing and, consequently, eviction of low-income tenants (Debrunner & Hartmann, 2020). In the Latin American context, this problem is even more pronounced; According to Akinwande & Hui, the impact of rapid urbanization can be visible in the generation of informal settlements and slums (Akinwande & Hui, 2022). UN-Habitat states this makes it one of the most significant challenges of these regions, as they possess the highest percentages of informal housing in the world (Nations, 2016).

In Colombia, the national cluster of protection (EHP) estimates that around 4,6 million people are at high risk of human rights vulnerability due to the internal armed conflict that historically has affected the country. For example, in 2022, just between January and May, 33.859 people were force-displacement to their homes due to the internal war that has lasted more than 50 years(GIFMM, 2022). Furthermore, 139.900 people were affected by natural disasters losing their residences, an issue that affects more than 101.8 million people worldwide every year.

High-degree prefabrication can offer a cost-effective construction workflow responding to the housing deficit and environmental crisis. Construction systems such as modular timber has shown less material waste, lower construction cost, and shorter installation programs, saving up to 50% embodied carbon, and 35% embodied energy in comparison with conventional building methods (Ramage et al., 2017). Among the benefits, this production method increases the manufacturing quality of building components, offering rational material usage that allows an optimal recycling sequence of buildings and their parts (Albus, 2018). Finally, these solutions could be the answer for a fast autonomous assembly system that aims to cover the national housing emergency.

This research aims to analyze and evaluate the impact of the digital manufacturing milling process in the current construction industry as a solution for effective production, building and assembly methods in independent construction projects of wood households in Colombia. In other words, a construction process that requires minimal experience in the field for its execution on-site. Thus, the final goal of this research aims to develop a simple wood-to-wood connection system that offers alternative housing dedicated to low-income populations located in need of rapid response.

2. COLOMBIA

The country is situated right on the top of the South American continent. Embraced by the Caribbean Sea and the Pacific Ocean at the north of the territory and delimited by the Amazon River on the south. Considering this hydrographic source as one of the most important in the world. A place with abundant natural resources and unique and complex ecosystems.

CLIMATE

The climate condition of the territory is typically tropical, and due to its location, the country shows limited temperature variability across seasons. Moreover, there are significant geographical variations across the territory. From the Andina mountains to the amazon rainforest, this geographical variation determines four main climatic zones in the land Figure 3. The lower – tropical zone (24°C–27°C) below 900 meters, spreads over 86% of the country. With alternating dry and wet seasons corresponding to summer and winter. The temperate zone (18°C) at 900m to 1,980 meters is the most productive land and is home to most of the population. The cold zone (13°C–17°C) at 1,980m to 3,500m this region supports 25% of the population, including the capital Bogotá. And finally, the Paramos zone (at 3,500 to 4,500 m) goes up to the permanent snowline (Climate Centre, 2021).

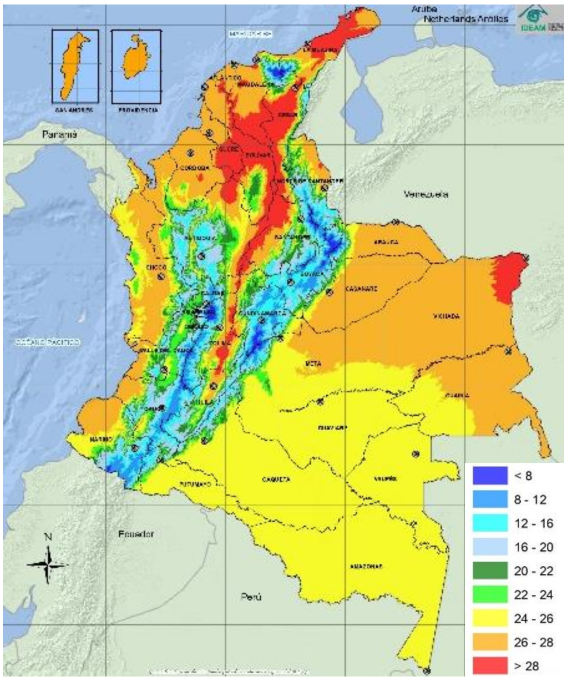


Figure 3. Climatic Zones in Colombia. Source: IDEAM

HUMIDITY

The topographic conditions drive the regional humidity of Colombia. The Andean mountains are divided into three branches, which separate the country into four basins: Caribbean, Pacific, Orinoco, and Amazon regions. The country's proximity to the Caribbean Sea and the Atlantic Ocean, as well as the constant solar radiation, are leading factors of the moisture difference across the territory. This phenomenon follows the heat and rainfall amounts of each region. The following map, Figure 4, shows relative humidity intervals depending on regions. They are displaying an average of 80% - 85% in a great part of the country. But a considerable variation in the overall territory from 65% to 95% relative humidity can be seen. Understanding this factor is essential for designing and applying rural housing in several humid environments.

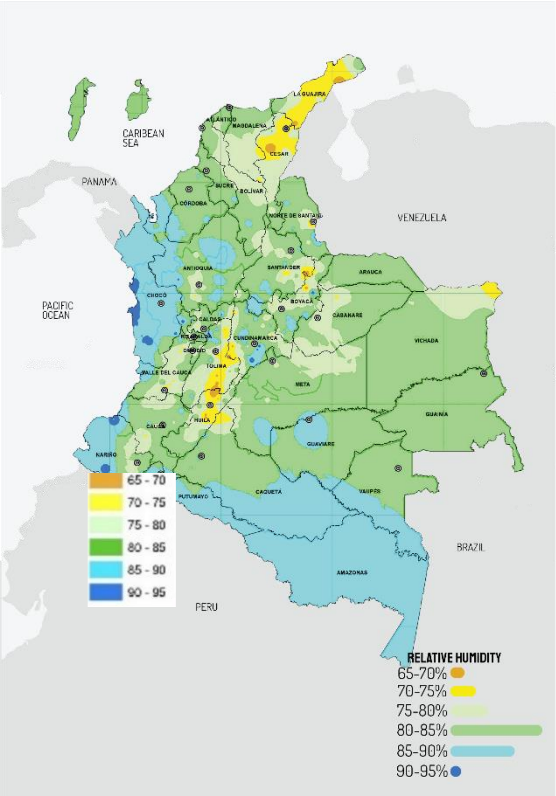


Figure 4 Relative humidity in Colombia. Source; IDEAM – http://atlas.ideam.gov.co/visorAtlasClimatologico.html

SOCIAL CONDITIONS

Colombia faces the second-highest rate of internal displacement linked to violence and conflict in the world, it is estimated that in 50 years since the beginning of the arm conflict between guerillas and government, more than 8.3 million people have been displaced; 10% of this displacement occurred after the peace agreement signed in 2016 (GIFMM, 2022). In 2022, just between January and May, 33.859 individuals were force-displacement. With an estimated population of 49 million people, this country is the third most populated in Latin America. Presenting one of the highest levels of inequality in the world, 27 % of the total population live below the poverty line (Climate Centre, 2021), and this figure reaches 43.3% in rural areas (world bank group, 2020). Coincidentally, the regions in need of a better housing, is the most exposed to the conflict as they are in rural zones with low governmental protection Figure 5.

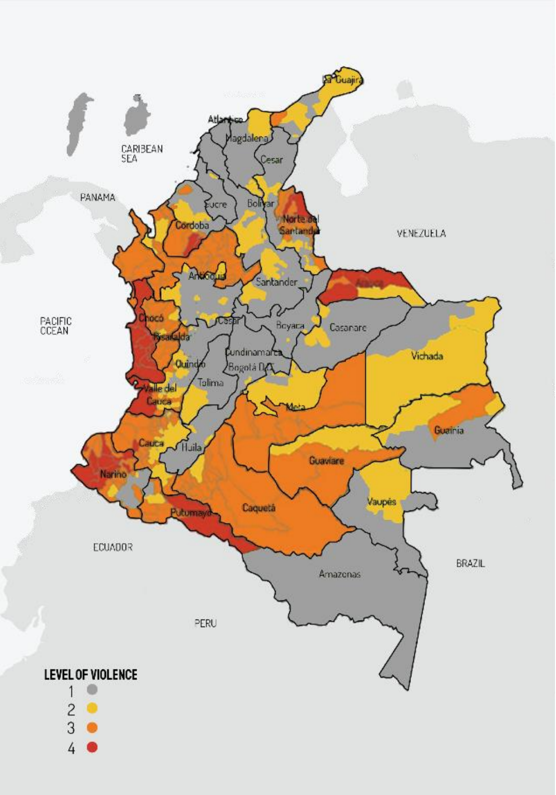


Figure 5. Level of Violence in the country. Source: (GIFMM, 2021)

3. PREFABRICATION IN CONSTRUCTION

The idea of autonomous construction housing could be the solution to improve the living conditions of rural areas as an approach to the social and environmental crisis. The urgent implementation of a rapid construction and assembly process can be empower by the use of prefabricated and automated manufacture, making planning and construction more efficient, and therefore, more economical (Albus, 2018).

DEFINITION

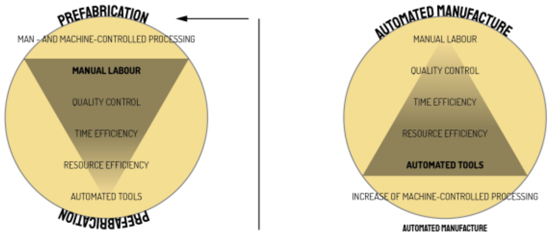


Figure 6 classification categories of building systems. Taking from Albus (2018)

According to Albus (2018), author of the book *"Construction and design Manual Prefabricated housing"*, there is a distention between prefabrication and automated construction. The first terms refer to the process of constructing parts before assembly in an Off-site location, consequently, reducing the workload in an On-site construction. Nevertheless, this definition does not specify the production method that is implemented, or the labor demand necessary to produce these components in house (Albus, 2018). On the other hand, automated construction refers to the process that involves controlled digital production using automated tools during fabrication or construction. The use of machine-based processes and digital control fabrication minimize the amount of manpower required, while at the same time increasing production quality.

Furthermore, Albus (2018) stresses the importance of dividing the building into elements, parts, and sub-components in a logical manner to optimize prefabrication as an efficient solution for transportation and on-site assembly. The combination of automated fabrication technologies and the analogue process could provide an alternative of low investment and progressive growth to populations in high risk in need of rapid solutions, like in the Colombia Conflict.

PRE-ASSEMBLY

The success of prefabrication is rooted in the standardization and pre-assembly of building elements. This approach establishes an efficient model by encompassing a range of production scales. According to a study by (Barlow et al., 2003), standardization serves three key purposes in the manufacturing sector. Firstly, it ensures complete and consistent interchangeability of parts, as well as the simplicity of attaching one part to another. Secondly, it creates a universal connectivity logic within the manufacturing process, driven by savings in assembly time and costs. Lastly, it enhances the predictability of both production and processes.

Conversely, pre-assembly involves breaking down construction into segments during the production process. This permits the distribution of tasks related to subassemblies and components across various departments or alternative supply chains in the industry, leading to advantages in quality control and cost-effectiveness (Barlow et al., 2003). In the construction field, this approach is exemplified by strategies such as minimizing the number of joints to ensure a more durable system and enhance assembly efficiency. Consequently, utilizing a smaller quantity of parts helps avoid defects.

I. SUB-QUESTION

One of the sub-questions this research aims to answer is regarding climatological conditions in combination with building process:

Could a construction system create an Off-site production of prefab housing elements and an On-site assembly method that responds to the high humidity variables affecting moisture stability and, ultimately, assembly effectiveness of wood construction in Colombia's rural areas?

CATEGORIZATION OF BUILDING SYSTEMS

The initial step in addressing the opening sub-question involves comprehending the fabrication and construction processes inherent in the modular building industry. Building upon the research conducted by Juta Albus, which delves into the evaluation of industrially manufactured building systems, it is possible to establish a framework for classifying building systems. This classification arises from a methodical categorization of typological, structural, construction, and material attributes.

Consequently, in line with the author's findings, the primary differentiation stems from the adaptable opportunities presented by the construction system, classified as either a *closed or an open building system*. The first refers to a self-contained construction approach wherein parts and components are designed for compatibility within a specific solution. Conversely, the second concept permits the interchangeability of parts or components, thus offering heightened flexibility in both design and planning (Albus, 2018).

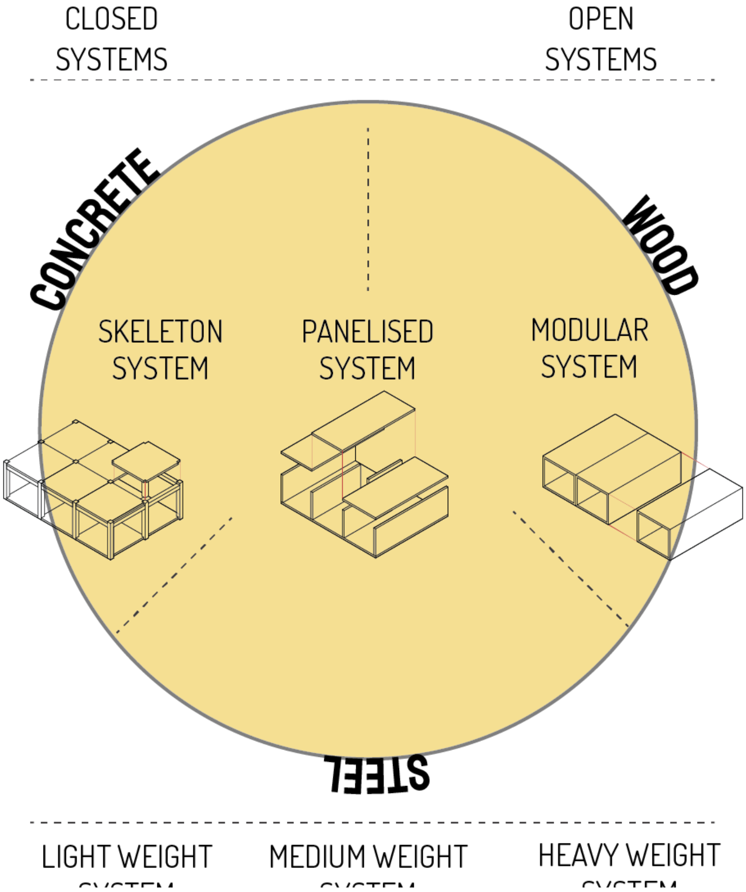
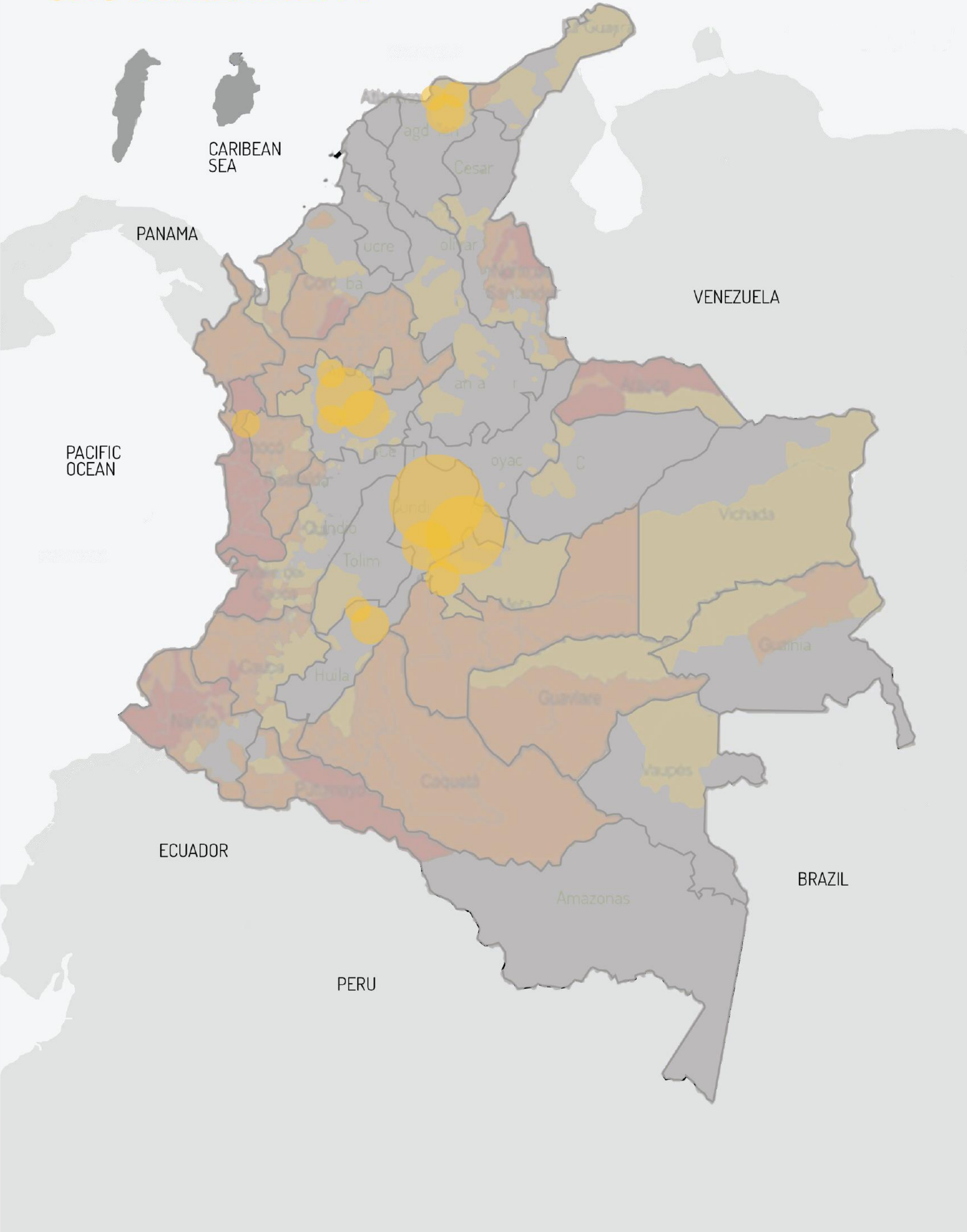


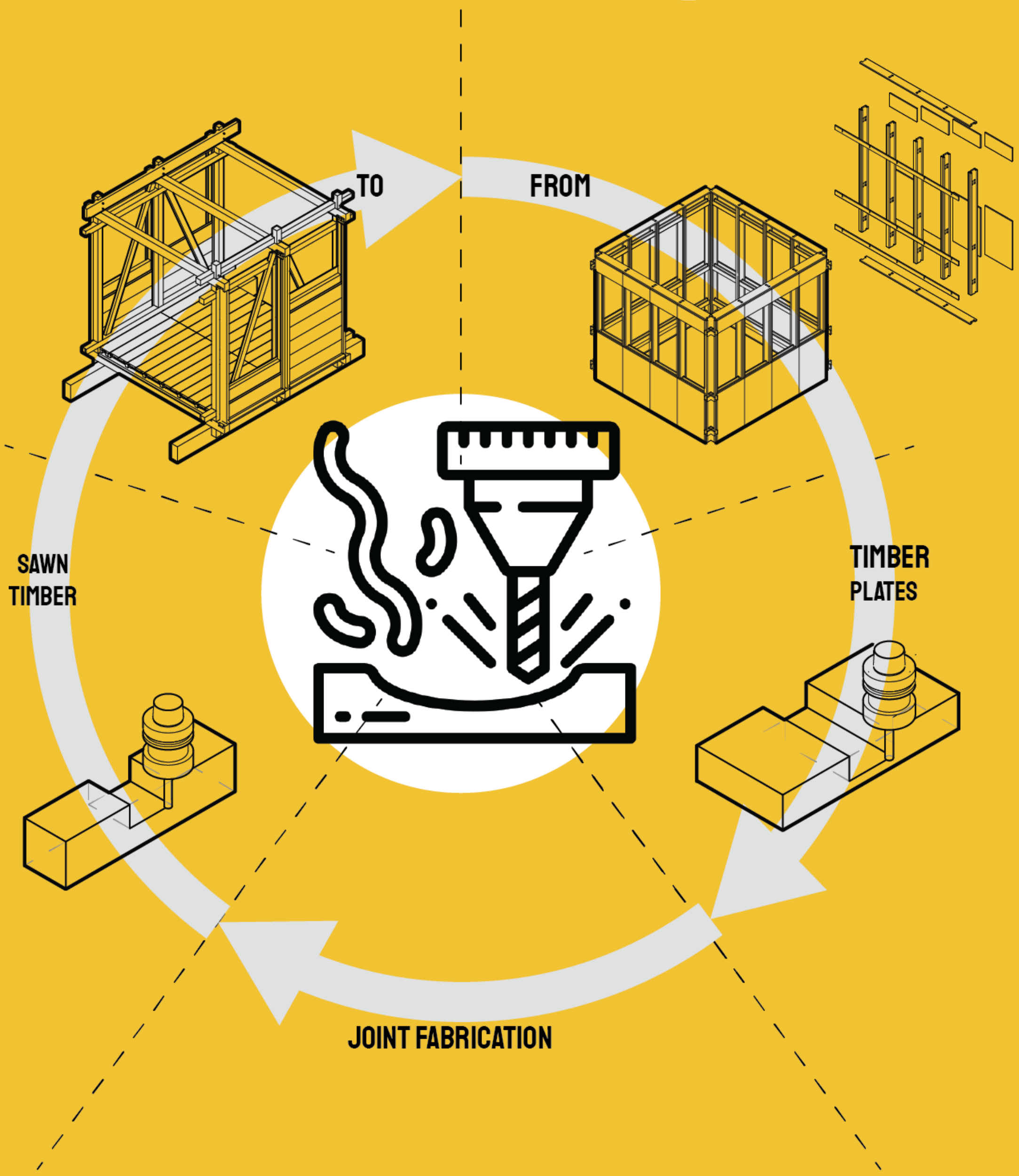
Figure 7 Buildoing systems (Albus, 2018)

AREAS OF CONFLICT

CNC AVAILABILITY



CNC MILLING



4. STATE OF THE ART

Architects and designers have explored the idea of autonomous construction housing for decades. For example, in 1974, American designer Ken Isaacs published the book "how to build your own living structure", offering society a complete and detailed guide for modular construction methods of a multifunctional and flexible indoor structure called "the microhouse" Figure 8 (Isaacs, 1974). Using 4x4' and 2x2 beams, this wooden structure aimed to provide a simple and versatile construction system that could adapt to time, use, and user.

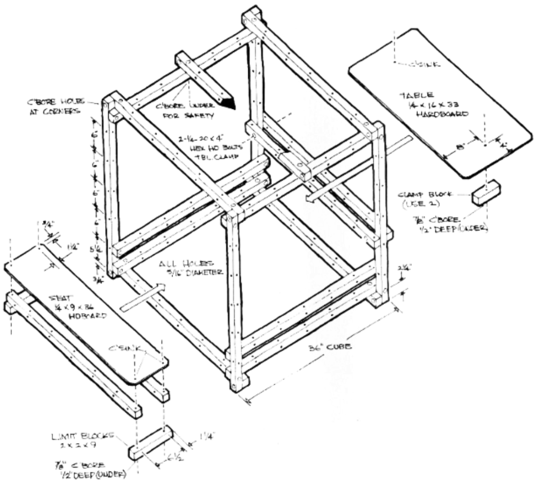


Figure 8 The microhouse – taken from (Isaacs, 1974).

PACKAGED HOUSE

The idea of standardization is not new; in 1942, architects Konrad Wachsmann and Walter Gropius developed a unitized building system based on the floor, wall, and roof panels. Thus, by using an internal metal wedge connector in the timber structure of the walls, the method enabled the rapid interlocking of horizontal and vertical elements. This technical advancement allowed efficient prefabrication and rapid assembly, requiring no additional scaffoldings. Furthermore, the production of standardized components using highly automated milling equipment reduced the amount of manual labor in factories and buildings sites. An exemplary building manual gave step by step explanation of the assembly process, which enabled five unskilled workers to complete a building within one day (Albus, 2018). Despite the technological progress, the system lacked user acceptances, which drastically impacted the demand, subsequently, closing the production.

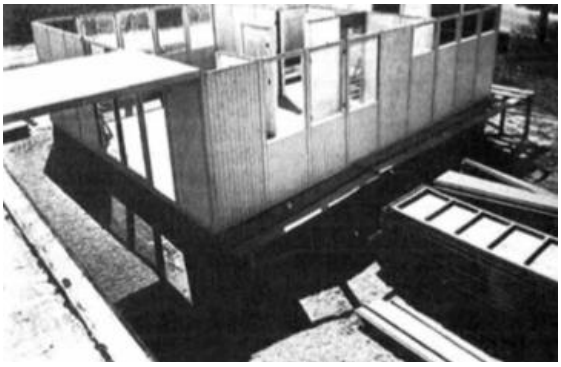


Figure 9 The packed House 1942 by Konrad Wachsman and Walter Gropius.

MR. MANUEL HOUSE

Experiences of prefabrication performed by unskilled labor can be found in Latin American context. Autonomous constructions using digital fabrication for vulnerable communities, such as the WikiHouse open-source project in Brazil, attempts to prove the technology potential in modern times. By implementing this available online system, the author seeks an alternative solution to the large housing deficit of almost 6 million units, representing 8% of the total housing in the country. The original WikiHouse building system uses modular components prefabricated by a CNC machine to supply flexible design, easy manufacturing, and high-performance homes for small-scale buildings worldwide Figure 10. The construction proposes simple assembly logic of plywood sheets modules.

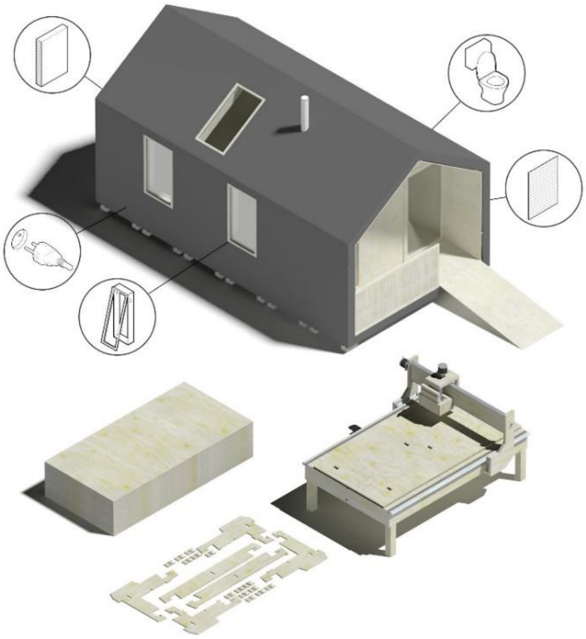


Figure 10 WikiHouse modular building system

In the Brazilian context, this modular building aimed to prove the possibility of low-cost quality residences. The prototype intends to tackle local material constraints, transportation, and construction speed using community participation as a low-experience workforce (Rocha et al., 2020) seen in *Fig. 10*. After completion, the structure made from 150 OSB plates forming six structural frames showed several limitations; First, the economic visibility was restricted to the ownership of the CNC machine, as equipment outsourcing proved to be the highest operational cost. Second, the module component lacks dimensional logic as the elements surpass the transportation capacity on the site. Third, the assembly logic of individual structural frames proved to be labour-demanding. Each element required a day of pre-assembly and exceeded the weight workers could carry, using more than five people to position one frame. Lastly, the technical detailing of structural elements showed high complexity; therefore, additional skilled labour was necessary for monitoring and execution to realize the building.

Figure 11 Mr Manuel WikiHouse.

HOUSE MAGAZINE

This second prototype, developed by architect Clarice Rohde and the Federal University of Rio de Janeiro, illustrates other possibilities for the digital fabrication of Latin America's low-cost housing. Despite using the same open-source WikiHouse framework, this structural module was simplified, proving a more efficient assembly time frame compared to the previous example. Furthermore, in collaboration with architecture students, professors, and staff, the team built a double inclination roof house module called "casa Revista"; which resembles the cultural and architectural heritage of the region, aiming to provide a conscious design that responds to the climate tropical conditions, by increasing natural ventilation (Henriques, 2018).

This research seeks to prove autonomous and collaborative construction parameters to empower the resident-builder format (Passaro & Rohde, 2016). After completion, the architect highlighted the challenges faced in the construction process. Despite the simplicity of the building technique, and the fast learning curve of people involved in the assembly method, the interlocking sequence of numerous structural segments is labour demanding with the dependency of multiple operators necessary for construction (Passaro & Rohde, 2016). To illustrate, the frame as a component needed to fit simultaneously at 18 points with other sections.

Moreover, the assembly dependency between building layers and joinery connections proved insufficient building optimization as instances like envelopes were required in some sections to finish the structural skeleton.

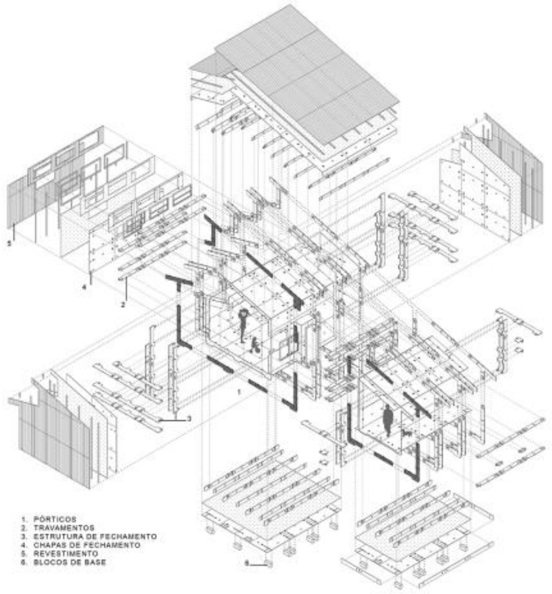


Figure 12 Mr Manuel WikiHouse.

THE DIAMOND SUITE

The Diamond suite is a digitally fabricated low-cost modular house developed by The New Makers company in The Netherlands. Using a CNC 3-axes milling machine, the project fabricates multifunctional building components from OSB plates. As the primary premise, this development proposes a simple assembly process requiring minimal construction experience to tackle the industry's current workforce shortage. Thus, proposing a fast assembly unit of typo tap and pocket joinery solutions implemented across the habitational walls, floors, and roof modules. Furthermore, the assembly logic divides the pieces into elements, and the ensemble of multiple pieces forms components. Finally, several components result in a building, providing a hierarchic approach of construction blocks that come together to facilitate the workflow and building development. This strategic construction system allows the in-house assembly of 6 unites every two weeks by a team of 15 builders. Despite being a European project, the Diamond Suite shows the value of working with components for efficient assembly workflows. Contrary to the previous examples, this building product demonstrated the capabilities of wooden prefabrication using logical building sequences.

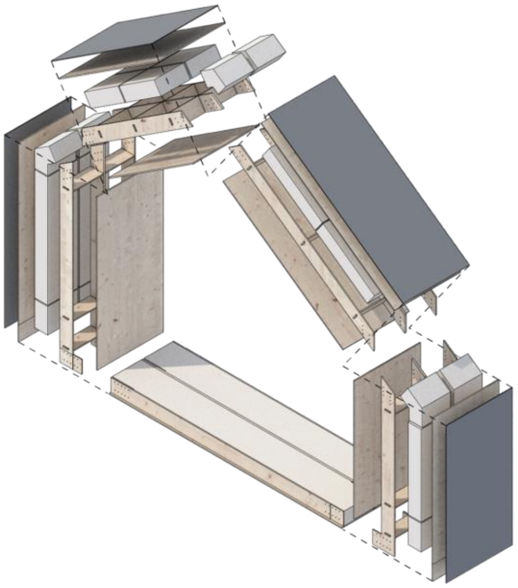


Figure 13 typical structural module of Diamond Suite units

NATIONAL PREFABRICATION

A heavy cement infrastructure dominates the country's building industry, where implementing reinforced concrete, steel, and ceramic blocks is common in small and large-scale housing. Due to the large availability of knowledge, trained labour, and cost efficiency, the building sector has relied on these construction systems and materials for decades. Nevertheless, small national wood enterprises are present in the territory. For instance, "Inmunizar" is a company dedicated to harvesting, sectioning, drying, and treating dimensional wood products for the construction industry. This organization uses a vacuum pressure system to treat the material against corrosion and water resistance. Thus, implementing these elements for manufacturing housing at the end of the cycle Figure 14. Nevertheless, the construction does not present components, or assembly methods that suggest an optimal prefabrication process, and rather evidence a more traditional process.

Figure 14 pre-fab house from inmuniza company source: https://inmunizar.com.co/sitio/portfolio/mixed-plywood/

The previous example is considered prefabricated wooden housing in Colombia, showing the need for more innovation in this industry. Other applications of more high-tech wooden products in the industry show signs of progress in forestry development. Nevertheless, the exorbitant cost of EWPs (engineering wood products) that allow high precision makes this construction inaccessible to most of the Colombian population.

For example, the company Wood Plumage produces personalize Glulam prefabricated structures dedicated to prosperous clients Figure 15, due to high material pricing. The previous contextualization brings the opportunity to solve an evident challenge:

2. SUB-QUESTION

How to bring the benefits of assembly efficiency produced by digital manufacturing using materials of less precision, such as locally sawn timber available in the Colombian Forestry industry?

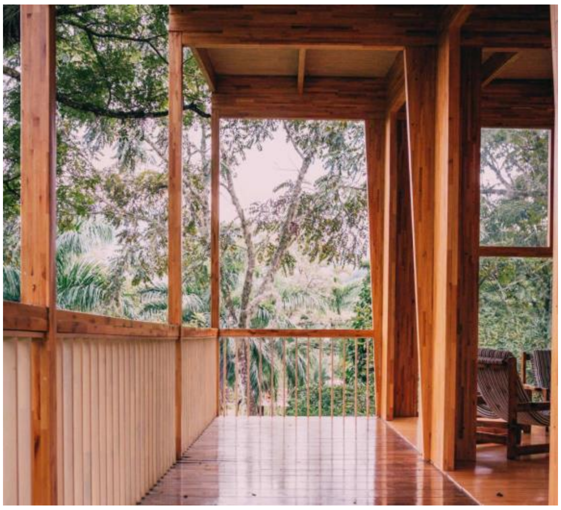


Figure 15 Glulam timber house – source: http://plimare.com/site/madera-clt/

ASSESSMENT OF CURRENT DEVELOPMENTS

Projects like WikiHouse are evidence of a technical gap and overengineering structures that demand simple assembly solutions to benefit the construction time frame and user.

The implementation of such systems, with poor contextualization of the social, environmental, material, and economic factors, has failed in previous attempts. Modular construction led by digital fabrication could dramatically impact the building industry aiming to create affordable housing with a powerful historical and cultural matter. However, applying specific parameters is necessary as boundary conditions for implementation in Latin America:

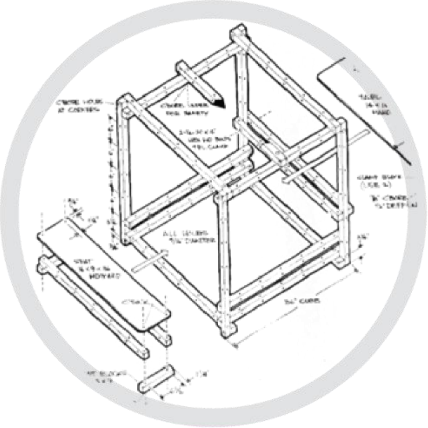
1. The relevance of **scale** in structural components to minimize the number of people in the construction process.
2. urgency to simplify and typify **interlocking details** to speed up the building process.
3. Development of **modules** that facilitated unit transportation, handling, and assembly.
5. Implementation of **Local materials** provide by the industry and the site.

1942

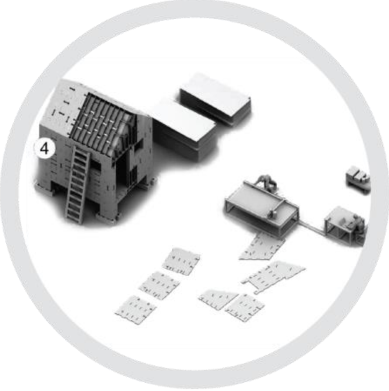
Wachman & Gropius
The Packed house

1974

The microhouse
Issacs



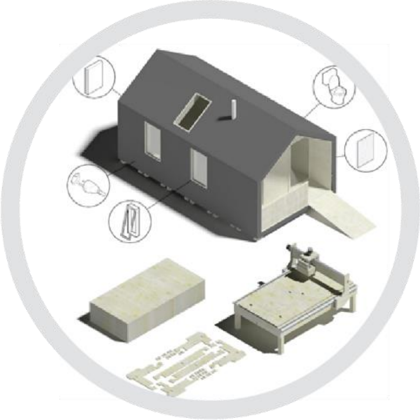
2005



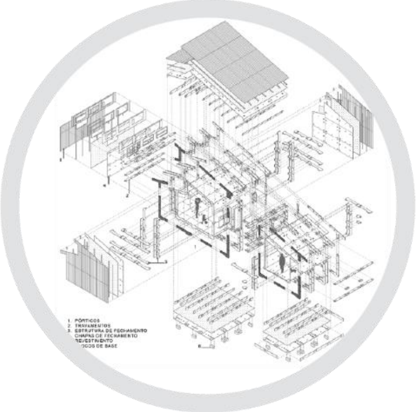
Instant House
Larry Sass

2011

The Wikihouse
Several Organisations



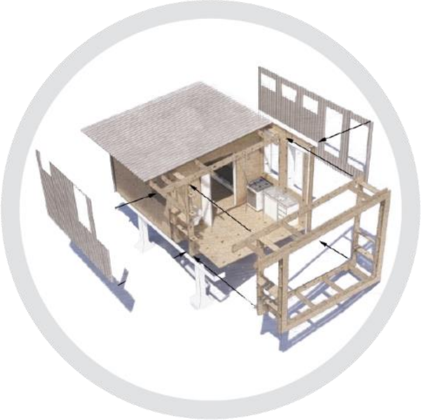
2015



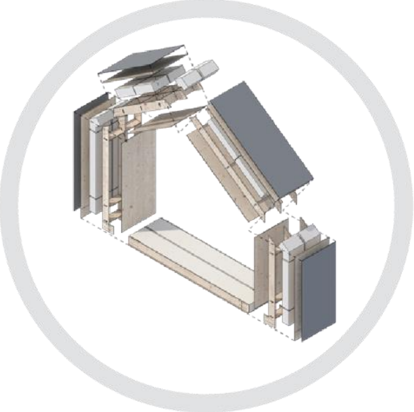
Casa Revista
Federal University Rio de Janeiro

2020

Wikihouse
Sr. Manoel



2021



Diamond Suite
The New Makers

WOOD

THE INDUSTRY AND MATERIAL SCIENCE

6. THE WOOD INDUSTRY

THE WORLD SCENARIO

To Understand the current national industry situation is necessary to have a world perspective of the wood industry. As a natural material, timber is a fiber structure composite, and despite having excellent mechanical properties, this element is susceptible to local failure. Thus, new development such as wood engineering products or (EWP's) were created to overcome these limitations. These products offer stable dimension with uniform structural material properties (Gong, 2021)) increased the overall mechanical characteristics due to the application of adhesives with the heat and pressure on the elements; Because of the superior efficiency, this kind of goods are in high demand worldwide.

Coniferous wood is an essential material for manufacturing EWPs products. This softwood species commonly used in CLT systems are lightweight, compatible with adhesives necessary for fabrication, and optimal for heat and pressure processes, opposite to its counterpart hardwood subspecies (Juan Picos, 2019). As a result, the consumption percentage of coniferous timber has grown exponentially. China is an example of this rapid change, considering one of the biggest timber importers, and EWP producers in the market. Evolving from 6 million of cubic meters (Mm3) of raw material to 35 Mm3 per year. Thus, due to this great demand, Latin America, Oceania, the European Union, and Russia cover their supply.

Latin and Central America possess 24% of the total global forest of the world, and Biomass covers 46 % of this region (Hyde et al., 2022). North American forests have a dense population of coniferous due to their high latitude (55*S) location, commonly related to subarctic climates(Veblen et al., 2005). This condition allows an abundant growth of *Genus Pinus* on the overall region ending in Mexico. Conversely, coniferous is less present in southern regions due to the subtropical climate conditions. Nevertheless, most of these species can be found in the montane forest of the Andean region (Veblen et al., 2005), as seen in brown Figure 16. Mostly located on the eastern side of the cordillera above 2300 meters in Colombia and descending progressively to 1000 meters in southern countries like Ecuador. Conifers shows a large abundance in Chile, Brazil, and southwest Argentina Figure 17. The material shows a dominant extension due to optimal environmental conditions such as mean temperature and precipitation values. Thus, the prolific development of the wood industry in these regions is evident as there is a vast presence of high-quality EWP wood products, contrary to Colombia.

Figure 16 Coniferous in South America source: Own (Veblen et al., 2005)

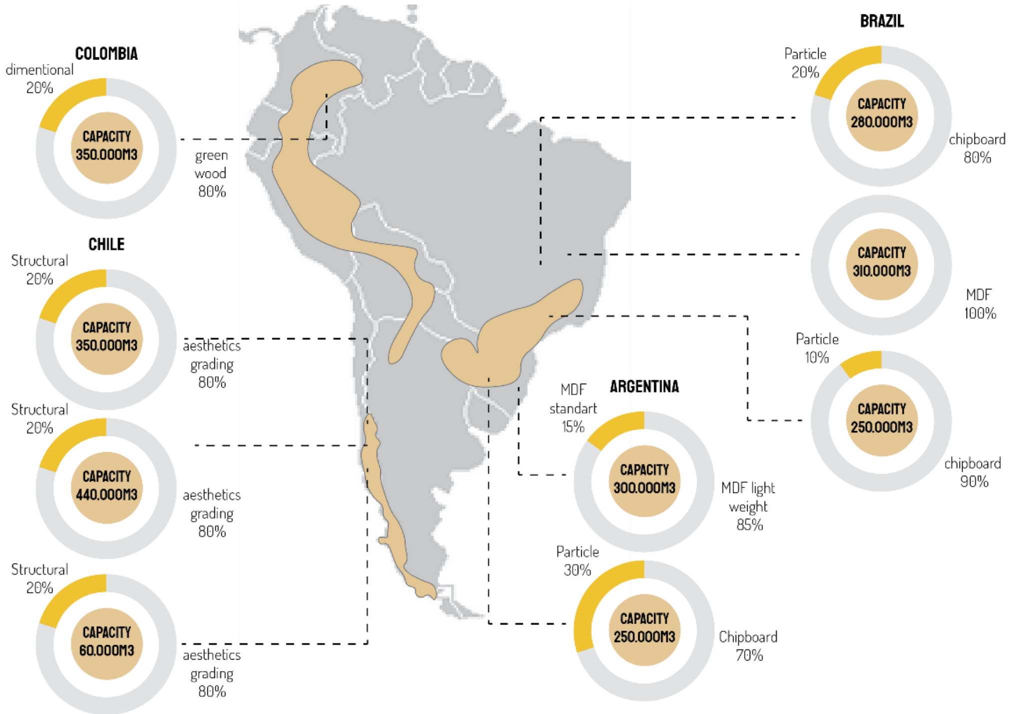


Figure 17 Location of EWP factories in Latin America - type of products Source: Refocosta international production report

COLOMBIAN FORESTRY INDUSTRY – SOCIO/ECONOMICAL BACKGROUND

Colombia is a tropical country with the potential of 25 million ha (Mha) of available commercial forest plantations (Kant & Isuflari, 2022). However, despite the figures, the wood industry is underdeveloped. Previous attempts to increase the industry resulted in small glulam construction and manufacturing companies. However, the incorporation the Andean Forest into the economy caused adverse effects on the Biomass. In 1997, illegality reached 42% of the national wood production, equivalent to 2 million m3 logs, due to a lack of governmental control (Guillaumet et al., 2022). Creating laws that tend to protect the forest and restrict deforestation to limit the production of wood and control plantations. As a result, today, the annual production per capita represents just 0.18 m3 below countries like Ecuador, Uruguay, and Chile.

The growth of commercial plantations in the Colombian market is essential to protect the biomass. Currently, 50% of the national forest supply comes from the natural forest (Hyde et al., 2022). The national deforestation rate has increase due to illegal Coca plantation accounting for more than 149 hectares in the territory (GIFMM, 2022). Consequently, increasing the legal wood industry has become a priority for the national development plan in Colombia. Hence, the Commercial Forest Plantation for the Wood Production (PFCm) value chain policy, was released in 2019 by the Ministry of Agriculture and Rural Development of Colombia (MADR). This policy's main objective is to expand commercial forest plantations from the current 0.3 million of hectares to 1.5 Mha by 2038.

This governmental measurement strives to increase the international market shear of Colombian exports, raise the national demand, and improve the quality and technology implementation of wood forest products. (Hyde et al., 2022). Predicting an increment in the wood construction goods, and a reduction of wood cost in the national market.

Currently, the production of more advance composites such as (EWP's) Figure 17 or engineering wood products is concentrated in Argentina, Chile, and Brazil Figure 15 due to high-level harvest of coniferous species in these countries. This allows an economical cost-benefit in a local level. Nevertheless, in Colombia, where the production of EWP's is scarce in a mass produce level, the acquisition costs exceed the capabilities of the industry for fabrication process describe in *section 4.* Therefore, Answering the (*2. sub-question)* is essential for the research.

WOOD PRODUCTS

Traditional timber ranges between types of trees, applications in the market, and cross-sectional areas. However, in the construction industry some specific characteristics were identified from the current wood market Figure 18. This data illustrates the gap between dimensional timber and (EWP) engineer wood in regards of sizes, price, and Moisture content. And therefore, the necessity to rethink the digital manufacturing process from the site specifications.

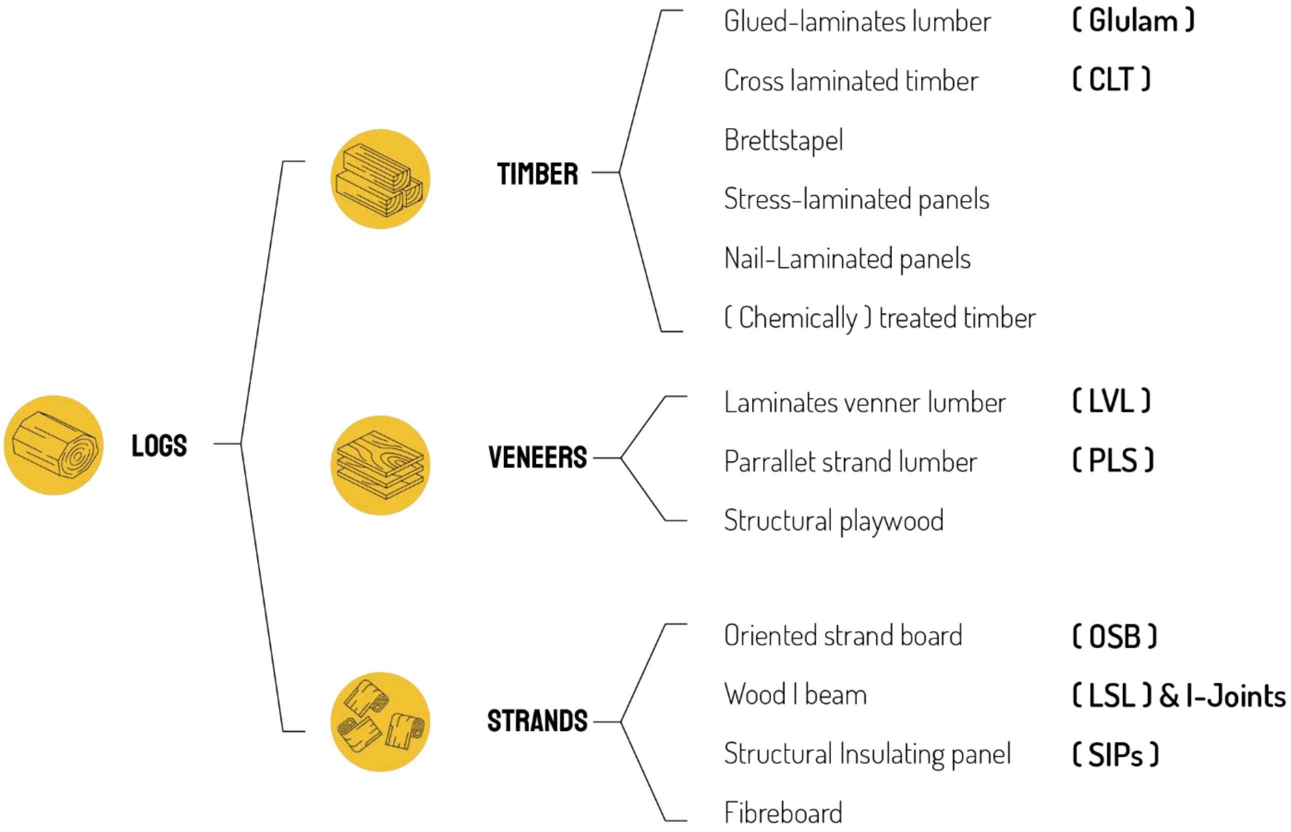
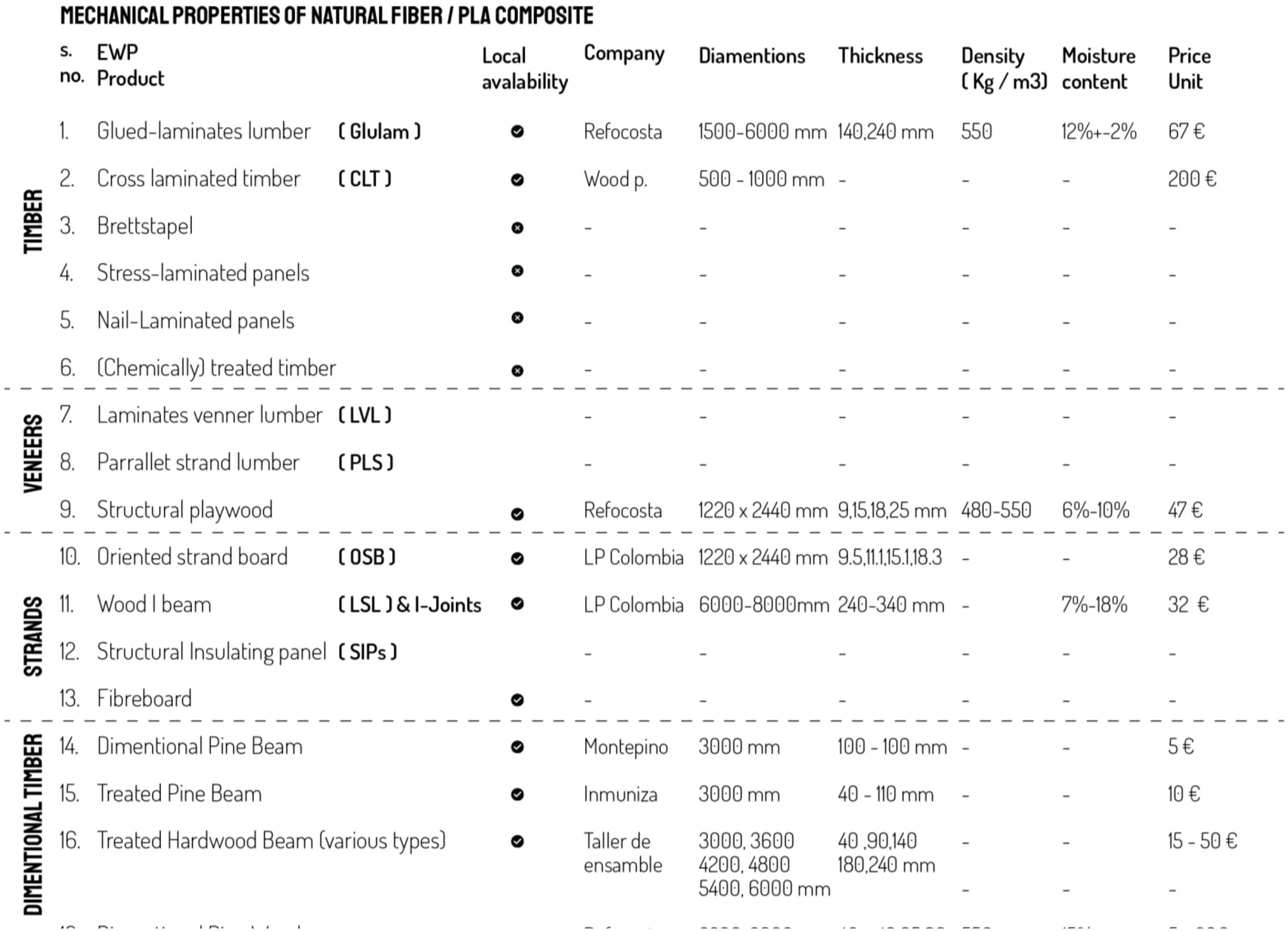


Figure 18 EWP - Classification



MECHANICAL PROPERTIES OF NATURAL FIBER / PLA COMPOSITE

	s. no.	EWP Product		Local avalability	Company	Diamentions	Thickness	Density (Kg / m3)	Moisture content	Price Unit
TIMBER	1.	Glued-laminates lumber	(Glulam)	✓	Refocosta	1500-6000 mm	140,240 mm	550	12%+-2%	67 €
	2.	Cross laminated timber	(CLT)	✓	Wood p.	500 - 1000 mm	-	-	-	200 €
	3.	Brettstapel		⊗	-	-	-	-	-	-
	4.	Stress-laminated panels		⊗	-	-	-	-	-	-
	5.	Nail-Laminated panels		⊗	-	-	-	-	-	-
	6.	(Chemically) treated timber		⊗	-	-	-	-	-	-
VENEERS	7.	Laminates venner lumber	(LVL)		-	-	-	-	-	-
	8.	Parrallet strand lumber	(PLS)		-	-	-	-	-	-
	9.	Structural playwood		✓	Refocosta	1220 x 2440 mm	9,15,18,25 mm	480-550	6%-10%	47 €
STRANDS	10.	Oriented strand board	(OSB)	✓	LP Colombia	1220 x 2440 mm	9.5,11.1,15.1,18.3	-	-	28 €
	11.	Wood I beam	(LSL) & I-Joints	✓	LP Colombia	6000-8000mm	240-340 mm	-	7%-18%	32 €
	12.	Structural Insulating panel	(SIPs)		-	-	-	-	-	-
	13.	Fibreboard		✓	-	-	-	-	-	-
DIMENTIONAL TIMBER	14.	Dimentional Pine Beam		✓	Montepino	3000 mm	100 - 100 mm	-	-	5 €
	15.	Treated Pine Beam		✓	Inmuniza	3000 mm	40 - 110 mm	-	-	10 €
	16.	Treated Hardwood Beam (various types)		✓	Taller de ensamble	3000, 3600 4200, 4800 5400, 6000 mm	40 ,90,140 180,240 mm	- -	- -	15 - 50 € -

Figure 19 Price Comparison Wood products in Colombia

NATIONAL WOOD PRODUCTION

Taking in consideration the previous statement, identifying local productions, abundancy, material properties, and biodiversity of the wood industry will provide a better understanding of how digital manufacturing can impact the local issues presented in *section 1*.

According to the National statistics report of Forestry industry, at present, the territory possess 538.762 hectares of commercial harvesting wood, showing an increment of 0.22% in 2 years (*Boletín Estadístico Forestal*, 2022). Colombia is divided in 5 mains regions: Andina, Orinoquia, Caribe, Pacific, and Amazonia Figure 20; each of these zones is established by a group of several departments, forming the national territory that represents Colombia. From the main five regions, the Andina zone contributes 44% of the national production, follow by the Orinoquia with 33%. The other areas add to the remaining national production. Furthermore, from these figures, the Antioquia, Vichada, and Meta departments present the largest individual commercial areas with 21.7%, 19.7%, and 12.0% of harvested wood *Table 1*.

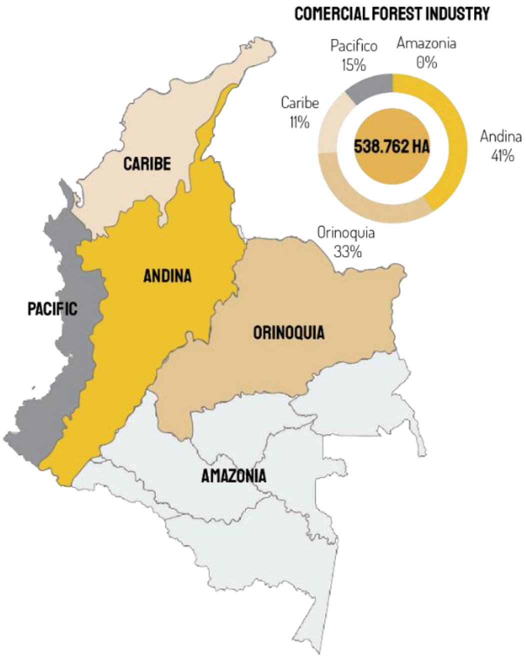


Figure 20 Regions in Colombia

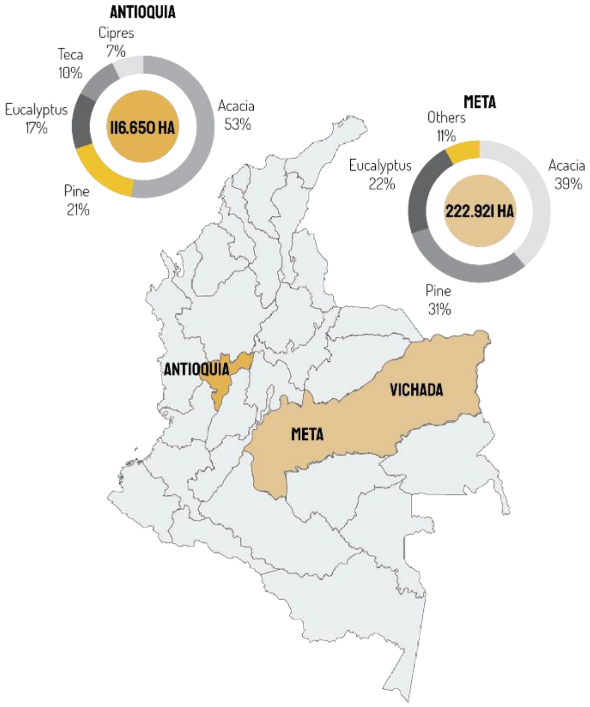


Figure 21 Most productive deparments in wood harvesting. source: own - data taked from the Report of forestry industry 2022

Taking in consideration the climatological characteristics explain in *section 2,* the second sub question formulated in relation to the material behavior and the humidity variables of the territory have a great importance. As this research aims to investigate digital fabrication process using local resource.

Wood is a hygroscopic material, meaning that moisture has a great impact in the strength and behavior of the cells; In its green state, green wood can contain 30% or more moisture (Karagüler & Kaya, 2017). When wood is harvested a stabilization process being to level the humidity difference between the material, and the environment where this element is exposed. A study conducted in 2017 found that, this process could take about 30 to 40 days to reach equilibrium in environments with high relative humidity (80%), such as the ones in Colombia. affecting the volume of the samples due to shrinkage (Pálková et al., 2017).

This research aims to study how this stabilization process can affect the detailing of milling joints in different wood products, and therefore, provide to the scientific community an assessment of shrinkage ratios, and assembly wood details in several stages.

Table 1 . Distribution of Forestry areas across the country

REGION	HARVEST AREA (HA)	%
Antioquia	116.650,54	21,7%
Vichada	106.271,32	19,7%
Meta	64.664,32	12,0%
Córdoba	36.141,73	6,7%
Caldas	29.336,85	5,4%
Valle del Cauca	27.282,22	5,1%
Cauca	25.927,30	4,8%
Santander	20.417,88	3,8%
Magdalena	15.128,08	2,8%
Huila	12.014,18	2,2%
Bolivia	11.857,92	2,2%
Risaralda	10.545,41	2,0%
Cundinamarca	9.808,12	1,8%
Cesar	9.606,20	1,8%
Tolima	9.309,22	1,7%
Casanare	7.192,49	1,3%
Boyacá	6.180,86	1,1%
Quindío	5.950,49	1,1%
Sucre	5.625,86	1,0%
Atlántico	2.206,06	0,4%
North Santander	1.533,80	0,3%
Nariño	1.404,42	0,3%
Choco	1.126,61	0,2%
Guajira	701,25	0,1%
Arauca	609,64	0,1%
Caquetá	600,87	0,1%
Guaviare	378,94	0,0%
Putumayo	194,38	0,0%
Guainía	4,45	0,0%
Vaupés	0,54	0,0%
Amazonia	0,29	0,0%
	538,762	100%

WOOD TYPES IN THE COMMERCIAL FORESTRY INDUSTRY

In the national commercial wood industry, it is possible to find a wide range of species, and types of trees. From the Report of national forestry, a variety of wood products can be seen Figure 22. Nevertheless, the commercial harvest shows eight of the most produce types of the species. The most cultivated tree in Colombia is the Acacia Mangium, stablished in the Orinoquia region with 67.732 Ha, representing (12.6%) of the national production, this is a fast-growing specie originate from Australia; Among its common applications, the wood is used for sawn timber building for heavy constructions, such as beams, particles boards, and medium density fiberboards. Followed by the Pinus Patula, with (11.1%) of the national production covering 59.798 (Ha) of harvested area. This type of tree is mainly found in the Antioquia, located in the Andes region; In third place the Pinus Caribe, covers 50.074 Ha of the territory and (9.3 %) of total production.

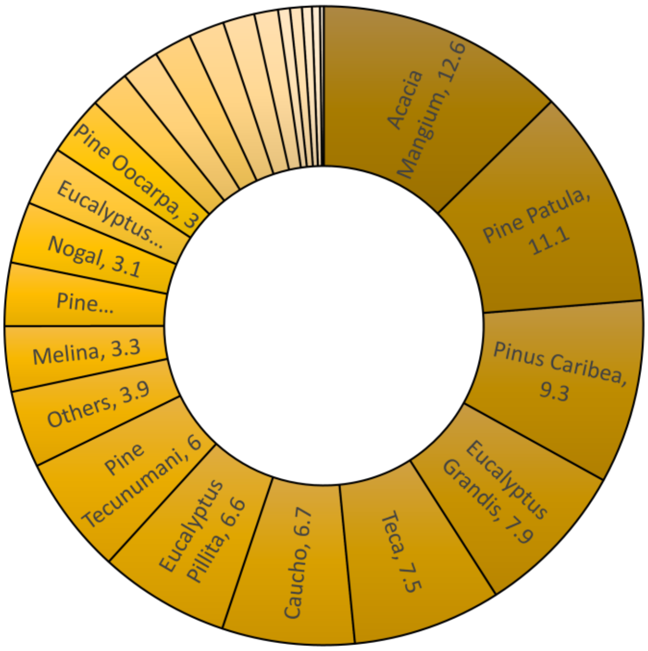
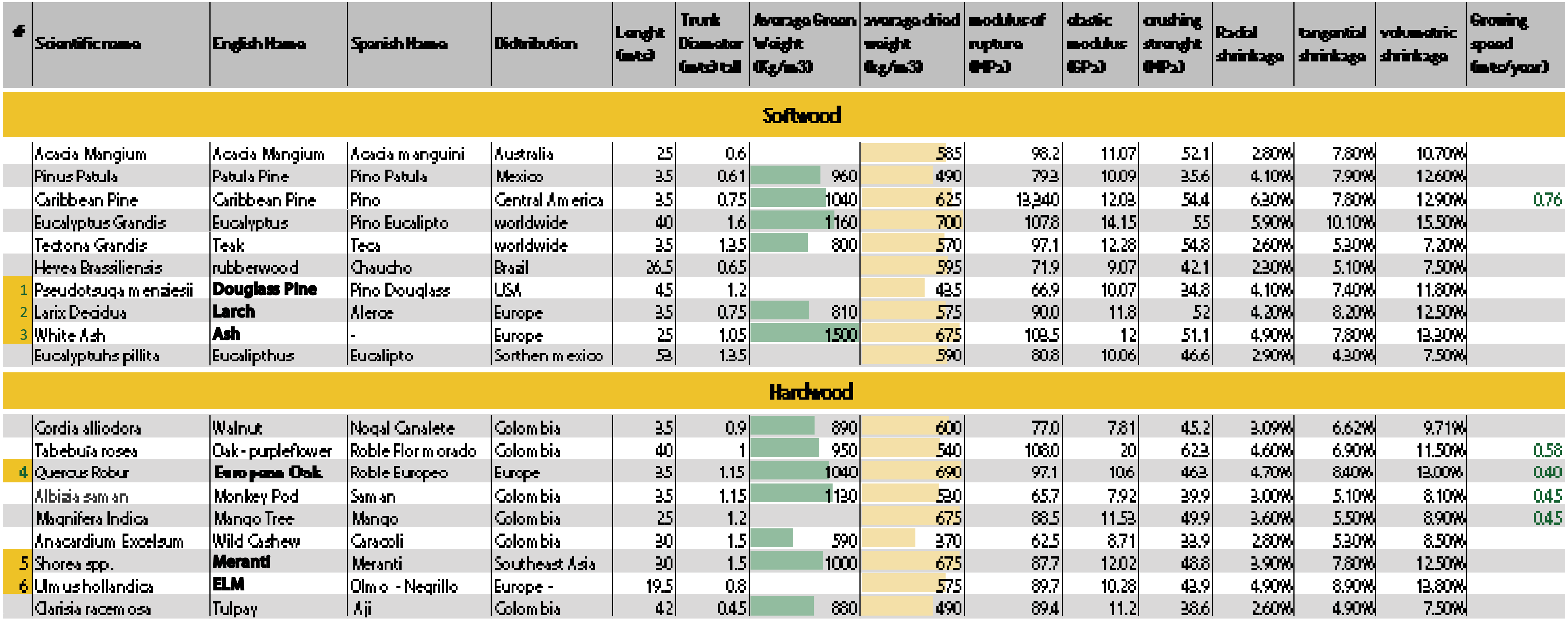


Figure 22 Trees in the commercial forest industry

Table 2 mechanical and pysichal charactyeristics of wood



#	Scientific name	English Name	Spanish Name	Distribution	Lenght (mts)	Trunk Diameter (mts) tall	Average Green Weight (Kg/m3)	average dried weight (kg/m3)	modulus of rupture (MPa)	elastic modulus (GPa)	crushing strenght (MPa)	Radial shrinkage	tangential shrinkage	volumetric shrinkage	Growing speed (mts/year)
							Softwood								
	Acacia Mangium	Acacia Mangium	Acacia manguini	Australia	25	0.6		585	98.2	11.07	52.1	2.80%	7.80%	10.70%	
	Pinus Patula	Patula Pine	Pino Patula	Mexico	35	0.61	960	490	79.3	10.09	35.6	4.10%	7.90%	12.60%	
	Caribbean Pine	Caribbean Pine	Pino	Central America	35	0.75	1040	625	13,340	12.08	54.4	6.30%	7.80%	12.90%	0.76
	Eucalyptus Grandis	Eucalyptus	Pino Eucalipto	worldwide	40	1.6	1160	700	107.8	14.15	55	5.90%	10.10%	15.50%	
	Tectona Grandis	Teak	Teca	worldwide	35	1.35	800	570	97.1	12.28	54.8	2.60%	5.30%	7.20%	
	Hevea Brasiliensis	rubberwood	Chaucho	Brasil	26.5	0.65		595	71.9	9.07	42.1	2.30%	5.10%	7.50%	
1	Pseudotsuga menziesii	**Douglass Pine**	Pino Douglass	USA	45	1.2		435	66.9	10.07	34.8	4.10%	7.40%	11.80%	
2	Larix Decidua	**Larch**	Alerce	Europe	35	0.75	810	575	90.0	11.8	52	4.20%	8.20%	12.50%	
3	White Ash	**Ash**	-	Europe	25	1.05	1500	675	109.5	12	51.1	4.90%	7.80%	13.30%	
	Eucalyptuhs pillita	Eucalipthus	Eucalipto	Sorthen mexico	53	1.35		590	80.8	10.06	46.6	2.90%	4.30%	7.50%	
							Hardwood								
	Cordia alliodora	Walnut	Nogal Canalete	Colombia	35	0.9	890	600	77.0	7.81	45.2	3.09%	6.62%	9.71%	
	Tabebuia rosea	Oak - purpleflower	Roble Flor morado	Colombia	40	1	950	540	108.0	20	62.3	4.60%	6.90%	11.50%	0.58
4	Quercus Robur	**European Oak**	Roble Europeo	Europe	35	1.15	1040	690	97.1	10.6	46.3	4.70%	8.40%	13.00%	0.40
	Albizia saman	Monkey Pod	Saman	Colombia	35	1.15	1120	520	65.7	7.92	39.9	3.00%	5.10%	8.10%	0.45
	Magnifera Indica	Mango Tree	Mango	Colombia	25	1.2		675	88.5	11.53	49.9	3.60%	5.50%	8.90%	0.45
	Anacardium Excelsum	Wild Cashew	Caracoli	Colombia	30	1.5	590	370	62.5	8.71	33.9	2.80%	5.30%	8.50%	
5	Shorea spp.	**Meranti**	Meranti	Southeast Asia	30	1.5	1000	675	87.7	12.02	48.8	3.90%	7.80%	12.50%	
6	Ulmus hollandica	**ELM**	Olmo - Negrillo	Europe -	19.5	0.8		575	89.7	10.28	43.9	4.90%	8.90%	13.80%	
	Clarisia racemosa	Tulpay	Aji	Colombia	42	0.45	880	490	89.4	11.2	38.6	2.60%	4.90%	7.50%	

WOOD CATEGORIZATION

The categorization of wood falls into two main groups; the first class is called angiosperms, like oak, birch, beech, and ash, commonly known in the timber industry as a hardwood material. In contrast, the second group or gymnosperms, present a less dense material structure known as softwood (Ramage et al., 2017). This second type of wood is inexpensive, highly available in quantity and dimensions, and easily manipulated into engineered timber. As Ramage (2017) explains, timber density is considerably lower than other structural materials such as concrete or steel; this physical property enhances efficiency in long-spam in structures, resulting in a substantial load carried by its self-weight as seen in Figure 23.

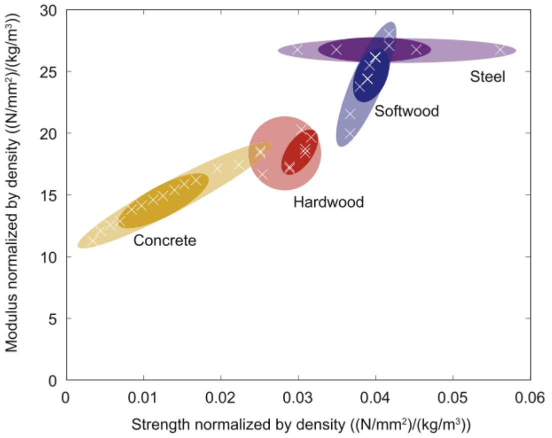


Figure 23 strenght normalize by density source: (Ramage et al., 2017)

DISCUSSION

The preliminary evaluation of the material shows several mechanical properties, including shrinkage, modulus of elasticity and density, as seen in *Table 2.* the material characterization in relation of digital fabrication takes in consideration, milling efficiency, production time, structural performance, volumetric stability due to moisture content, and assembly execution. This research aims to explore two kinds of material Soft and hard wood, common types of lumber in the Colombian market. The final goals are to determine the performance of this material in a digital fabrication process; identify advantages and disadvantages; and ultimately concluding the most appropriated characterization for Colombia's construction system, and so the third sub-question arises:

3. SUB-QUESTION

How can various types of wood impact the manufacturing execution in terms of milling time, quality, and structural performance of a novel connection?

MATERIAL ASSESSMENT

EXPLORING THE MOISTURE INDUCES EFFECT AS ASSEMBLY STRATEGY FOR WOOD STRUCTURES.

In order to achieve the objectives of this research and address the primary question outlined in Sub-Question 1 (Chapter 3), it is imperative to begin by comprehending the material variables and their influence on the potential moisture-induced process. Wood, being inherently hygroscopic, is susceptible to alterations in its physical and mechanical properties as a consequence of increased moisture content resulting from its exposure to the environment.

WOOD QUALITY AND MOISTURE

Moisture induce process as assembly method is not currently widely research. (Arzola-Villegas et al., 2019) argues that this scarcity of research can be attributed to the inherent challenges associated with experimental techniques required to assess the molecular-scale capabilities of this process. Moreover, the author stresses the complex dynamics of wood's interaction with water, often regarded negatively due to the potential for moisture accumulation within the inner cells. This accumulation creates an ideal environment for the proliferation of fungi and invites insect attacks, ultimately resulting in material degradation, even affecting metal fasteners. As argued by some experts (Arzola-Villegas et al., 2019) (Ramage et al., 2017), (Ross et al., 2009), exceeding a moisture content of up to 20% could trigger corrosion effects. This benchmark is a fundamental focal point to evaluate the benefit vs disadvantages of the proposed joinery system. The moisture induce process cannot exceed the value of 20% in order to preserve the physical and mechanical qualities of the specimens. However, the content of the material should be enough to guarantee and increase the interlocking properties of the wood connections. As Pieter Ross et expresses , even a durable timber such as hardwood Oak will eventually decay given a prolonged moisture content over 20% MC (Ross et al., 2009).

PERSPECTIVE TO THE FUTURE APPLICATIONS

Despite the negative effects, ideas of using moisture changes in wood cells have shown benefits in torsional behavior; moisture active shape memory; and Thermally-induce shape memory effects. As an example, a cooled wood veneer in a loaded position is capable of recovering its original form when heated (Ugolev, 2014) consequence of the moisture change content in the material. Further research into the potential applications in construction could lead to sustainable groundbreaking applications in the industry.

DIMENSIONAL CHANGE

The effects of moisture swelling and shrinkage at a bulk level are extensively documented. Swelling is anisotropic, having physical properties which differ values when measured in different fiber directions; from dry to wet, wood generally swells 10% from tangential direction, 5% radial direction, and 0.2% from the longitudinal direction as seen in Figure 25 (Arzola-Villegas et al., 2019) (Karagüler & Kaya, 2017)(Of et al., 1950). Nevertheless, as further explained in this document, the type of wood and its density are essential features to determine the dimensional change due to moisture saturation, and ultimately understand how to work with several types of wood as an assembly system.

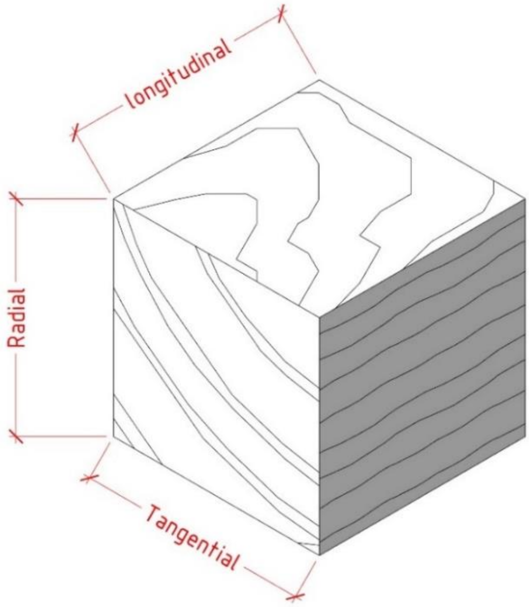


Figure 24 wood fiber direction

FROM THE NUMERICAL THEORY TO THE PRACTICE

As discussed in the preceding sections, there is a well-established body of research on dimensional changes in materials. Existing literature commonly references standard values for tangential, radial, and longitudinal shrinkage, typically around 10%, 5%, and 0.2%. To empirically validate these values, we will employ numerical calculations and utilize the GRANTA Edupack 2020 database. This verification process serves a larger research objective, which is to investigate the impact of specific Relative Humidity (RH) values during the production and assembly processes. Understanding how environmental factors affect materials will enhance their practical application in the construction industry.

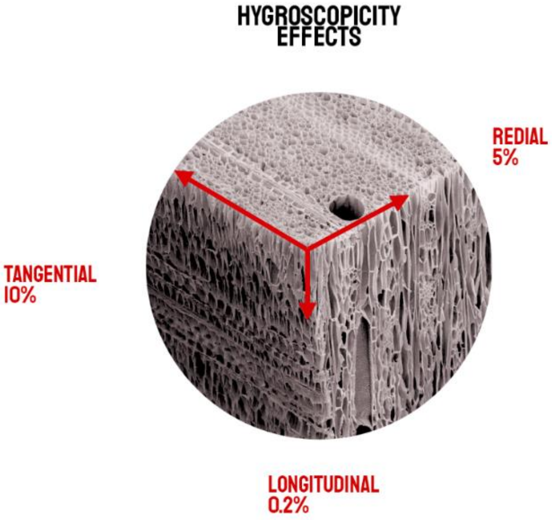


Figure 25 Fiber direction shrinkage ratio taken from PhD candidate Max Salzberger.

EQUILIBRIUM MOISTURE CONTENT

The Moisture content of wood is directly related to the humidity and temperature of the surrounding air known as equilibrium moisture content (**EMC)**. This value represents the amount of water contained in wood, which usually oscillates between 30% to 60% in its green basis or freshly cut (Bajpai, 2018). Consequently, the alteration of water contained in the wood cells produces a volumetric change known as shrinkage or swelling.

Although previous research, such as adata offering a reasonably accurate estimation of Equilibrium

Moisture Content (EMC) in various wood species, it is worth noting that the EMC can also be determined through numerical calculation. The Hailwood and Horrobin equation, developed in 1946 and described by (Mitchell, 2018), serves as a valuable tool in this regard. Given sufficient and accurate information, this equation can be employed to predict the moisture content of wood as it approaches equilibrium with its ambient temperature and relative humidity (RH). Yet, it is important to notice that process time until fully saturate the wood cells cannot be predicted using this method. Where EMC is the equilibrium moisture content (%), h is the relative humidity expressed in decimal form (%/100), T is the dry-bulb temperature in $^{\circ}F$ And w, k, k_1, k_2 are coefficients defined.

$$EMC = \frac{1800}{W}\left(\frac{kh}{1-kh} + \frac{(kh)}{1-kh} + \frac{(k_1kh)+(2k_1k_2k^2h^2)}{1+(k_1kh)+(k_1k_2k^2h^2)}\right)$$

$$W = 330 + 0.452T + 0.00415T$$

$$K = 0.791 + 0.000463T - 0.000000844T^2$$

$$K1 = 6.34 + 0.000775\mathrm{T} - 0.0000935\mathrm{T}^2$$

$$K2 = 1.09 + 0.0284T - 0.0000904\mathrm{T}^2$$

The change between fully saturated wood to any moisture content can be obtained from the following equation. Notice, the number 30 refers to the average moisture content of all fresh wood species (30%):

$$S_m = \frac{S_v(30-M)}{30}$$

The equilibrium moisture content (**EMC**) occurs when the wood has reached a water content equilibrium with its environment and is no longer gaining or losing moisture. This process is defined by the fiber saturation point (**FSP**) of the material. Values can be calculated using the formula given by Vorreiter, Trendelenburg and Krzysik (Jankowska & Kozakiewicz, 2016). Thus, using the S_v Volumetric shrinkage coefficient of the specific wood sample, G_{H_2O} – Density of water, and G_0 – Density of dry wood, the **FSP** can be obtained:

$$FSP = S_v \cdot G_{H_2O} / G_0$$

In previous equations the value S_v or volumetric shrinkage is needed to obtain the fiber saturation point; These values can be obtained from data bases, or literature research. However, a more accurate method can be implemented taking into consideration that tropical wood may differ in values compared to information obtained from literature. Thus, using the wood dry density p_g, volumetric shrinkage coefficient can be obtained:

$$S_v = 26.5p_g$$

Finally, from the S_v value base on the density of the material, an approximation of the tangential shrinkage S_t can be acquire using the following equation for any given wood:

$$S_t = (2/3) * Sv$$

EQUILIBRIUM MOISTURE CONTENT

As an example, a common softwood species is taken to prove the mathematical formulation. The *Pseudotsuga menziesii* known by its scientific name or Douglass Pine shows a dry density of 435 Kg/m3, a tangential shrinkage of 7.40%, Radial shrinkage 4.10%, and a volumetric shrinkage of 11.80% this Information is taken from GRAMTA Edupack 2020, as well as the wood data base website. The porpoise of this exercise is to demonstrated the visibility of the theory to further used in local Colombian wood specimens less investigate.

Volumetric shrinkage

$$S_v = 26.5p_g$$

$$S_v = 26.5 * 435g / m^3$$

$$S_v = 11.52\%$$

Tangential shrinkage

$$S_t = (2/3) * Sv$$

$$S_t = (2/3) * 11.52$$

$$S_t = 7.68\%$$

Fiber Saturation Point Douglas Pine

$$FSP = S_v \cdot G_{H_2O} / G_0$$
$$FSP = 11.52 \cdot 997 / 435 Kg / m^3$$
$$FSP = 26.40$$

Fiber Saturation Point Oak

$$FSP = S_v \cdot G_{H_2O} / G_0$$
$$FSP = 11.5 \cdot 997 / 540 Kg / m^3$$
$$FSP = 21.23$$

Equilibrium Moisture Content

$$EMC = \frac{1800}{W}\left(\frac{kh}{1-kh} + \frac{(kh)}{1-kh} + \frac{(k_1kh)+(2k_1k_2k^2h^2)}{1+(k_1kh)+(k_1k_2k^2h^2)}\right)$$

PRELIMINARY CONCLUSION

Iterative calculation processes involving multiple wood specimens enable the determination of shrinkage ratios and Fiber Saturation Points (**FSP**) across various wood types. From the preliminary calculation using Douglas Pine, can be seen this method as a reliable source, showing similar shrinkage ratio values in comparison to the data obtained by GRANTA and other sources.

However, it is imperative to stress that this mathematical approach yields results that are not uniformly consistent when compared to findings from literature research and database sources, particularly evident within certain hardwood categories. The modest deviations observed in these instances may be attributed to various factors, including environmental conditions during data collection or deviations in material properties within specific wood subclasses. Notably, hardwoods exhibit a more complex cellular structure, comprising a fiber ratio of 50% and water conduction vessels at 30%, rendering them less homogeneous compared to the more uniform structure found in softwoods(Ramage et al., 2017).

Despite these methodological deviations, the mathematical approach remains a valuable primary source for initial comparisons, offering insights into the relative behavior of different wood types.

RESULTS

Nevertheless, upon contrasting outcomes derived from various soft and hardwood types, a preliminary interpretation emerges, highlighting Douglass pine as the most viable choice for increasing volume in wooden elements, as illustrated in the graph *Fig. 25* due to its (**FSB**) percentage capacity.

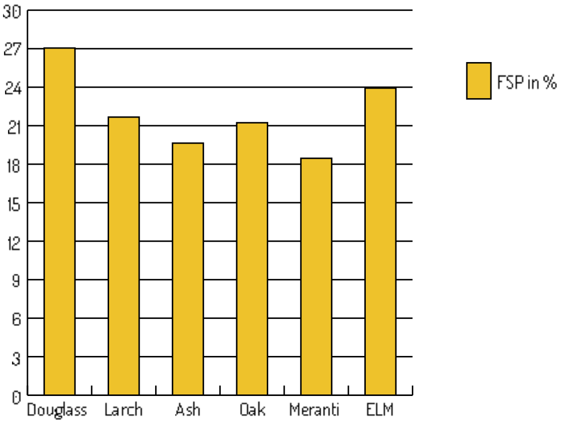


Figure 26 Fiber Saturation Point of wood speciments

The initial examination arises from the mathematical theory: *Does the Fiber Saturation Point play a key role in the establishment of a system characterized by natural interlocking connections resulting from shrinkage and swelling changes?* It stands to reason that a higher Fiber Saturation Point would result on a greater volumetric change limit due to the cellular saturation capacity.

Secondly, in light of the compiled data concerning shrinkage ratios across various wood species, it becomes evident that tangential dimensional change, at 10% seen in yellow in the graph bellow Figure 26, represents the most noticeable value. This prompts a relevant question: *What is the magnitude of the impact of these changes in comparison to other fiber directions, and how do they correlate with tolerances in prospective structural joinery details?*

Third, are the theorical shrinkage fiber direction ratios a reflexional of the real material behavior, or would the experiment deviate from these values?

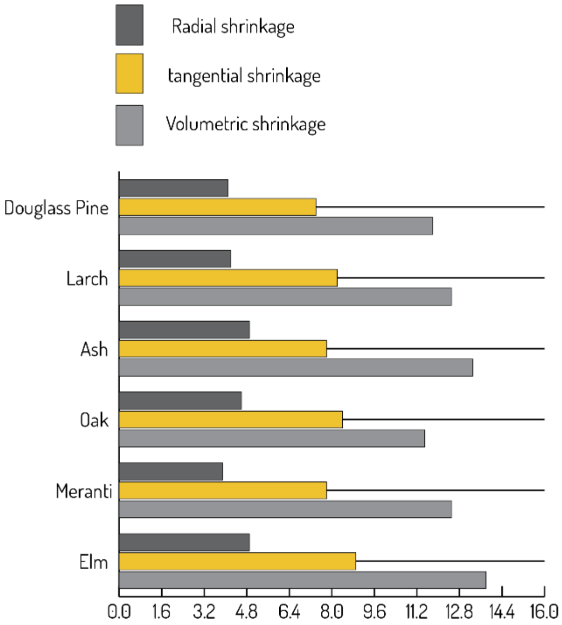


Figure 27. Tangential, radial and longitudinal Shrinkage of several wood spicies

Based on the data presented in Figure 27, which compiles wood shrinkage ratios from various sources, a preliminary observation can be drawn. Species such as Elm, Larch and Douglass pine appear to exhibit the highest volumetric performance, rendering them promising candidates for application in the creation of novel wood-to-wood joinery connections, particularly within moisture-induced processes. Conversely, the remaining samples appear to share similar characteristics, suggesting comparatively lower performance, position Oak Hardwood as the lowest tangential shrinkage ratio with 6.90%. it is important to note that this preliminary assessment is made independently of the material's mechanical and structural performance.

It is important to emphasize, however, that these conclusions are grounded in theoretical information. Thus, in order to validate these concepts and establish a basis for further advancements in this new system, an empirical approach is essential. Consequently, conducting an experiment to validate these initial observations becomes crucial. The results of this experiment will ultimately determine the most suitable material for the proposed construction system.

7. DEVELOPING AN EXPERIMENTAL METHOD

In order to initiate a scientifically rigorous experimentation designed to quantify dimensional changes within specific fiber directions, the establishment of a controlled and stable environment is essential. Such an environment ensures precise isolation and measurement of critical variables, including Relative Humidity (RH) and temperature (T) in degrees Celsius (°C). This controlled setup is crucial for conducting a comprehensive monitoring process to elucidate the influence of these variables on the physical characteristics of wood, ultimately impacting fiber saturation.

To facilitate this experimental work, the Laboratory of Heritage within the Faculty of Architecture and Built Environment at TU Delft University, under the guidance of Professor Dr. Barbara Lubelli, offers access to the requisite equipment and essential chemical components necessary to execute this procedure effectively.

Figure 28 Heritage and technology Laboratory TU Delft.

This experiment aims to identify the moisture content capacity of several wood specimens subjected to changes in relative humidity and temperature difference. The final goal of this process aims to:

1. Understand the effects of RH in the swelling process of the wood elements and conclude if this environmental factor can drastically alter the building process for interlocking wood connections and fiber direction.
2. Proof theorical standard values for wood swelling in different wood specimens and material species in Colombian scenarios.
3. Recognize the ideal wood specimen base on its fiber dimensional change capacity.
4. Simulate scenarios of production and later assembly within the environmental conditions to demonstrate how this construction system can be operated from multiple locations across the Colombian territory.

Databases and literature research has standardized shrinkage coefficients, fiber saturation, and volumetric shrinkage for the most common wood species used in the current construction industry. Moreover, these numbers can be verified using the mathematical methods established in the literature research and comparing them with specific values of wood used in the research project. Thus, taking into consideration this information, is possible to preselect specimens of wood with more capacity to dimensional change, as well as identify wood local availability. For the experimentation certain specimens were selected using databases, and comparing the radial, tangential, and volumetric shrinkage coefficients. This information can be seen in table 3.

SPECIMEN CHARACTERIZATION

First, the batch of samples will be divided into two main types, softwood, and Hardwood. Softwood cells are longitudinally position parallel to the trunk forming most of the mass. This configuration presents a more homogeneous composition, as seen in Figure 30. On the contrary, Hardwood is formed by two types of fibers, 50% of the trunk volume represents the wood, which provides the structural support, and water conducting vessels forms 30% of the trunk Figure 29. This cellular structure of the wood will drastically impact moisture cell saturation, and ultimately the reconfiguration of the wood dimensions.

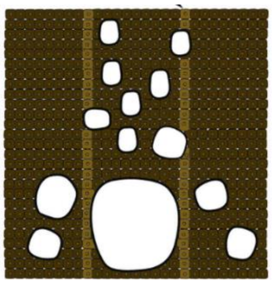


Figure 29 Hardwood cellular strucutre

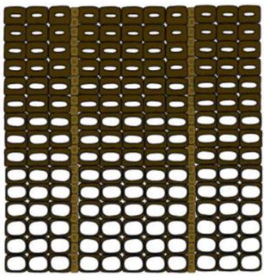


Figure 30 Softwood cellular structure

COMPARISON SPECIMEN PROCESS

Through a comparison analysis of dimension change between the several types of wood in diverse conditions, this experiment looks to identify the effects of humidity delta values to alter the physical aspects of wood fiber direction.

Despite having extensive literature regarding the aspect ratio of dimensional alteration in wood elements due to humidity stabilization process. No research has explored the benefits of shrinkage and swelling effects on traditional wooden connections. Moreover, the differential aspect ratio between fiber directions can be used to enhance the interlocking mechanism of wooden constructions. Thus, this study aims to find optimal RH and temperature values to use the theorical material change into practice.

For the experiment set up, the research uses samples of softwood and hardwood specimens of 65mm x 65mm x 65mm. With this standard measure is possible to identify the direction of fiber that results in more dimensional change due to high humidity exposure.

Figure 31 Wood samples for experimentation

To keep consistent material conditions, all wood samples were selected to align the Tangential, Radial, and Longitudinal fiber directions. This alignment ensures that during the experimentation process, direct comparisons of shrinkage ratios can be drawn across various wood

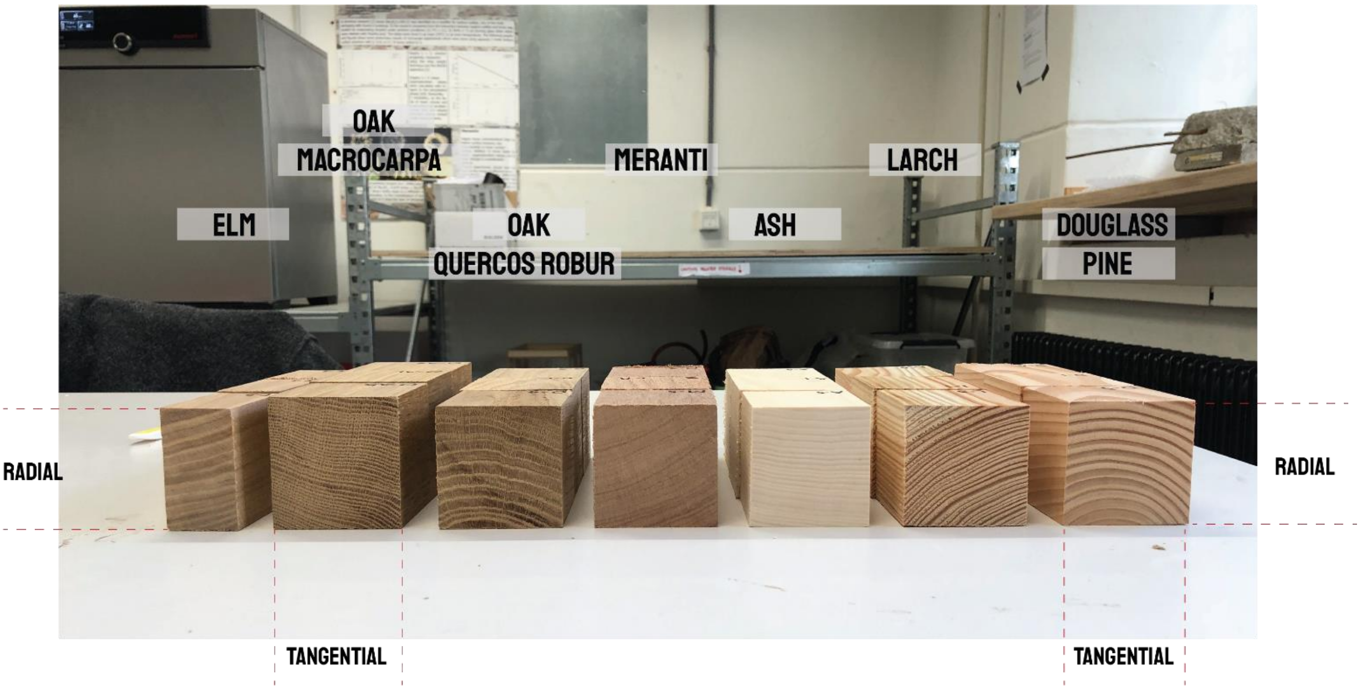


Figure 32 Wood samples tangential radial fiber direction (heritage and technology Laboratory – TU Delft University)

types, as seen in Figure 32. The generous sponsorship and provision of materials by Lorin Brasser's LB Workshop and Tree TimberRE Engineered. Thanks to their contributions, it is possible to access wood specifications related to grain direction, which are not typically available in the market due to cost constraints.

MATERIAL SELECTION

The selection of wood types employed in this research aligns with a comprehensive study of Colombian wood specimens, as documented in *Table 2*. In this table, moving from left to right, key attributes can be seen: the scientific specimen name, country of origin, trunk characteristics including height and diameter (critical considerations for subsequent design phases and wood element sections), material density, mechanical properties relevant for structural analysis, and shrinkage ratios. These shrinkage ratios are derived from diverse sources, encompassing databases, literature research, and software-generated data. Several sources were consulted to collect this material, and some values might deviate as the information overlaps according to location and species.

The selection criteria for wood types were guided by their similarity to the materials naturally occurring in the studied territory, commonly utilized in the region. It's important to emphasize that this selection doesn't necessarily align with the current landscape of the Colombian wood industry, as illustrated in Figure 22. The industry predominantly focuses on softwood materials like Acacia Mangium, Patula Pine, and Caribbean Pine for export purposes.

In contrast, emerging evidence highlights the advantages of employing tropical hardwood materials in indigenous structures, especially in environments characterized by high moisture levels (Javadi & Farina, 2020). Drawing from the information gathered during the preliminary material assessment, six distinct wood types were chosen to explore the potential benefits of the proposed moisture induce system. These selections encompass a range of characteristics, including both softwood and hardwood classes, as well as varying shrinkage ratios, as visualized in Figure 24 and Figure 25.

EXPERIMENT SET UP

Karagüler and Kaya, authors of the study titled "Effect of Relative Humidity and Moisture on the Durability of Spruce and Laminated Timber" (Karagüler & Kaya, 2017), outlined a methodology to investigate the influence of environmental conditions on the material. Thus, by selecting three types of wood specimens with a moisture content of 12+-2% conditioned at a relative humidity of 60%. Their study examined the effects of increased relative humidity, reaching up to 90% RH, using climate chamber equipment.

Similarly, in alignment with this research approach, our experimentation aims to employ a climate chamber. This equipment allows to replicate the environmental conditions prevalent in the Colombian territory, which is pertinent to both wood production and assembly processes. Based on the climatological data (**Chapter 2**) and an assessment of available machinery (**Chapter 9**), it is evident that the majority of CNC equipment and material production facilities are situated in regions characterized by an average temperature range of 20 to 23 degrees Celsius and a relative humidity of approximately 60%. Conversely, the regions requiring housing solutions exhibit environmental conditions with higher temperatures, around 28 degrees Celsius, and relative humidity levels ranging from 80% to 90%, as delineated in *Table 3*.

Table 3 production and assembly environmental characteristics of the Colombian territory

	Temperature	*RH*	*Location*
Production OPT. 1	20°C	60%	Antioquia
Production OPT. 2	28°C	80%	Atlántico
Assembly	28°C	85%	Bolivar
Assembly	26°C	85%	Cordoba
Assembly	28°C	90%	Choco, Vichada

However, due to constraints related to energy consumption and monitoring capabilities, we devised an alternative experimental setup in collaboration with Dr. Barbara Lubelli's specifications. This setup aimed to replicate Relative Humidity (**RH**) levels that closely matched those required based on our data, while ensuring a controlled environment with gradual RH increments. It's crucial to note a significant deviation from the initial setup involving the climate chamber: the absence of temperature control. The new experimental equipment lacks a heating control system. This limitation provides us with an opportunity to explore the impact of temperature on the material in subsequent stages of experimentation.

To replicate the required environmental conditions, three key elements were employed:

Refrigerator as a Climate Chamber:
Initially, we substituted a conventional refrigerator for the climate chamber. This refrigerator provided a sealed environment, effectively restricting the exchange of air temperature and ventilation with the surrounding room environment. It's worth noting that the refrigerator was disconnected to maintain a stable temperature, which hovered around 23 degrees Celsius. This temperature corresponds to the typical conditions observed in the laboratory during the months of May and June, which is close to the summer season. Given that the laboratory is situated on the underground floor, temperature conditions were naturally cooler and more stable compared to the rest of the building.

Computer Ventilator:
Secondly, we integrated a small ventilator repurposed from a computer system, complete with external cabling. This addition was crucial in ensuring uniform conditions throughout the entire experimental volume. Consequently, both relative humidity and temperature were maintained consistently across the top and bottom sections of the enclosure.

Chemical Formula:
Lastly, we employed a chemical reaction that involved a combination of Potassium chloride with demineralized water. This formula facilitated the elevation of relative humidity (RH) values, effectively simulating the desired conditions of assembly. The use of this chemical mixture in conjunction with the ventilator induced a convection effect, where the liquid underwent continuous evaporation. As a result, this ongoing chemical process achieved and maintained relative humidity values at approximately 85%.

Figure 33 experiment set up.

TIME ESTIMATION FOR FIBER SATURATION

According to Karaguler & Kaya, when the air humidity changes too quickly, swelling and shrinking cannot follow this process, and time internal stress occurs, resulting in cracks (Karagüler & Kaya, 2017). As a natural process, swelling occurs by the absorbed water that builds between the fibers, shrinking occurs by the opposite reaction as it loses content.

The generation of cracks could induce a reduction of load bearing capacity of the material. Therefore, slow time adaptation is necessary to keep the integrity of the internal fibers. Literature research has revealed an experimentation process necessary from 21 (Mougel et al., 2011) to 42 days (Karagüler & Kaya, 2017). However, numerical methods were not mentioned to predict the fiber saturation process in the climate chamber. Thus, making unclear the timetable necessary.

To determine the time, it is essential to establish an experimental methodology that exams several specimens in several periods of time, to monitor fiber saturation point, volumetric change, and possible cracks due to humidity induced process.

MONITORING PLAN

Thus, following the recommendations proposed by papers of Mougel at al, as well as Karaguler & kaya, a monitoring process was plan with the laboratory to induce all wood specimens for a period of 30 days.

In this procedure, conducted at weekly intervals (7 days), the refrigerator is opened, and samples of the same wood type are extracted for observation and verification of their physical conditions. Three pivotal factors were taken into account: the initial size of the blocks, measuring 60x60x60 mm, the moisture content of the wood specimens, and the Relative Humidity in the controlled environment, in this case the fridge. The tools employed for this process encompassed a digital caliper, a BOSCH wood moisture sensor generously provided by the Laboratory Figure 34. , and a moisture sensor to measure RH values in the volume. The perforation moisture sensor equipment enabled the selection of various types of wood, spanning both hard and soft specimens, ensuring the highest precision in evaluating each sample moisture content.

Figure 34 Moisture sensor monitoring process of Larch wood piece on initial experimentation estage.

EXPERIMENT ECCENTRICITIES

All specimens were originally intended to follow to the standard dimensions of 60x60x60 mm. However, due to constraints related to the availability of Elm wood, an exception was made, and these specimens were shaped with dimensions of 65x65x35 mm. It's important to note that this variation in size is oriented in the tangential and radial fiber directions, and therefore is not possible to maintained identical conditions as the rest of the group. The sole adjustment involved the longitudinal fiber direction, characterized by a lower shrinkage factor, which was scaled proportionally to align with the overall dimensions. This method guarantee a close comparison with the rest of the group.

The Ash wood type was sourced from a freshly cut trunk, sectioned, and dimensioned to the standard 60 mm cube in order to facilitate comparison with the other samples. Unfortunately, because this material still contained a significantly high moisture content with a value of 25.4% within its cells Figure 35, it is reasonable to anticipate that the shrinkage effect would manifest with considerably higher ratios in comparison to the rest of the specimens.

Furthermore, the moisture-induced process conducted within the refrigerator would have insignificant impact on this material not showing any signs of swelling. You can easily identify this wood type in Figure 32, as the one with the lightest color, positioned third from left to right. In the subsequent discussion of results, it will become evident how the shrinkage effect evolves from the green state to moisture stabilization within the environment. Despite the limitations imposed by the availability of the material, this aspect provides a valuable opportunity to illustrate the effects of the moisture process using green wood rather than seasoned wood.

Figure 35 Ash moisture sensore value beginig of experiment

SAMPLE PLACEMENT AND SORTING

For the purpose of validation, each wood type is represented by three identical specimens with consistent dimensions and fiber direction. This replication not only allows for cross-referencing data to identify any discrepancies or errors but also serves as a means to confirm the accuracy and success of the results obtained.

In the image below, you can observe four distinct wood types, each comprising three sample numbers (1, 2, 3). To facilitate tracking and record-keeping, each batch of material is labeled with a unique code with the initial of the wood type, and a number. Additionally, a database is maintained to meticulously document the recorded data, encompassing moisture content and dimensional changes monitored on a weekly basis. This systematic approach ensures the robustness and reliability of the findings.

Figure 36 samples placement in fridge chamber (Elm, Larch, Oak, Meranti)

Furthermore, an additional two samples from each wood specimen have been set apart outside the scope of this experimental setup. The first group is reserved for a subsequent experiment within a laboratory oven. This test aims to demonstrate the influence of temperature at 32°C on cellular dilation when combined with relative humidity levels. This supplementary experiment was necessitated by the absence of temperature control in the initial experiment setup.

In contrast, the final cluster serves as a control batch, intended for the purpose of comparing the material subjected to moisture induction with specimens kept under standard room temperature and relative humidity conditions. This batch was deliberately excluded from the primary experiment, with one sample from each wood specimen, in order to confirm that room conditions do not significantly affect the experimentation process. Furthermore, it enables a direct comparison of the final results with all the specimens, which should unmistakably exhibit notable dimensional variations among the group samples. The environmental characteristics of the experiments, as well as material codes can be seen in the table below *Table 4.*

Table 4 batch samples per experiment

		Experiment 1	*Experiment 1*	*Experiment 1*	*Experiment 2*	*Control*
RH		85%	85%	85%	85%	40%
T°C		23°C	23°C	23°C	32°C	23°C
DOUGLAS	**D**	1	2	3	4	5
LARCH	**L**	1	2	3	4	5
ASH	**A**	1	2	3	4	5
OAK QR	**O**	1	2	3	4	5
MERANTI	**M**	1	2	3	4	5
ELM	**E**	1	2	3	4	5
OAK HO.	**OA**	1	2	3	4	5

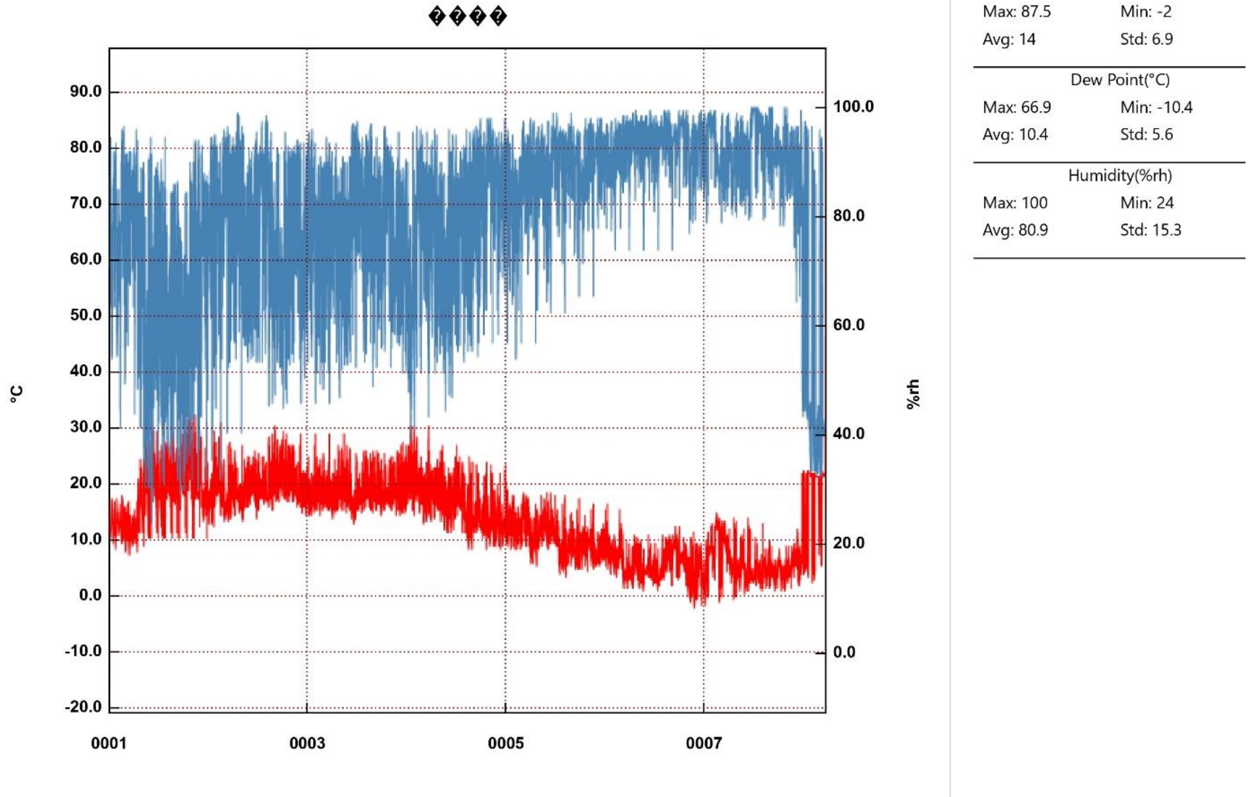


Figure 37 Relative Humidity, temperature and Dew Point values collected by moisture senser in 30 days Period

MOISTURE SENSOR

In order to maintain meticulous control over Relative Humidity (RH) and temperature values throughout the duration of the test, a moisture sensor was strategically placed inside the refrigerator. Any fluctuations in environmental conditions could potentially compromise the test's integrity, as it might lead to a lack of consistent moisture stress on the material, consequently affecting its performance. To validate the effectiveness of the experiment setup, the data collected by the moisture sensor is presented in Figure 37.

In this graph, the red line represents the internal temperature, exhibiting a range from 20 to 27 degrees Celsius. The blue line illustrates the progressive increment in relative humidity within the enclosed environment. It's noteworthy that the initial stages display lower RH values, approximately around 40%. However, as the process advances, there is a gradual and continuous increase in RH values, stabilizing at around 85%, as indicated by the data collector on the right side of the graph. On average, a humidity level of 80.9% was attained during this test. The lower peaks visible in the graph correspond to moments when the refrigerator had to be briefly opened for monitoring purposes. Consequently, minor oscillations in the RH value can be observed throughout the process.

Figure 38 Moisture sensor, and experiment set up

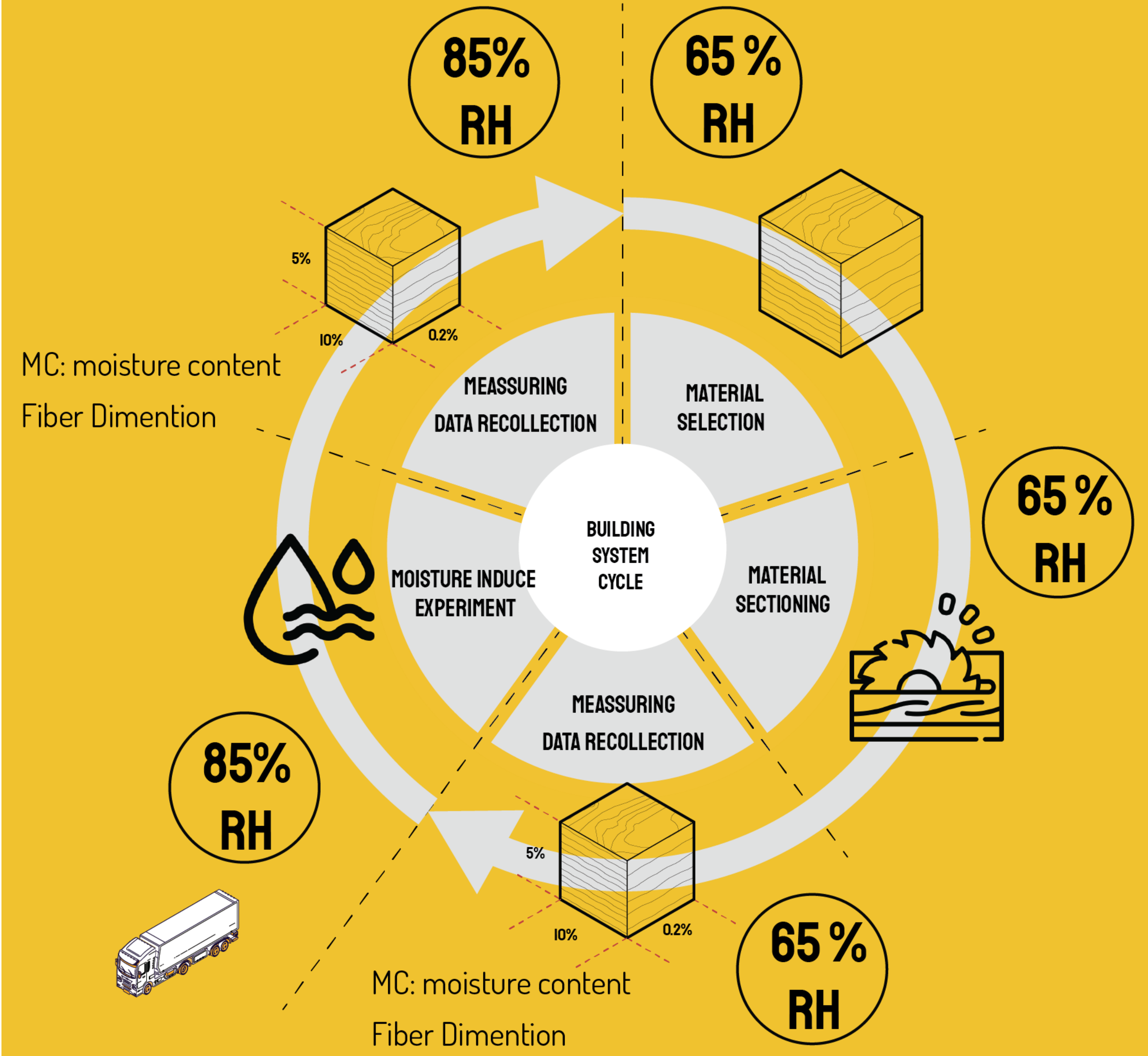
MATERIAL MOISTURE CONTENT

The initial Equilibrium Moisture Content (EMC) of the wood specimens was assessed using the BOSCH moisture sensor, yielding fluctuating values of approximately 10% with a margin of ±2% just before commencing the experiment Figure 35. It's important to note that an exception to this characteristic was observed with the Ash samples. These specimens, in their green state, initiated the experiment with a notably higher moisture content of approximately ±25%, as previously mentioned in the eccentricities section.

EXPERIMENT OBJECTIVE

In regions of Colombia where this system is essential, temperature factors typically range between 26 to 30 degrees Celsius, as elaborated in Section 2 detailing the socio-economic conditions of the territory. However, for the sake of ensuring consistency among the samples and considering that the majority of the region experiences these temperature conditions, an average of this range is employed.

The ultimate objective of this stage is to investigate the effects of Relative Humidity (RH) on wood dimensions. This investigation seeks to comprehend how these climate conditions can be harnessed to enhance volumetric swelling in fiber directions. Subsequently, this knowledge can be integrated into a building system that leverages the natural reactions of the material for assembly and interlocking of building components, thereby minimizing reliance on steel brackets and adhesives. This approach is designed to simplify the recycling process and promote sustainability in construction practices within the region.



BUILDING SYSTEM CYCLE

MATERIAL SELECTION

MATERIAL SECTIONING

MEASSURING DATA RECOLLECTION

MOISTURE INDUCE EXPERIMENT

MEASSURING DATA RECOLLECTION

85% RH

65 % RH

65 % RH

65 % RH

85% RH

MC: moisture content

Fiber Dimention

MC: moisture content

Fiber Dimention

MONITORING PROCESS MOISTURE CONTENT EXPERIMENT I

Douglas Pine
11.5%
Day 1 - Experiment

Larch
10.9%
Day 1 - Experiment

Ash
25.4%
Day 1 - Experiment

Elm
10.5%
Day 1 - Experiment

Quercus Robur - Oak
9.2%
Day 1 - Experiment

Moisture Sensor
Day 1 - Experiment

Figure 39 Moisture Content Speciments experiment 1 - Day 1

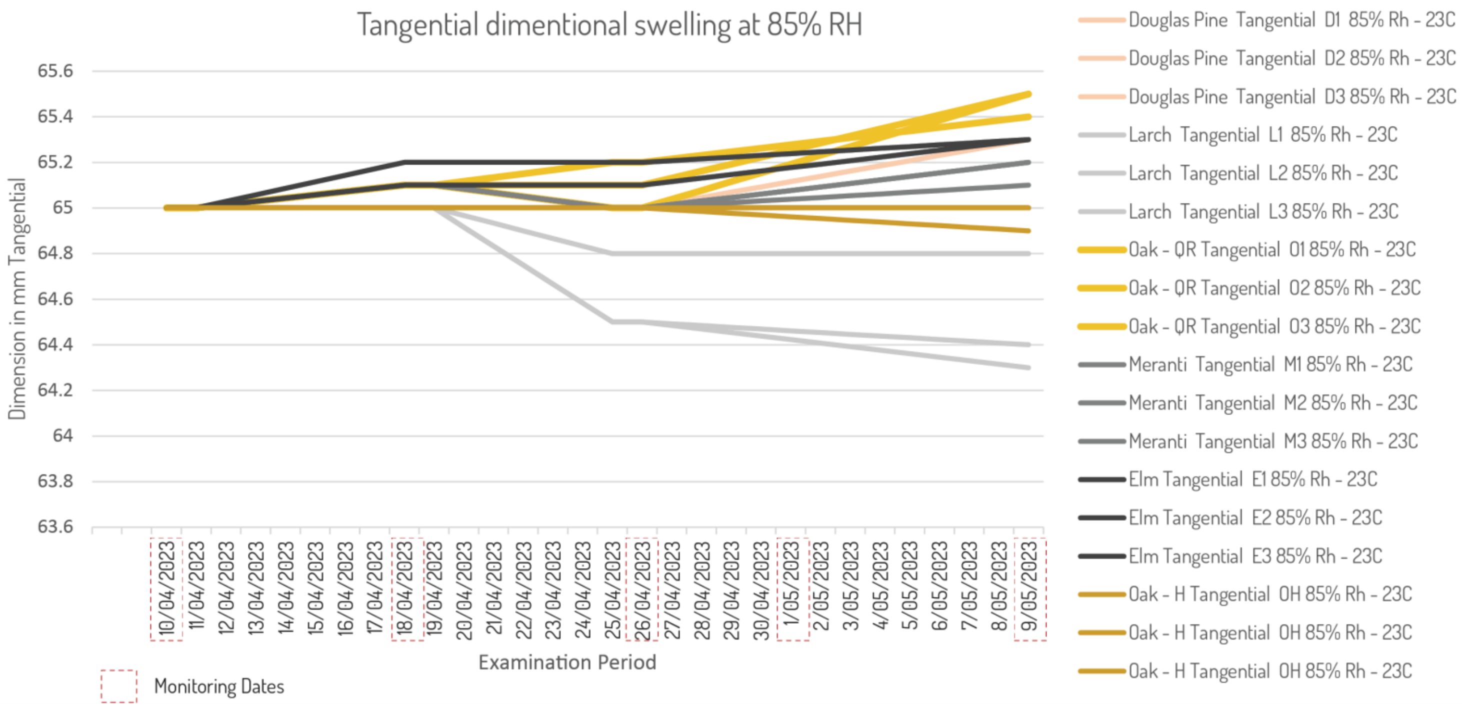


Figure 40 Results tangential dimensional swelling due to moisture induce process at 85% relative Humidity

DISCUSSION EXPERIMENT I - FRIDGE

Each specimen was subjected to two main scenarios following the climate conditions of the studied location (Colombia). First, most of the wood was stabilized at a RH (relative humidity) of 60%, and a temperature of 23 degrees Celsius simulating material growth and CNC manufacturing process of wood building elements. Second, an RH of 85% and a temperature of 23 degrees is used at the Fridge conditions to simulate assembly of wood building components.

RESULTS

In Figure 40, the graph illustrates the transition of Tangential fiber saturation from 60% relative humidity up to 85%. As previously emphasized, the objective of this process is to showcase the potential for material assembly in environments characterized by higher moisture levels compared to the wood's production and milling stages. It is crucial to note that the data pertaining to Radial and Longitudinal fiber directions has been omitted due to minimal changes in their results. However, these values were consistently monitored to corroborate their impact on dimensional changes. This highlights the significant influence of the tangential fiber direction on material saturation, resulting in dimensional alterations and cellular structure swelling.

As previously mentioned, Ash was excluded from the final results due to its initial high moisture content. This particular specimen was chosen to observe how the system behaves with green wood, or wood stabilized to the same final moisture value Figure 42. Consequently, it becomes evident that the rapid transition from 30% green wood to final environmental humidity leads to a substantial shrinkage, underscoring the importance of maintaining control over material

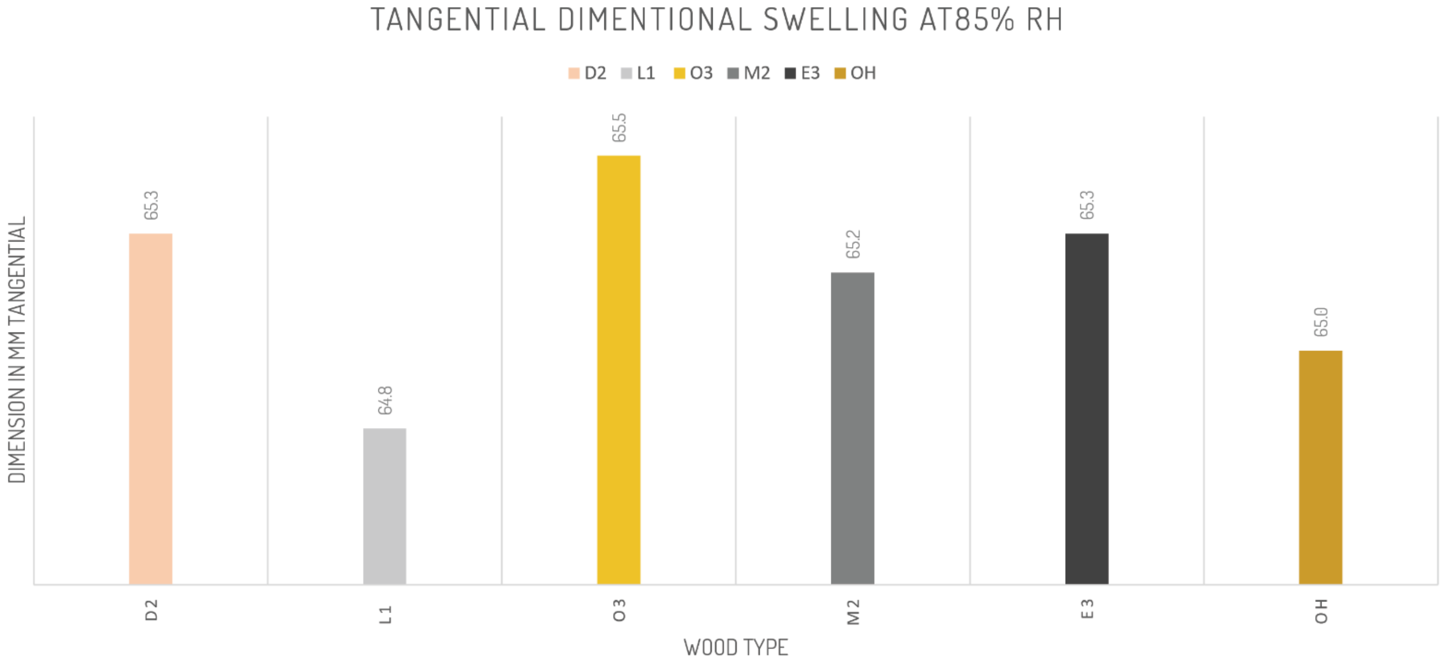


Figure 41 Final dimensional change in tangential fiber direction after 30 days

moisture content to achieve the desired effects.

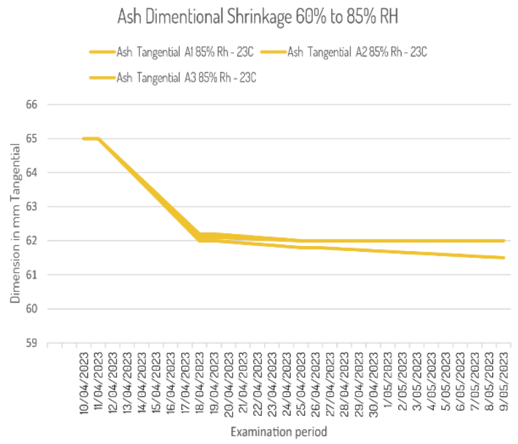


Figure 42 Ash shrinkage ratios at 85% RH

CONCLUSIONS EXPERIMENT I

Upon a comprehensive 30-day assessment of all wood specimens, several material conclusions can be drawn:

1. The experiment effectively validates dimensional changes along the fiber direction, aligning with existing literature. All samples, regardless of wood type, displayed significant tangential dimensional swelling or shrinkage after 30 days.

2. The experimentation underscores the importance of producing wood pieces that adhere to clear fiber direction, diverging from the mixed grain direction commonly encountered in the wood industry. This highlights how the sectioning of wood elements can be seamlessly integrated into the design, fabrication, and assembly processes of construction components.

3. The experiment convincingly demonstrates the influence of increasing Relative Humidity (RH) on wood dimensions. This discovery holds promise for various industries, particularly in the assembly of interlocking wood-to-wood elements as a means of reducing the reliance on adhesives or screws. Consequently, it facilitates a more sustainable repurposing workflow.

4. Contrary to initial predictions, Fiber Saturation Point (FSP) did not emerge as the primary determinant of dimensional change. This underscores the complexity of the interaction among various factors in this process. Additionally, there is no discernible trend indicating that softwood or hardwood exhibits superior dimensional behavior. An illustration of this observation is the

comparison between Douglas Pine and Oak Quercus Robur, as depicted in Figure 41, which illustrates the final swelling dimensional changes after 30 days. Consequently, there is no clear correlation between softwood and hardwood in terms of greater swelling results. Instead, each material subclass exhibits unique behavior, irrespective of their FSB or shrinkage ratios. This highlights the importance of individual testing to tailor materials for future applications.

5. The finding in regards of Swelling tolerances can be integrated into the design formulation for wood-to-wood connections taking into consideration a +0.05 mm change in total tangential factors. Further research will evaluate the application of this physical changes into the manufacturing process, and more into the structural applications of this principal in the assembly of wood structures and components

Material Selection for Further Experimentation – Experiment I :

Considering the natural material capabilities observed, Oak Quercus Robur (O3) has emerged as the top performer in terms of dimensional changes when exposed to temperature conditions ranging from 23 to 27 degrees Celsius and a relative humidity of 85%. However, to comprehensively conclude this material experiment, it is essential to investigate the influence of higher temperature values on the material's performance. This additional investigation will provide a more holistic understanding of the material's behavior under varying environmental conditions.

EXPERIMENT SET UP II

In order to prove the effect of temperature in moisture induce process is necessary to create an additional testing to verify the influence of temperature in the wood cells. The understanding of this results will determine the environmental conditions where this principle can be use, not just in Colombia, but in further applications around the world.

FUNCTION OF TEMPERATURE VS. RH

Despite unknown time, according to the already mentioned mathematical formulation is possible to estimate values of **EMC (**equilibrium moisture content**)** from wood samples. This formulation does not take into consideration wood properties of specific types, and therefore, is just an approximation of the material behavior with the immediate environment. Nevertheless, this algorithmic approximation demonstrated the low dependency between heat and dimensional change.

Equilibrium Moisture Content

$$EMC = \frac{1800}{W}\left(\frac{kh}{1-kh} + \frac{(kh)}{1-kh} + \frac{(k_1kh) + (2k_1k_2k^2h^2)}{1 + (k_1kh) + (k_1k_2k^2h^2)}\right)$$

After running this equation at two different temperature values corresponding to 25°C and 28°C, the results show identical behaviors, as seen in Figure 43. Theorical validation demonstrated low influence of temperature into the physical aspects of the material change.

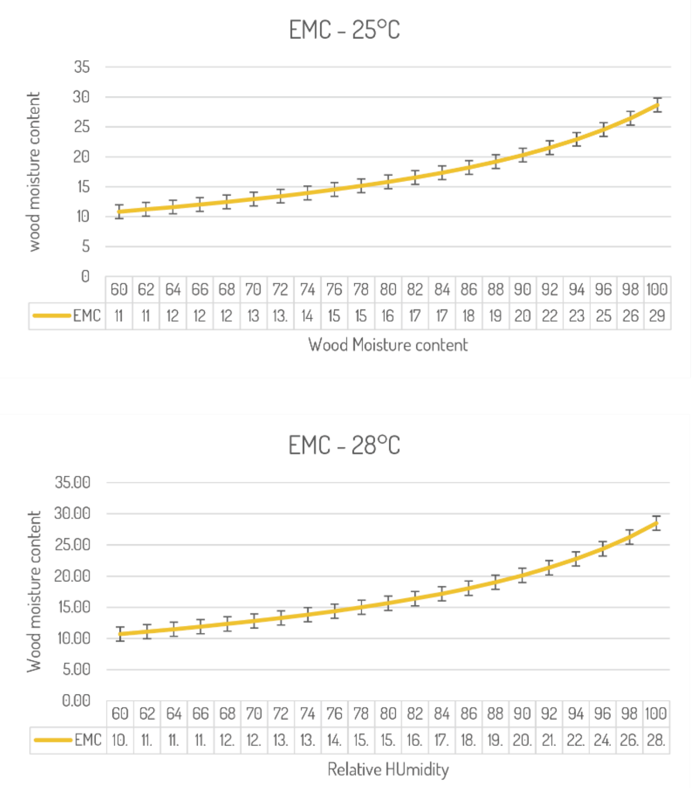


Figure 43 mathematical comparison of temperature influence on mateiral equilibrium moisture content

Despite mathematical evidence, it is necessary to scientifically prove the effect of temperature. Thus, a second experiment is formulated following the principles of the first exercise. Yet, in this assessment temperature is integrated into the method to monitor the effects of rise in temperature in the wood cells. As such, the same chemical compound, and the same type of wood will be used in this exercise. Nevertheless, the implementation of a control temperature oven is used to simulate RH and T values.

SET UP EXPERIMENT II

For this test, we will adhere to the same elements and timeframe as in previous experiments to ensure data comparability. However, due to the temperature factor, it is imperative to incorporate two pieces of equipment into the process.

UN-110 UNIVERSAL OVEN

The equipment, with dimensions measuring 400 x 400 x 600 mm, facilitates precise control over drying, heating, aging, burning, and hardening processes tailored for scientific research endeavors. The numerical control dashboard enables adjustments in humidity, heat, and process duration, as illustrated in Figure 44. For this particular test, climate conditions were set at 40% relative humidity (RH) to maintain consistent initial conditions, aligning with the previous experiment. Temperature settings were configured to 32°C, corresponding to the highest temperature recorded in the Colombian territory. As previously mentioned, the primary objective of this application is to compare the effects of heat on dimensional changes.

Figure 44 Screen control Pad - Oven at Heritage Laboratory

VACUUM DESICCATOR

This device removes air and moisture with the use of a vacuum pump. But, for other applications this equipment poses a valvule that allows complete insulation of inner conditions. As seen in Figure 45 one sample of each wood specimen was placed into the container on top of a white lead with some perforations. At the bottom of the desiccator the Potassium chloride is port to simulate same RH characteristic of 85% environmental relative humidity.

Figure 45 experiment set up for temperature comparison.

RESULTS AND DISCUSSION EXPERIMENT 2 - OVEN

As depicted in the image below, a temperature test was conducted over a 30-day period as part of the second experiment. The values and conditions remained consistent with those of Experiment 1, with the additional inclusion of a heat factor up to the limit of the Colombian territory at 32°C. After tabulating and comparing the results with those of Experiment number one, the following conclusions can be drawn:

Figure 46 Oven set up experiment

As predicted in the mathematical formulation, it appears that heat and dimensional shrinkage or swelling are not strongly correlated factors. Interestingly, the experiments in both I and II yielded nearly identical values of swelling.

From these findings, we can infer that the principle of moisture-induced processing for wood-based materials can be applied effectively in environments with low heat. However, it becomes evident that a high humidity environment is crucial for inducing material changes, particularly in the tangential fiber direction. For example, in the Netherlands, similar relative humidity values can be observed, resembling those depicted in the Colombian territory. Nevertheless, these values can drastically change across the day, making the process more unpredictable compared to constant conditions evident in Equatorial territories.

Material Selection for Further Experimentation – Experiment I :
Consequently, this research will proceed with the development of a new construction system based on Oak Quercus Robur hardwood species, which will undergo further milling and structural analysis. Nevertheless, other samples such as Douglas Pine, a common European species (D2) and Elm (E3), as observed in Figure 41, also exhibit promising potential applications for moisture-induced processes.

COMPARISON AMONG SAMPLE GROUPS.

Figure 48 provides a comprehensive comparison among three distinct sample groups, each subjected to different environmental conditions and moisture processes:

The first group serves as our control batch, meticulously stabilized at a constant 60% relative humidity. These samples were carefully positioned within the Laboratory of Heritage, undergoing a 30-day period of controlled environmental exposure. The primary purpose of this control group is to establish a benchmark reference for the experiment, enabling a clear demonstration of the moisture-induced process results.

The second group represents the samples placed within the refrigerator unit, maintained at a temperature range of 23°C, coupled with a relative humidity of 85%. A striking disparity becomes evident when comparing the first and second groups, specifically denoted as D-5 and D-1, respectively. The marked volumetric difference observed between these two sets of samples underscores the significant impact of moisture value manipulation on the wood's dimensional changes.

Lastly, the third group encompasses the oven samples, which closely align with the trends observed in the refrigerator experimentation group. However, discernible distinctions emerge when comparing the outcomes of the first and second experiments. These discrepancies are attributed to the relatively limited duration that the specimens spent within the moisture-inducing process in the oven, resulting in subtle tangential dimensional differences.

This comprehensive comparative analysis of the three sample groups sheds light on the multifaceted effects of moisture manipulation on wood specimens under varying environmental conditions, offering valuable insights into the dynamic behavior of the material and their potential dimensional change integration in the building environment.

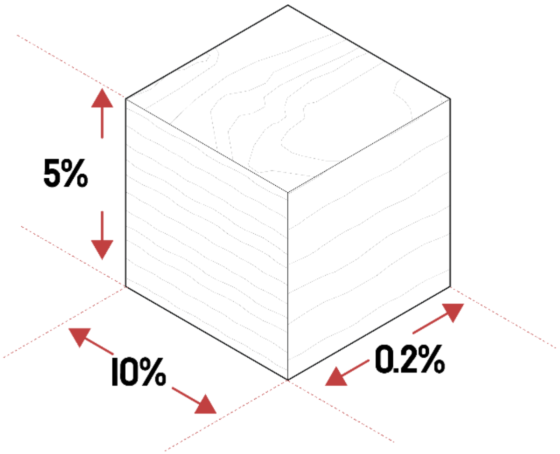
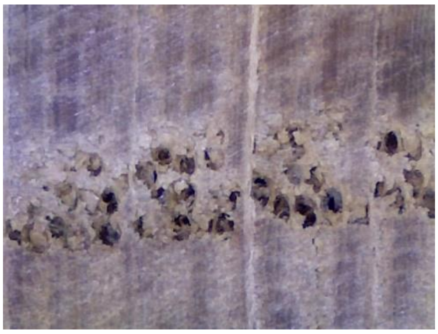


Figure 47 Fiber ratios

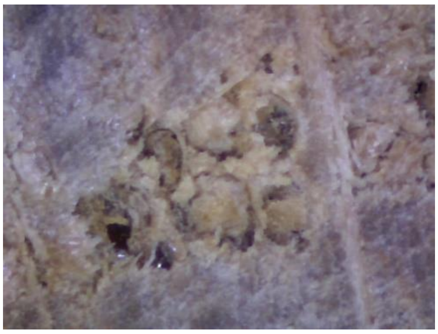
In a wider scope is possible to evaluate the benefits of this research in construction practical applications. For example, the research of experimental investigation on adhesive free laminated Oak timber beams and timber to timber joints using thermo-mechanical compressed wood dowels, conducted by El-Houjeyri et al, demonstrated the scientific potential into this material principle in component base construction products. This research presents the benefits of adhesive free wood products (AFEWP's) As an alternative of EWP's which poses a high degree of petrochemicals (El-Houjeyri et al., 2019).

EXPERIMENT SET UP – RH 60 AT 23 DEGREES.

Oak Quercus Robur O-5 Tangential and Radial structure

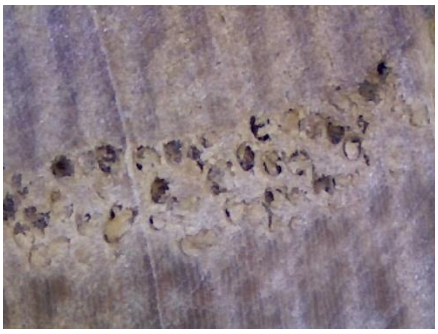


Oak O-5 Tangential and Radial structure x 200

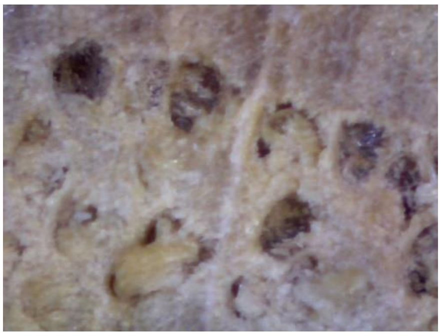


EXPERIMENT SET UP – RH 85 AT 23 DEGREES.

Oak O-5 Tangential and Radial structure



Oak O-5 Tangential and Radial structure x 200



In the following images a scope magnificent device was used to compare the fiber stress 200 times bigger than the original scale. In this 4 examples you can see the vessels, use to transport water across the trunk. Unfortunately, is not evident to see the fiber stress, as these changes happened in a bigger scale.

MOISTURE CONTENT EXPERIMENT COMPARISON

CONTROL SAMPLE

Relative Humidity 40 % - 23° C

CONTROL SAMPLE - FRIDGE

Relative Humidity 85 % - 23° C

CONTROL SAMPLE-OVEN

Relative Humidity 85 % - 32° C

Figure 48 Final dimensional comparison among Experiment set up and control samples.

WOOD

MATERIAL PREPARATION

THE WOOD INDUSTRY IN NL

MASTER SOURCE

Throughout this research project, various wood material experiments were conducted to assess the effectiveness of the moisture-induced process for assembly joinery connections. This research was made possible with the support of TREE_TimberREengineered, LB Workshop, and the collaboration of material sourcing and preparation from Lorin Brasser, Pierre Jannen, and Gilbert Kosmap.

SUPPORT TEAM

Lorin Brasser

Material source and preparation support

Gilbert Koskamp

Material source sponsor

TREE_TimberREengineered –

Material Sponsor

8. THE WOOD INDUSTRY IN NL

PREPARING THE WOOD BEAMS FOR CNC MANUFACTURING

Results from the material moisture induced process have revealed the advantages of Oak Quercus Robur timber elements. This experimentation dictates the types of optimal values for applications in the principles of wood interlocking joint systems using the moisture of the environment as assembly method. Thus, from the initial 5 woods species is possible to take design decisions based on the material performance.

Second production.

After the identification of optimal material, longer wood pieces will be taken to the climate chamber up to production values (67mm x 67mm x 400mm). The fiber direction conditions necessary for this research project are rather difficult to find. The support Team that provides, arranges, and prepared the material for every experimental stage allowed the continuation of this research.

Each piece was processed using the planner machine of the TU Delft University, as well as LB Workshop with the support of Lorin Brasser. guarantee constant material optimal characteristics for CNC manufacturing was essential.

Material of CNC Manufacturing

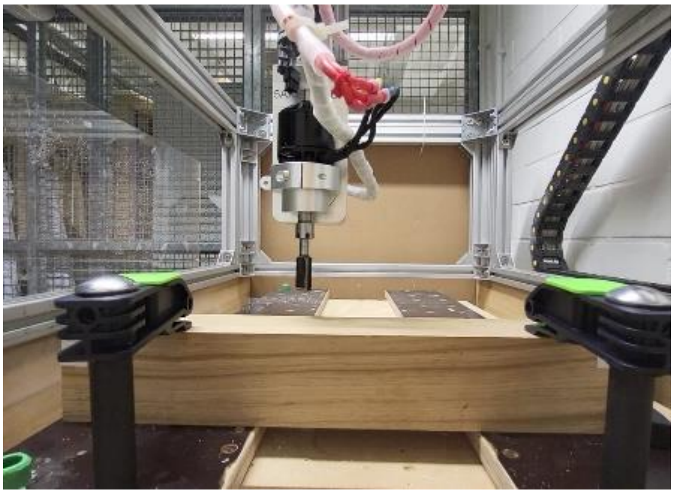


Figure 49 Manufacturing process TH Koln University

All material needs to be prepared prior to the CNC manufacturing process. Once all dimensions are square guarantee samples of 63 mm x 63mm x 400mm were used to fabricate the joinery elements Using the CNC machine format 800mm by 1200 mm. Again, the moisture content of these pieces shall be preserved to the values taken from the climate chamber, making the time a critical aspect of the process.

Figure 50 Prototype samples Cross-Half Lap Oak

Finally, the manufactured pieces will return to the Heritage lab for assembly and exposure to a second Climate Chamber stabilization process following the data from table 1 for **assembly 1,2, or 3** depending on the results of stage 1. T 28 – RH 75%, T 26 – RH 80%, T 28 RH 90%

Important: check the maximum capacity of climate chamber for assembly process.

Observation: make 2 of the same samples for structural testing

THE WOOD PROCESS

THE WOOD SECTION LOGIC AND DRYING PROCESS

SOFTWOOD COMMON DIMENTIONAL SECTIONS IN MM

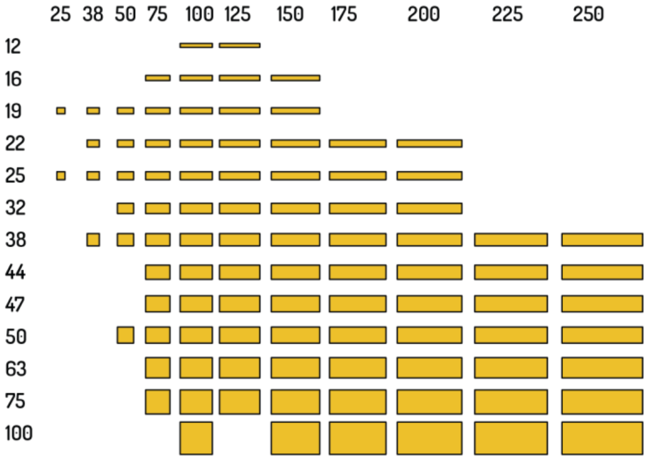


Figure 51 Softwood sectioning Diagram

This diagram shows the section logic of wood elements in the industry. The smaller the cross-section, the shorter it needs the piece to dry. On the contrary, the bigger the cross-section, the longer this element requites to fulfill the moisture stabilization process with the environment. As a rule of thumb, 2 centimeters of wood per year dries at air conditions in the Netherlands.

Reflection for design

A reflection necessary to take into consideration is time / energy that require bigger cross sections prior to the use in the building industry. And therefore, how to create a building or product that reduces this time material cycle. In the picture bellow is possible to see the strategy use in the traditional mill industry, which sections the trunk into vertical slots of approximately 50 mm, accelerating the drying process.

Figure 52 Trunk section - traditional sawn factory – The Netherlands

9. TRADITIONAL WOOD CONSTRUCTION

Traditional wood construction peaked in colonial times until the middle of the last century (Guillaumet et al., 2022). This building material was influenced primarily by Indigenous communities in the pre-colonization period, with living examples such as the Bohio. During the Spanish colonization in the XIX century, a more technical advance building system was developed to face the seismic conditions. Thus, the traditional woodworking techniques and adobe constructions produced a new structure optimization. Hence, with the development of the Bareque technics (wood and soil structures) in the Caldas region, the building evolved to apply carpentry solutions in its constructions (Eugenia & Gama, 2007). Consequently, the implementation of hardwood and bamboo in essential structural points created a characteristic architectural language of the region Figure 53.

These techniques spread across the territory, presenting technical variations due to the material availability of the location. The structural technique of the region shows several solutions. The horizontal elements, in general, are supported on beams transmitting loads to the vertical pillars, which simultaneously transfer loads to the foundation (Eugenia & Gama, 2007). Then, reinforced concrete and masonry became more relevant, relegating the wood industry to secondary sub-structures, and material support for the concrete industry (Guillaumet et al., 2022).

Figure 53 Typical Colonial House - Caldas Region – Colombia source:

Similarly, to the Post and Beam systems, heritage from European constructions and Spanish architecture can be found in Colombia. Wood connections such as Dovetail, mortise and tenon and splice details are used to solve structural connections(Armar, 1899). Despite having specific architectural results in the building form, these joints can be found in multiple heritage constructions worldwide.

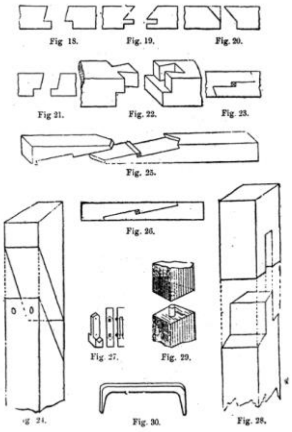


Figure 54. Typical joinery solutions Spanish architecture.

Boundary Conditions:

1. Prevalence of architectural form
2. Double inclination roof
3. Balcony
4. One floor construction

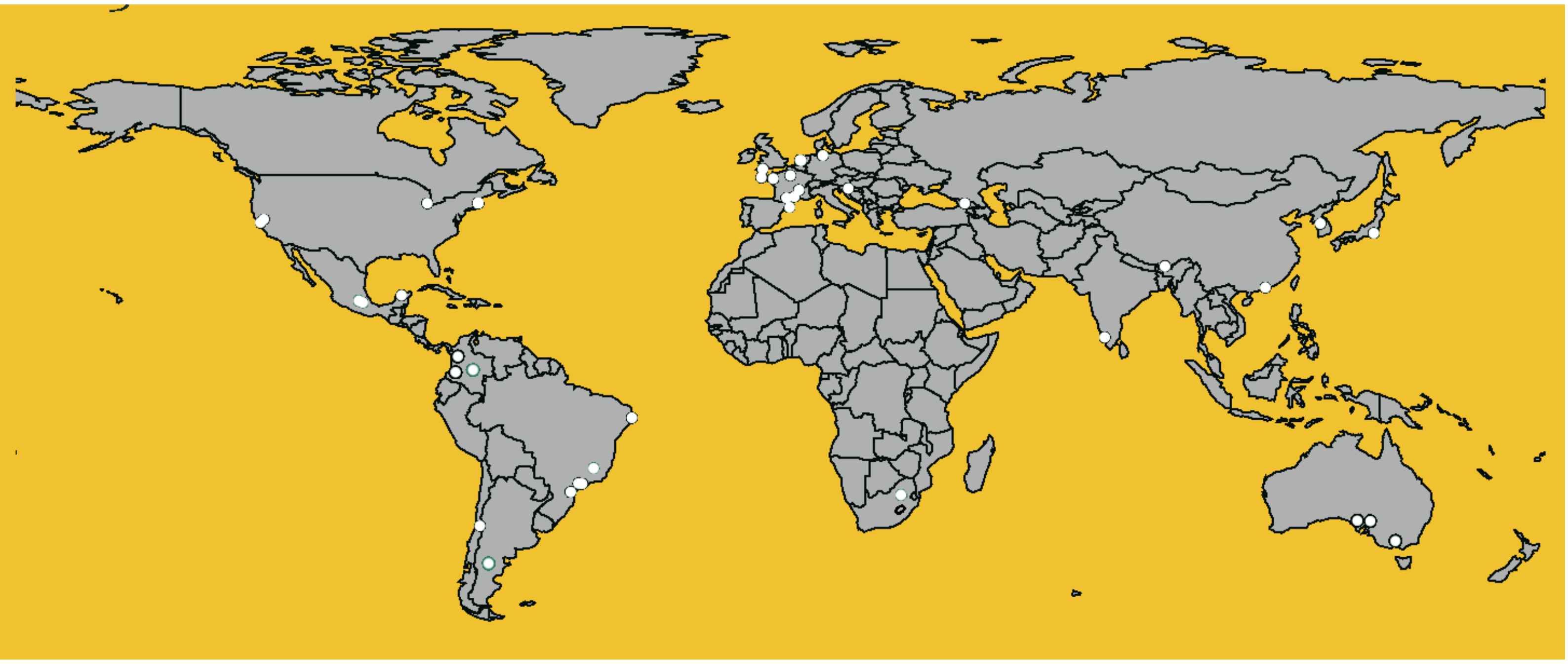


Figure 55 Fab Lab network location worldwide source: www.fabcity.com

THE GOAL

The country is characterized by a long tradition of woodworking solutions in the rural housing of the territory, despite the technological advance of such a technique. More industrialized systems have replaced these construction methods. Partially, long-forgotten wood hand craftsmanship cannot be implemented in today's practice due to the highly specialized wood artisanal cost. However, digital manufacturing can reintegrate a long construction tradition into today's building. Technological progress has opened the possibilities to new machinery, such as CNC milling, or robotic arms, enabling high-accuracy cuts for assembly at a reduced cost. And therefore, shorter construction and assembly time with a high aesthetic appearance (Rodríguez-grau et al., 2022).

Thus, by the reinterpretation of the ancestral wood solutions, this research could develop a system of joinery details, which offers the fast assembly of timber elements. By using digital fabrication processes, traditional carpentry can be reclaimed for the construction of rural affordable housing in the national territory.

10. DIGITAL MANUFACTURING

TRADITION AND TECHNOLOGY

Digital manufacturing has the power to create constant, quality, and precision to the building process. Such a technologies make it possible to reintroduce long-forgotten, expensive to produce carpentry techniques, such as dovetail connections, which allow production of any desired shape and prefabrication degree (Weinand, 2022). The use of prefabrication allows rapid construction and assembly process creating a cost effective project development (Albus, 2018). the implementation of traditional joinery connection cold further enhances the assembly of modern constructions. A good example of this cooperation between tradition and technology can be seen in the research project of Bohme, Zapata, and Marino (2017). This study aims to bring back the joinery solutions of Valparaiso's architectural heritage. In this way, the technological innovations a 6-axes robotic arm could replicate complex timber connections at a competitive cost (Bohme et al., 2017). These technologies enable flexible and versatile movements that are similar to those of a human arm (Takabayashi et al., 2018). The application of such a solutions could bring back novel wood to wood connection previously replaced by metal fastener (Bohme et al., 2017). The result of this convergence brings the traditional hardwood timber framing and the interlocking of wooden wedges back together.

Figure 56 - knot compose of T-bridle jointed post and top plate with notched tie beam, and oblique mortise. Source: (Bohme et al., 2017)

Other examples of this experimentation have taken place in the reinterpretation of Japanese architecture. Traditional Japanese wooden buildings are extremely complicated to construct, these buildings also have historical and cultural value, and registration of culturally important properties continues to increase each year (Takabayashi et al., 2018). The author states, the number of skilled workers capable of maintaining and repairing these buildings is decreasing every year. This project explore robotic processing aiming to maintain and process parts of Japanese traditional wooden buildings, which are too complex in the mainstream building process. Takabayashi argues, most researchers are constrained by the tools, and therefore, traditional details end up changing to accommodate the production limits (Takabayashi et al., 2018)

Figure 57- process part of japanese structural node source: (Takabayashi et al., 2018)

Contrary to the preservation of these traditions, other studies aim to reinterpret the joinery solutions to facilitate the fabrication according to the technology constraint. For example, the research "paradoxical territories of traditional and digital craft in Japanese joinery" shows the capabilities of a 3–axes CNC milling machine to produce Japanese connections. As Ali(2018) mentions, the movement restriction of the CNC in their three planes forces the detailing to adjust to the requirements and working conditions of the system; nevertheless, the results reveal how the analysis of the technology and the tradition converge into new developments (Ali, 2018).

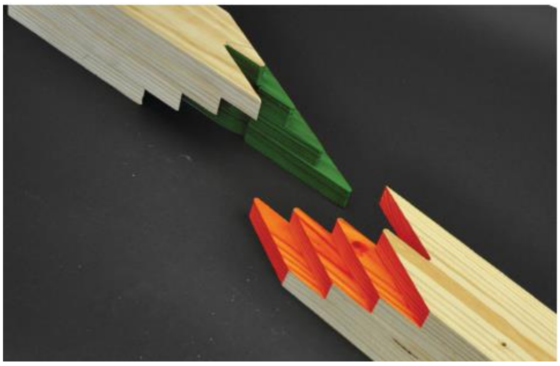


Figure 58 - MiyaJimi Splice CNC source: (Ale,2018)

TECHNOLOGY VARIETY

Currently, a broader range of machinery processes can create products in the building industry. Technologies such as CNC 3-axes, 5-axes, robotic milling, or even more traditional Industrialized equipment's like the Hundegger timber beam processor, are some of the existing alternatives to produce Wood to Wood connections. Each technology can be compared in terms of initial cost, flexibility, availability in the specific market, milling time, equipment scale, energy performance, precision, and working area.

Taking in consideration the contextualization of the project, the research will focus on manufacturing methods widely available in Colombia, neglecting technologies that are unavailable in the country.

Hundegger for instance (*Hundegger USA*, 2023), is a high precision automated machine use in the timber industry for structural joinery fabrication such as mortise and tenon. Nevertheless, the initial price, and the equipment dimensions overpass the research constrains.

CNC milling or robotic manufacturing lead by computational design will play an essential role in the design, fabrication, and planning stages to mark the difference between one-time design or a serial production (Weinand, 2022). Each method possesses specifications that might drastically affect the product; and therefore, the technology selection will impact the principle of (DfMA) or design for manufacture and assembly. Breaz (2017) argues, such considerations define technology implementation by geometric constraints, material properties like wall thickness, overall dimensions, weight, shape, complexity, surface finish, production volume, time-to-market, tolerances, and precision requirements (Breaz et al., 2017).

II. THE LOCAL PRODUCTION

Academia and governments have discussed integrating local production, material, and knowledge to diminish poverty and overconsumption. One example of this philosophy is the **Fab City Initiative** started by (IAAC), MIT University, and the major of Barcelona city in 2001. This solution aims to develop locally productive and globally connected self-sufficient cities in at least 50% of its industry by 2054, creating a network of fabrication centers using digital technologies and data to impact communities (Ladera, 2011).

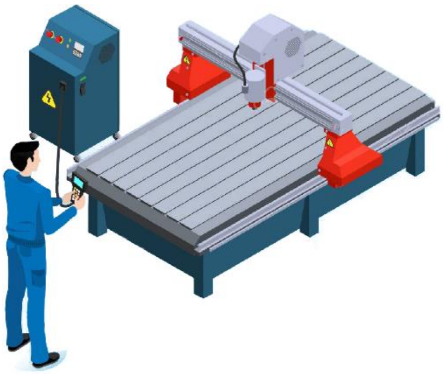
THE PANORAMA IN COLOMBIA

In Colombia, there are 12 Fabrication centres associated with this initiative spread across the territory (*Fab City*, n.d.). Most of these laboratories aim to create a social construction through the capacitation of their communities in digital technologies, traditional fabrication, and digital manufacturing, such as CNC milling and 3D printing (*Fab City*, n.d.). Nevertheless, a very limited amount of manufacturing laboratories with far more sophisticated equipment can be found in Colombia.

For example, Los Andes University, located in Bogota City, counts with CNC milling machinery and one 6-axe robotic arm destined for educational purposes available exclusively to their students (*Los Andes University*, 2023). Previous examples have shown the benefits, in flexibility, design freedom, and complexity, as seen in *section 6* of this equipment.

CNC MILLING MACHINES

Nevertheless, the CNC Milling technologies have been wildly spread in the country likewise in the industry and the Academia. This research project aims to implement highly available technologies in the territory for the benefit of a social reconstruction. And therefore, the exploration of these manufacturing methods with new structural applications.



12. PRECEDENTS OF CNC CONNECTIONS

THE CHALLENGE OF USING SAWN TIMBER

Material is an essential aspect of the research, not just due to the environmental repercussions that this decision may impact in the long-term spectrum (LCA). Furthermore, the specifications and quality of these products will affect the manufacturing execution. Traditionally CNC milling machines are used to process 2-Dimentional plates, well known as EWP products. The manufacture of this engineered wood shows superior stable dimensions and uniform structural material properties (Gong, 2021) due to the application of adhesives with the heat and pressure on the elements.

In Colombia, the absence of affordable EWP products seen in *section 5*, forces the research to investigate primary less specialist supplies. Opening the opportunity to explore the implementation of low-tech materials in the digital fabrication of structures. Despite the absence of enough research, some studies are showing the potential of sawn-timber building connection with CNC milling setups.

One examples is the Mono-Material wood wall research, which reveals the potential of CNC manufacturing interlocking assembly solutions in sawn timber elements (Bucklin et al., 2021). Figure 59. Thus, combining the structural capabilities of low-process dry wood elements with the energy performance throughout high milling detailing. This research demonstrates the prospective of CNC 3 -axes machines in the development of new structural implementations for novel connections.

Nevertheless, despite the fabrication of this solutions, the lack of standardized dimensions of wood elements is an issue the researcher stressed, these additional tolerances affected the system drastically in the assembly process and the compatibility of pieces (Bucklin et al., 2021). Showing necessary further research development to bring these applications into practice, with considerations such as wood stabilization in high moisture environments, milling accuracy, interlocking precision, and material performance in tropical contexts.

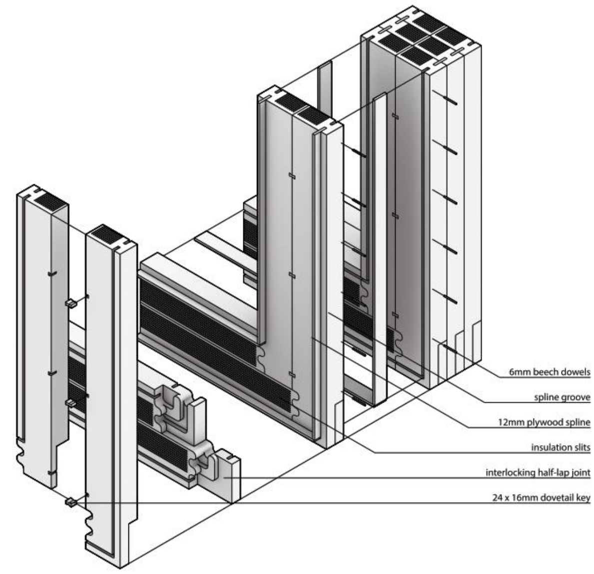


Figure 59 mono-material wall with interlocking joinery (Bucklin et al., 2021)

PARAMETERS OF THE RESEARCH

13. Wood types – hardness relation with milling performance.
14. Wood shrinkage due to moisture stabilization process.
15. Milling accuracy of wood connections.
16. Interlocking precision – tolerances in connection points.
17. Structural performance material / joint.

Therefore, the construction of the main question emerges from a design problem. Currently a large range of applications seen in the literature study explores the fabrication of traditional joinery solutions using Robotic flexible manufactures and EWP products; a technology that is accessible to a restricted number of people. Yet, CNC milling, a large available and affordable technology seems to have a larger potential in the construction industry for engineering of novel connections using sawn timber, as seen in the previous example.

CNC

THE UNDERSTANDING OF 3-AXIS TIMBER MANUFACTURING

EXPLORATION OF TRADITIONAL WOOD JOINERY IN THE CNC MANUFACTURING PROCESS

THE GOAL

Throughout the various chapters, the literature review has provided numerous examples of fabrication methods in conjunction with traditional timber materials. Research papers, articles, and scientific publications have highlighted the advantages of innovating wood-to-wood construction methods to promote sustainability. Additionally, these sources have shed light on the material's limitations and constraints.

In this chapter, we will delve into the progression of the research. We will begin by exploring the capabilities of CNC technology, followed by an analysis of appropriate joinery connections based on manufacturing limitations. We will also consider the structural requirements for optimal performance. Finally, we will conclude by demonstrating how this research can be applied to a construction system that seeks innovation through a comprehensive understanding of the material, local production considerations, environmental conditions, and assembly methods.

UNDERSTANDING CNC TECHNOLOGY

Although I had prior experience with CNC manufacturing processes, my familiarity was primarily limited to plate-based production. Thus, delving into digitally manufacturing sawn timber elements required a comprehensive understanding of the machinery's capabilities, general conditions, and limitations. These considerations encompassed various aspects such as material constraints, maximum size, positioning, reference points, and other fundamental details essential for a computational manufacturing process.

It's important to note that the available technology significantly influences the conditions of the manufacturing methods. However, each CNC machine possesses distinct configurations, working areas, and degrees of milling axes. Throughout the course of this research project, several CNC machines were employed. It commenced with the use of the machine available within the Faculty of Architecture and Building Sciences at TU Delft University. As the thesis progressed, other equipment was utilized at times due to logistical constraints or material-specific requirements. Nevertheless, each machine played a pivotal role in advancing this study to its subsequent stages.

First approximation to equipment

To gain insights into large-scale prefabricated housing manufacturing, which heavily relies on CNC machinery, I visited The New Makers company. Their CNC machine, with a working space of 1220 x 3000 mm and a 4-Axis setup, provided valuable insights. While such technology may not be accessible in Colombia, this visit served as an essential starting point to understand the potentialities of fabrication and, conversely, to comprehend the inherent constraints of a rudimentary manufacturing setup.

Figure 60 CNC Machine for big formats 1220 mm x 3000mm The New Makers

Tooling capabilities

The tooling available at the company provides a vast array of manufacturing methods. This includes the incorporation of cuts for assembling small components into the plates, employing special cutting strategies like 45°,60°, or 90° angles, creating pockets, and implementing other specific building details tailored for precise assembly requirements. Consequently, the extensive capabilities of this advanced manufacturing method significantly enhance the overall construction workflow.

Figure 61 Mills use in TNM production process.

Milling Bits and Holders

In Fig. 65. Is possible to see the variety and scale of the wide range of milling bits at this company. The conditioning of mill size is determined by the spindle power, as well as the scale of the tool holder collector chuck, in general a mill could reach up to 40mm diameter for a high milling performance, yet, the most common tool in their prefabrication process was a router bit of 16mm used for contour cutting.

TU Delft cnc Machine

Contrary to more common high-end manufacturing setups, the 3-Axis CNC machine available at TU Delft University is orientated towards educational purposes. As such, it presents smaller working areas, fewer number of movement axes, and restriction of working range. The first aspect to take into consideration is the freedom of movement. As indicated in the diagram in Figure 62, a 3-Axis CNC machine is conditioned by three essential movements, the X, Y, Z axis.

Z - AXIS

The diagram illustrates the logic of the Z-axis, which marks the first machinery movement, involving vertical motion. It offers a free working area of **100 mm** from the reference point of the milling endpoint to the working bed. This constraint is standard in most CNC setups and presents the initial manufacturing restriction for this research.

y - AXIS

CNC machinery is traditionally used for plate-based materials or engineered wood products (EWPs), leading to a standardized working area dimension of 1220 by 2440 mm. This measurement is determined by the extruded frame holding the spindle and is usually the shorter side of the equipment. The initial equipment used at TU Delft University had an 800 mm limit. For this research, this dimension was limited to 1200 mm.

x – AXIS

This axis represents the final movement of the machine and refers to the longer side of the panels. The movement is controlled by two guiding rails located on each side of the equipment and, in high-end manufacturing machinery, could reach up to 3000 mm.

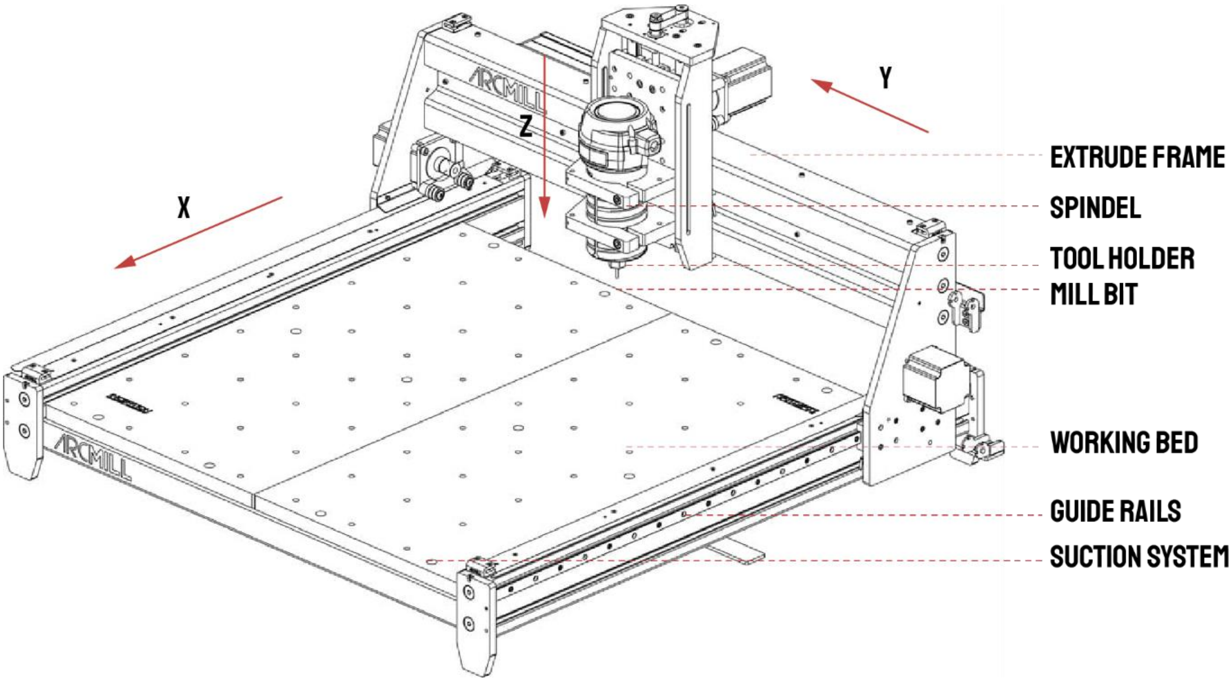


Figure 62 3 - Axis CNC machine and parts

Restrictions on movement

As previously seen, the available equipment features unconventional working dimensions for the X and Y axes. Consequently, specific measurements will not serve as design guidelines due to these conditions. However, as outlined in the Z-axis restrictions, the **100mm** milling limit will be strictly enforced for any wood element produced in this project. This implies that no beam or element can exceed this limitation along the Z-axis. Conversely, the X and Y axes offer more flexibility in manufacturing conditions, with a maximum limit of 3000mm considered for the production of construction elements.

Milling Anchorage

An essential aspect of the manufacturing process concerns the material placement on the working bed. As previously mentioned, the CNC is traditionally used to further re-process EWP plates into precise parts. And due to the surface area that this element holds, a vacuum suction system is used to temporarily attach the material to the bed, other less advanced systems uses clamping methods to achieve the same purpose. The implications of this system in the production process guarantee the precision of position, as well as stability during the routing process. Vibrations may alter the quality of the parts, as well as creating dis-alignments in the final result of tolerances. For this project, the tolerances are a great constraint, as traditional joinery system requited a tight-fitting connection in order to guarantee structural performance, as explained in literature research. Consequently, for sawn timber this topic of material position became a focal limitation of the production process, and therefore, a problem to tackle from.

As timber elements in general have considerably lower surface area over the working bed in comparison to panels, the vacuum suction system is less effective in the manufacturing process, this brings precision issues in the milling. During the prototyping stage, most of these considerations will be addressed.

MILLS AND HOLDERS TU DELFT

After comprehending the general restrictions of movement and placement in a CNC machine, it's necessary to investigate deeper into the tooling and attachments commonly used in the industry. As seen in Figure 61, in a high-end manufacturing environment, milling categorizations and functionalities can vary based on specific product requirements, such as additional components integrated into the assembly. Nevertheless, characteristics like height and diameter are geared towards maximizing performance. As mentioned in the TNM scenarios, these mill bits work with a 16mm diameter for standard cuts due to the size of the holder collector chuck. However, these high-end manufacturing options are less common in rudimentary environments, such as the equipment available at the faculty. Therefore, this project will focus on the most traditional milling and routing mills.

Restrictions on milling range

A common characteristic observed in the TU Delft equipment, as well as other CNC machinery along this research was the short range of the mill length. As seen in Figure 63, a maximum distance of **60 mm** can be used in the fabrication of any routing operation. Also, contrary to the collector holders used to anchor the bits into the machine at high manufacturing companies, the working equipment possess a limited mill bit diameter of **10 mm**. These two conditions represent the second restriction of the research.

Figure 63 mill and holder collector dimensions

Figure 64. TU Delft CNC Machine - CAM LAB faculty of architecture

MILLING OPERATIONS

This process is closely related to the type of software implemented in the numerical control process. Some fabrication laboratories use 3D model information to produce parts such as solid works. Following already existing software integration in the CAM-LAB of the faculty of architecture, the reading process of design parts is based on vector lines that are translated into milling operation of numerical layer control.

Software – Desk Proto

The selected software, Desk proto is a 3D CAM program (**C**omputer **A**ided **M**anufacturing) software. This platform allows the operator to import 3D as well as 2D vector files such as DXF, EPS, SVG among others. Based on CAD data documents the software calculates CNC toolpaths and then write NC program files for any CNC milling machine, 3-axis, 4-axis, or 5-axis movement.

The main reason for the selection of this program is due to the already set workflow use in the CAM Lab office from the faculty of architecture and building environment of the TU Delft University. Thus, using a free version of the expert mode of the software it is possible to set all necessary conditions for the manufacturing process.

Observations of the platform:

Figure 65 Software logo taken from the platform

This software is user-friendly and straightforward to operate. The plug-in provides a comprehensive breakdown menu that guides the user through the selection of various parameters, including layer selection, spindle feedrate speed, Z-axis movement settings, milling operation, vector line operation, cutting direction, and layer height per pass. This checklist-style approach ensures the accurate configuration of production settings.

Vector line operation

As highlighted in the software section, the control of milling files can be facilitated through the utilization of two distinct file types: a 3D model and a 2D vector drawing. For the precise manufacturing of joinery connections, the preference leans towards employing the latter, which is a 2D vector drawing. Several compelling reasons justify this choice.

First and foremost, the 2D vector drawing format aligns seamlessly with the stringent accuracy prerequisites essential for crafting joinery details intended for CNC machining. This file type offers the advantage of easy adjustment to a 0.0 tolerance, simplifying the identification and rectification of any discrepancies or errors that may arise during the design phase. Furthermore, in instances where specific layer heights or other specifications are necessitated, these details can be readily fine-tuned within the software environment, affording greater flexibility and precision.

In contrast, a 3D model presents certain inherent limitations. It represents a static volume, rendering it susceptible to potential issues related to misalignments and accuracy. Detecting alignment problems within a 3D model can prove challenging, and effecting alterations or adjustments often necessitates the arduous process of regenerating the entire document from scratch. These considerations underscore the distinct advantages offered by the 2D vector drawing approach, particularly when striving for precision and ease of modification in joinery connection design for CNC machining.

In Figure 66, the layering logic is visually represented from top to bottom. This process involves the creation of a 2D vector line that precisely defines the location of the detail to be machined. Within the CNC software, each layer is assigned a specific height, indicating the level at which the machining process should cease. It's important to note that in this context, the term "layer 0.0" serves as a reference point denoting the bottommost layer or the working bed. This reference point establishes the baseline from which the Z-Axis height of each subsequent layer is measured.

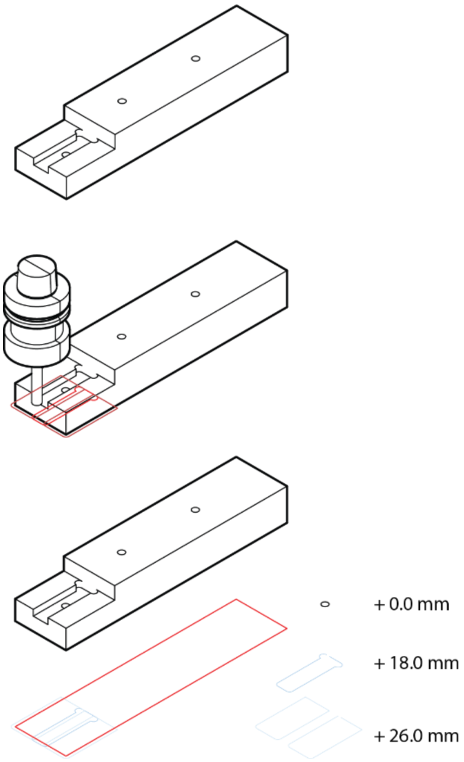


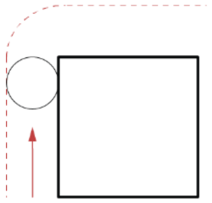
Figure 66 vector line operation

Milling toolpath

The milling toolpath relates to the vector line specified along the X and Y axes of the working bed. This line serves as a reference for the routing tool or mill radius and designates the point of reference where the vector line should be followed to execute each operation. In most equipment, three options are available, each depending upon the specific milling operation desired:

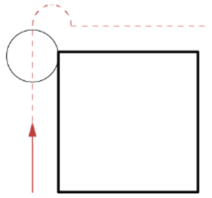
Outer offset

The toolpath follows the outer contour of the volume, creating an offset based on the diameter of the tool. One advantage of this method is the potential for orthogonal corners, as the mill bit has additional space for free movement. This methodology is typically employed in the fabrication of profiling operations.



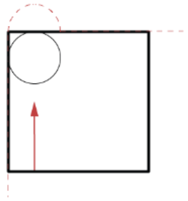
Center of line

As the title suggests, the mill follows the vector line as a central axis. This operation can be used for a variety of purposes but is most effective in engraving or profiling processes.



Inner line

This toolpath is employed for creating inner details, typically within a limited area. An important consideration when milling details is the 90-degree angle, which requires an additional step to ensure flush corners for the assembly process due to bit geometry.

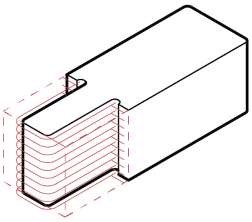


Milling operations

To comprehend the milling operation and its workflow, the TOI-Pedia website from TU Delft University offers a comprehensive manual that guides the production of files categorized based on the milling process. As outlined by this platform, we can classify milling operations into the following groups:

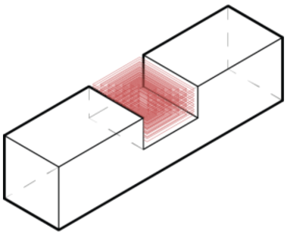
Profiling

This operation focuses on milling contours of any given piece. For this process a vector line is marked to mill along the limit specified.



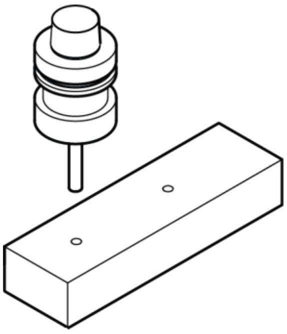
Pocketing

In this operation, the detail can be milled to a final height. And the goal is to subtract material up to the limit indicated by the area specified by the drawing.



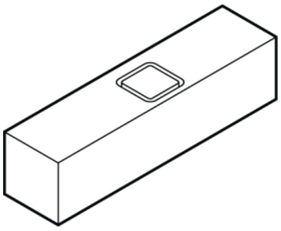
Drilling

This operation is indicated by a point in the drawing, designate drill holes which can be graduated up to any given height.



Engraving

Contrary to pocketing is an operation that subtracts material from an indicated line in the interior of a volume.



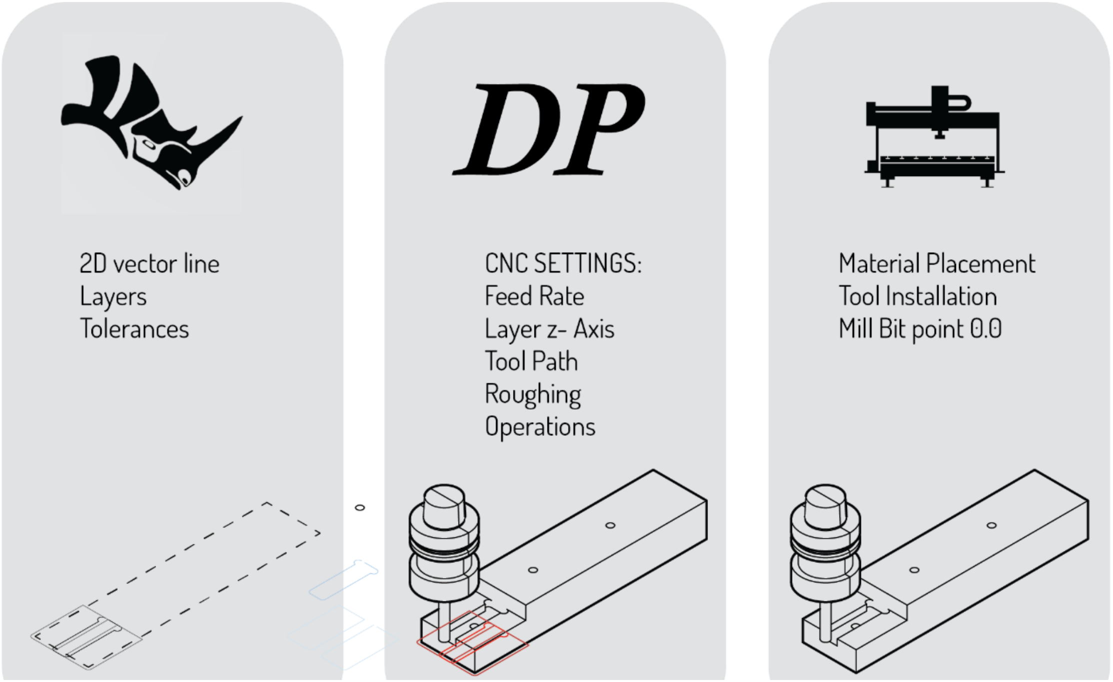


Figure 67 CNC computational Workflow

Figure 68. First CNC manufacture wood prototype

FIRST PROTOTYPE

In this first approximation of the production process, the intension of the exercise aims to explore the possibilities of Machinery, workflow, milling process, alignment, speed rate, material position, accuracy, and in general terms limitations, advantages, and disadvantages of using this equipment for sawn timber products.

MATERIAL POLICY AT TU DELFT UNIVERSITY

As a general rule, all wood fabrication processes within the Faculty of Architecture impose limitations on the use of hardwood specimens. This restriction aims to prevent significant deterioration on milling equipment, machinery, and tools.

RESEARCH LIMITATIONS

Due to this constraint, it is not feasible to conduct an extensive range of tests to assess material performance in the routing process. Consequently, this aspect of the research has been omitted, as it is not possible to conduct a comparative analysis of the effectiveness of softwood versus hardwood production.

THE GOAL

However, it is essential to explore the practical implementation of CNC technologies in the manufacturing process of sawn timber elements. Production assessments, encompassing factors such as tooling, material setup, layer heights, and other production-related conditions, will help identify the most suitable joinery connection from a manufacturing perspective. The outcome of these assessments will lead to the second major conclusion, where we will select the most efficient wood-to-wood joinery connection using a 3-Axis CNC machine.

Ultimately, the final conclusion of this exercise will determine, based on manufacturing performance, the most optimal details, joinery connections, material setups, and manufacturing strategies for the development of this project. Thus, the first approximation of the manufacturing process is done.

THE FIRST TEST

Using a radiata Pine wood beam of 43 x 69 x 300 mm we aim to manufacture the fabrication of simple mirror column elements with an internal pin connection. In this process several milling operations are used to understand the complexity and limitations of milling operations. Thus, a pocketing, as well as drilling process is used to check the maximum capabilities of accuracy in this production process.

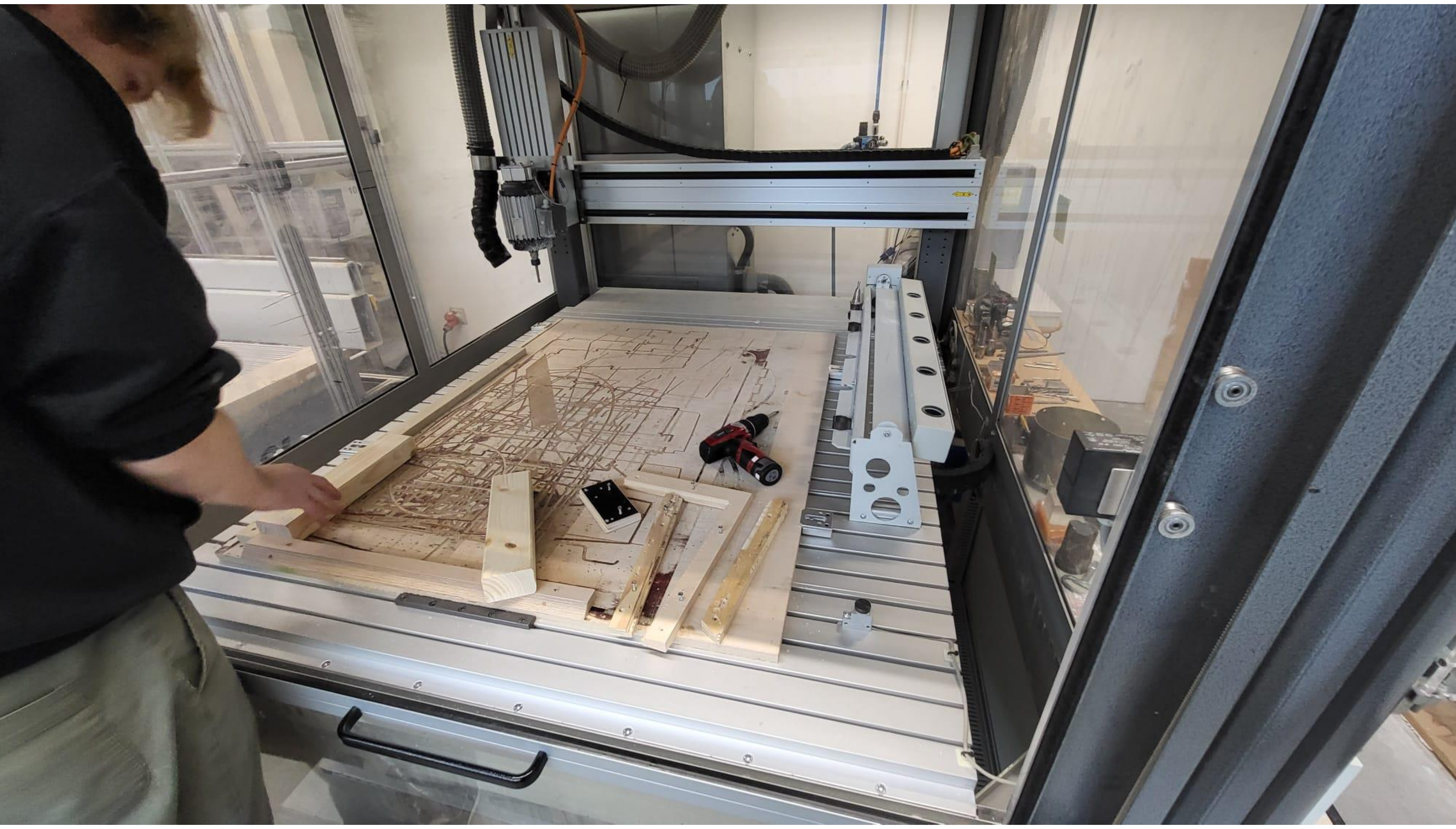


Figure 69 Working bed and anchorage system.

MATERIAL PLACEMENT

The primary significant challenge, as mentioned earlier, involves the evaluation of the timber beam anchorage system on the CNC working table. In the case of the TU Delft machine, a fastening method is used to position elements onto the bed. In principle, the larger the surface area, the more stability the machine offers. However, as illustrated in Figure 70, the wood beam represents a significantly small portion of the overall working area. Given this imbalance in volume versus wood ratio, the existing suction system requires additional support points, and a frame must be constructed to ensure the stability of the piece during the milling process.

Figure 70 Preparation of the frame for piece fitting

This solution demands meticulous attention to detail, particularly because the 0 point or starting point is situated in this corner of the bed. Even a minor deviation in the beam's placement can lead to a significant misalignment in the overall structural element. As observed, the TU Delft bed incorporates a plywood plate on the surface with a 45-degree angle, which simplifies this procedure to some extent. However, a robust anchorage system remains essential to minimize errors.

MILLING BIT STARTING POINT

Figure 71 Starting point.

The starting point is the crucial setting of the manufacturing process. As beams are intended to be used in its total body to reduce waste and maximize production effectiveness, there is not space for mistakes. A misplace of the beam or starting point results in obsolete elements. In this case Figure 72, as it was the first test of all prototyping process, we expected issues.

Figure 72 First CNC Sample of the research - starting point mistake.

Once the starting point is calibrated into the process, this configuration can be saved for future productions. Thus, allowing for a more accurate timber detail manufacturing production.

PRE-PROCESS WOOD MACHINING

As you can observe in some of the pictures, this wood specimen has already undergone a machining process, resulting in all sides being properly planed, chamfered, and squared. However, in later examples featuring other sawn timber materials, you may notice the consequences of an uneven or improperly squared cross-section. These issues can lead to alignment errors and accuracy problems, underscoring the importance of preparing timber elements meticulously before proceeding with any CNC machining operations.

MAXIMUM MILLING HIGH

The maximum milling height from the working bed up to the milling bit does not exceed 100 mm, as explained in the TU machine setup. Consequently, it is not possible to work with structural elements with larger cross-sections. In the picture, you can observe a foam prototype mimicking the maximum height of 100 mm. This prototype was used to verify the spindle's free movement above the section, with a range of 5 mm for movement in the X and Y directions.

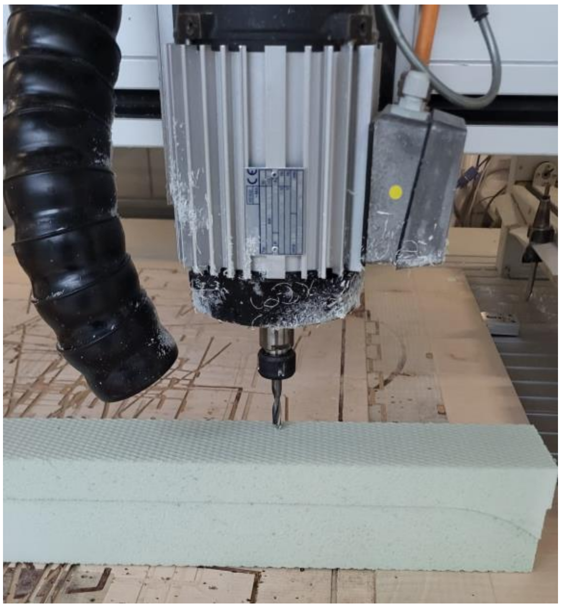


Figure 73 limit working hight 100 mm

ROUTING SETTINGS

Mill bit: 10 mm diameter flat tip

Speed rate: 600 mm/min

Step down layer per pass: 2.0 mm

The milling bit used is the largest available in the workshop. However, the routing settings are not optimized for manufacturing performance but are instead focused on low maintenance to reduce wear and minimize production noise, following the maintenance policy. This approach significantly reduces manufacturing performance and obscures the true picture of production effectiveness.

THE RESULT

Figure 74 quality Test- First Prototype

In conclusion, this initial prototype has showcased the precision and accuracy achievable with the equipment, thereby highlighting the capabilities of this technology when applied to sawn timber materials.

RECAP OF MILLING CONDITIONS

Spatial limitations

1. Z-Axis Working height limit 100 mm
2. Y-Axis Dimensional limit 1200 mm
3. X-Axis dimensional limit 3000 mm

Tooling limitation

4. Maximum Mill bit Diameter 10 mm
5. Maximum Mill bit high 60 mm
6. Free movement limit after material 5 mm
7. Feed rate conditions: 600 mm/min
8. Step Down layer conditions: 2.0 mm

THE GOAL - FOUR FUNCTIONS

Material

This detail harnesses the natural properties of moisture-related swelling and shrinkage to optimize construction and assembly performance, guided by the wood fiber direction of the elements.

Fiber Direction:

As discussed in the Material Chapter, the alignment of fiber direction within the joint geometry is of central importance to achieve the greatest volumetric change effect. To create a secure interlocking effect, each element should align with the tangential fiber grain direction, as this orientation yields the highest change ratio.

Mechanical properties

The wooden joinery connection is designed to meet the structural requirements for a single-floor housing structure in the Colombian territory. To achieve optimal structural performance, it is essential that the elements within the connection are aligned parallel to the grain direction.

DFMA + D

The details follow Design for Manufacturing and Assembly conditions. Additionally, the exploration of the Dis-Assembly process will be integrated into the methodology to explore possibilities.

Manufacturing Performance

The Detail follows production requirements, aiming to develop efficient, simple, and flexibility manufacturing workflow. Allowing the possibility of a mass production system without the integration of complex set ups.

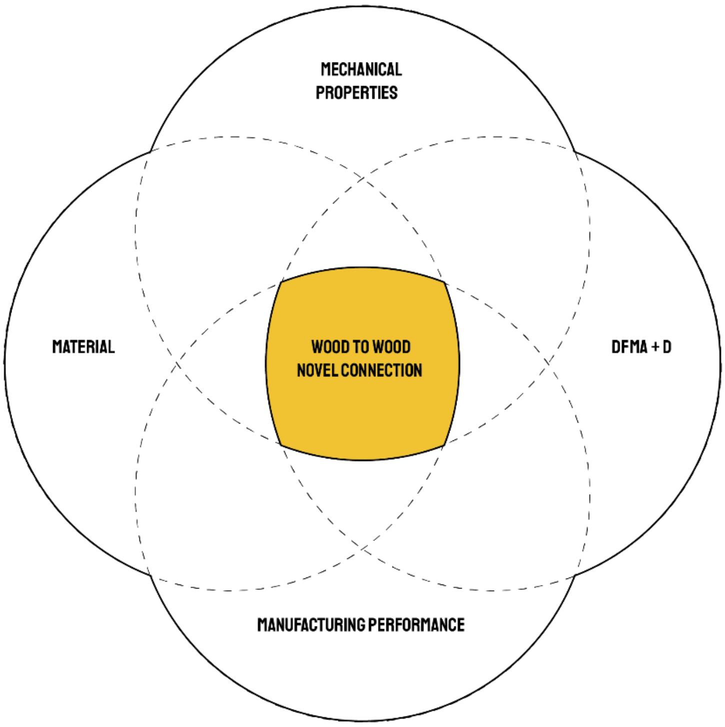


Figure 75 Principles of Wood to Wood joints

13. THE JOINTS

After identifying all spatial and routing requirements, the next step was to explore the possibilities for manufacturing wood-to-wood connections. The extensive literature research provided valuable insights into the various typologies and variations of wood connections.

To simplify the assessment process and understand the CNC limitations, advantages, and restrictions of the manufacturing process, three types of joints were selected for exploration. Each joint represents a different degree of complexity and assembly method. Therefore, we chose to work with a mortise and tenon joint, a Cross-Half-Lap joint, and a T-joint. These selections encompass most of the variations and possibilities related to production requirements.

For this prototype stage, Douglas Pine beams measuring 72 x 72 x 400 mm were used to produce the specimens.

PRODUCTION REQUIREMENTS

The main purpose of this assessment aims to understand the following characteristic:

- Production conditions
- Fiber Direction
- Material Placement
- Milling time
- Detail Accuracy
- Assembly
- Material Waste

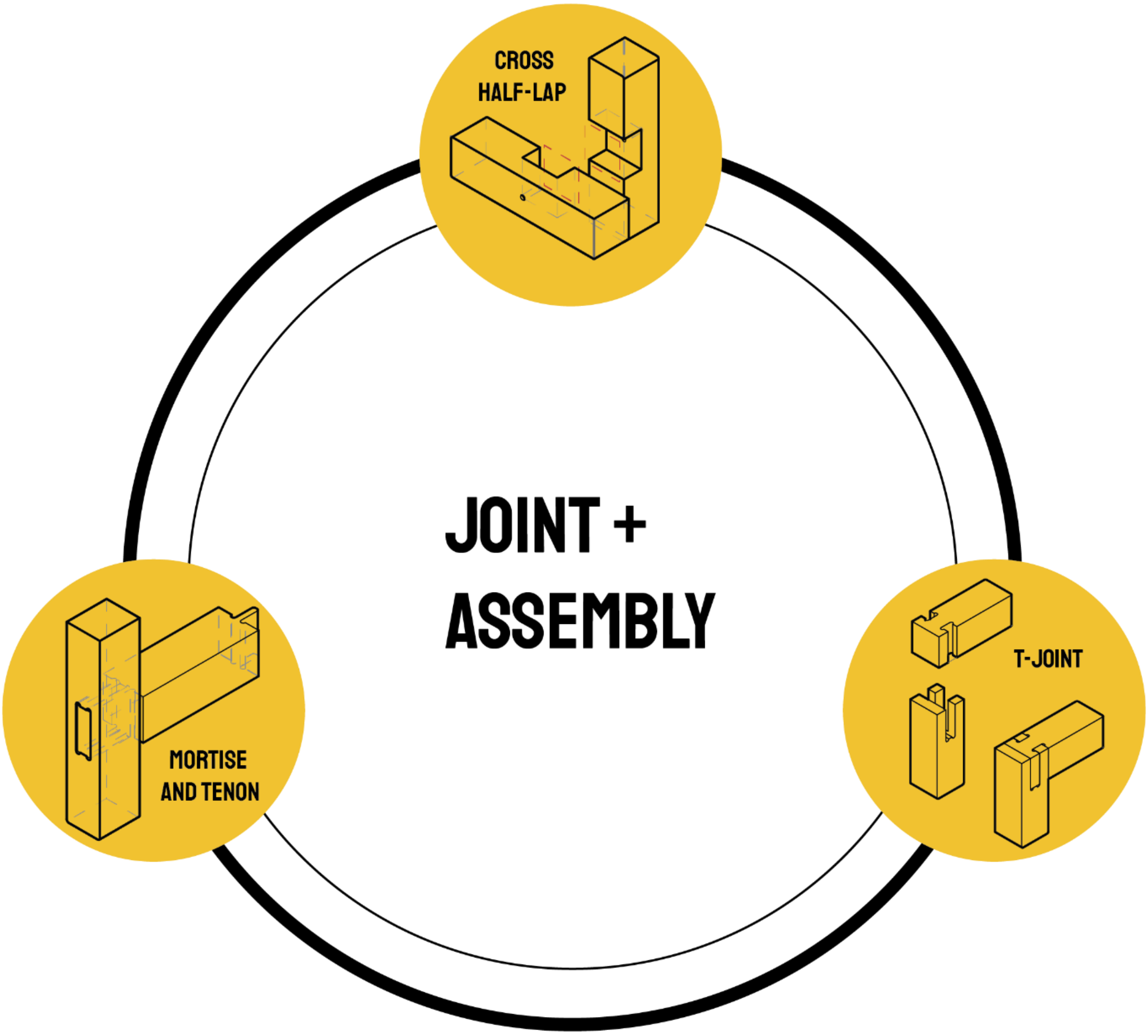


Figure 76 Wood-towood connections for CNC assesment

PRODUCTION REQUIREMENTS

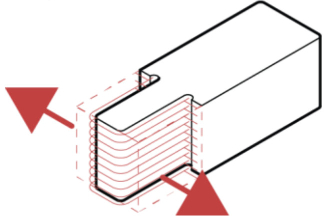
The primary goal of this prototype is to evaluate milling calibration, range, material setup, and the performance of a small-scale mortise and tenon joint. For this initial exercise, a mixed fiber direction in the material was used, primarily due to budget constraints. However, it is assumed that a tangential fiber direction can be achieved for subsequent experiments.

CNC PRODUCTION CONDITIONS

The fabrication of each component follows:

Fiber Direction:

In this diagram, the fabrication of the tenon follows the tangential fiber direction, which is done to maximize the volume in the connection, ultimately resulting in a tight-fitting assembly.



Milling Range

As shown in Figure 77, the cross-section of the mortise cannot be fully covered by the milling bit. Therefore, a rotation strategy needs to be implemented to align each face and manufacture one side at a time.

Figure 77 milling range for big Cross-sections

Material Set – up and Accuracy

This aspect is directly related to the quality of the manufacturing process since increased vibrations within the workpiece can result in reduced quality and accuracy. Hence, it is crucial to establish a stable setup to maintain ideal tolerances. Additionally, the necessity for a rotation strategy during production requires high precision to lift the piece and position the element in the opposite direction accurately.

Figure 78 First material mold anchorage system

Milling Accuracy

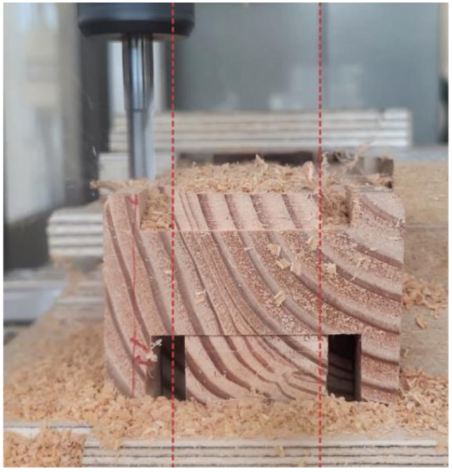


Figure 79 Production Mis-allingment

Production time

Milling time will be evaluated in terms of the beam **set up** on the **working bed**, the **routing time**, **detail corrections** if necessary, and the **assembly of the joint**. The assessment of the process from beginning to the end gives a clear Understanding of joint performance in a full building system.

MATERIAL WASTE OPTIMIZATION

This category relates to the assessment of the type of waste generated by milling operations. For instance, in the mortise and tenon fabrication process, the wooden block can be viewed as the negative space resulting from the tenon manufacturing process. When producing traditional timber joints, two types of waste can be identified, and the decision to up-cycle or downcycle the material depends on its final stage.

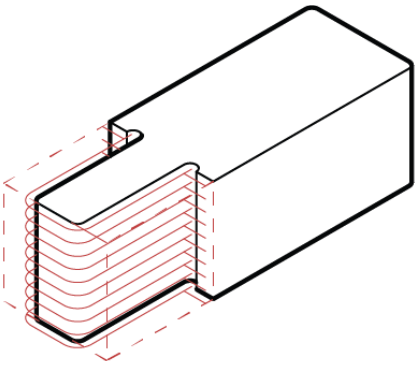
Saw Dust

This type of waste is primarily generated by the rotational movement of the mill bit within the material substrate. It aligns with the toolpath pattern configurations designated for each operation.

Figure 80 Type of waste

Wood Blocks

This type of waste arises from a profiling operation intended to create a specific shape. For instance, in the Tenon diagram, you can identify the Tenon's toolpath guides delineated in red. The outcome of this operation results in the dissection of part of the wood. During the milling operation process, it was noticeable that this type of waste poses a risk in the machine, as the high-speed revolutions push the piece across the working space. It is essential to avoid such configurations as they are difficult to control and could potentially damage the machine, especially the spindle. Furthermore, due to the small dimensions of these pieces, downcycling is the most economical option.



ASSEMBLY PROCESS

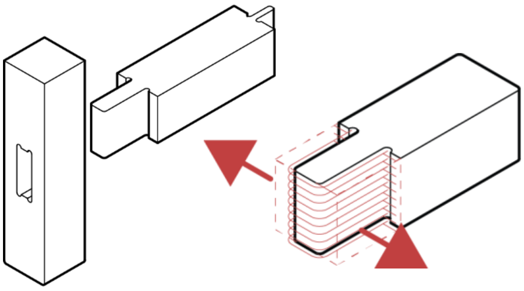
In pursuit of establishing a low-tech construction process that is accessible to inexperienced users, the assembly methodology incorporates non-electrical tools with minimal skill requirements. These tools include hammers, presses, or other implements that ensure a tight-fitting assembly method.

Figure 81 Assembky method - Mortise and Tenon

MORTISE AND TENON

TYPE OF JOINT

Traditional timber structures with wood-to-wood connection can be seen in various countries like China, Japan, Korea, and many others, in specific a mortise and tenon joint beam to Column are widely seen (Chen et al., 2016). Their applications are from big to small scale elements, such as post and beams structures, mitre-gates, and furniture where the tenon are fixed into the mortise using wooden dowels of greenheart material (Van De Kuilen et al., 2014). This thesis focuses on material capacity to suppress additional hardware for a simpler assembly process.



CNC PRODUCTION CONDITIONS

Fiber Direction:

The fiber direction of the tenon is positioned in the tangential direction to increase tight-fitting assembly. These conditions will be measured in a later stage from a tensile test.

Material waste:

As seen in the results section, 87.7% of material was, 12% was waste divided in 10% for dissection of the material resulting in blocks, and 2% on pure sawdust produced by the profiling operation.

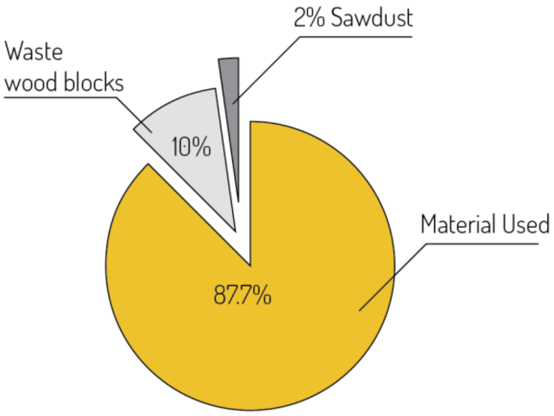
Process milling time

The profiling of tenon joints takes 10 minutes, nevertheless, the rotation of elements creates misalignment causing unnecessary postprocessing, and as result an inefficient assembly. process. blocks, and 2% on pure sawdust produce by the profiling operation.

Figure 82 Mortise and tenon prototype - Douglas Pine

RESULTS

MILLING WASTE RESULT



MILLING TIME

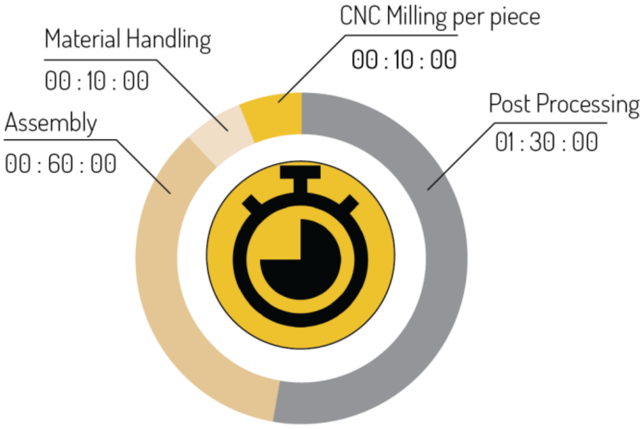
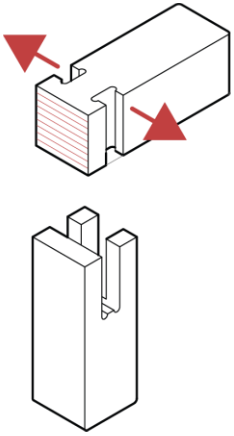


Figure 83 production, and material waste data

T-JOINT

TYPE OF JOINT

According to some researchers the T-Shape tenon connections shows higher rotational stiffness in comparison to the Dovetail mortise and tenon joints (Fang & Mueller, 2018). Due to the geometrical optimization, these connections allow a vertical assembly method giving a degree of construction freedom. This methodology is specially used in low rise structures.



CNC PRODUCTION CONDITIONS

Fiber Direction:

The T joint beam works in the tangential orientation, while the column works in the opposite direction locking the element with the column once the material is fully saturated.

Figure 85 T joint Assembly

Material waste:

The waste factor of T joint shows 91.5% of material efficiency. And a sawdust production of 8.5% as a result of the milling process.

Process milling time

CNC milling process is considerably higher compared to Mortise and tenon with about 25 minutes per pieces. Assembly show a high point of complexity, as the tight fitting characteristic creates a complex process of alignment.

Figure 84 T-joint

Results:

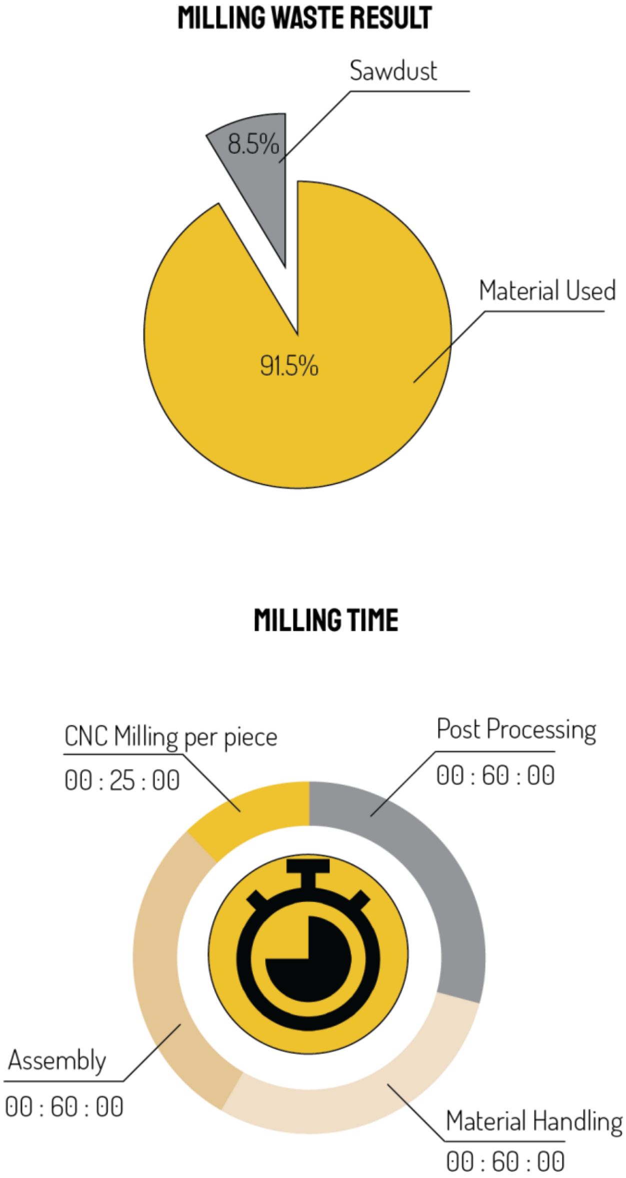


Figure 86 production, and material waste data T-Joint

CROSS-HALF LAP

TYPE OF JOINT

CNC PRODUCTION CONDITIONS

Fiber Direction:

The fiber direction strategy aims to improve the compression properties of the joint intersections. This type of connection carries load by contact points, and a traditional Pin is used to overcome lateral forces(Branco & Descamps, 2015). This research aims to evaluate the best material configuration of the fiber direction to increase tight fitting properties. Thus, two kinds of samples were fabricated, one with joint parallel to the grain, and one perpendicular to measure the compression factor in these two scenarios as seen in Figure 89.

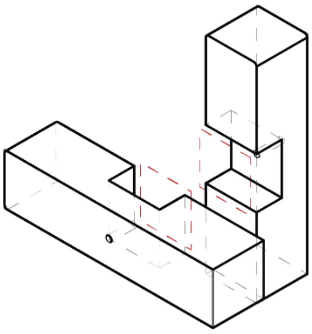


Figure 87 Cross Half Lap Joint

Material waste:

This type of joint used 88% of the total specimen, leaving 12% of sawdust in the manufacturing process, and zero split material.

Process milling time

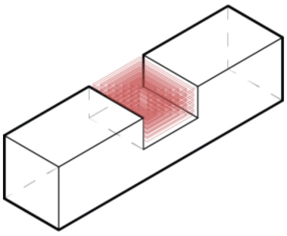


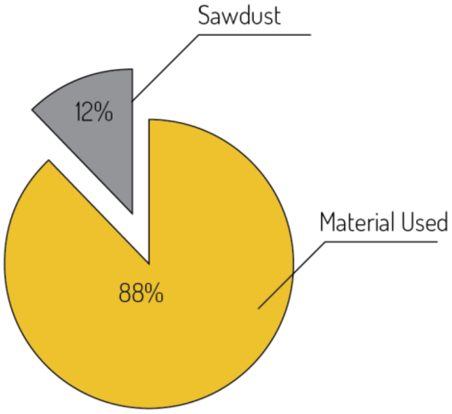
Figure 88 MIlling operationg - pocketing

From all the specimens this joint requires the most material routing, as a pocketing operation needs it to remove the equivalent of the cross-section up to half of the section in the Z- Axis, as seen in Figure 90.

Figure 89 Cross-Half-lap joint, parallel and perpendicular to the grain

RESULTS

MILLING WASTE RESULT



MILLING TIME

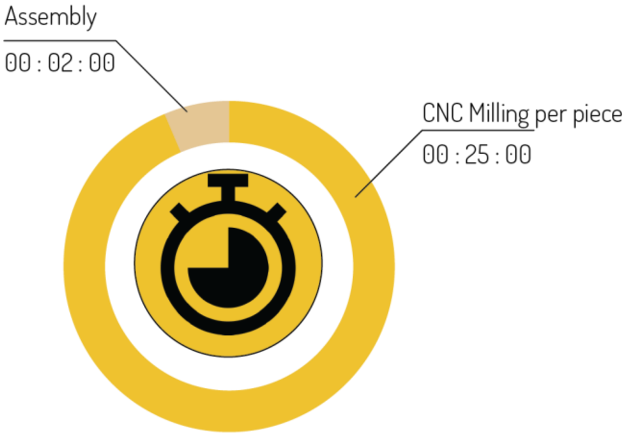


Figure 90 production, and material waste data Cross-Half-Lap Joint

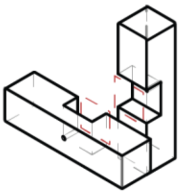
JOINT ASSEMBLY ASSESSMENT

JOINERY ASSESSMENT

In the independent assessment of joint

JOINT ASSEMBLY

HALF-LAP



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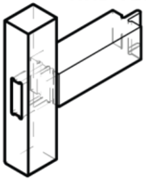
MORTISE AND TENON



score
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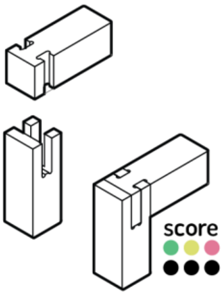

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			HALF-LAP ASSESSMENT			MORTISE AND TENON ASSESSMENT			ASSESSMENT	
ASSEMBLY DIS+ASSEMBLY	**ASSEMBLY**									
	Speed	●●●	●●●	🟢⚪⚪	✓	●	⚪⚪🔴	✗	●●	⚪🟡⚪
	Simplycity	●●●	●●●	🟢⚪⚪	✓	●●●	🟢⚪⚪		●	⚪⚪🔴
	Unexpirience Labour	●●●	●●●	🟢⚪⚪	✓	●	⚪⚪🔴	✗	●	⚪⚪🔴
	Herarchy	●●	●●●	🟢⚪⚪	✓	●●	⚪🟡⚪		●●	⚪🟡⚪
	Modularity	●●●	●●	⚪🟡⚪		●●●	🟢⚪⚪		●●	⚪🟡⚪
	Design Freedom	●●	●●●	🟢⚪⚪	✓	●●	⚪🟡⚪		●	⚪⚪🔴
	DIS-ASSEMBLY									
	Speed	●●	●	⚪🟡⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Simplycity	●●●	●●●	🟢⚪⚪	✓	●●	⚪🟡⚪		●●	⚪🟡⚪
	Unexpirience Labour	●●	●●●	🟢⚪⚪	✓	●	⚪⚪🔴	✗	●	⚪⚪🔴
	Herarchy	●●●	●●●	🟢⚪⚪	✓	●	⚪⚪🔴	✗	●●	⚪🟡⚪
	Modularity	●●	●●	🟢⚪⚪	✓	●●			●●	⚪🟡⚪
CONNEECTION TYPE	**ASSEMBLY**									
	Speed	●●●	●●●	🟢⚪⚪		●	⚪⚪🔴	✗	●●	⚪🟡⚪
	Interlocking	●●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●●●	
	Dis-Assemblly	●●	●	⚪🟡⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
	Herarchy	●●	●●	⚪🟡⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
	Modularity	●●	●●	⚪🟡⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
	Design Freedom	●	●●●	⚪🟡⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Rotational Stiffnes	●●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●	⚪⚪🔴
	thight fit contact	●●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
MILLING	**MATERIAL**									
	Milling time	●●	●●	⚪🟡⚪		●●	⚪🟡⚪		●	⚪⚪🔴
	Simplicity	●●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●	⚪⚪🔴
	Rotation corrections	●●●	●●●	🟢⚪⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Service Are	●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
	hight	●●●	●●●	🟢⚪⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Stabilisation	●●●	●●●	🟢⚪⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Hardeness	●●●	●	⚪🟡⚪		●●	⚪🟡⚪		●●	⚪🟡⚪
	Manual Corrections	●●●	●●●	🟢⚪⚪		●	⚪⚪🔴	✗	●	⚪⚪🔴
	Waste	●●●	●●●	🟢⚪⚪		●●	⚪🟡⚪		●●	⚪🟡⚪

Table 5 material, production and assembly assesment of wood to wood Joints production, a comparison can be drawn from the CNC manufacturing conditions. These factors include the material handling within the machine, including the rotation steps required to mill each face of the timber; the individual milling production time per beam; any post-processing steps needed to rectify tolerance errors; and ultimately, assess the assembly of the joint. The following conclusions were formulated.

Mortise and Tenon

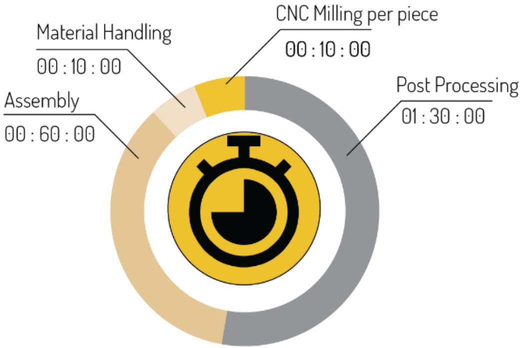


Figure 91 Mortise and tenon CNC assessment

T- Joint

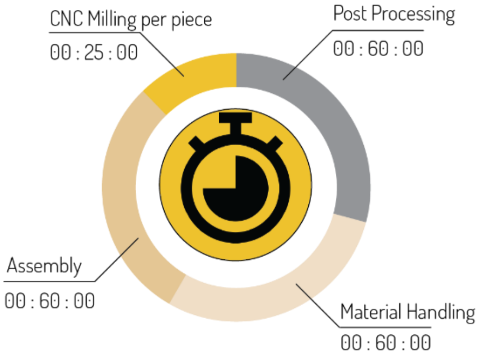


Figure 92 T-Joint CNC Assessment

Cross-Half lap

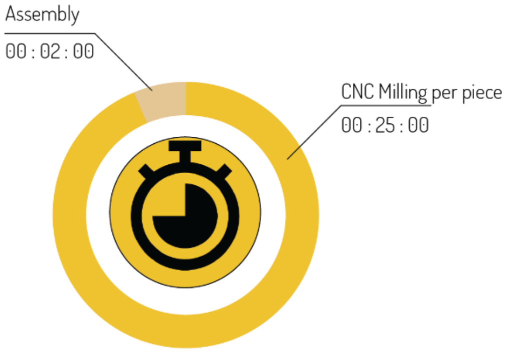


Figure 93 Cross-Halft Lap CNC Assessment

CONCLUSION OF CNC JOINTS

CNC milling

First and foremost, it is important to note that manufacturing traditional joinery connections like mortise and tenon or T-joints using this type of technology isn't well-suited. The manufacturing process is designed around a 2D strategy for panel production, and attempting to create complex geometry requires additional manual labor, which can quickly diminish the quality and production efficiency of wood elements. This often leads to the necessity of post-production steps to correct any misalignments, essentially reverting to more traditional carpentry craftsmanship.

Assembly

The assessment of assembly times is a crucial aspect of this project. The goal is to develop an assembly method that is accessible to individuals with minimal experience while maintaining high alignment accuracy. However, when evaluating the assembly times for the mortise and tenon as well as T-joint connections, it was observed that the average assembly time per joint was approximately 60 minutes. If these joints were to be implemented in a construction site for a housing project, it would significantly impact efficiency and require a substantial amount of manpower, making it an unviable option.

THE SELECTED JOINT

Contrary to the negative repercussion on the previous two joint examples, the Cross-Half lap joint presents an outstanding performance in manufacturing as well as assembly. From the CNC milling time overview, despite showing a higher production time, this detail achieved excellent precision resulting in time savings of about 150 minutes compared to the Mortise and Tenon, and T-joint connections.

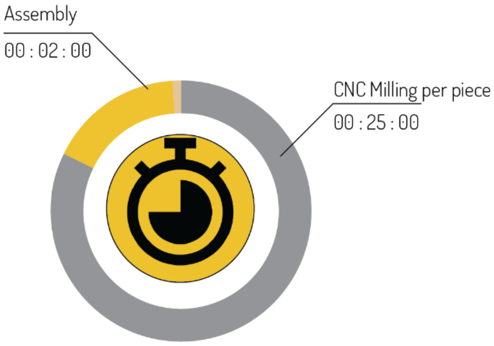


Figure 94 time saving Cross-Half Lap

MILLING TIME

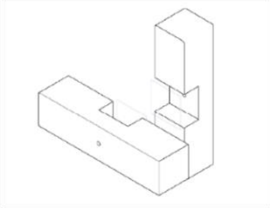
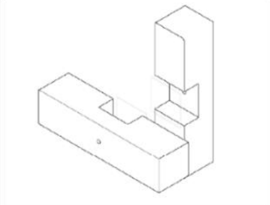
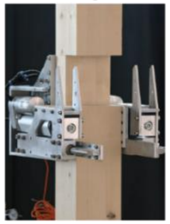
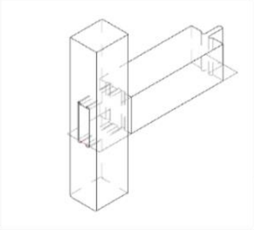
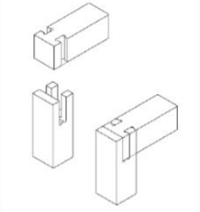
MATERIAL HANDLING

JOINT ASSEMBLY

POST PROCESSING

CNC ASSESMENT CRITERIA

INTERLOCKING TIMBER JOINTS

	no.	Project Name	Cross Section	Joint	Institusion	Anchorage	Assembly Method	Observations	Manufacture CNC Time	Time Evaluation	
HALFT-LAP	1.	CantiBox 	100 x 100 mm	Half-Lap 	Gramazio Kohler	Bolt & interlocking 	Robotic Clamps 	The Clamp system is use to **overcompensated** possible manufacture issues such as **tolerances.** Thus, elements can be force in place disregarles misalignments, as well as **transfering forces** by the compress contact area characteristic of the joint.	00 : 30 : 00	Fabrication time p.p Assembly time Post-Processing CNC Corrections	00 : 30 : 00 00 : 02 : 00 00 : 00 : 00 00 : 00 : 00
HALF-LAP	2.	Timber Assembly with Distributed Architectural Robotics, 2018-2022 	100 x 100 mm	Half-Lap 	Gramazio Kohler	High Force interlocking 	Robotic Clamps 	high-force robotic-clamps are used to operate in collaboration with an industrial robotic arm to overcome challenges of timber joint assembly, such as providing **large assembly forces and avoiding misalignments**.	00 : 30 : 00	Fabrication time p.p Assembly time Post-Processing CNC Corrections	00 : 30 : 00 00 : 02 : 00 00 : 00 : 00 00 : 00 : 00
MORTISE AND TENON	1.	Post and Beam 	300 x 120 mm	Mortise And Tenon 	-	interlocking 	Manual Process 	-	00 : 10 : 00	Fabrication time p.p Assembly time Post-Processing CNC Corrections	00 : 10 : 00 01 : 00 : 00 01 : 30 : 00 00 : 10 : 00
T-JOINT	1.	CantiBox 	100 x 100 mm	T-JOINT 	MIT	interlocking 	Manual Process	The T* type joint, which uses a T-shaped tenon instead of a dovetail, experimentally shows high rotational stiffness.	00 : 10 : 00	Fabrication time p.p Assembly time Post-Processing CNC Corrections	00 : 25 : 00 01 : 00 : 00 00 : 20 : 00 01 : 00 : 00

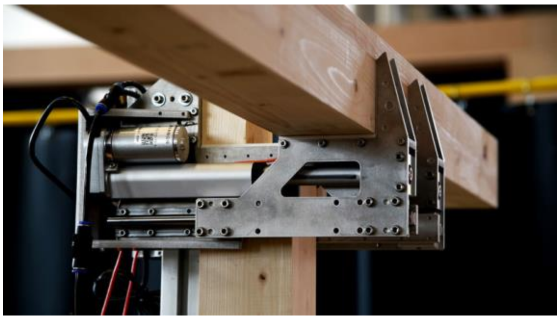
PERSPECTIVE OF FUTURE APPLICATIONS FOR CROSS- HALF LAP

Considering the performance achieved through the assessment of joinery design and assembly processes, it becomes evident that the Cross-Half Lap joinery connection offers the most favorable results for the application of CNC 3-Axis technologies and assembly methodologies. Moreover, this type of detail exhibits a flexible manufacturing setup. Thanks to its simple pocket detail, wood elements can be manufactured using a variety of equipment, ranging from rudimentary to highly efficient technologies.

The concept of flexible manufacturing detail benefits the implementation of these construction systems in various locations, under different conditions and budgets. For instance, it can be fabricated in Colombia using a basic CNC 3-Axis machine or a high-powered Hundegger equipment in Germany. This low interdependency between technology and detail offers a cost-effective solution that can adapt to diverse manufacturing environments.

REFERENCE OF A CROSS-HALF LAP

An illustration of this forward-looking concept can be found in projects like the automatic assembly of jointed timber structures with robotic clamps (Leung et al., 2021), The Canti Box , and the Design and assembly automation of the Robotic Reversible Timber Beam(Kunic et al., 2021). These projects have showcased the benefits and potential applications of integral Cross-Half-Lap connections due to their structural effectiveness, as well as their implications for future assembly methodologies involving robotics. One common theme across these projects is the importance of achieving tight-fitting connections, which is facilitated by the precision of tolerances and is exemplified by the use of hydraulic clamps in assembly processes. In this research, a similar assembly process is emulated using a table clamp press.



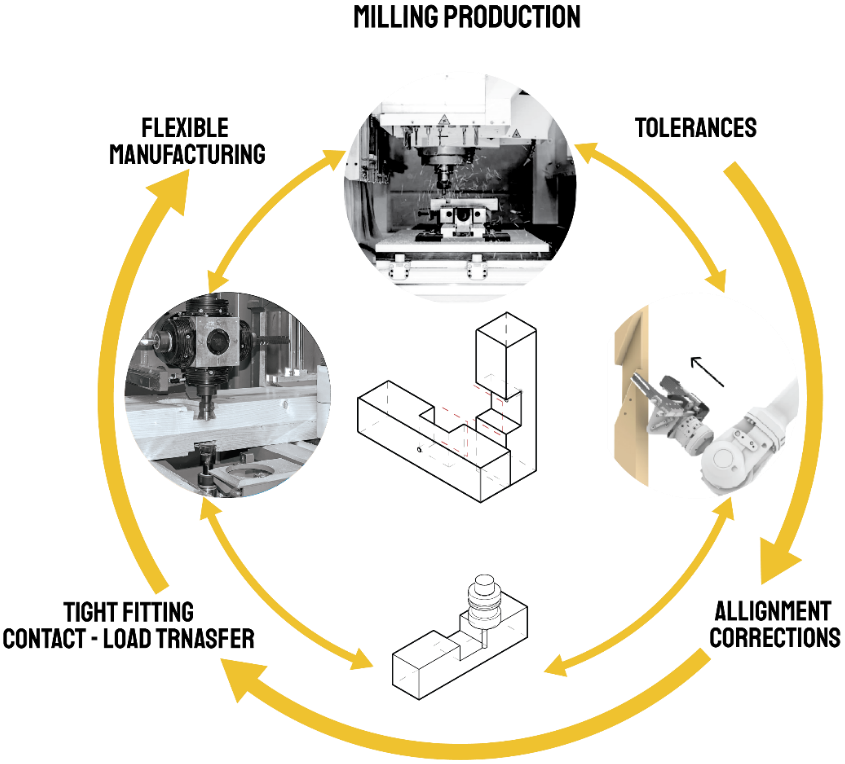


Figure 95 Manufacturing flexibility Diagram

TH CNC KÖLN

MANUFACTURE OF HARDWOOD JOINTS

14. MANUFACTURING OF HARDWOOD JOINTS – TH KOLN

As previously detailed, the first section of the CNC chapter delves into comprehending the technology, describing the equipment, outlining manufacturing conditions, and subsequently assessing three of the most common joints. This study primarily focuses on the equipment available at the Faculty of Architecture and Building Sciences of TU Delft University.

Material
The experimental phase of material assessment has showcased the characteristics of various wood species concerning their reactions to high relative humidity conditions, especially in the context of assembly methods. As a result of this systematic experimentation, the final conclusion has identified Quercus Robur Oak Hardwood as the most suitable material for execution in this research.

Cross-Half Lap Joint
In summary, a comprehensive analysis, including both a general overview and specific evaluation of each CNC process, has demonstrated that the Cross-Half Lap joint exhibits the most efficient manufacturing process and delivers superior assembly performance when using a table clamp system.

TU DELFT ROUTING PRE-SETS

ROUTING SETTINGS

It is essential to keep in mind that the milling conditions established for wooden parts at TU Delft University prioritize low maintenance effectiveness over production efficiency and high performance. These conditions have a detrimental effect on production time, resulting in an inefficient manufacturing process for the studied joints. Additionally due to this policy, it is not possible to manufacture hardwood specimens.

Mill bit: 10 mm diameter flat tip

Speed rate: 600 mm/min

Step down layer per pass: 2.0 mm

Figure 96 CAM LAB - TU Koln Faculty of Architecture

FIRST CNC TEST OF A HARDWOOD SPECIMEN

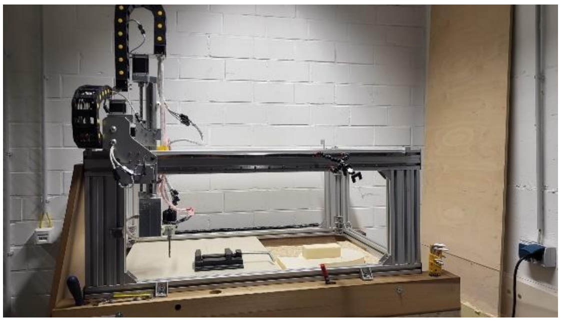


Figure 97 4 - Axis CNC Machine

In order to effectively demonstrate the findings of this research through a practical prototype that integrates digital manufacturing processes and capitalizes on the inherent material properties, it was essential to outsource this stage of the research.

In collaboration with the faculty of architecture institute of Design at TH Koln in Germany, the support of Tobias Scheeder, Jurek Waters, and the external third Mentor Max Salzberger; it is possible to access to the CAM LAB. where prototyping testing would evaluate the effectiveness of the technology with high density Hardwood specimens.

Collaborators

External Advisor - Tobias Scheeder

Third Mentor - Max Salzberger

MATERIAL HARDNESS AND MACHINE CAPABILITIES

The CNC equipment available at this laboratory possesses an additional degree of freedom, as shown in Figure 98, where the spindle incorporates a rotational pivot. Consequently, this equipment can be classified as a 4-Axis CNC machine. However, to maintain consistent manufacturing conditions similar to those established in the Netherlands, this additional axis is restricted in movement, effectively simulating a 3-Axis mechanism.

Figure 98 4- Axis CNC Machine, TH Koln CAM LAB

An important aspect of this manufacturing process is the material's resistance to cutting. To simplify data classification, the Janaka Hardness standard can be used. This methodology quantifies the resistance to denting and wear of wood samples by measuring the force required to embed a steel ball into the wood up to half of the sphere's diameter (11.28 mm) (Wood & Birch, 2000). Utilizing this value to compare material milling resistance to the cut, the graph in Figure 99 illustrates the types of wood with varying levels of resistance to the routing process. For instance, in extreme scenarios, a softwood specimen like Douglas Pine exhibits a resistance of about 450 Foot-pound (ft.lb). In contrast, Oak Quercus Robur demonstrates significantly higher resistance, with values oscillating around 1125 ft.lb, highlighting the challenge of working with this hardwood.

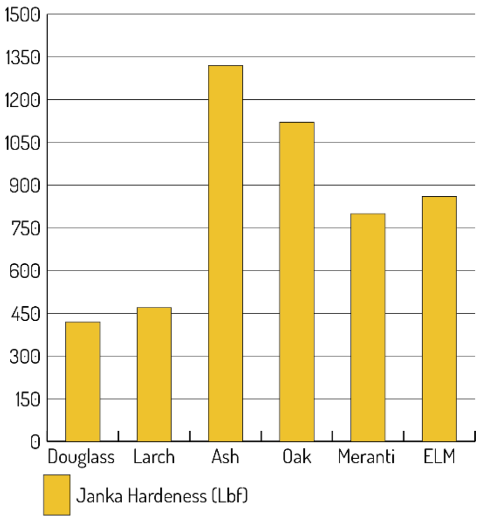


Figure 99 Janka Hardeness

PROTOTYPE MANUFACTURING FAILURE

During this prototype stage, specimens of Quercus Robur Oak measuring 72 x 72 x 400 mm with a Janka Hardness of 1250 (ft.Lb) were used to fabricate cross-Half Lap joints. Manufacturing conditions had been previously tested in the Netherlands using Douglas pine beams. However, the evaluation of material resistance was not conducted until this point in the research.

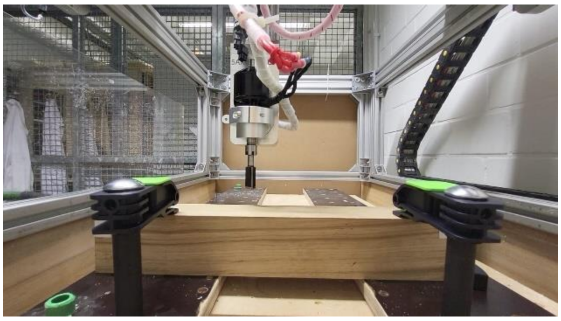


Figure 100 CNC test of Hardwood Oak Beams

Due to the low stiffness of the spindle upper structure, a bending moment during the contact point to the beam occurs. This set up shows low advanced capacity in fabrication. The material resistance is greater than the overall frame, showing elastic capacity in the production. As a result of this low performance of the frame, vibration, and low accuracy is observed. Therefore, is necessary to change the set up.

Figure 101 Tobias & Max Wood Workshop, Koln, Germany

MATERIAL SET UP – WOOD WORKSHOP

This second attempt to achieve a stiffer milling process was carried out in Max Salzberger and Tobias Scheeder's wood workshop. Although the setup was less sophisticated compared to the one at TH Koln, the robustness of the spindle structure allowed for consistent production with minimal variations and high precision. It's worth noticing the limited vertical space from the milling bit to the working bed. The beam prototypes measuring 67x67x400 mm could not fit within the working bed, so it was necessary to create a pocket to position the elements.

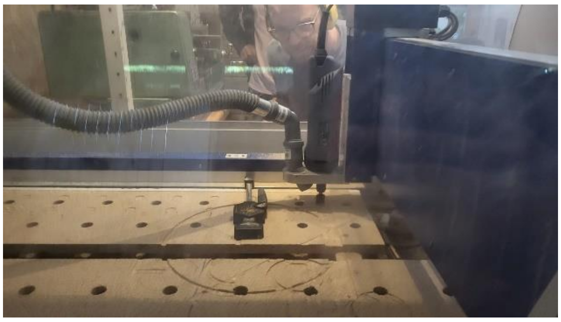


Figure 102 Pocket milling for Beam placement.

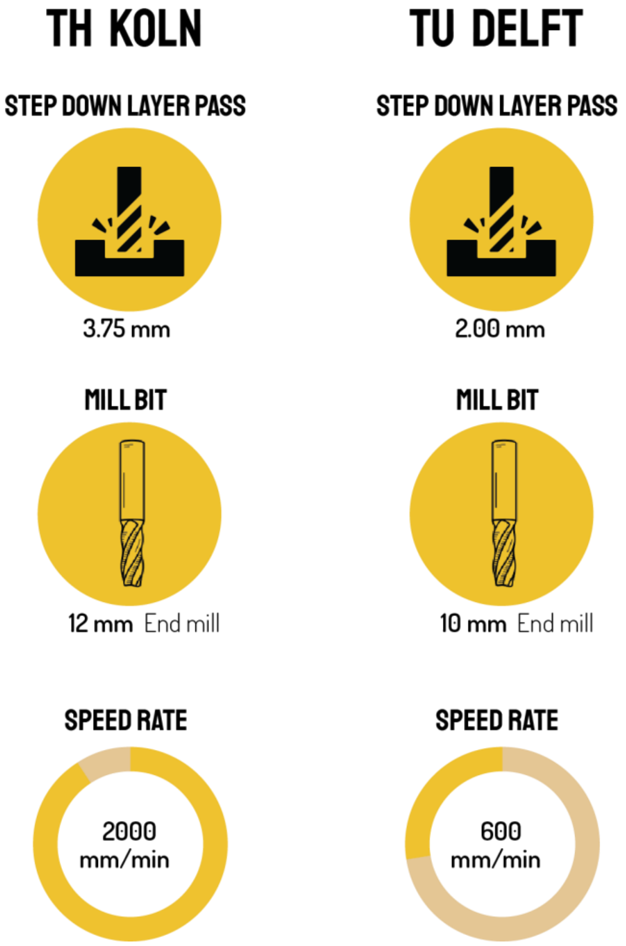


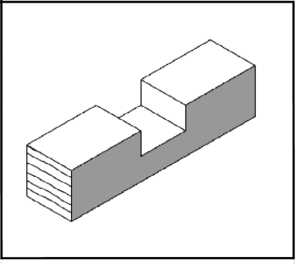
Figure 103. Milling Setting Comparisons

LIST OF MATERIALS AVAILABLE - CROSS HALF-LAP

PLANED BEAMS - GRAIN - 18%

	#	CROSS - SECTION	LENGTH	MOISTURE CONTENT	GRAIN DIRECTION	CHECK LIST	ELEMENT	JOINT GRAIN DIRECTION	PRODUCITON	HUMIDITY
🟥	1	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	60%
	2	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	
	3	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	85%
	4	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	
	5	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	60%
	6	67 x 67 mm	400 mm	18%	Tangential		Beam	II - Tangential	0:02:47	
	7	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	85%
	8	67 x 67 mm	400 mm	18%	Tangential		Beam	II - Tangential	0:02:47	
	9	67 x 67 mm	400 mm	18%	I - Radial		Column	I - Radial	0:02:47	60%
	10	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	
		NO PLANED BEAMS - II GRAIN - 10.5%								
🟦	1	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	60%
	2	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	
	3	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	85%
	4	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	
	5	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	60%
	6	65 x 67 mm	400 mm	11%	Tangential		Beam	II - Tangential	0:03:33	
	7	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	85%
	8	65 x 67 mm	400 mm	11%	Tangential		Beam	II - Tangential	0:03:33	
	9	65 x 67 mm	400 mm	11%	I - Radial		Column	I - Radial	0:03:33	60%
	10	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	

II - Tangential



I - Radial

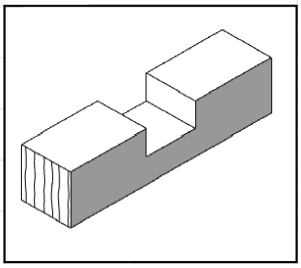


Table 6 Production characteristics of Cross-Half Lap joints

SPECIMEN DESCRIPTION

Red cluster

In Table 6, the production list of Cross-Half Lap joints planned for fabrication is detailed. Two groups of specimens were selected for material behavior study. The group denominated the Red cluster had the following characteristics:

Moisture content

The beams were exposed to dry conditions, resulting in a moisture content oscillating around 18%

Materia Preparation

The specimens were meticulously prepared to achieve perfectly square dimensions, with a cross-section of 67 x 67 x 400 mm. This thorough material preparation was conducted to enhance precision and reduce tolerance issues in the assembly process.

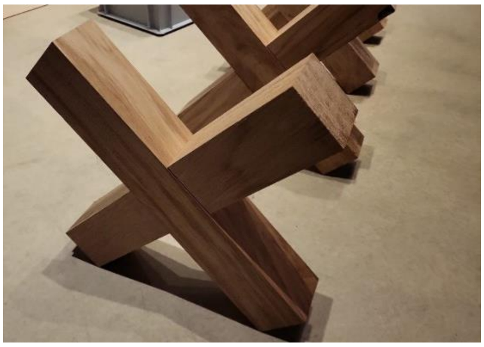


Figure 104 Cross- Half Lap Prototype, Koln, Germany

Blue cluster

On the other hand, the Blue cluster, presented the following characteristics:

Moisture Content

In contrast to the Red group, this second batch of specimens was previously part of a construction frame, which required a stress-drying process to achieve low moisture content values for quality control. As indicated, the material stability showed 11% moisture content.

MILLING TIME 18% MC	**MILLING TIME** 11% MC
00 : 02 : 47 Fabrication time per joint	00 : 03 : 33 Fabrication time per joint

Material Preparation

This material originated from beam elements measuring 140 x 160 mm. To minimize material waste, the cross-section of the samples was reduced, but the exact dimensions are not specified in the text.

Grain direction

The column that describes the joint grain direction shows the configuration of the joints, either orthogonal or parallel to the grain. This diversification in the prototypes aims to validate the consequences of fiber direction swelling on tension performance in the joints and monitor this characteristic in the milling performance.

CNC MILLING SETTING COMPARISON

The prototype stage of Cross-Half Lap joints produced in Cologne (Köln) is focused on optimizing the manufacturing process, simulating a high industrial production line. As seen in Fig. 91, it's possible to compare the milling settings between both scenarios. The configuration in Germany is significantly more advanced, directly impacting the production time per piece. For instance, the spindle's speed rate is 70% faster than the configuration in the Netherlands, which dramatically affects the milling speed. Moreover, the bit used in this second prototype has a larger diameter, covering more surface area over the joint. Lastly, the Step-down layer pass, which is the configuration that controls the Z-Axis for every milled layer, is almost 2.00 mm higher. As a result, the milling path is reduced by almost half.

CONCLUSIONS

Machine format

Despite having an excellent performance, the format of the CNC machine is not suitable for the fabrication of long timber elements in most of the equipment used in this research. On one hand, there are restrictions with the stiffness of the machine frame, resulting in vibration and low precision. On the other hand, the possible cross-section of structural elements is far superior to the machine set up, meaning, that not every FAB LAB in the Colombian territory can be potentially use for this fabrication process.

Direction of the grain

A hypothesis of the fabrication predicted a lower material resistance when the mill bit followed the direction of wood parallel to the grain. Nevertheless, as seen in the table of Cross-Half lap fabrication, the milling time was consistent in every fiber direction, demonstrating a poor correlation between milling performance and fiber resistance to the cut.

Material Hardness

In spite of using a Harwood specimen with a high density, and high Janka hardness as the Oak Quercus Robur characteristics were presented; These experimental exercises demonstrate the capabilities and versatility of the milling performance in a wide range of material. Thus, allowing a certain degree of flexibility in the material selection to achieve a good manufacturing and structural performance.

Moisture content

Contrary to the fiber direction, an aspect the clearly impacted the milling time performance was the moisture content of the specimens. As seen in table 6, two sets of beams were used in the fabrication stage. The Red group of beams with a moisture content of 18% presented lower milling time, This is due to the water content in the wood cells, providing to the material a momentary softer characteristic, Thus production one Cross half lap element in 2 minutes and 47 second. The opposite scenario that could be identify is the group in blue. The wood moisture content presented a considerably lower value (11%) resulting in a more solid compact specimen. Resulting in a 16 second higher milling time difference with 3 minutes and 33 seconds.

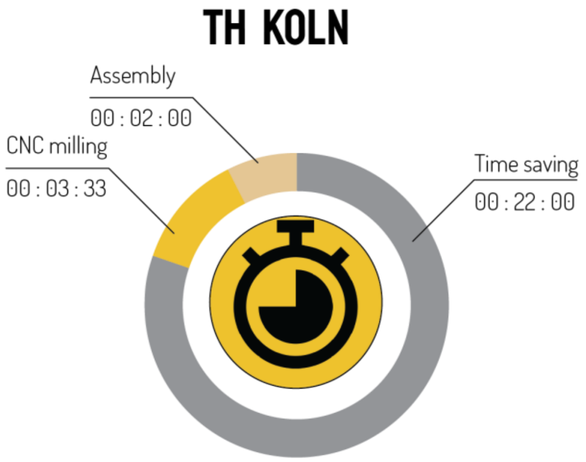


Figure 106 TH Koln Manufacturing saving time analysis

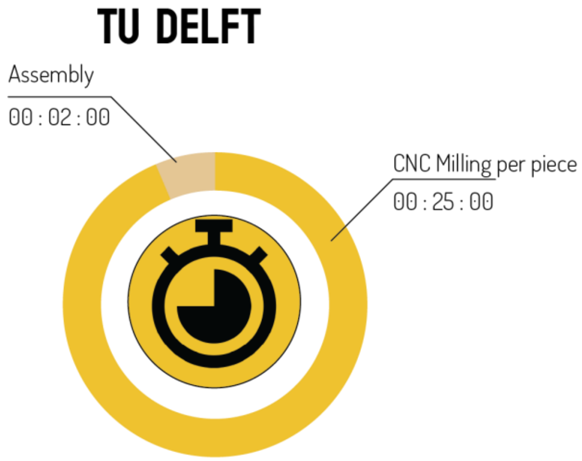


Figure 105 Time analysis TU Delft

JOINT

STRUCTURAL CHARACTERIZATION OF WOOD-TO-WOOD JOINERY CONNECTIONS

15. STRUCTURAL RESEARCH FRAMEWORK WOOD TO WOOD JOINERY.

The use of wood joinery connection largely disappeared with the introduction of metal fasteners that continue to dominate post-industrialization timber connections (Fang et al., 2019). The current mass timber buildings use steel fasteners often designed as one-life spam structure use. Contrary to this conception, the use of interlocking joinery can allow for a more sustainable, non-destructive disassembly of timber structures (Fang et al., 2019). For example the Ecole Polytechnique Federale de Lausanne or (EPFL) is developing a new application method for load bearing components, such as steel and timber structures coming from abandon households (Wolf et al., 2023). Showing the trend of circularity, and second life purpose of these materials.

Taking in consideration that, the building industry is one of major factors of environmental impact in the planet, relating to 40% of total carbon emissions produced; 28% of this value accounts for building operations, while the remain 12% represents the manufacturing of new construction materials. In countries like United State, from 144 million tons of construction waste produced in 2018, 90% came from demolition (Ahn et al., 2022). It is necessary to develop new solutions that contribute to increase the (EOL) end of life of building materials.

Wood as a construction material is uprising in the building practice due to its carbon storage capabilities, and manufactured possibilities (Gong, 2021). Prefabricated timber constructions can bring benefits to a social reconstruction of rural Colombia. Likewise, this method brings better performance of materials and its End of Life (EOL) (Ahn et al., 2022). Moreover, the use of prefabrication allows rapid construction and assembly process creating a cost effective project development (Albus, 2018).

PROBLEM STATEMENT

The current construction demolition represents 90% of the industries waste; researchers argue deconstruction rather than demolition is an essential aspect to achieve better material (END OF LIFE) in circular economies. The effect of this decision will reduce construction waste and diminish the need for new material use (Ahn et al., 2022) (Campbell, 2018). Nevertheless, better building practices for an optimal design, manufacture, assembly, and deconstruction (D+MA + D) method is lacking in the field. Especially in the implementation of affordable traditional wood-to-wood connections as a modern low embodied solution in timber buildings (Ahn et al., 2022) (Mehra et al., 2021).

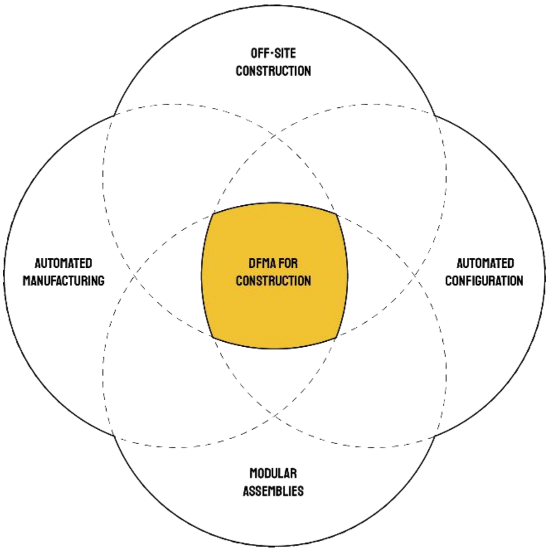


Figure 107 (DfMA) Design for manufacturing and assembly

9.1 SUSTAINABILITY

Traditional carpentry offers a sustainable solution in wood joinery for structural elements compare to adhesives, or mechanical joints such as metal plates or nails (Rodríguez-grau et al., 2022). Some researchers have shown the effects of wood adhesive waste, like formaldehyde and isocyanates on human health (El-Houjeyri et al., 2019). Moreover, in construction practice, the plates, nails and adhesives in many old joinery show deterioration due to corrosion, cause by temperature fluctuation, and high humidity conditions. (Rodríguez-grau et al., 2022). Colombia is a country with drastic climate conditions, temperature oscillation between regions, and humidity changes due to rain seasons. Wood – to – wood connection presents itself as sustainable and optimal solution for local specific requirements.

New innovations in digital fabrication suggest cost of milling details could become competitive in comparison to fasteners (Fang & Mueller, 2018). At the same time, offering benefits on construction speed, and assembly method. Human craftmanship involves a process of marking, comparing, tool shifting and repositioning wood elements for the traditional method. Contrary to this Hight demand steps, more effective manufactories, making the human effort on cost and time of such operations drastically reduce and optimize on the production of various shapes. (Takabayashi et al., 2018)

9.2 STRUCTURAL CHARACTERIZATION OF NOVEL CONNECTIONS

A novel connection refers to the structural construction of a wood-to-wood detail in timber frames. As the previous examples show, traditional wood construction applies interlocking carpentry elements for the building process. The structural characterization of such systems is determined by the tight-fit contact between multiple parts to transfer shear forces (Apolinarska et al., 2021). Due to this specification is possible to understand why adhesives in timber construction have excellent performance. A high surface contact connection can be achieved using synthetic glue in timber structures, making deconstruction impossible for a sustainable process (Mehra et al., 2021).

On the other hand, steel connectors show high load-carrying capacity and ductile behavior. Commonly used in modern timber, this system allows rapid assembly; nevertheless, this solution presents stress concentration due to stiffness differences between materials in timber constructions. Conversely, mono-material structures have a better energy dispersion. A key factor for the structural performance of this type of joint is defined by the (embedment) or compression of one element into another with a 0 mm tolerance accuracy; this capacity increase if the direction of the wood grain is opposite to each other, resulting in a better rotational stiffness of the parts (Fang et al., 2019).

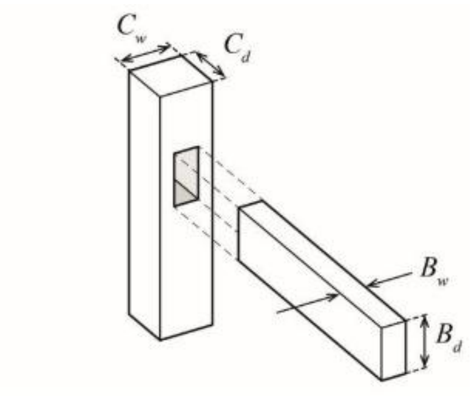


Figure 108 mortised column with through-beam tenon

9.3 STRUCTURAL PERFORMANCE

These traditional techniques can provide structural efficiency, simple assembly, and disassembly process for repurpose and remanufacturing of buildings. From a practical matter, these joints must ensure, strength, flexibility, toughness, and appearance; And due to the limited format of wood measurement, these solutions are necessary to increase the effective length of construction elements (Rodríguez-grau et al., 2022).

Digital fabrication can reduce variations that hand crafting produces. Nevertheless, there are some challenges to reintroduce joinery connections into modern construction. The main obstacle is characterize and codify the mechanics of these joints (Fang et al., 2019). Furthermore, due to the heterogeneous properties of the wood, these highly precise details can be influenced by changes in temperature and humidity between fabrication and assembly. These environmental conditions affect the tightness of the fit between parts. In practice, most typical connections are press-fit elimination this issue (Fang et al., 2019). Therefore, due to high humidity and temperature change across the country, the fabrication of these pieces should be thought from a press and lock type of system.

A research conducted by Rodriguez-Grau et. (2021) proves the effectiveness of wood-to-wood oblique joints of radiata pine beams in bending performance. Thus, the assessment of several joints systems, which included steel plates, bolts, and multiples wood joint alterations shows the superiority in high ductility, and high energy absorption of traditional wood joins.

After performing a 3-point compression test, the results of the experimentation show significant loss of flexural strength, about 55% compared to a beam without joinery details. Nevertheless, the findings of this research showed the effectiveness of carpentry splice joints (ROVS) in comparison with steel plates (MC), bolts, and nails. Therefore, proving superiority over more modern connections.

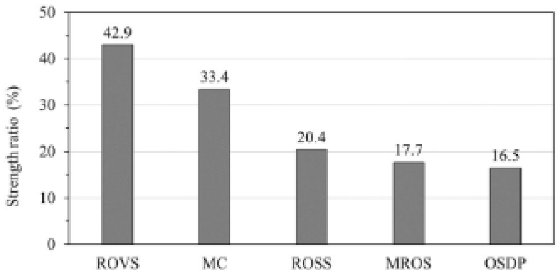


Figure 109 - Strength ratio with respect to the control specimen source:

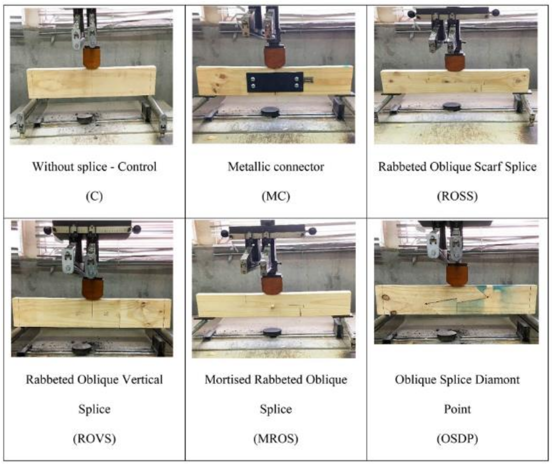


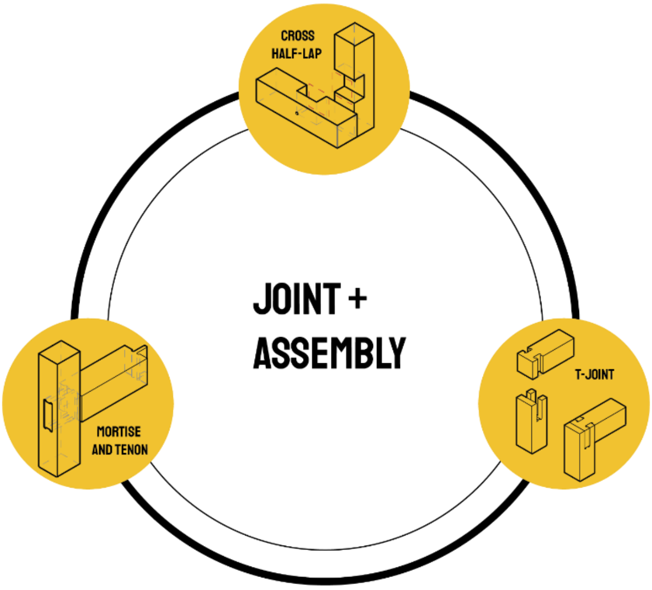
Figure 110. 3 - point bending test comparisong splice, steel plate, bolt connections source:

TYPE OF JOINERY

Joinery can be classify into three main categories according to (Rodríguez-grau et al., 2022) splice, or a joint in a single direction generally implemented in beams; assembly as a joint, which produce solutions in different directions; and coupling, or overlapping connections to increase the cross sectional area, and therefore a larger resistance.

Aiming to create a lightweight timber structural solution, the joinery global class will be based on assembly as a joint type of connections. Taking in consideration the design constrains of traditional joinery for structural performance explained in *section 9.2*, the research will discard details that (1) dismiss tight-fit contact between multiple parts to transfer shear forces, (2) does not present unidirectional perpendicular to the grain direction on the connections, as the systems strives to achieve a good rotation stiffness. Nevertheless, due to the diversity of classes further assessment in the assembly logic, and further CNC restriction is necessary to select the most appropriated detail. The overall structure aims to follow architectural characteristic of the territory mentioned in *section 5, (traditional wood construction).* form, language, hierarchy.

STRUCTURAL CHARACTERIZATION WOOD-TO-WOOD CONNECTIONS



MATERIAL BACKGROUND

Wood is a hygroscopic material, meaning that moisture has a great impact in the strength and behavior of the cells; In its green state, green wood can contain 30% or more moisture (Karagüler & Kaya, 2017). Nevertheless, after reprocessing and manufacturing these values decrease according to the industry standards between 12% to15%. Using a test setup in the Laboratory of heritage of TU Delft University, wood-to-wood joint connections are expose to a moisture saturation process of the wood cells to increase its volume, and ultimately create an assembly interlocking application in construction.

CREATING AN EXPERIMENTAL PROCESS TO PROVE JOINERY CAPACITY WITH MOISTURE.

The following section describes the guidelines for conducting structural experimentation to compare three wood-to-wood joinery solutions in traditional timber constructions manufactured by a CNC fabrication method.

The primary objective of this experimentation is to determine the influence of the moisture induce process in the performance of the carpentry traditional joints. Nevertheless, two main aspects will be evaluated in this test. Firstly, the impact of moisture induces process in wood-to-wood joints in comparison with the same type of detail and joints without moister increasement to determine the interlocking capabilities.

Secondly, identify the Ultimate moment capacity and characterization of the connection types (Mortise and tenon), (T- join), and (cross half-lap joint) structural performance. The result of this examination will conclude the most adequate detail for a fast assembly construction process in further design applications.

MATHEMATICAL CALCULATION

JOINT MODEL

NUMERICAL SIMULATION

MECHANICAL TESTING

MATHEMATICAL FORMULATION JOINT CAPACITY

Historically, timber structures have utilized joinery connections with an interlocking method based on geometric configurations. Depending on the shape of these connections, higher values of rotational stiffness can be achieved, as noted by Fang and Mueller (Fang & Mueller, 2018). In modern construction, especially in low-rise structures, interlocking connections have found application. Numerous examples have demonstrated the effectiveness of this type of construction in withstanding forces such as earthquakes and wind loads.

Workflow analysis

To comprehensively assess the structural characteristics of the studied joint, a three-step approach will be employed to validate the effectiveness of this research. First, a mathematical model will be developed based on existing literature research. This model aims to establish a mathematical correlation between joint geometry and its load-carrying capacity, allowing for the measurement of various types of joints. Second, a numerical simulation using Ansys Workbench 2021 will be conducted to verify the calculations and predictions made by the mathematical model. Finally, a mechanical experiment will be carried out to demonstrate the relationship between the fiber direction of the wood grain, the wood connection design, and the impact of moisture on joint performance.

Literature Research of mathematical calculation

A study on load carrying capacity of Mortise and tenon joints in wooden Mitre Gates propose a mathematical model to characterize geometrical wood to wood joints and ultimately understand the Ultimate Bending moment (Van De Kuilen et al., 2014). A further study in bending moment capacity of rectangular joints propose an alternative simplification of the calculation proposed by (Kasal; & Eckelman, 2005).

First Method

$$M = \frac{\sigma \cdot (b \cdot d^2)}{6}$$

σ = modulus of rupture / type of wood / fiber direction

b = Thickness

d = depth

Second Method

$$\sigma = \frac{M}{W}$$

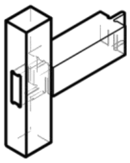
$$W = \frac{1}{\sigma} \cdot b \cdot h^2 = \frac{1}{6} \cdot 27mm \cdot 76mm^2 = 25{,}992mm^3$$

$$M = \sigma \bullet w = 66.9 \cdot 25{,}992 = 1{,}738{,}864.8Nmm$$

$$F = \frac{1.74}{0.6} = 2.9Kn$$

MORTISE AND TENON

FIRST METHOD



$$M = \frac{\sigma \cdot (b \cdot d^2)}{6}$$

σ = modulus of rupture / Douglas Pine

b = Thickness

d = depth

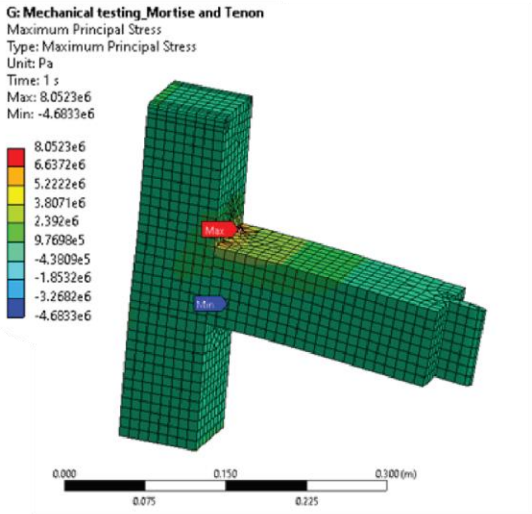
ULTIMATE BENDING MOMENT

$$M = \frac{66{,}9N/mm^2 \cdot (27mm \cdot 76mm^2)}{6} =$$

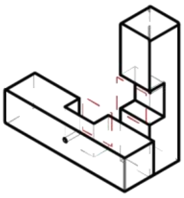
$$M = 1.74Kn/m$$

FORCE CAPACITY

$$= \frac{1.74Kn/m^2}{(60mm/100)} = 2.9Kn/m$$



CROSS-HALF LAP



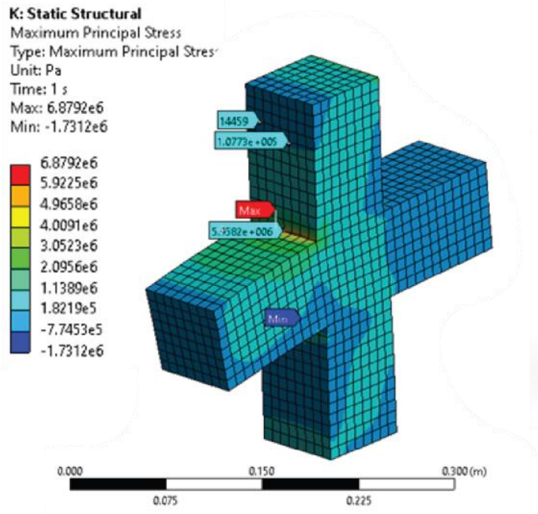
ULTIMATE BENDING MOMENT

$$M = \frac{66{,}9N/mm^2 \cdot (38mm \cdot 76mm^2)}{6} =$$

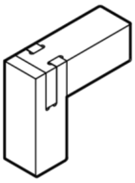
$$M = 2.45kNm$$

FORCE CAPACITY

$$= \frac{2.45Kn/m^2}{(60mm/100)} = 4.04Kn/m$$



T-JOINT



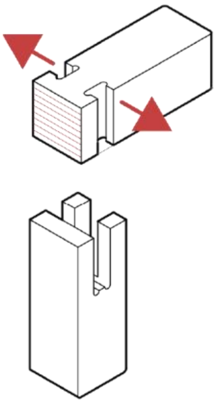
ULTIMATE BENDING MOMENT

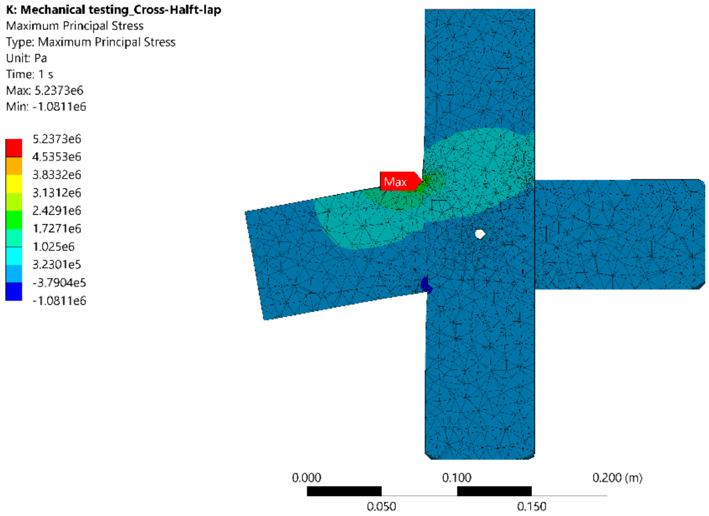
$$M = \frac{66{,}9N/mm^2 \cdot (24mm \cdot 76mm^2)}{6} =$$

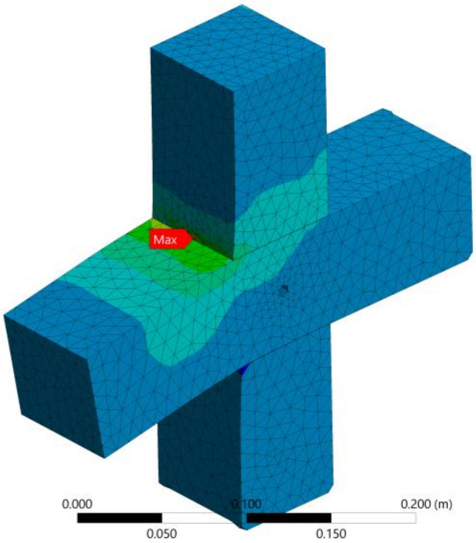
$$M = 1.54Kn/m$$

FORCE CAPACITY

$$= \frac{1.45Kn/m^2}{(60mm/100)} = 2.41Kn/m$$







STRESS ANALYSIS OF CROSS HALF LAP JOINTS

The load selected to conduct the characterization of the joint was based on the requirements of Euro Code number 5 for residential housing. These guidelines take into consideration Life Load, Dead Load, building material layer, and self-weight of beams to assigning the right point of load to the wood-to-wood connections in the Numerical simulation conducted in Ansys Work Bench 2021.

Total floor load

The following load analysis intends to determine the main load on the slap to be transferred to the main beams, and subsequently to supporting columns, and finally to footing.

Calculating Load on Slabs and Beams

Floor Component Calculation

$$Weight-QercusRobur=(0.032m\cdot 2)\cdot\frac{675Kg/m^3}{1000}=0.05kN/m^2$$

$$Weight-Guttex=(0.06m)\cdot\frac{50Kg/m^3}{1000}=0.003kN/m^2$$

$$TotalFloorWeight=0.05Kn/m^2+0.003Kn/m^2=0.053Kn/m^2$$

Selft Weight Beam

$$Density-Oak=\frac{675Kg/m^3}{1000}=0.68kN/m^2$$

$$Beam=0.1m\cdot 0.15m\cdot 0.68kN/m^2=0.01kN/m^2$$

$$Safty-factor=1.5\cdot 0.01kN/m^3=0.015kN/m^2$$

Total Weight Dead Load

$$DeadLoad=0.003kN/m^3+0.05kN/m^3+0.01kN/m^3=0.07kN/m^3$$

Total Load

$$Total-Load=0.07kN/m^2\cdot 1.75kN/m^2=1.82kN/m^2$$

Safety Factor

$$Total-Load=0.07kN/m^2\cdot 1.75kN/m^2=1.82kN/m^2$$

Final Load

$$Final-Load=1.82kN/m^2+1.35kN/m^2=2.45kN/m^2$$

Final Load

$$S2=\frac{WxL}{2}$$

$$S2=\frac{2.45kN/m^2}{2}=1.23kN/m^2$$

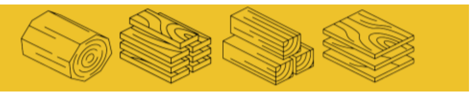
$$S2=1.23kN/m^2\cdot 0.015kN/m=1.24kN/m^2$$

Beam Total Load

$$W=1.24kN/m^2\cdot\frac{2440}{1000}=3.03kN$$

$$N=3029N$$

$$N=\frac{3029N}{2440}=1.24N/mm$$



Observations

First Conclusion

The mathematical model proved to be accurate using the formulas stablish by (Van De Kuilen et al., 2014) as well as (Kasal; & Eckelman, 2005) later verified in Ansys Workbench 2021. Therefore, making this method a reliable source and process to identify structural performance of several wood-to-wood joint connections.

From this process, an oversimplification of the mathematical calculation was used base on (Kasal; & Eckelman, 2005), as a result, it is possible to compare several types of connections using the same mathematical equation.

$$M = \frac{\sigma \cdot (b \cdot d^2)}{6}$$

σ = modulus of rupture / type of wood / fiber direction

b = Thickness

d = depth

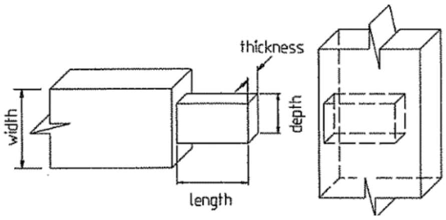


Figure 111 mortise and tenon dimensions guide

Second Conclusion

Based on the formula, four main characteristics were needed to proceed with the calculation **1)** cross-section dimensions, **2)** type of wood **3)** Fiber direction of element **4)** and modulus of rupture, based on characteristics **2** and **3.** The prototype joints were manufactured using a Douglas Pine wood species of 76mm x 76mm cross-section. The modulus of rupture was stablished according to GRANTA Edupack 2020 data base, with a fiber direction parallel to the grain of $66{,}9 N / mm^2$ (direction with the highest capacity in comparison to transversal orientation).

The numerical model was proved using rhino models of the specimens previously manufacture by the CNC machinery exported into Ansys workbench 2021. It is important to highlight that the tension test experiment was not performed using the software. The main purpose of the experiment seeks to demonstrate the principles of moisture induce advantages in wood which cannot be predicted in the numerical model. Therefore, real experimentation was necessary to prove the effectiveness of the process.

CONCLUSIONS

From the mathematical and numerical analysis, it can be concluded that the Cross-Half Lap connection shows superior structural ultimate bending moment performance with (2.45 kN/m). In contrast, the Mortise and Tenon joint presents almost half of the structural performance with (1.74 kN/m). Lastly, the T-joint connection appears to be the least optimal for housing structural applications (1.54 kN/m). Thus, according to the data, the Cross-Half Lap Joint presents itself as the most structurally optimal choice.

Based on the previous numerical analysis, the T-joint will be excluded from further research consideration as its overall CNC manufacturing performance, assembly, and structural capacity seem inefficient for any application.

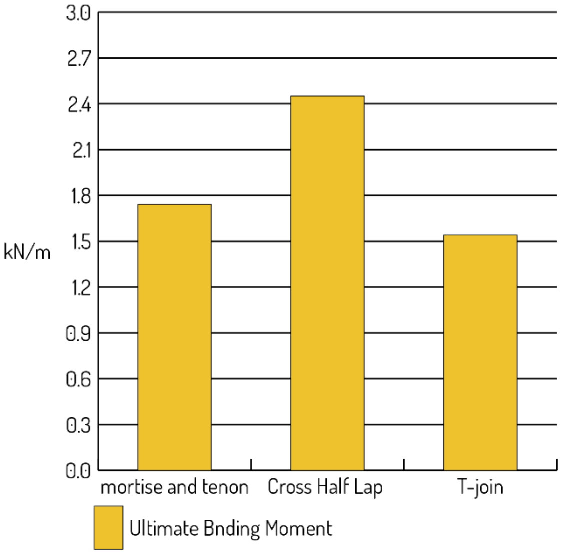


Figure 112 Ultimate Bending Moment Capacity

STRUCTURAL ANALYSIS BUILDING ELEMENTS

STRUCTURAL ANALYSIS OF WOOD BEAM

Beam Dimension

Based on the beam total load calculation is possible to make a dimensioning and mechanical analysis of the main beam elements as well as understanding the joint ultimum bending moment. The result of this assessment would dictate the cross-section of beam floor elements. The characterization of this sections inform the wood-to-wood joint capacities to transfer loads, as well as the weight of the building elements.

The considerations of structural regulations were taking following the recommendations of Eurocode number 5, due to the lack of documentation regarding Colombian wooden structures.

Beam Total Load

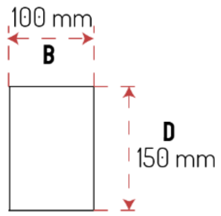
$$W = 1.24kN/m^2 \cdot \frac{2440}{1000} = 3.03kN$$

$$N = 3029N$$

$$N = \frac{3029N}{2440} = 1.24N/mm$$

Second moment of inertia – calculating an optimal cross-section

To proceed with the displacement calculation two fundamental factors are pre-design dimensions and design to support the loads. First, the second moment of inertia of the beam based on a two-pin connection support strategy which will be used in the house.



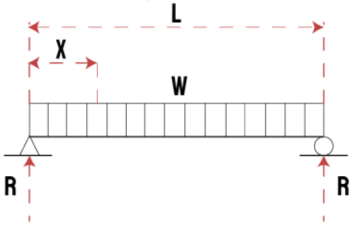
$$I = \frac{b \cdot d^3}{12} = \frac{100mm \cdot 150^3 mm}{12} =$$

$$I = 28125000mm^3$$

MATHEMATICAL PROOF OF FLOOR BEAM DISPLACEMENT

After the Load determination, and the pre-dimension of a beam cross-section base on the type of support, we proceed to calculate the maximum displacement of the beam base on five aspects. The length of the beam (**L**), the Load of the element determined by the building codes, and the type of sue (**W**), the Unit Load (**P**), the modulus of elasticity of the material, in this case Quercus Robur Oak hardwood (**E**), and finally the second moment of inertia (**I**), as described in the beam diagram.

BEAM DIAGRAM



CONDITIONS

L: 2440 mm
W: 3029 N
P: 1.24N/mm
E: 22780
I: 28125000 mm4

$$w_{\max} = w(\frac{L}{2}) = -\frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I}$$

$$w_{\max} = w(\frac{L}{2}) = -\frac{5 \cdot 1.24N/mm \cdot 2440^4 mm}{384 \cdot 22780N/mm^2 \cdot 28125000mm^4} =$$

$$w_{\max} = -0.89mm$$

NUMERICAL SIMULATION

After the calculation is determined, a beam displacement in the Z axis predicts a -0.89 mm. For this research purpose, this values is considered optimal as there is an overmentioned of the elements due to safety factors apply in the Load analysis. In conclusion, the 150mm x 100 mm cross-section is ideal for the type of design.

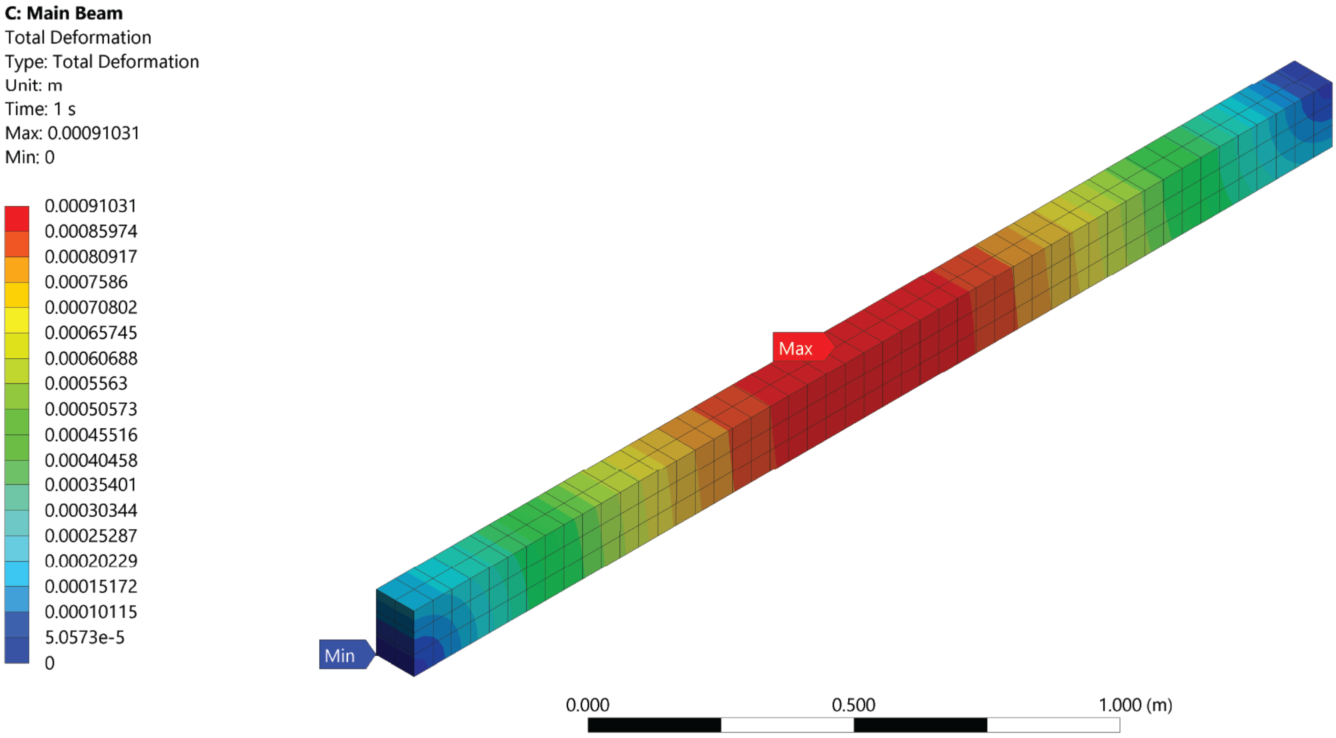


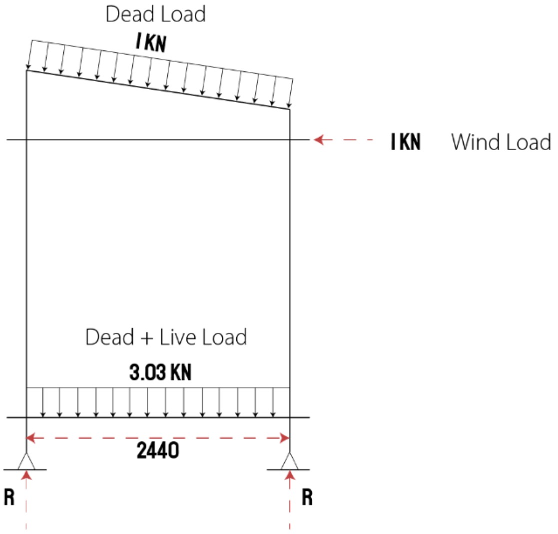
Figure 113 Structural analysis Beam deformation

SIMULATION OF THE BENDING MOMENT STRUCTURE

The assessment of load and cross-sectional properties enables a comprehensive study of the joint's moment capacity, providing valuable insights into the system's capabilities. By integrating the previously calculated parameters and replicating the material properties in a numerical simulation, we can ascertain the system's ultimate performance.

In this simulation, it is evident that the maximum bending moment for the joint reaches an 1582.9 N/m or 1.58 kN/m. This significant moment capacity underscores the structural robustness and reliability of the wood-to-wood joint, using a cross-section of 100x150mm.

MOMENT DIAGRAM



The numerical simulation not only validates the theoretical calculations but also reinforces the practicality and strength of the joint, making it a compelling choice for structural components in the construction industry.

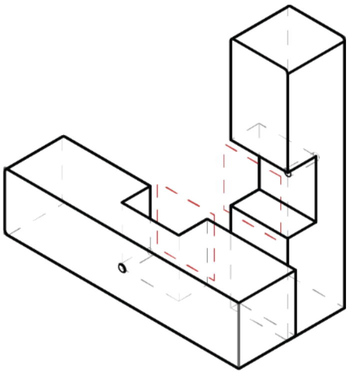
$$M = \frac{97.1N / mm^2 \cdot (50mm \cdot 150mm^2)}{6} =$$

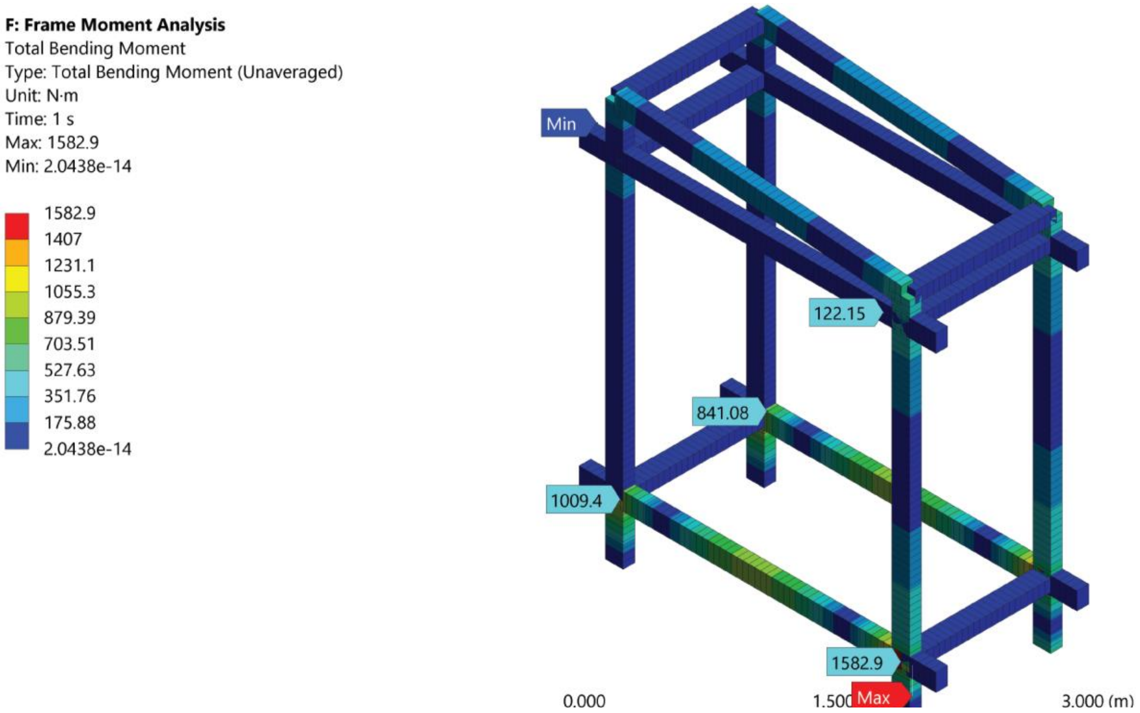
$$M = 18.20Kn / m$$

If we assumed element cross-sections are designed as 100mm x 100 mm. The joint capacity will still be in the optimal performance range.

$$M = \frac{97.1N / mm^2 \cdot (50mm \cdot 100mm^2)}{6} =$$

$$M = 8.1Kn / m$$





F: Frame Moment Analysis
Total Bending Moment
Type: Total Bending Moment (Unaveraged)
Unit: N·m
Time: 1 s
Max: 1582.9
Min: 2.0438e-14

Figure 114 Ultimate Bending moment Joint Analysis

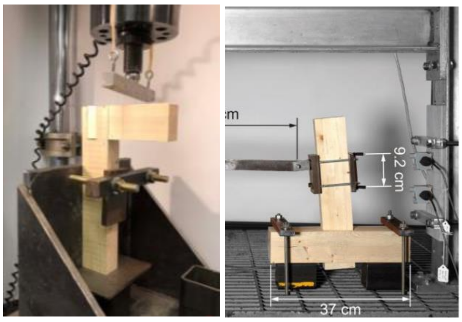
MOISTURE INDUCE

MECHANICAL TESTING OF MATERIAL IMPACT IN THE JOINERY PERFORMANCE

EXPERIMENTATION METHOD – P2

TYPE OF JOINERY

Step 1: The identification of structural parameters in relation to the final objective is distinguished from the literature research. Consequently, the following steps to achieved wood-to-wood connection will further implement structural analysis in relation to (1) tight-fit contact area to transfer shear forces, (2) unidirectional perpendicular to the grain direction of wood connections (3) rotation stiffness, (4) characterizations of joint assembly. To arrive at a conclusion First, using the Finite element stipulate by (Fang & Mueller, 2018) the actual load deformation, or moment – rotation of some alternative will be study. This experimentation can be proof in an actual tension compression test similar to the one present in (Fang et al., 2019) (Tanahashi & Suzuki, 2015).

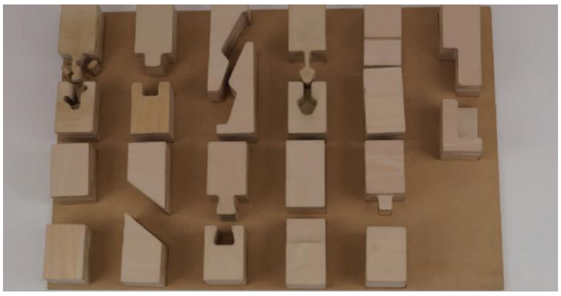


MATERIAL

Step 2: In the preliminary research of material properties, 8 potential samples were identified from the commercial forestry industry. Among the most command species soft and hardwood types can be selected for the catalogue. the following stage is based on Research - by -prototyping conditions. In this matter, as seen from Fig 32. Using European wood, with similar conditions to the Colombian parameters, an assessment of milling performance will be organized. The main porpoise of this experimentation aims to determine optimal material constrains, density, hardness in relation to milling speed, definition of 45-degree angle constrains, tolerances for assembly and volumetric shrinkage. Using two baches of the same detail assemble in three different scenarios:

1. Right after milling.
2. Two days after milling.
3. One week after milling.

Using simple mortise and tenon details. The specification of a joint is not necessary in this stage, the material properties of fitting system and generalization of the tolerances is the most urgent necessary data.



For this experimentation, a 3-axes CNC equipment will be use from TU Delft the additional objectives of this experimentation aims:

1. Define working conditions, high and width limitations.
2. Establish an operation system of 0.0 later system of different heights to model the prototypes. (for this process a rhino + grasshopper will be use)
3. Create a tooling catalogue of mills to stablish the most versatile and appropriate for resistance / performance efficiency.

ASSEMBLY LOGICS

Step 3: Depending on the results of stage 1 experimentation, a typo detail will be used to stablish a global connection system of post and beams using the parameters identify in section 4:

11. The relevance of **scale** in structural components minimizes the number of people in the construction process.
12. urgency to simplify and typify **interlocking details** to speed up the building process.
13. Development of **modules** that facilitated unit transportation, handling, and assembly.
14. Implementation of **Local materials** provided by the industry and the site.

Moreover, further exploration of the architectural definition, forms and components is necessary to determine the general structure.

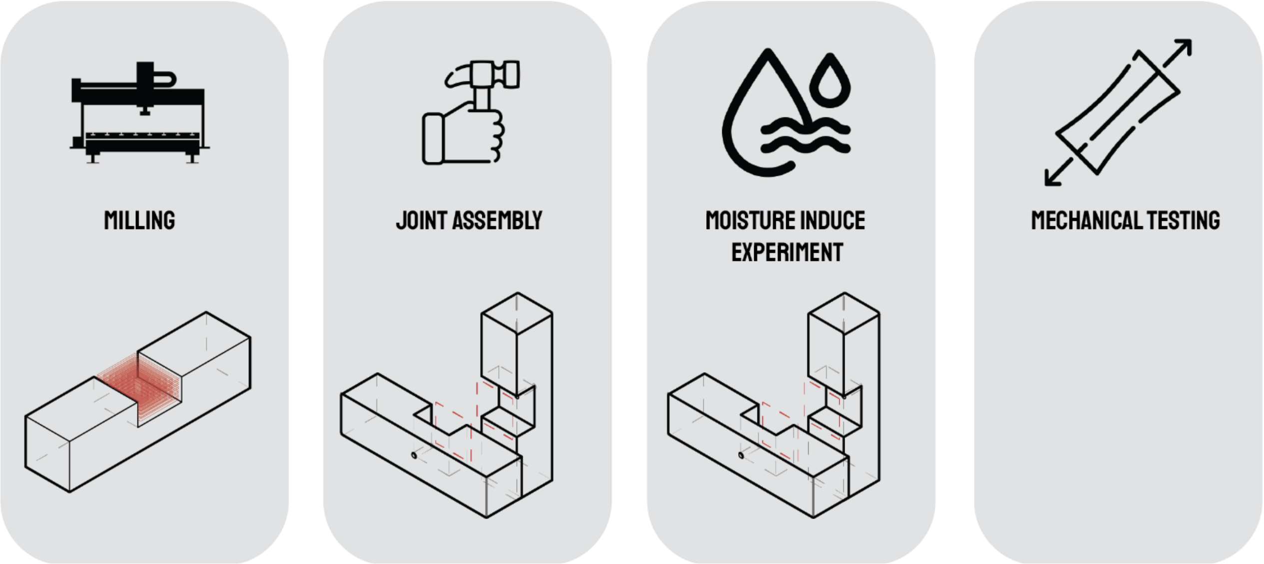


Figure 115 rout planning for moisture induce wood joints

16. EXPERIMENTATION PROCESS OF MOISTURE INDUCE WOOD JOINTS

Figure 116 Mositure Induce Wood Connections Testing Set Up

To assess the influence of high relative humidity on the interlocking capability, a follow-up experiment will be conducted, keeping the same protocols as the initial material exercise. The objective of this testing is to simulate environmental conditions at 60%-65% relative humidity, which is the anticipated production and assembly environment. Subsequently, after subjecting the samples to a moisture-inducing process at a constant relative humidity of 85%, it is expected that all joints will securely lock into the assembly, creating a more efficient and tightly fitting detail. This, in turn, is anticipated to result in improved performance under tensile and compression stress conditions.

SPECIMENS AND EXPERIMENTAL VARIATION

For this experiment 6 Douglas Pine specimens were produced at TU Delft University: 2 Mortise and tenon, 2 Cross half-lap, and 2 T-joints joinery connections as depicted in table 7. Each Specimen will be exposed to two different RH scenarios to compare and validate the theory of volumetric swelling proved in the first material experiment.

Table 7 Sample Batch for experimentation

joint	*Specimen variation*	*Climate Chamber*
Mortise and Tenon	M - RH 65 %	
	M -RH 85 %	Moisture Induce
	M -RH 65 %	
	M -RH 85 %	Moisture Induce
Cross Half-Lap	H - RH 65 %	
	H - RH 85 %	Moisture Induce
T-Joint	T - RH 65 %	
	T - RH 85 %	Moisture Induce

FIBER DIRECTION

Most of the specimens maintained the tangential fiber direction. However, in the case of the Cross-Half Lap joint, one specimen had the beam fiber direction parallel to the grain, while the other samples had specimens with fibers perpendicular. This decision aims to demonstrate the impact of fiber direction on structural performance as well as interlocking optimization.

Mortise and tenon

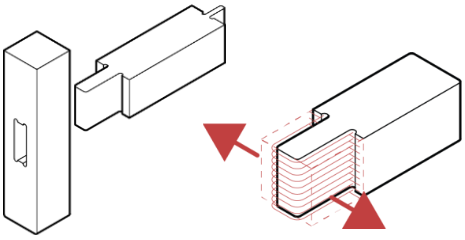
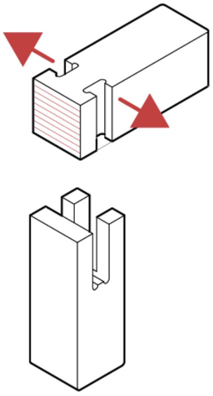
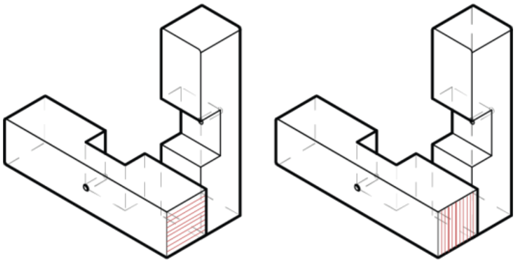


Figure 117 Tenon Fiber Direction

T-joint



Cross Half Lap



FIBER MOISTURE CONTENT – WOOD JOINTS

Figure 118 Cross- Half Lap Moisture Content

The initial moisture content of Douglas mortise and tenon, as well as Cross half Lap joints presented 10.5% Moisture content. After a constant exposure of 85% RH for three weeks values the wood cell reached 18.60% MC and approximately +- 0.5 mm of swelling tolerances, similar to experiment number one.

LABORATORY SET UP – TENSILE TEST:

Laboratory of material and mechanics of 3ME faculty – TU Delft University:

In this experiment, we aim to evaluate the ultimate bending moment capacity of moisture induce wood-to-wood connections using a Zwick Roell static material testing machine with a maximum testing capacity of 100 Kn. The laboratory equipment includes a small anchorage steel platform system measuring 400 mm by 400 mm. To conduct the experiment, all samples will be securely attached to this plate using two main anchorage systems based on the type of mechanical testing. The goal of this exercise is to accurately compare the characteristic specifications of each specimen described in the following.

By employing this setup and equipment, we aim to accurately prove the ultimate bending moment capacity already calculated in the numerical and mathematical model. Secondly, determine the influence of moisture induces in the wood connections as a mechanism of assembly and interlocking, which will be examinate by the tensile test in the several specimens.

1. Influence of moisture induce wood joinery connections at tension force apply to
2. Ultimate bending moment capacity at compression test
3. Fiber direction affects structural performance, as well as the moisture interlocking mechanism.

TENSILE TEST MORTISE AND TENON – SET UP

A tension test was performed in the mortise and tenon specimens, a clamp system for tension tests. Following the setup depicted in the provided image.

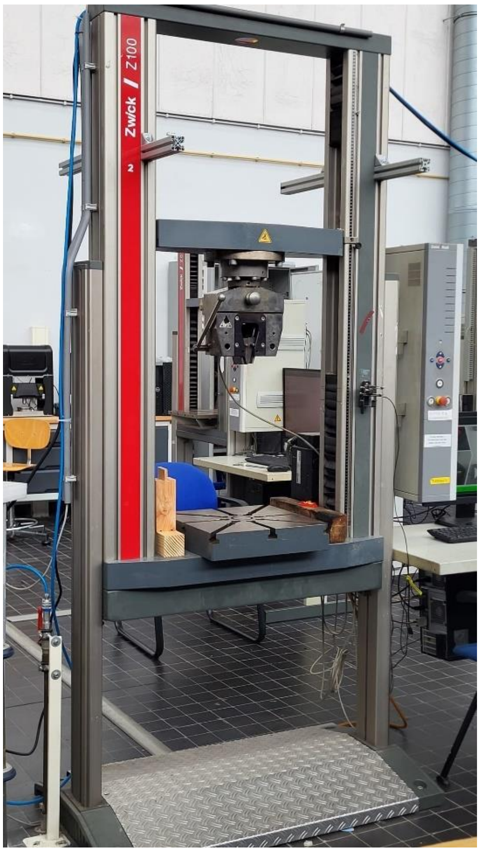


Figure 119 Equipment Zwick Roell static material machine

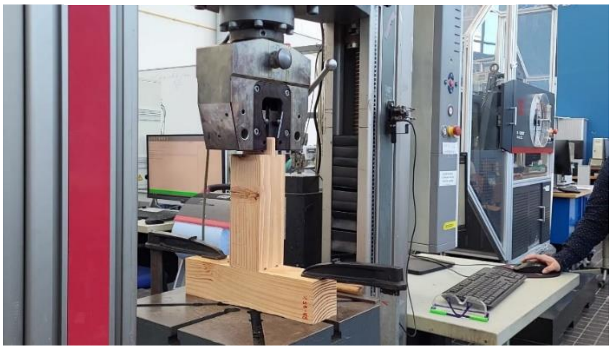


Figure 120 Tension Test capacity of Mortise and Tenon Joints

Joint	*RH*	*Climate Chamber*
Mortise and tenon	M-RH-65%	
Mortise and tenon	M-RH-85%	Moisture induce

Figure 121 Results of mechanical testing om ,prtise and teno to tension stress

RESULTS

An outstanding result reveals the potential of relative humidity effects integrated into the design and production method of prefabricated wood households. The optimization in structural capacity of Mortise and Tenon joints under tensile stress due to wood cells swelling can be seen in Figure 121. Both prototypes present in this experiment were identical in physical characteristics in dimensions, as well as fiber direction.

In the graph, it is possible to see rather different mechanical behaviors. On one hand, the specimen exposed to a constant moisture stress environment of 85% Relative Humidity presented a load resistance to tensile stress of about (1300 N). Contrary to the significantly lower value of the control batch of about (700N), which under constant room conditions poorly performed in tensile capacity. This first approximation showed a structural performance improve of about 50% compared to traditional joinery connections.

As predicted from the material experiment, significant tangential swelling impacted the tight-fitting behavior of the joint, resulting in superior performance.

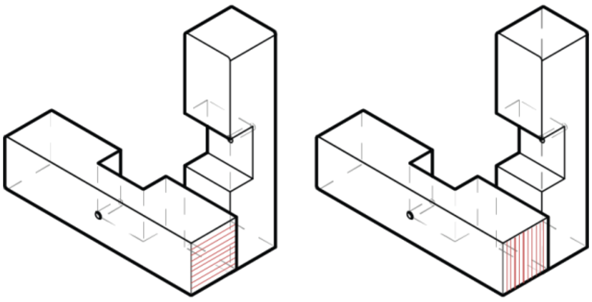
Figure 122 Mortise and tenon maximum displacemnet

COMPRESSION SET UP – CROSS-HALF -LAP

For compression tests of the Cross – Half Lap Joint a pin connection was developed to perform the test, Using a 8 mm bolt bar in combination with a 4 mm caliper L-profile the joints is anchorage to the steel table.

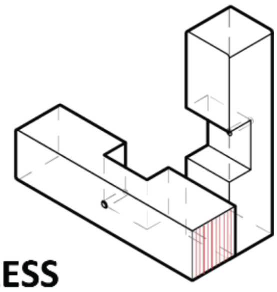
Figure 123 Cross -Half Lap joint Under Compression

As previously mentioned, a variation of this test was performed to measure structural impact of beam elements under fiber direction considerations, evaluating parallel and perpendicular grain. Thus, two semi-identical prototypes were measured under constant compression strength. The specimen in yellow presents a beam perpendicular to the grain. And therefore, is possible to see failure in the limit of (14000 N). On the contrary, the spciment with grain direction parallel to the grain shoed higher structural resistance to compression strength, with about 1850 N of Load pressure limit.



CONCLUSION

In the design integration of beam elements as well as Joinery connections the tangential side represents the best interlocking performance. coincidence this configuration is parallel to the grain direction, meaning that the orientation of Structural Beam elements will present a far superior performance in the interlocking process as well as the total deformation of the element.



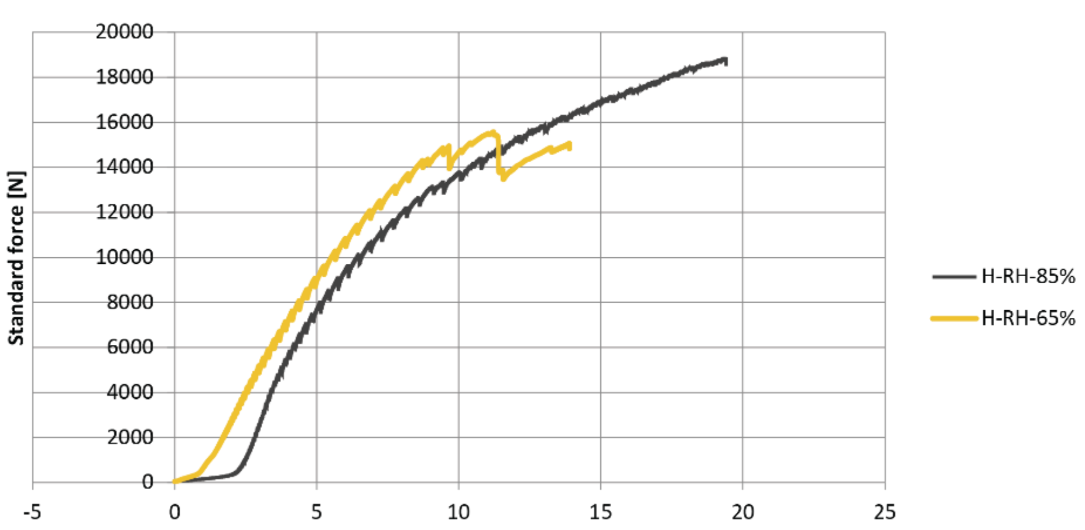


Figure 124 Cross- Half lap compression test result - Douglas Pine samples

MOISTURE EXPERIMENT – CROSS HALF LAP (QUERCUS ROBUR – OAK

Figure 125 Climate chamber Cross- Half Lap

The Cross-half lap joint is selected as the optimal wood to wood connection due to the structural capacity, as well as the efficient manufacturing CNC production process in comparison with other wood connections previously studied such as mortise and tenon and T-joints.

This Final experiment aims to test the hypothesis proof in experiment 1 were small samples tested to moisture stress revealed; where Oak shows to be the most successful material for the volumetric change, as it had the higher change values in mm. Thus, the experiment uses the selected Joint and the selected material to prove the benefits of interlocking connections using increment of environmental humidity as assembly strategy.

SPECIMENS AND EXPERIMENTAL VARIATION

For this experiment, ten Cross Half Lap joints were produced, with three points of variation aimed at determining the optimal conditions for the building system. These variations included the fiber direction, moisture content, and milling path configuration.

FIBER DIRECTION:

Each Cross Half Lap joint was created using two reference elements, denoted as the "column" and the "beam," as indicated in the table. In all prototypes, the column was positioned on top of the beam, where tangential and radial elements were manufactured to measure the effectiveness of dimensional changes in creating additional pressure within the joint.

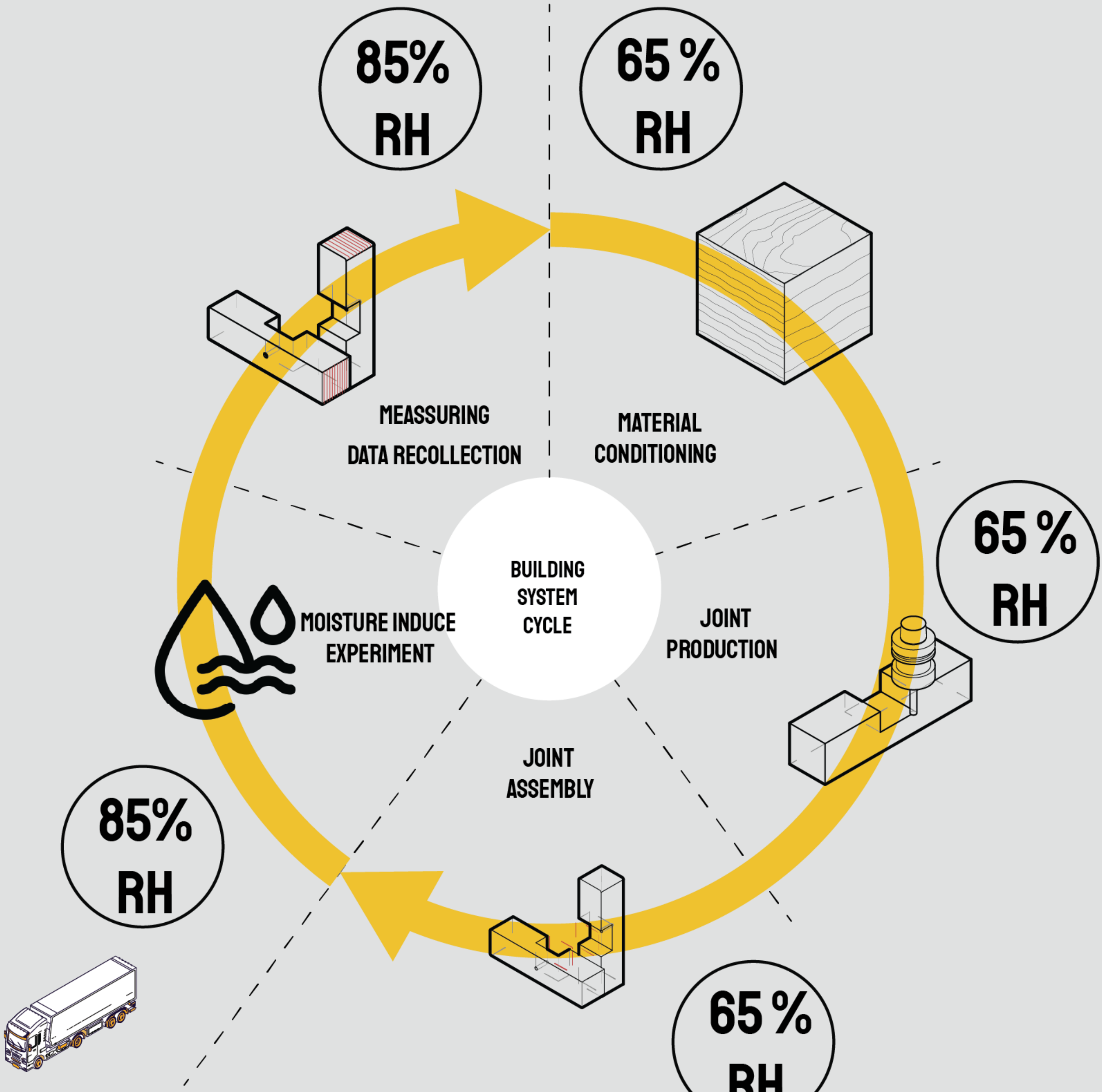
MOISTURE CONTENT

As you can see in the table below, Half of the joints were in a dry state with 11% moisture content represented with the blue tag on the table. The other half, corresponding to the red tag, were partially wet beams with a moisture content of 18%.

PRINCIPLE

The goal of this final test, which subjected structural wood beams to changes in relative humidity of delta values about 20%, aims to establish standard tolerance for assembly applications. The variety of specimens were manufactured with several iterations in fiber direction and tolerances. This analytical model will demonstrate the effectiveness of the swelling moisture process to increase the Tensile strength capacity. results of this test will be implemented in structural application for wood-to-wood interlocking connections of Cross-Half Lap constructions.

Figure 126 Cross Half Lap speciments for Tensile Test


85% RH
65 % RH
MEASSURING
DATA RECOLLECTION
MATERIAL
CONDITIONING
65 % RH
BUILDING
SYSTEM
CYCLE
MOISTURE INDUCE
EXPERIMENT
JOINT
PRODUCTION
JOINT
ASSEMBLY
85% RH
65 % RH

THE GOAL OF THE FINAL EXPERIMENTATION

This joint will be subjected to tensile stress conditions for evaluation. The objective of this examination is to illustrate the impact of moisture-induced processes on improving the performance of Cross-Half Lap joints under lateral forces. The ultimate goal and significant scientific contribution of this master's thesis are to demonstrate a significantly enhanced structural performance achievable by considering relative humidity in the prefabrication of wood structures, when these considerations are integrated into the manufacturing and assembly processes.

EXPERIMENT SET UP:

In order to accurately measure the pure tight-fitting resistance of the Cross-Half Lap joint under tensile stress, a specific test was designed to assess the capacity of the intersection point. Given the unconventional nature of this experimental method, it was necessary to fabricate a fixed-pin connection to securely pull one beam away from the other beam during the test.

Figure 127 Tensile test of Cross Half Lap Joints

The clamps are anchored on each side of the machine to hold the bottom half-lap beam securely against the steel plate. Additionally, a stainless steel tubular profile is utilized to exert equal tensile pressure on both sides of the beam from the bottom. Furthermore, there is a pin connection at the central axis of the beam, attached to the equipment, which evenly pulls the beam during the test.

QUESTIONS TO BE ANSWER:

As previously explained, two sets of groups were manufactured, and the following conditions are under evaluation:

The influence of initial moisture content on the interlocking performance of the joint, specifically, whether low moisture content (MC) is better than high MC.

The preparation and precision of wood beams: The red group features beams that are perfectly square with dimensions within a tolerance of +- 0.0, measuring close to a 67 x 67 mm cross-section. In contrast, the blue group is less machined, with beams having a tolerance of +- 1.5 mm (although variations exist in each piece). Therefore, the question at hand is flexibility in material preparation. Can less machined and less precisely prepared beam elements be employed in the manufacture of tightly fitting joinery connections while achieving comparable results?

Figure 128 Cross - Half Lap Set Up pin connection

RESULTS

The experimental test of the Cross-Half Lap joint can be considered a resounding success and a significant contribution to the field of science. The findings regarding grain direction, tolerances, and moisture content provide valuable insights into the influence of relative humidity on interlocking wood-to-wood joints.

Tolerances

A clear distinction is evident between the two groups in the graph. The BLUE group exhibits significantly lower tensile stress resistance compared to the RED group. It's important to note that the RED group features tight-fitting connections, thanks to its manufacturing precision with error tolerances of 0.0. In contrast, the BLUE group has tolerances ranging from +-0.5 to 1.5 mm, resulting in considerably looser joints. This distinction is clearly reflected in the graph, with BLUE group results clustered at the lower end.

Grain direction

Another intriguing outcome of this research is the comparison between tangential and radial grain directions in conjunction with the Cross-Half Lap joint.

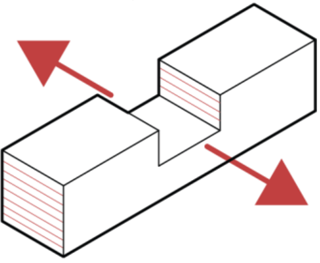


Figure 129 Cross Half Lap Tangential Direction

As depicted in Figure 129, the tangential grain direction leads to swelling, creating greater compression and a tighter connection in the joint's cross-sectional areas. When two elements with the same configuration are combined, it can be predicted that this joint will exhibit superior tensile performance compared to the other samples.

This hypothesis is supported by the graph below, which demonstrates that specimens Red 5-6-65% and RED-7-8-85% exhibit the highest tensile stress resistance within the batch.

Moisture Induce Process,

Lastly, the impact of moisture induction can be examined. As previously mentioned, the two top-performing samples (Red 5-6-65%) and (RED-7-8-85%) were produced under identical conditions, with both featuring tangential grain orientation for a tight joint fit. However, a comparison between these two specimens highlights the advantages of moisture induction.

As shown in the graph Figure 131, the specimen exposed to 85% relative humidity for a constant two-week period validates the effectiveness of this process in enhancing the joint's performance.

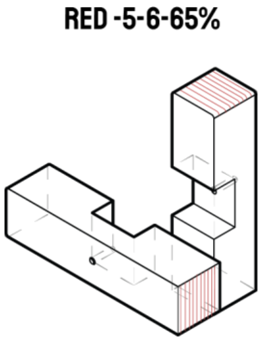


Figure 130 Red 5-6-65% no moisture stress

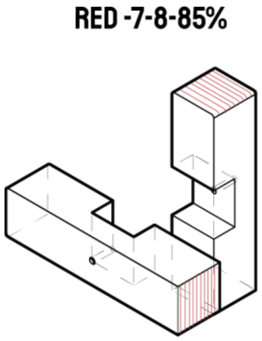


Figure 132 Red 7-8-85% Moisture Induce

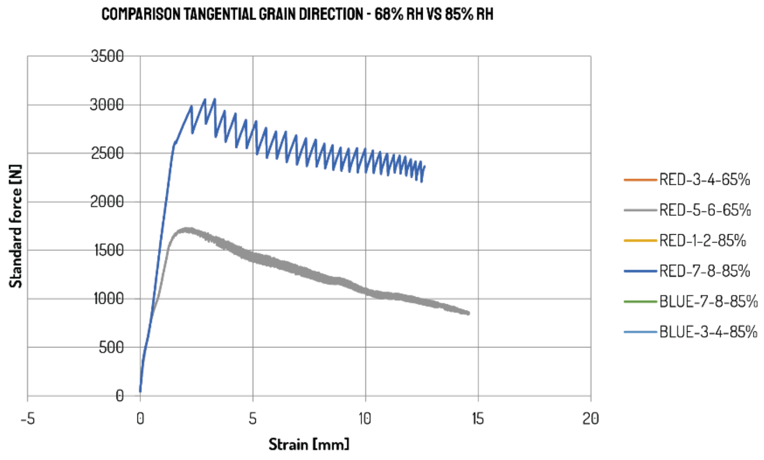


Figure 131 Comparisson Mositure induce

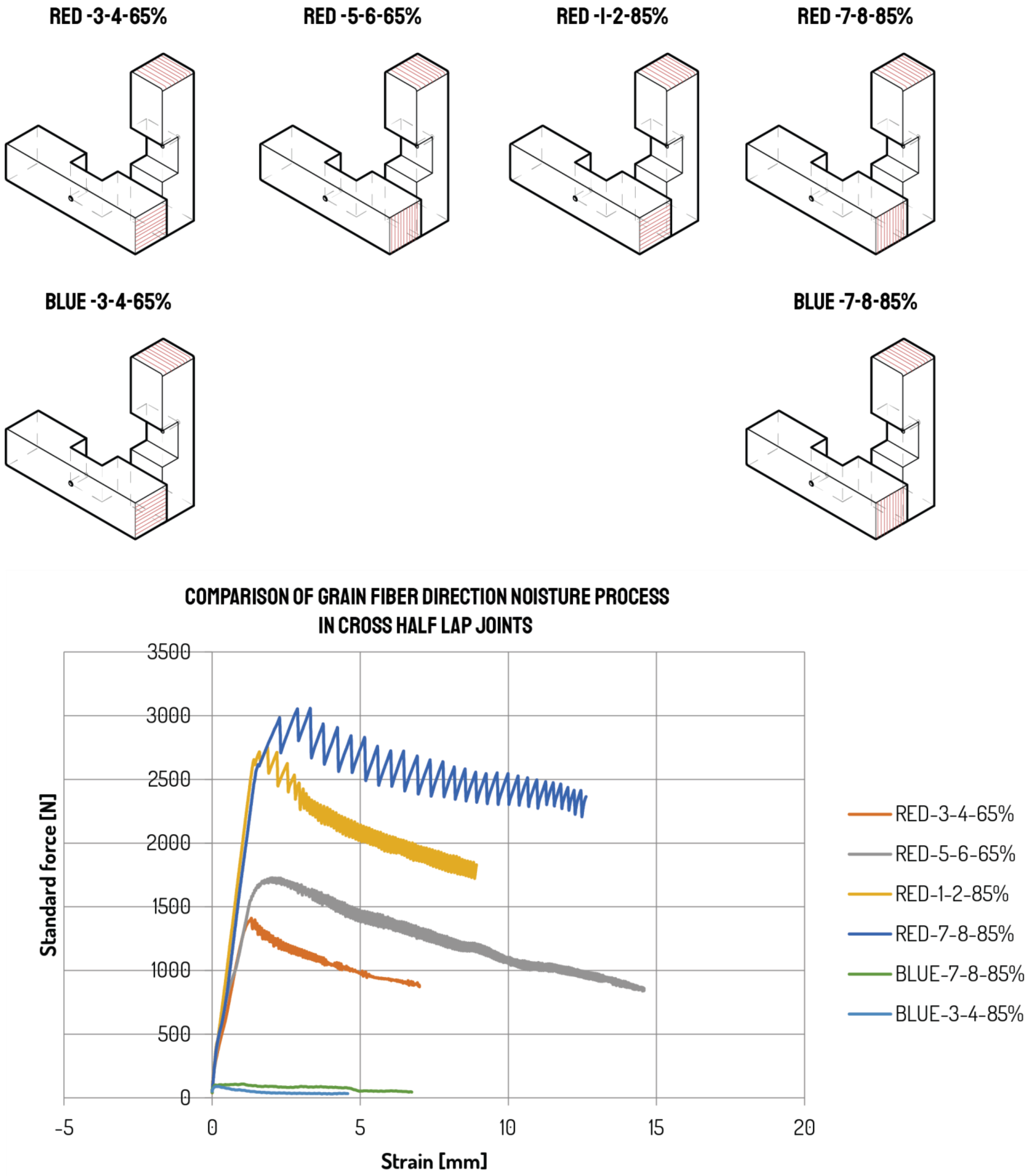


Figure 133 Tensile Test Result of moisture induce Cross Half Lap joints

LIST OF MATERIALS AVAILABLE - CROSS HALF-LAP

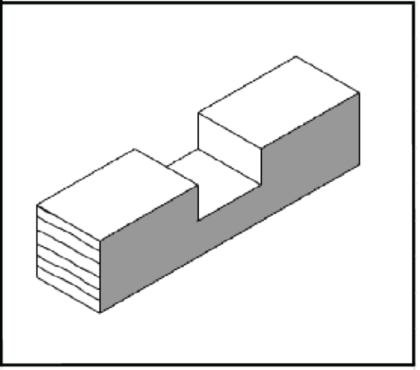
PLANED BEAMS - GRAIN - 18%

#	CROSS - SECTION	LENGTH	MOISTURE CONTENT	GRAIN DIRECTION	CHECK LIST	ELEMENT	JOINT GRAIN DIRECTION	PRODUCITON	HUMIDITY
1	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	
2	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	60%
3	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	
4	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	85%
5	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	
6	67 x 67 mm	400 mm	18%	Tangential		Beam	II - Tangential	0:02:47	60%
7	67 x 67 mm	400 mm	18%	Tangential		Column	II - Tangential	0:02:47	
8	67 x 67 mm	400 mm	18%	Tangential		Beam	II - Tangential	0:02:47	85%
9	67 x 67 mm	400 mm	18%	I - Radial		Column	I - Radial	0:02:47	
10	67 x 67 mm	400 mm	18%	I - Radial		Beam	I - Radial	0:02:47	60%

NO PLANED BEAMS - II GRAIN - 10.5%

#	CROSS - SECTION	LENGTH	MOISTURE CONTENT	GRAIN DIRECTION	CHECK LIST	ELEMENT	JOINT GRAIN DIRECTION	PRODUCITON	HUMIDITY
1	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	
2	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	60%
3	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	
4	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	85%
5	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	
6	65 x 67 mm	400 mm	11%	Tangential		Beam	II - Tangential	0:03:33	60%
7	65 x 67 mm	400 mm	11%	Tangential		Column	II - Tangential	0:03:33	
8	65 x 67 mm	400 mm	11%	Tangential		Beam	II - Tangential	0:03:33	85%
9	65 x 67 mm	400 mm	11%	I - Radial		Column	I - Radial	0:03:33	
10	65 x 67 mm	400 mm	11%	I - Radial		Beam	I - Radial	0:03:33	60%

II - Tangential



I - Radial

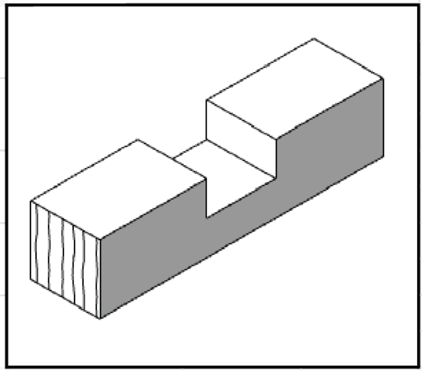
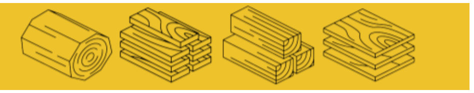


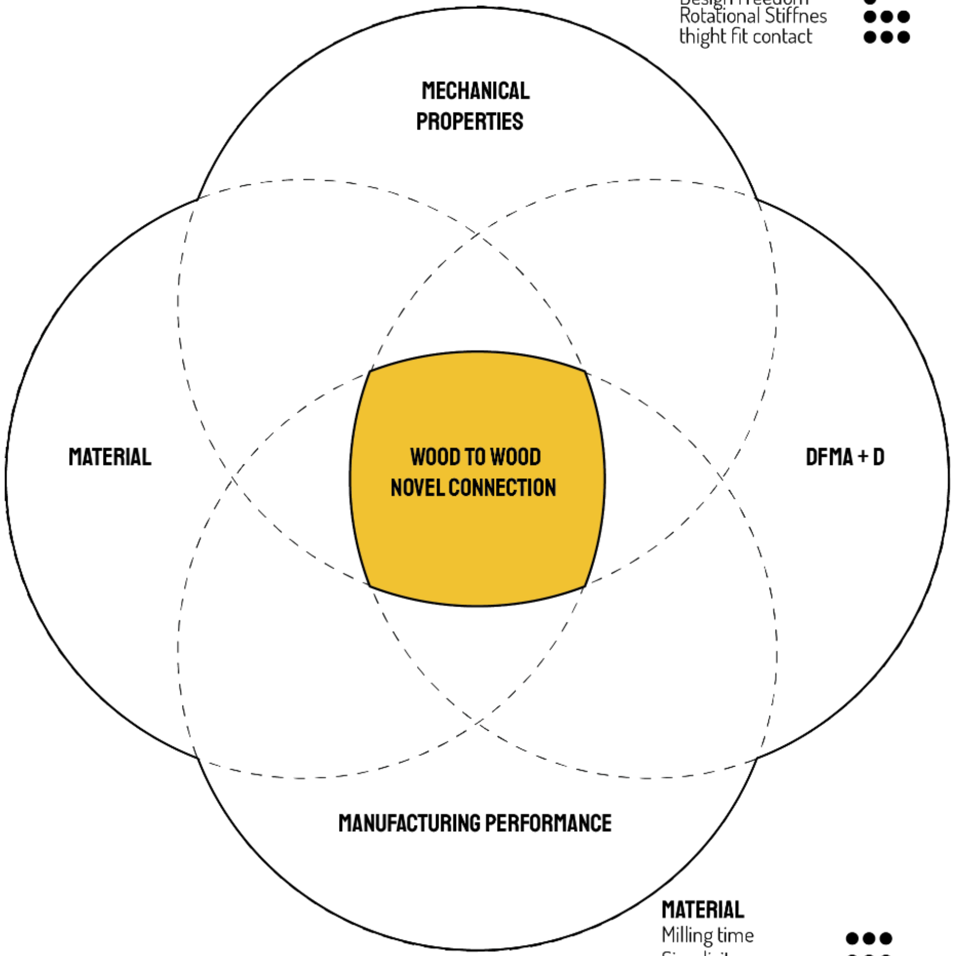
Figure 134 experimentation group, MOisture induce Cross -Half Lap joints



CONNEECTION TYPE

ASSEMBLY	
Speed	●●
Interlocking	●●●
Dis-Assemblly	●●●
Herarchy	●●
Modularity	●●
Design Freedom	●
Rotational Stiffnes	●●●
thight fit contact	●●●

MATERIAL	
Price	●●
Density / strenght	●●●
Volumetric shrinkage	●●●
Fungal Decay	●●●
weight	●●●
Moisture behaivour	●●●
Hardeness	●●●



ASSEMBLY	
Speed	●●
Simplycity	●●●
Unexpirience Labour	●●●
Herarchy	●●
Modularity	●●●
Design Freedom	●

DIS-ASSEMBLY	
Speed	●
Simplycity	●●●
Unexpirience Labour	●
Herarchy	●●●
Modularity	●●
Design Freedom	●

MILLING

MATERIAL	
Milling time	●●●
Simplicity	●●●
Rotation corrections	●●●
Service Are	●●●
hight	●●●
Stabilisation	●●●
Hardeness	●●●

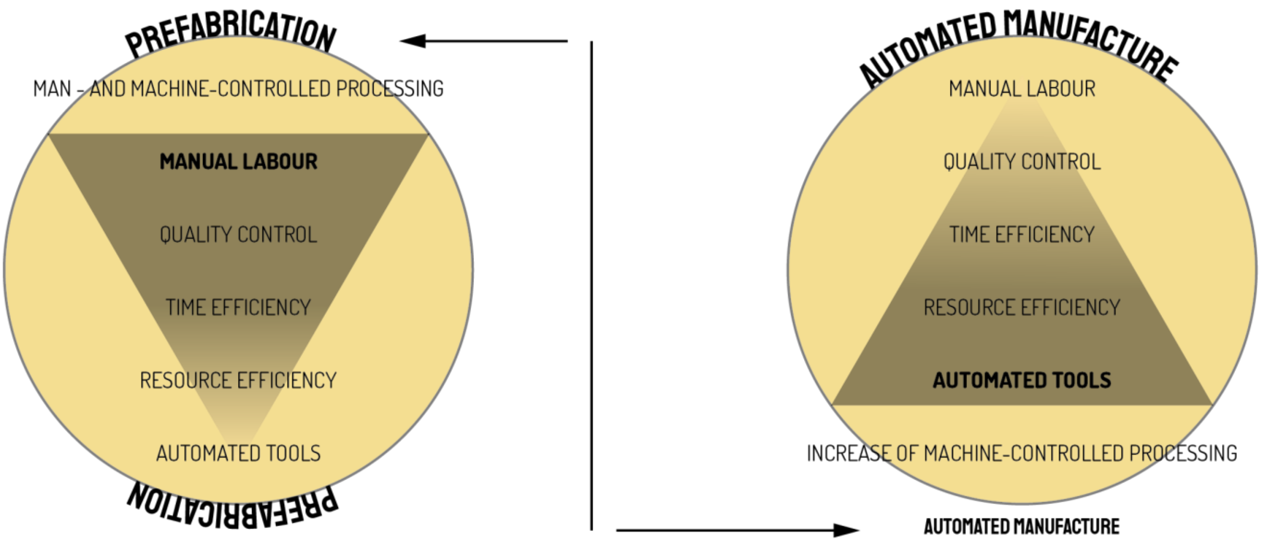
Figure 135 Parameters of design and implementation of novel connections

DESIGN

APPLICATION OF TECHNOLOGY IN A LATIN AMERICAN CONTEXT

AUTOMATED MANUCATURE FOR PREFABRICATION

STRUCTURAL MODULE



Construction and Design manual- Prefabricated housing Vol. 1. DOM-Publishers. www.dom-publishers.com

The idea of autonomous construction housing could be the solution to improve the living conditions of rural areas as approach to the social and environmental crisis. The urgent implementation of a rapid construction and assembly process can be empower by the use of prefabricated and automated buildings, making planning and construction more efficient, and therefore, more economical (Albus, 2018).

DEFINITION

According to Albus (2018), author of the book "Construction and design Manual Prefabricated housing", there is a distention between prefabrication and automated construction. The first terms refer to the process of constructing parts before assembly in an Off-site location, consequently, reducing the workload in an On-site construction. Nevertheless, this definition does not specify the production method that is implemented, or the labor demand necessary to produce these components in house (Albus, 2018). On the other hand, automated construction refers to the process that involves controlled digital production using automated tools during fabrication or construction. The use of machine-based processes and digital control fabrication minimize the amount of manpower required, while at the same time increasing production quality.

PRE-ASSEMBLY

The success of prefabrication is rooted in the standardization and pre-assembly of building elements. This approach establishes an efficient model by encompassing a range of production scales. According to a study by (Barlow et al., 2003), standardization serves three key purposes in the manufacturing sector. Firstly, it ensures complete and consistent interchangeability of parts, as well as the simplicity of attaching one part to another. Secondly, it creates a universal connectivity logic within the manufacturing process, driven by savings in assembly time and costs. Lastly, it enhances the predictability of both production and processes.

Conversely, pre-assembly involves breaking down construction into segments during the production process. This permits the distribution of tasks related to subassemblies and components across various departments or alternative supply chains in the industry, leading to advantages in quality control and cost-effectiveness (Barlow et al., 2003). In the construction field, this approach is exemplified by strategies such as minimizing the number of joints to ensure a more durable system and enhance assembly efficiency. Consequently, utilizing a smaller quantity of parts helps avoid defects.

THE BUILDING SYSTEM

STRUCTURAL MODULE

I. SUB-QUESTION

One of the sub-questions this research aims to answer is regarding climatological conditions in combination with building process:

Could a construction system create an Off-site production of prefab housing elements and an On-site assembly method that responds to the high humidity variables affecting moisture stability and, ultimately, assembly effectiveness of wood construction in Colombia's rural areas?

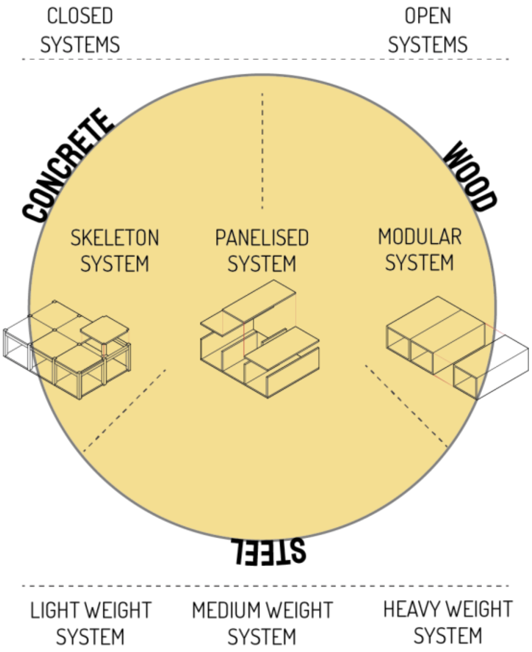
BUILDING CATEGORISATION

The initial step in addressing the opening sub-question involves comprehending the fabrication and construction processes inherent in the modular building industry. Building upon the research conducted by Juta Albus, which delves into the evaluation of industrially manufactured building systems, it is possible to establish a framework for classifying building systems. This classification arises from a methodical categorization of typological, structural, construction, and material attributes.

Consequently, in line with author's findings, the primary differentiation stems from the adaptable opportunities presented by the construction system, classified as either a closed or an open building system. The first refers to a self-contained construction approach wherein parts and components are designed for compatibility within a specific solution. Conversely, the second concept permits the interchangeability of parts or components, thus offering heightened flexibility in both design and planning (Albus, 2018).

DEFINITION OF COMPONENT WEIGHT

Distinction between structural typologies can be categorized in a systematic planning approach referring to the second level in Fig 5. Based on the previous statement there are three broad components systems: skeleton, panel-base, and modular building methods. These components can be further narrowed down based on material weight.

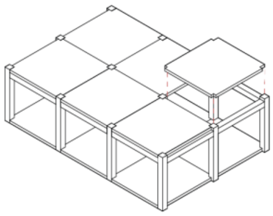


In accordance with the objectives of this research, which prioritize the development of a building system that facilitates effortless transportation, handling, and assembly within rural regions of Colombia, the proposition entails a reliance on lightweight elements. This approach serves to streamline the construction workflow, restrict the demand for an extensive labor force, and minimize the necessity for specialized construction machinery. Materials such as stone, concrete, light steel, metal, and composite concrete-wood elements are excluded from the purview of this research. This exclusion is rooted in the recognition of deficient infrastructure and a scarcity of specialized workforce within the rural locales under consideration.

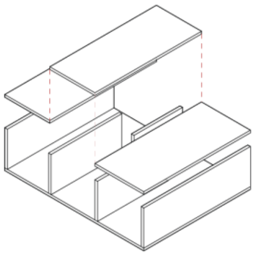
LIGHTWEIGHT SYSTEMS

This system relates to wood or timber elements, light steel components, and composites, selected due to their inherent ease of material handling. The differentiation among structural typologies can be systematically categorized, with a focus on lightweight systems well-suited for frame or panel constructions. This construction method encompasses a structural core, typically composed of timber or steel framing, followed by supplementary layers designed to meet technical, aesthetic, and structural prerequisites (Albus, 2018). The Lightweight of elements makes handling, transport, and assembly process much easier, which in turn improves on-site and off-site construction processes.

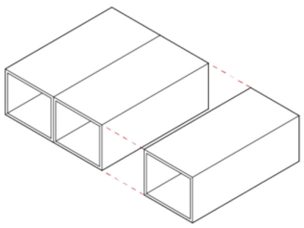
In this study, it is crucial to consider both handling and transportability as fundamental factors when establishing an effective and cost-efficient construction process, whether conducted on-site or off-site. Factors such as the weight of components, the necessary workforce, element dimensions for fabrication, packaging, and shipping constitute requirements that will shape the design process in alignment with these principles.



SKELETON SYSTEM



PANEL SYSTEM



MODULE SYSTEM

PREFABRICATION TYPES AND MODULES

THE HPUSING SYSTEM

WEIGHT REQUIREMENTS

According to the Occupational Safety and Health (OSH) directives in EU member states, weight limits allow a maximum of 30 kg per individual in any work lifting process (DG Employment, 2015). In the Netherlands, a mandatory limit of 23 kg is enforced in alignment with the guidelines set forth by the National Institute for Occupational Safety and Health (NIOSH). These guidelines establish the 23 kg weight limit as optimal under conditions that mitigate health-related risks(Manders, 2009). In light with these directives, the design must align with the legislation requirements and consider the maximum weight of building elements. This involves devising strategies that facilitate the handling of lightweight components into the construction process under.

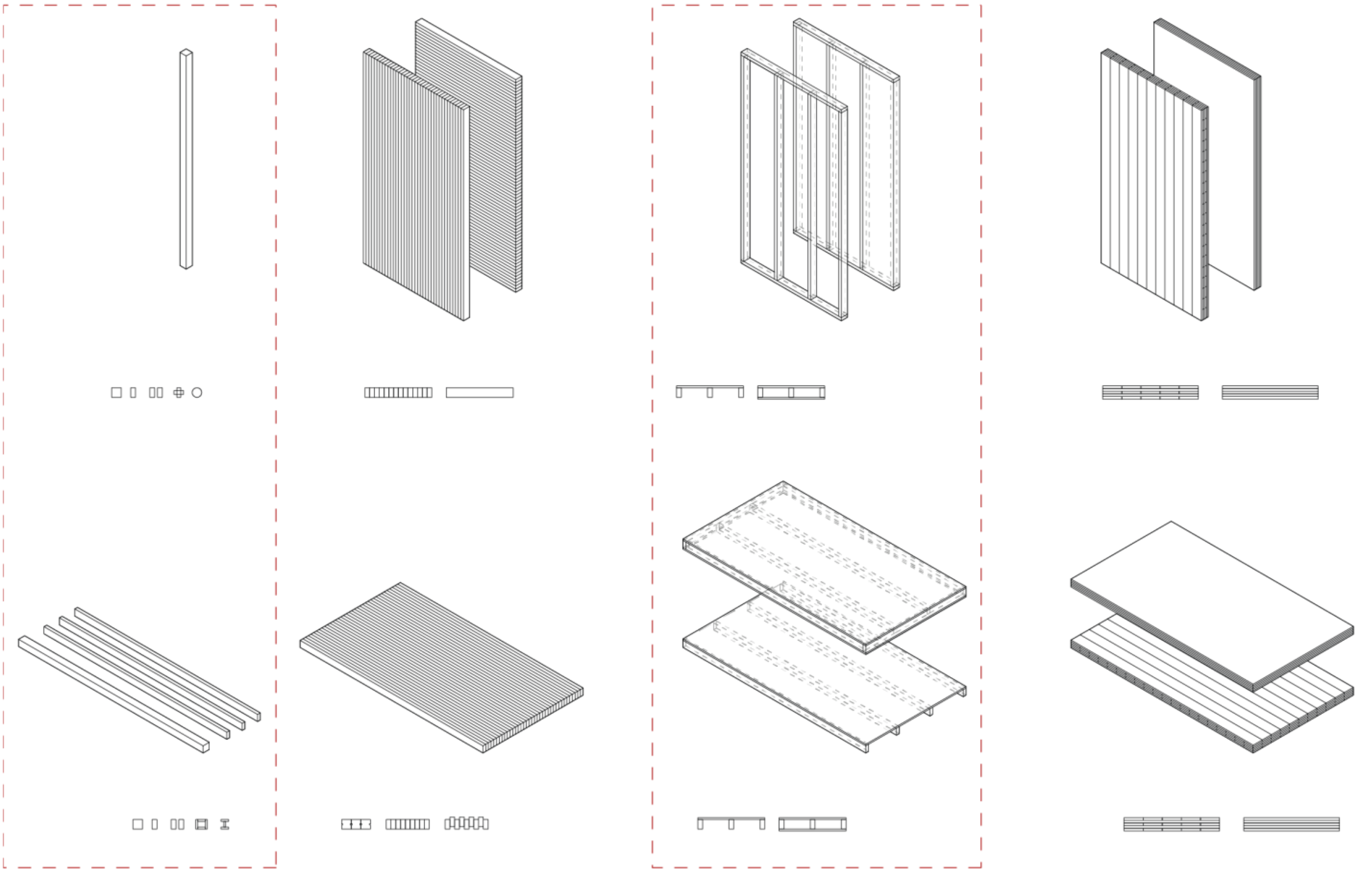
KIT-OF-PARTS / SELF BUILD HOME

A self-constructed dwelling, commonly known as a kit house, offers a highly economical solution for individuals in search of affordability. Within the domain of prefabrication, this method involves substantial client engagement in the construction process, with the manufacturer focusing primarily on fabricating and delivering building components to the site (Albus, 2018).The task of creating a system that caters to a client's or user's assembly workflow demands careful attention to structural integrity, component weight, assembly process, sequence, transportation, handling, and various other factors.

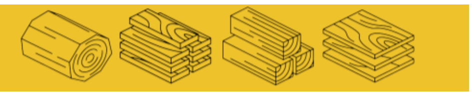
ASSEMBLY AND DIS-ASSEMLY

In the pursuit of developing a lightweight prefab building system, coupled with an automated manufacturing process, we have undertaken an analysis of common examples within the wooden building industry. This analysis seeks to elucidate the advantages and disadvantages inherent in their respective construction processes.

It is imperative to underscore that variables such as the choice of materials and construction methods hold significant sway in this assessment, given that the financial constraints of the project serve as the principal guiding parameters for the design. Therefore, with due consideration of the aforementioned context, Engineered Wood Products (EWPs) are included in this exercise. However, it is worth noting that the cost of these products renders them prohibitively expensive within the Colombian territory. Consequently, while the use of such materials may not be feasible, we can draw upon their assembly strategies as valuable insights that could be applied in practice.



OVERVIEW OF WALL AND FLOOR PARTS BUILD FROM WOOD



PRE-FAB SYSTEMS

MILLING

CONNECEECTION TYPE

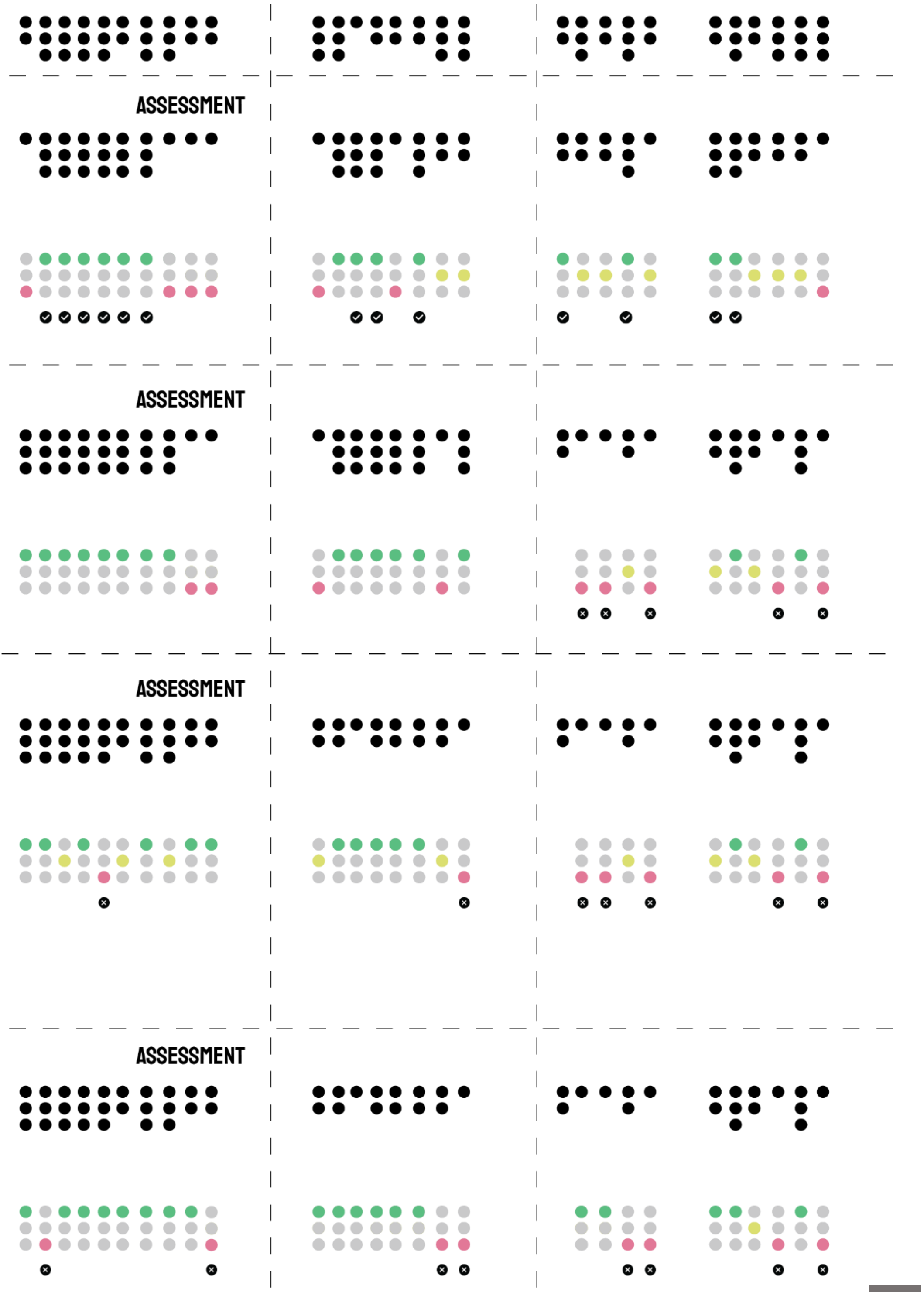
ASSEMBLY DIS+ASSEMBLY

MATERIAL
- Water Resistance
- Milling time
- Simplicity
- Rotation corrections
- Service Are
- material width
- Stabilisation
- Hardeness
- Manual Corrections
- Waste

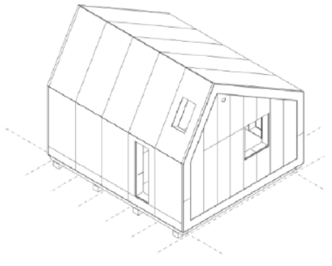
ASSEMBLY
- Speed
- Interlocking
- Dis-Assembly
- Herarchy
- Modularity
- Design Freedom
- Special tooling
- Additional hardware

DIS-ASSEMBLY
- Speed
- Simplycity
- Unexpirience Labour
- Herarchy
- Modularity

ASSEMBLY
- Speed
- Simplycity
- Unexpirience Labour
- Herarchy
- Modularity
- Design Freedom



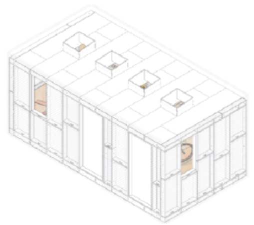
WIKI-HOUSE



ASSESSMENT

score

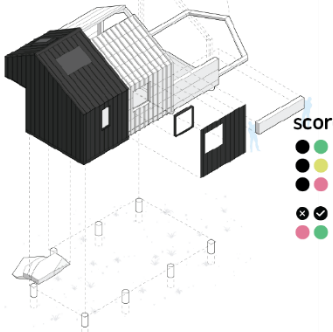
U-BUILD



ASSESSMENT

score

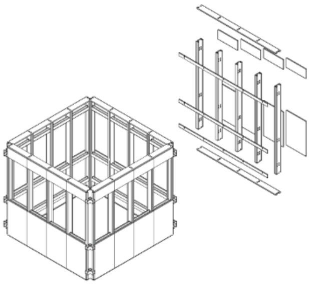
THE BACK COUNTRY HUB



ASSESSMENT

score

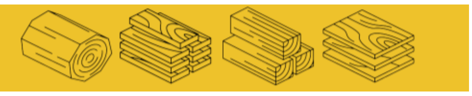
SI-MODULAR



ASSESSMENT

score

Moisture induce Wood-to-Wood joinery



WEIGHT STUDY

GRASSHOPPER SCRIPT

ELEMENT AND COMPONENT WEIGHT STUDY

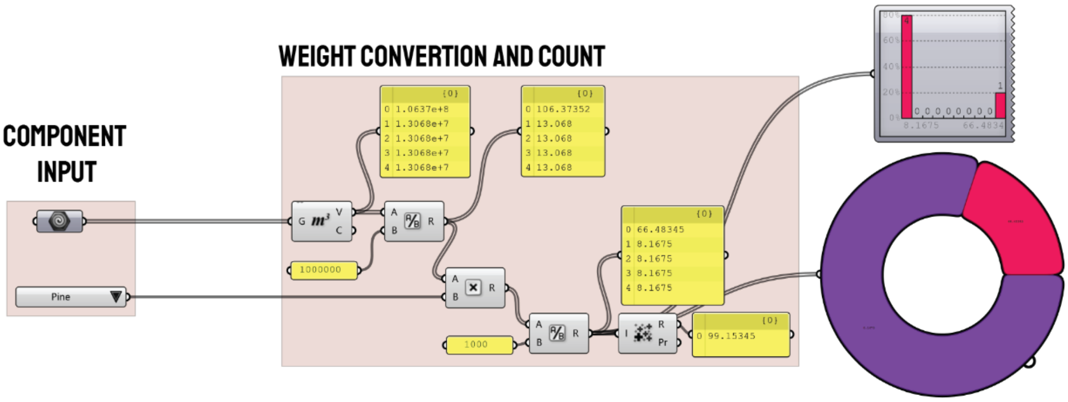
A Grasshopper script has been developed to speed up the evaluation of wooden components available in the market. This solution aims to efficiently identify optimal design strategies for various projects. By utilizing a Rhino model, the script calculates material quantities and density (measured in Kg/m3) with reference to the GRANTA EduPack 2020 Database, facilitating insightful weight comparisons.

For simplicity, the initial approximation of wood components employs the dried weight density of a commonly used wood species in the industry, specifically spruce pine (with a density of 625 kg/m3). This species serves as a representative benchmark for the analysis. Nevertheless, in further analysis of the research building design Oak hardwood (Quercus Robur) will be implemented into the script as this is the optimal material due to humidity and fungal decay in tropical conditions.

Through this initial analysis, a clear distinction emerges among different wooden elements, including sawn wood beams, frames, Cross-laminated timber (CLT) walls, and Dove-tail laminated timber (DLT). This exercise offers means of visualizing the nuanced differences between these components, aiding in informed design decisions.

CASE OF STUDY

In this rapid grasshoper exercise, by proceeding from left to right, you can observe the input information, which pertains to the geometry of the 3D model, along with the density of the material in dried weight (measured in Kg/m3). The second section showcases the calculation of the 3D sectional area, coupled with the conversion of units from millimeters to meters. Lastly, the graph illustrates the count of items, the weight of individual elements, and the comprehensive weight of the component as a whole. This swift visualization aids in compre-



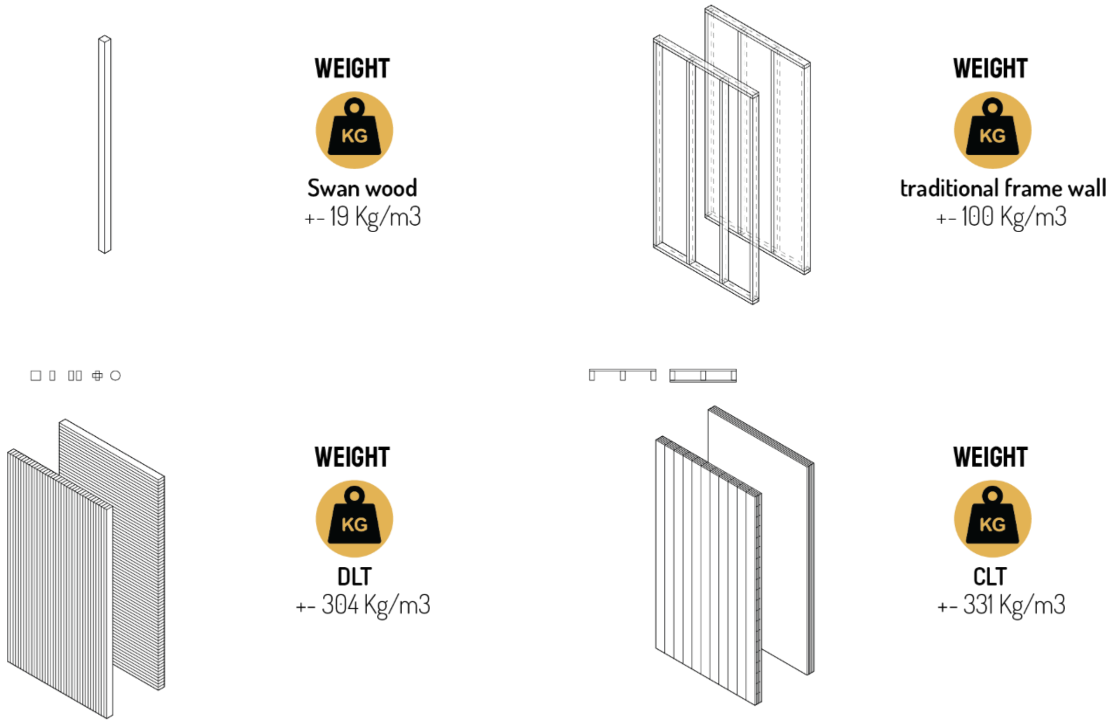
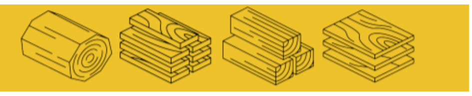
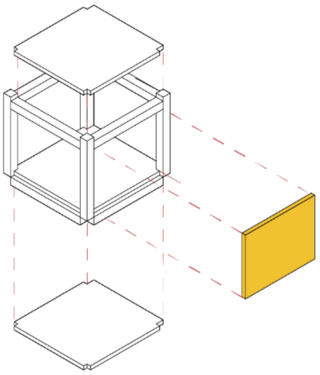


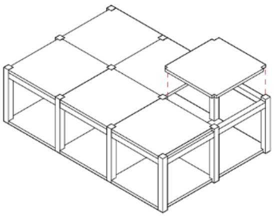
Figure 136 Weight Analysis Buildin components



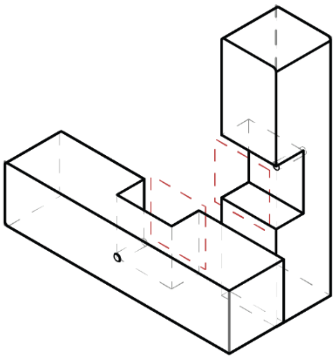
DESING RULSE

FROM THE STRUCTURE TO THE COMPONENTS





SKELETON SYSTEM



The Half-Lap joint system is use to **overcompensated** possible manufacture issues such as **tolerances.** Thus, elements can be force in place disregarles misaligments, as well as **transfering forces** by the compress contact area characteristic of the joint.

PRELIMINARY PROTOTYPE

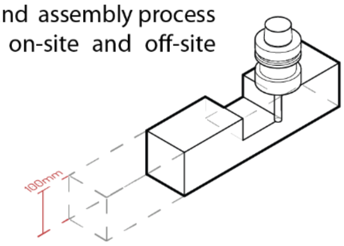
The TU Delft CNC machine with a working space of 800 x 800 mm was utilized to fabricated **two** preliminary **half-lap joints**. This allowed us to test the milling boundary conditions and determine the appropiated milling tools. We used **Douglass pine softwood** beams to produce four pieces measuring 76 x 76 x 400 mm.

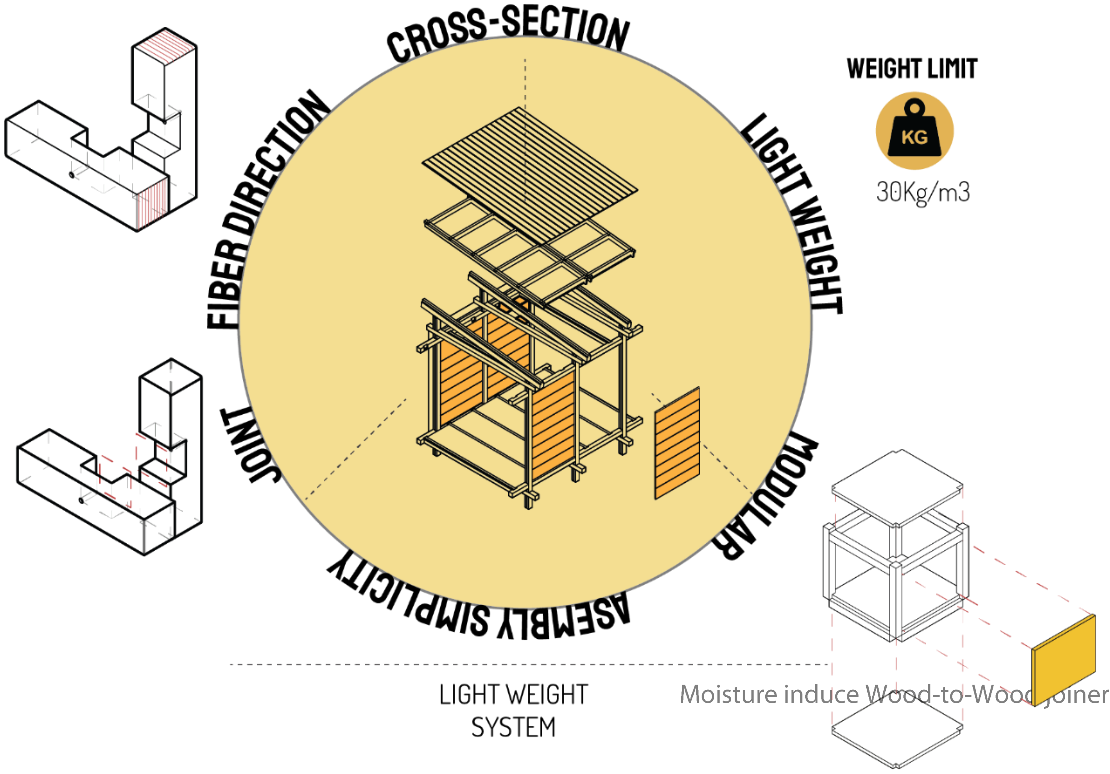
ESTRUCTURAL CONCEPT -AS SEMI PERMANENT SYSTEM

EWP'S

The idea of autonomous construction housing could be the solution to improve the living conditions of rural areas as approach to the social and environmental crisis. The urgent implementation of a rapid construction and assembly process can be empower by the use of prefabricated and automated buildings, making planning and construction more efficient, and therefore, more economical.

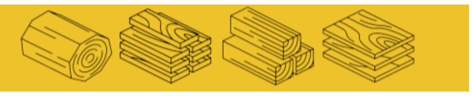
This system relates to timber elements and components, selected due to their inherent ease of material handling. The differentiation among structural typologies can be systematically categorized, with a focus on lightweight systems well-suited for frame or panel constructions. The Lightweight of elements makes handling, transport, and assembly process much easier, which in turn improves on-site and off-site construction processes.





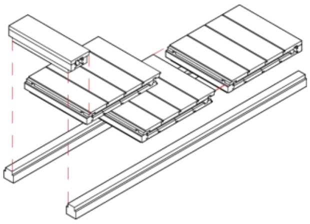
LIGHT WEIGHT SYSTEM

Moisture induce Wood-to-Wood joinery



LOAD CALCULATION - STRUCTURAL DIMENTION

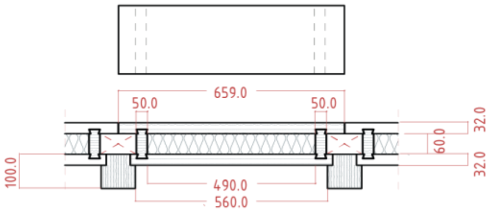
FROM ELEMENT TO STRUCTURE



DEAD LOAD CALCULATION

(a) Selft weight Slab= D x Material
D= Depth floor component= 124 mm
Oak Quercus Robur= 675 Kg/ m3
Insulation Guttex= 50 Kg/ m3

FLOOR WEIGHTCOMPONENT CALCULATION



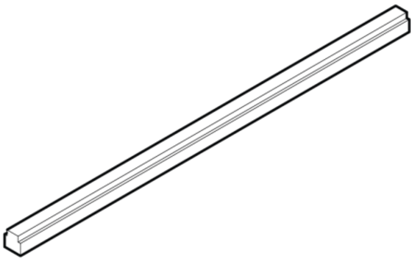
$$Weight - QercusRobur = (0.032m \cdot 2) \cdot \frac{675Kg/m^3}{1000} = 0.05kN/m^2$$

$$Weight - Guttex = (0.06m) \cdot \frac{50Kg/m^3}{1000} = 0.003kN/m^2$$

$$TotalFloorWeight = 0.05Kn/m^2 + 0.003Kn/m^2 = \boxed{0.053Kn/m^2}$$

SELF WIEGHT BEAM

Depht= 0.1m
Hight= 0.15m



$$Density - Oak = \frac{675Kg/m^3}{1000} = 0.68kN/m^2$$

$$Beam = 0.1m \cdot 0.15m \cdot 0.68kN/m^2 = 0.01kN/m^2$$

$$Safty - factor = 1.5 \cdot 0.01kN/m^3 = \boxed{0.015kN/m^2}$$

TOTAL WEIGHT DEAD LOAD

$$DeadLoad = 0.003kN/m^3 + 0.05kN/m^3 + 0.01kN/m^3 = \boxed{0.07kN/m^3}$$

LIVE LOAD

Residence Euro Code= 1.75kN/m2

TOTAL LOAD

$$Total - Load = 0.07kN/m^2 \cdot 1.75kN/m^2 = \boxed{1.82kN/m^2}$$

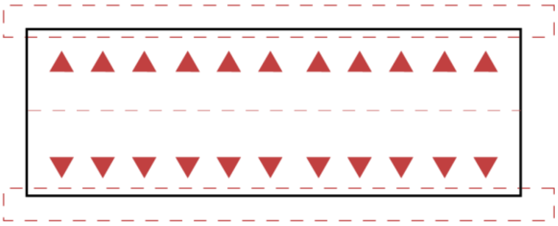
SAFTY FACTOR

Safty Factor= 1.35kN/m2

TOTAL LOAD

$$Final - Load = 1.82kN/m^2 + 1.35kN/m^2 = \boxed{2.45kN/m^2}$$

CALCULATION TOTAL LOAD FOR BEAM ONE WAY SLAP



$$S2 = \frac{WxL}{2}$$

$$S2 = \frac{2.45kN/m^2}{2} = 1.23kN/m^2$$

$$S2 = 1.23kN/m^2 \cdot 0.015kN/m = \boxed{1.24kN/m^2}$$

BEAM LOAD

$$W = 1.24kN/m^2 \cdot \frac{2440}{1000} = \boxed{3.03kN}$$

$$N = 3029N$$

UNIT LOAD

$$N = \frac{3029N}{2440} = \boxed{1.24N/mm}$$

BEAM FLOOR LOAD ANALYSIS

FROM THE STRUCTURE TO THE COMPONENTS

$$W = 1.24kN / m^2 \cdot \frac{2440}{1000} = \boxed{3.03kN}$$

BEAM LOAD

$$N = \frac{3029N}{2440} = \boxed{1.24N / mm}$$

UNIT LOAD

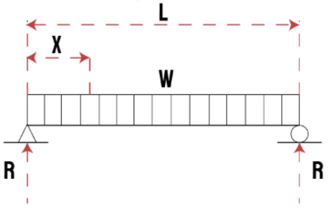
BEAM DIMENTION

UNIT LOAD

Base on the Load identify in the previous calculation is possible to make a dimentioning and mechanical analysis of the main beam elements as well as understanding of the Joint ultimum bending moment Capacity.

The considerations of structural regulations were taking follow the recomendation of Euro COse number 5, due to the lack of documentaion regardign Colombian wooden structure.

BEAM DIAGRAM



CONDITIONS

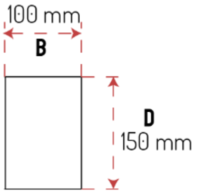
L: 2440 mm
W: 3029 N
P: 1.24N/mm
E: 22780
I: 28125000 mm4

BEAM SECOND MOMENT OF INNERTIA

$$I = \frac{b \cdot d^3}{12} = \frac{100mm \cdot 150^3 mm}{12} =$$

$$I = 28125000mm^3$$

CROSS-SECTION



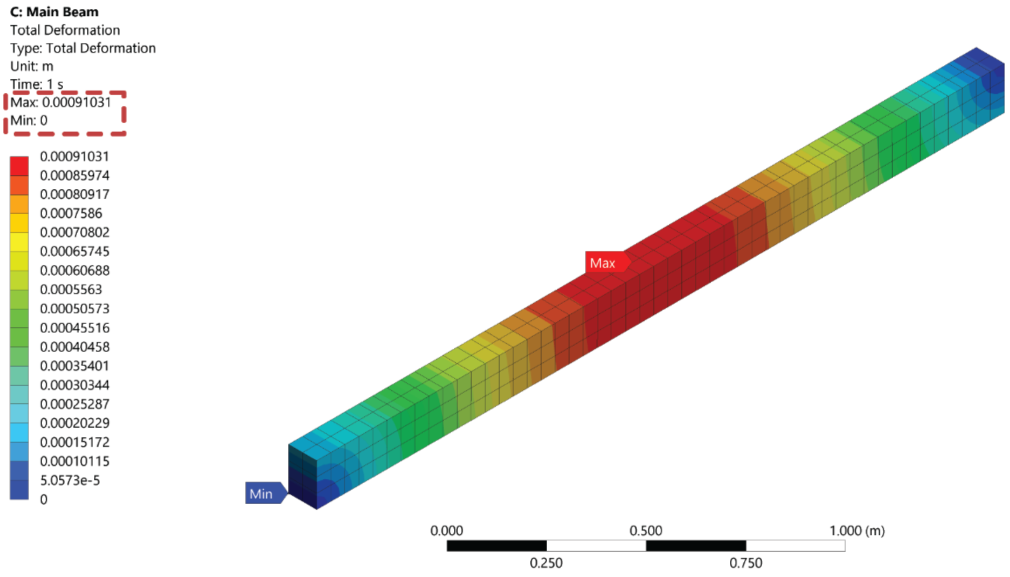
DISPLACEMENT

$$w_{\max} = w\left(\frac{L}{2}\right) = -\frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I} =$$

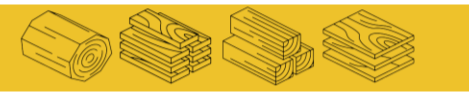
$$w_{\max} = w(\frac{L}{2}) = -\frac{5 \cdot 1.24N / mm \cdot 2440^4 mm}{384 \cdot 22780N / mm^2 \cdot 28125000mm^4} =$$

$$w_{\max} = \boxed{-0.89mm}$$

NUMERICAL ANALYSIS ANSYS WORK BEANCH 2021



C: Main Beam
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
Max: 0.00091031
Min: 0



ULTIMATE BENDING MOMENT ANALYSIS

FROM THE STRUCTURE TO THE COMPONENTS

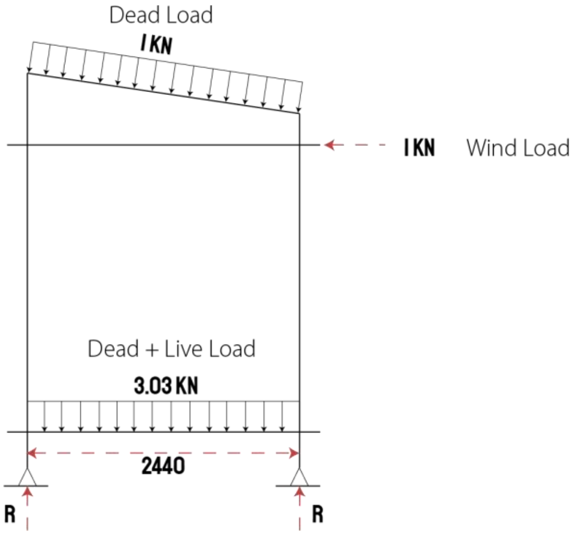
ULTIMATE BENDING MOMENT

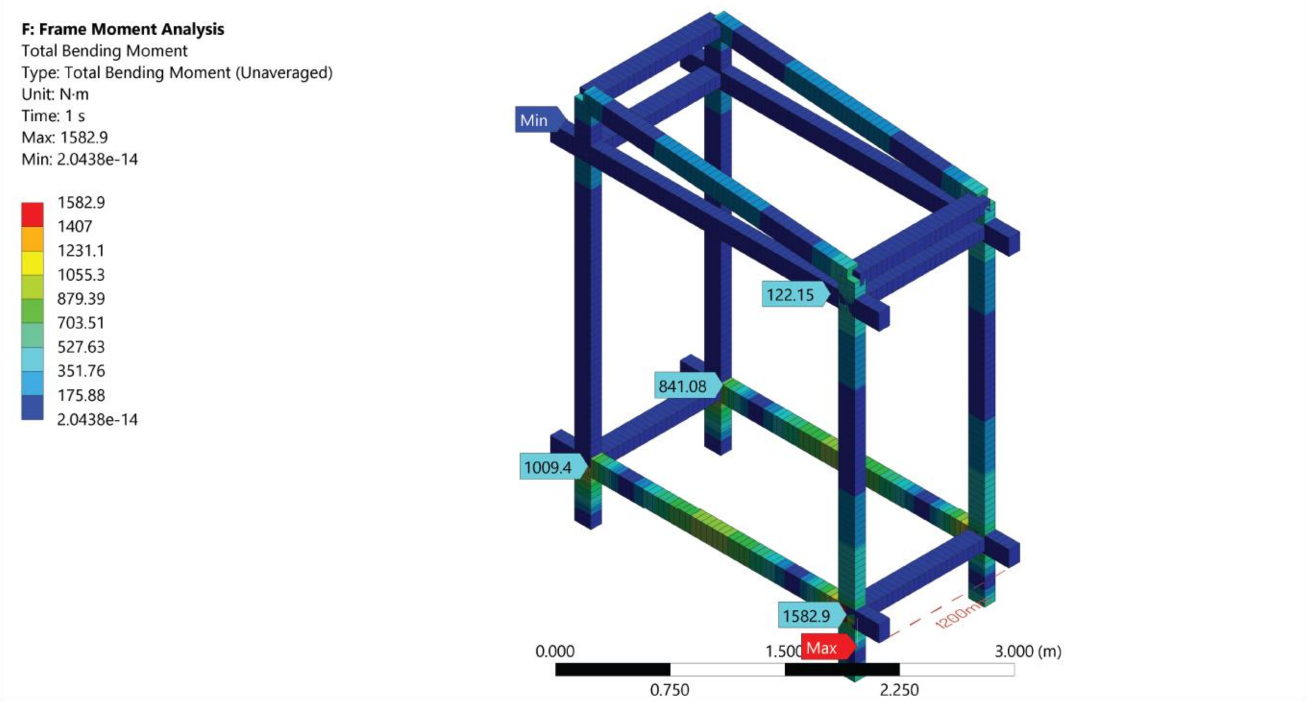
UNIT LOAD

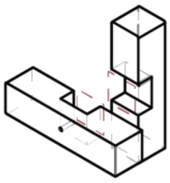
this analisys concerns the calculation of the frame structural performance , as well as the joints following the Dead and live load, as well as the wind load base on the Euro Code number 5. Thus is possible to male a dimentioning and mechanical analysis of the joints ultimum bending moment Capacity.

For the Calculation material properties concerning Oak Quercus Roubur with a Yong modulus of 22.78 Gpa, Modulus of Rupture of 97.1, elastic modulus of 10.6 Gpa.

MOMENT DIAGRAM




F: Frame Moment Analysis
Total Bending Moment
Type: Total Bending Moment (Unaveraged)
Unit: N·m
Time: 1 s
Max: 1582.9
Min: 2.0438e-14



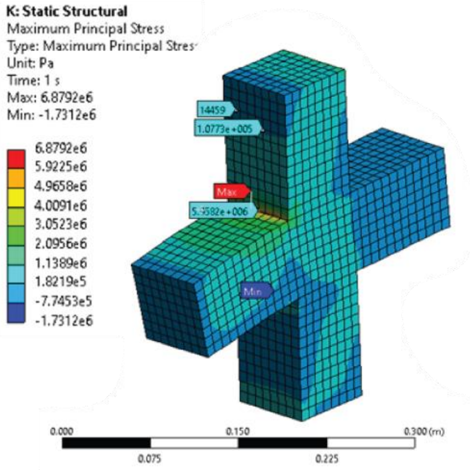
ULTIMATE BENDING MOMENT

$$M = \frac{66,9N/mm^2 \cdot (38mm \cdot 76mm^2)}{6} =$$

$$M = 2.45kNm$$

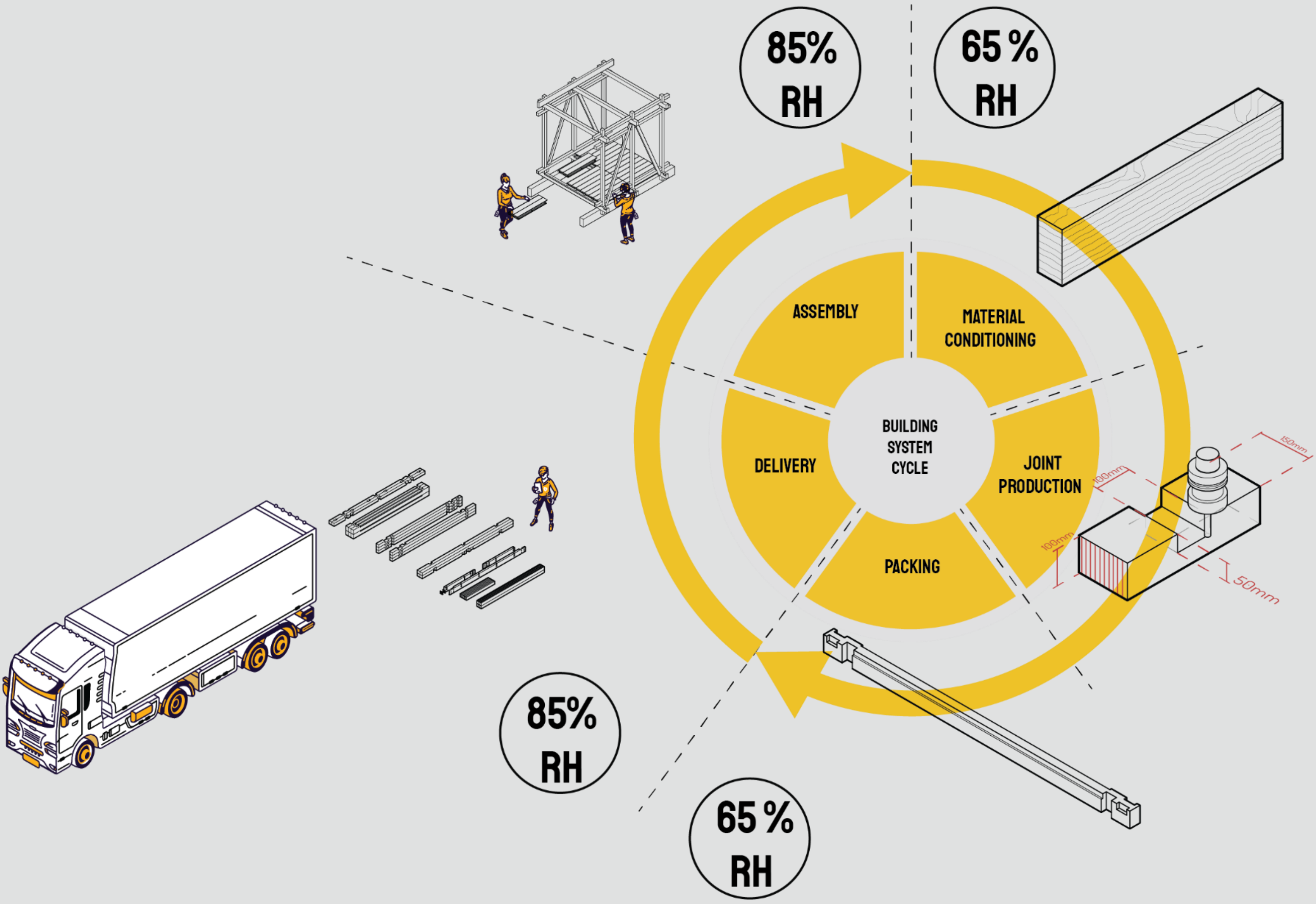
FORCE CAPACITY

$$= \frac{2.45Kn/m^2}{(60mm/100)} = 4.04Kn/m$$


K: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stres
Unit: Pa
Time: 1 s
Max: 6.8792e6
Min: -1.7312e6

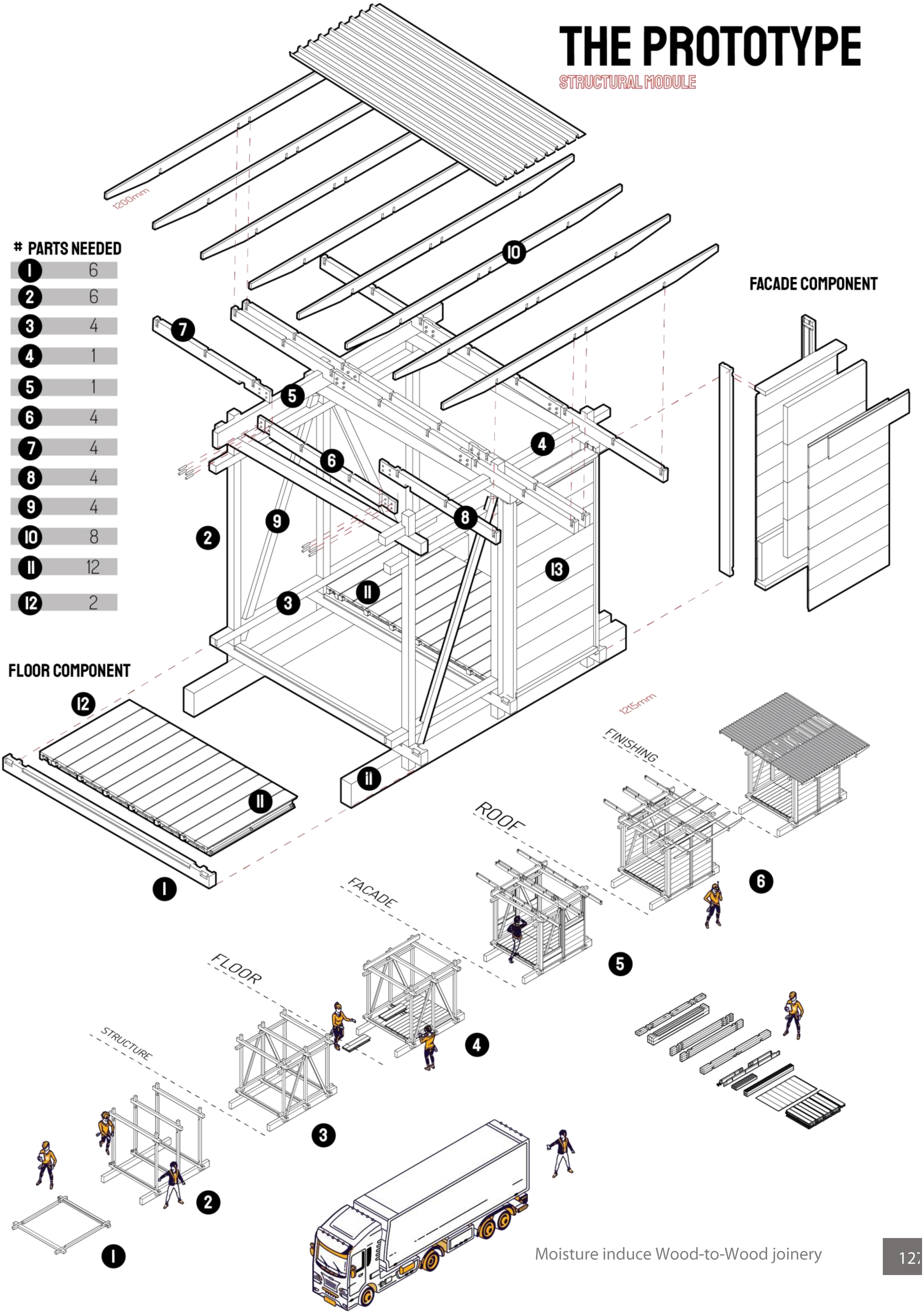
CROSS HALF LAP

STRUCTURAL
ASSEMBLY
CYCLE



THE PROTOTYPE

STRUCTURAL MODULE

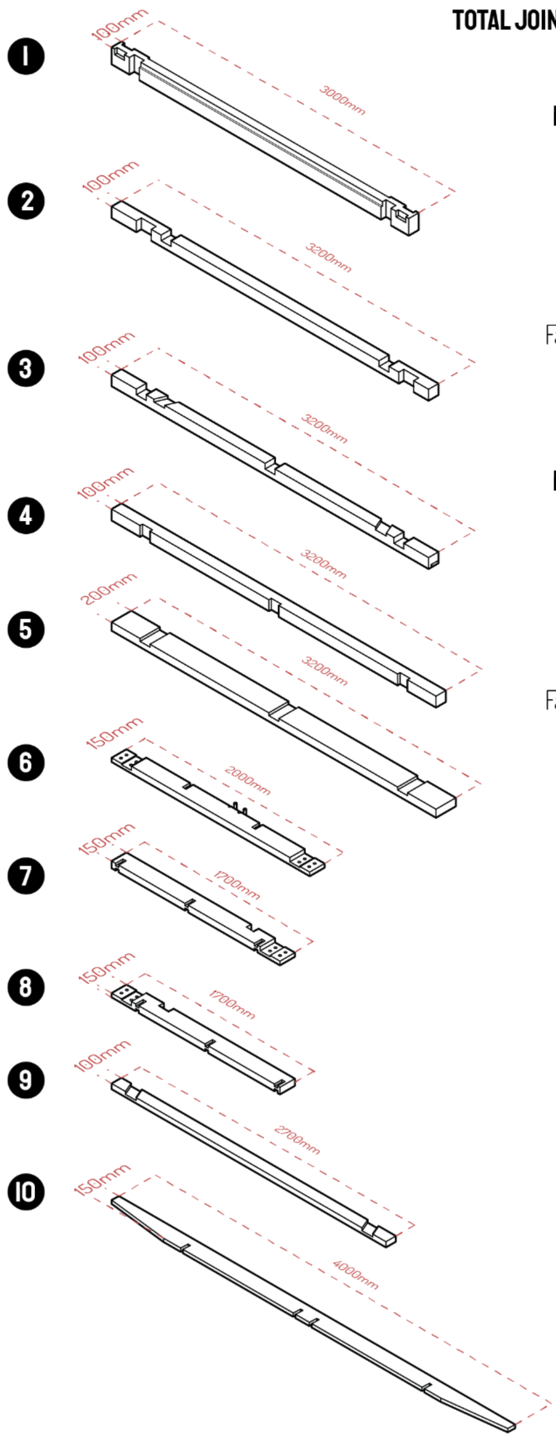


 # PARTS NEEDED

1	6
2	6
3	4
4	1
5	1
6	4
7	4
8	4
9	4
10	8
11	12
12	2

FAST ASSEMBLY

# PARTS NEEDED		MATERIAL	DIMENSIONS	# HALF-LAP PIECE		# TOTAL HALF-LAP	# POCKETS
1	6	Oak-QR	3000 x 150 mm x 100mm	1	2	12	-
2	6	Oak-QR	3200 x 100 X 100 mm	2	4	24	-
3	4	Oak-QR	3200 x 100 X 100 mm	3	4	18	-
4	1	Oak-QR	3200 x 100 X 100 mm	4	3	3	-
5	1	Oak-QR	3200x 200 x 75 mm	5	3	3	-
6	4	Oak-QR	2000 x 150 x 63 mm	6	2	8	4
7	4	Oak-QR	1700 x 150 x 63 mm	7	2	8	6
8	4	Oak-QR	1700 x 150 x 63 mm	8	2	8	6
9	4	Oak-QR	2700 x 100 x 50 mm	7	2	8	-
10	8	Oak-QR	4000 x 150 x 32 mm	8	-	-	4
			TOTAL JOINTS			92	16



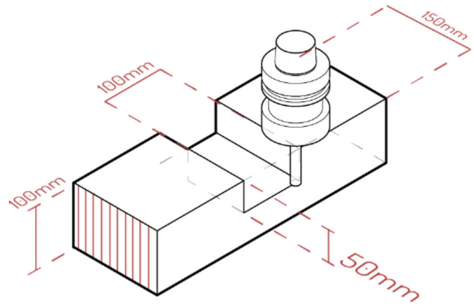
MILLING TIME
18% MC

00 : 02 : 47
Fabrication time
per joint

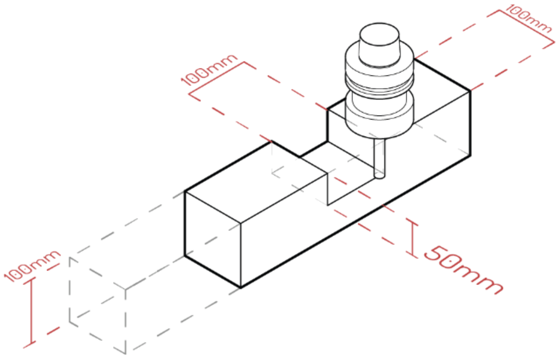
MILLING TIME
11% MC

00 : 03 : 33
Fabrication time
per joint

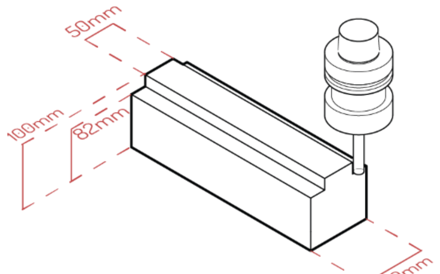
CROSS HALF-LAP TYPO DETAIL



CROSS HALF-LAP TYPO DETAIL (Columns)

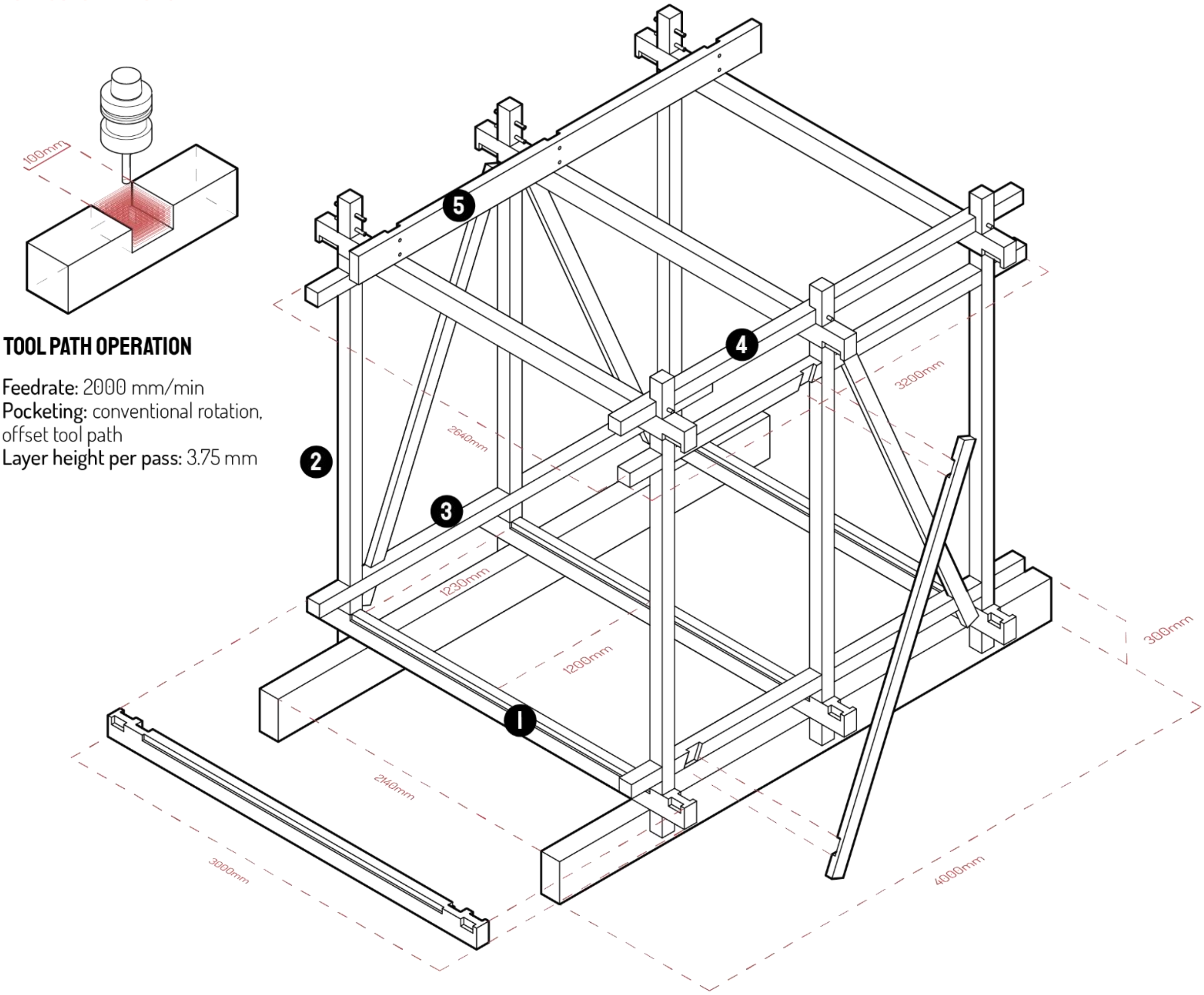


DOUBLE CONTOUR



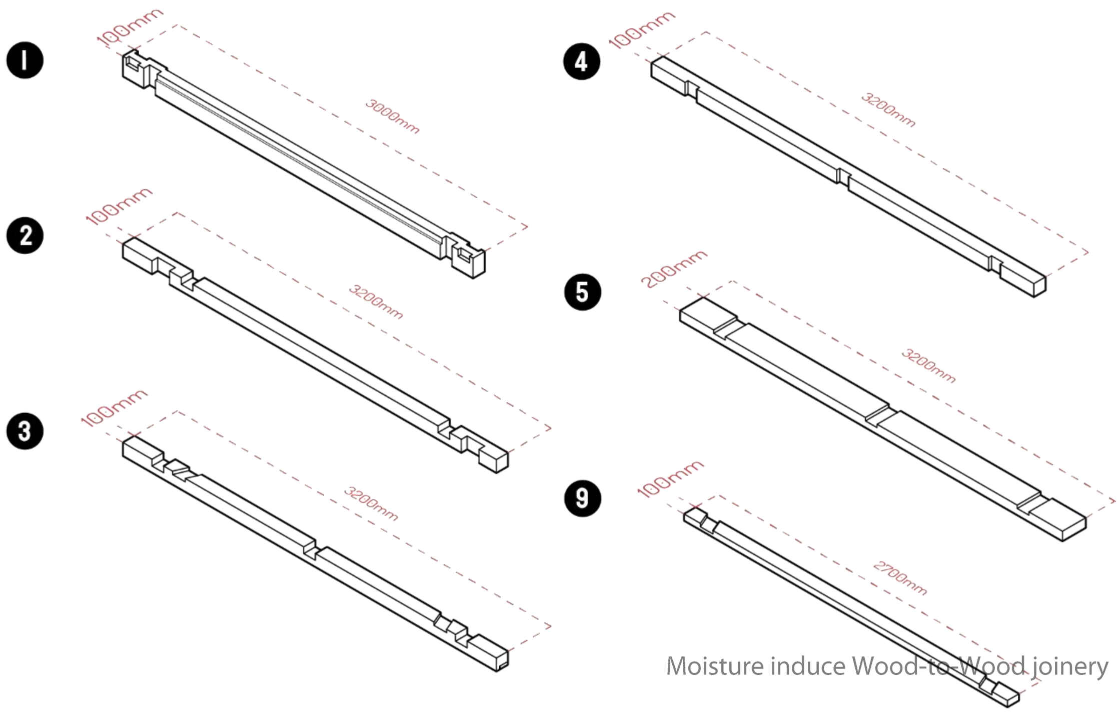
STAGE I - STRUCTURAL ASSEMBLY

STRUCTURAL MODULE



TOOL PATH OPERATION

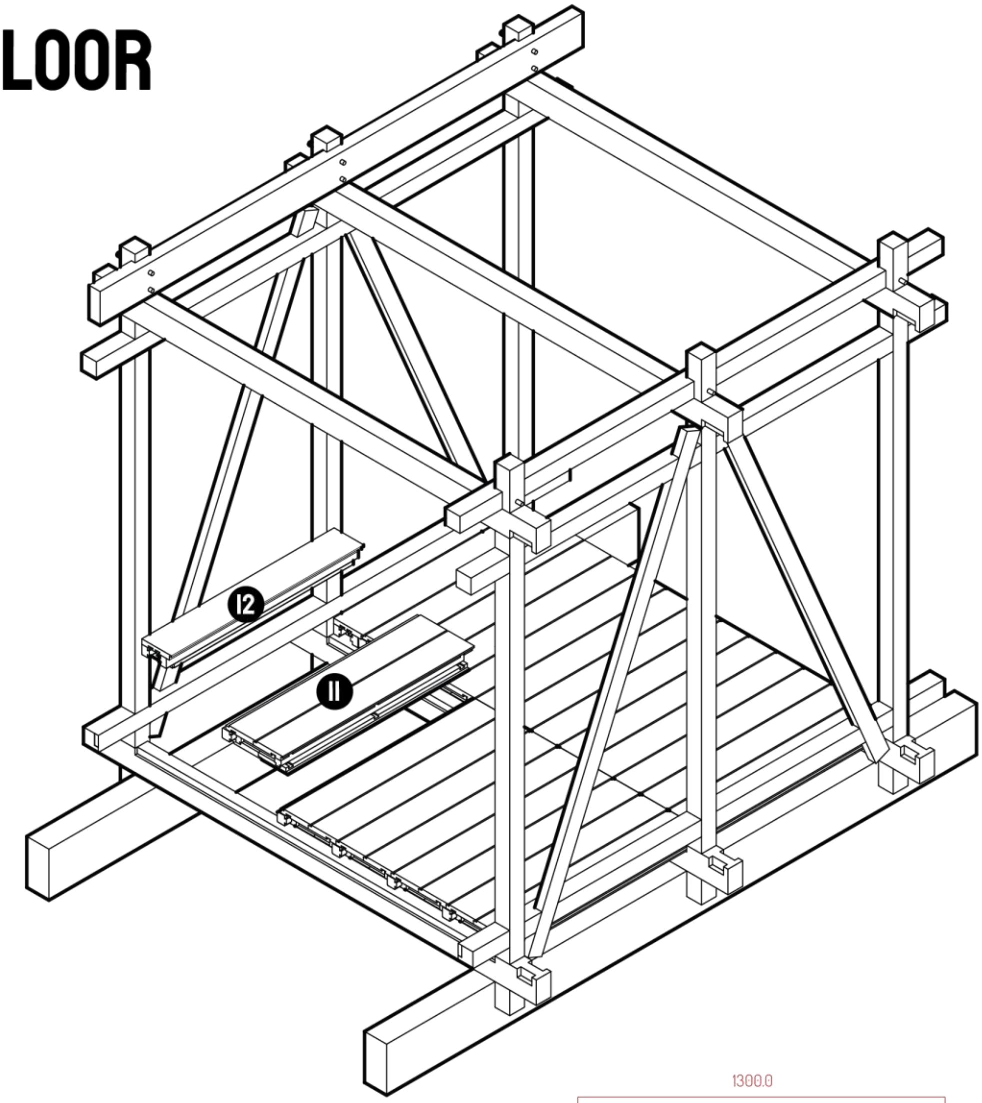
Feedrate: 2000 mm/min
Pocketing: conventional rotation, offset tool path
Layer height per pass: 3.75 mm

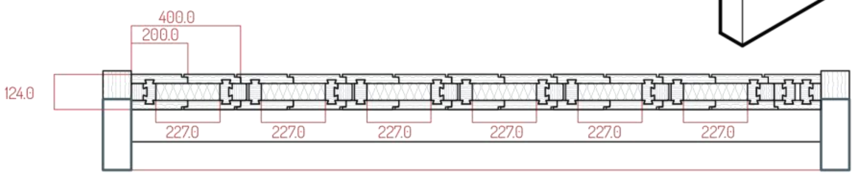


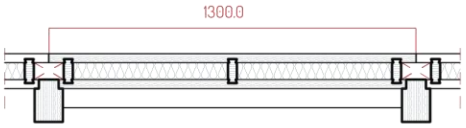
STAGE 2 - FLOOR

BUILDING COMPONENTS

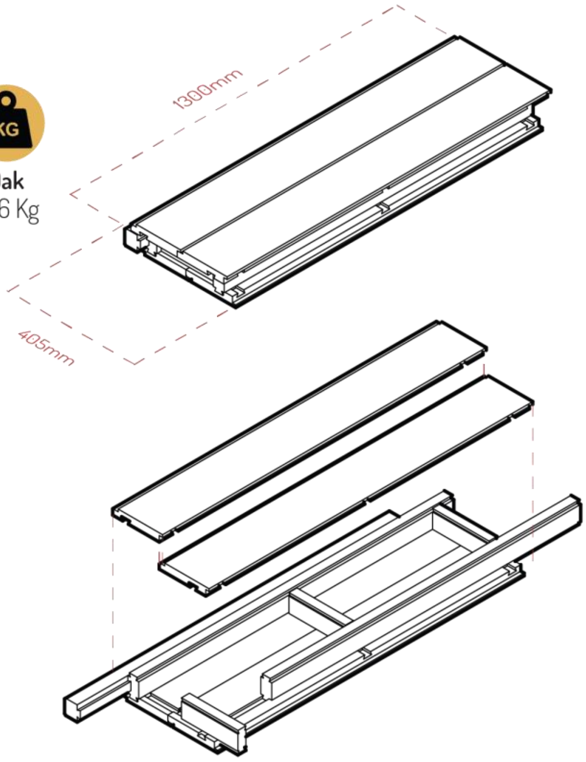
⑪	12
⑫	2





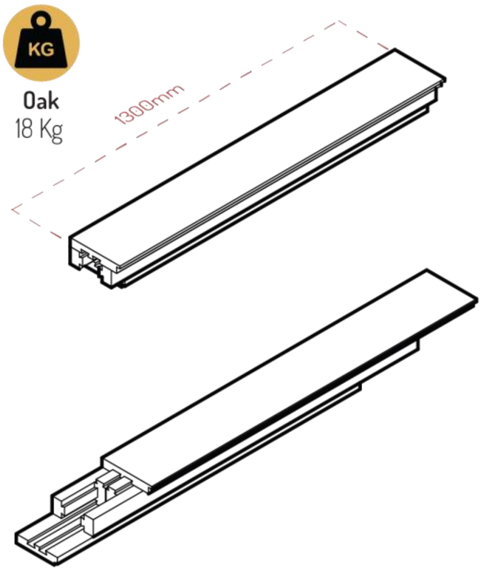


⑪



Oak
28.6 Kg

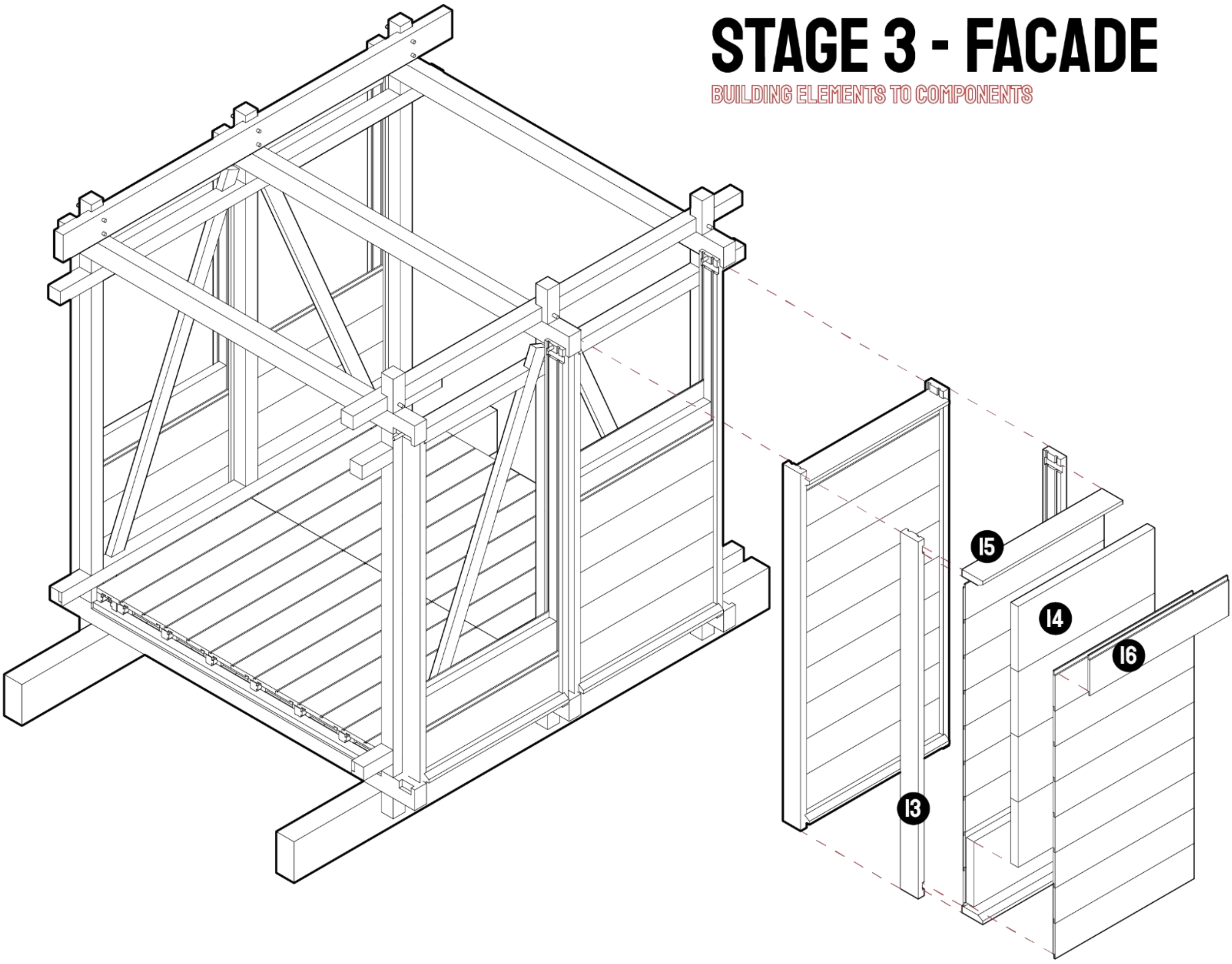
⑫



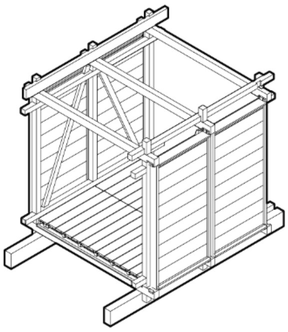
Oak
18 Kg

STAGE 3 - FACADE

BUILDING ELEMENTS TO COMPONENTS



#	PARTS NEEDED	MATERIAL	DIMENSIONS
⑬	2	Oak-QR	2600 x 150 mm x 50mm
⑭	5	Oak-QR	1149 x 474 X 63 mm
⑮	2	Oak-QR	1178 x 175 X 50 mm
⑯	18	Oak-QR	1169 x 300 X 18 mm



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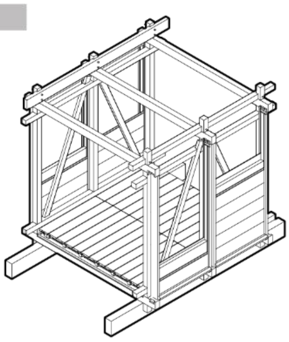
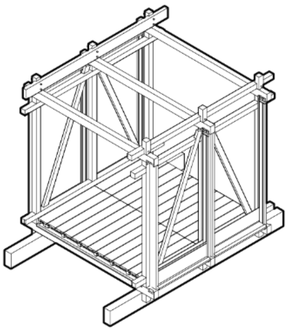
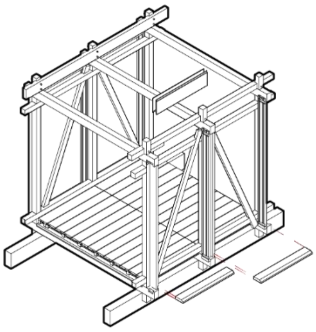


❸



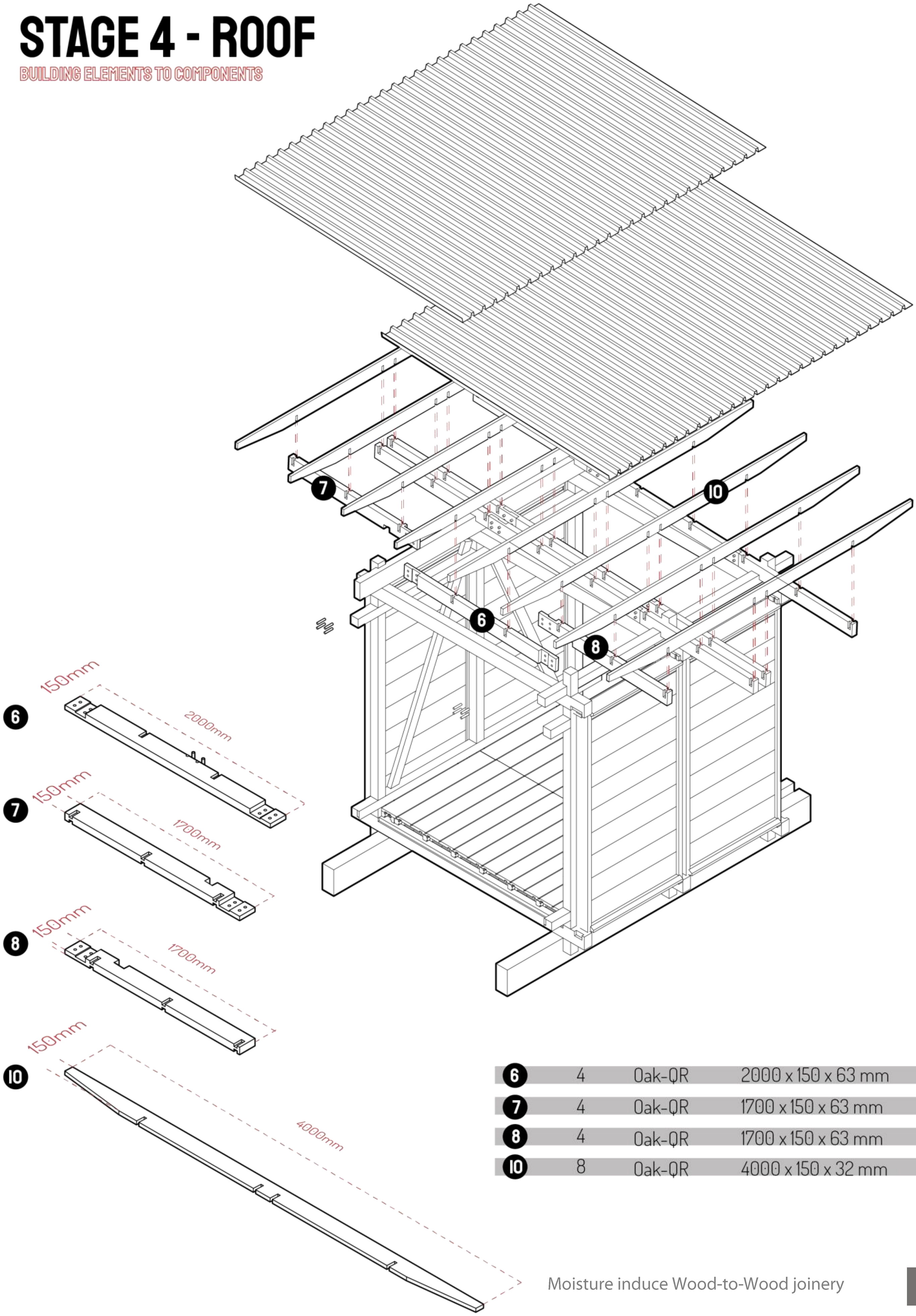
❷



❶

STAGE 4 - ROOF

BUILDING ELEMENTS TO COMPONENTS



6	4	Oak-QR	2000 x 150 x 63 mm
7	4	Oak-QR	1700 x 150 x 63 mm
8	4	Oak-QR	1700 x 150 x 63 mm
10	8	Oak-QR	4000 x 150 x 32 mm

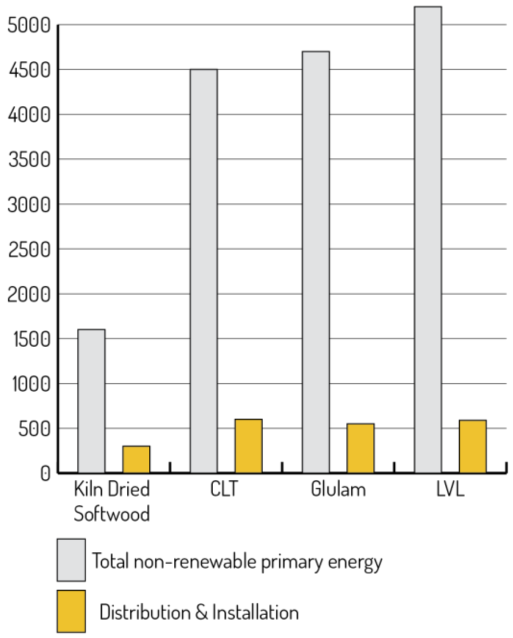
COMPONENT ASSEMBLY - ADHESIVES AND SCREWS OR NOT?

REDUCING MATERIAL WASTE

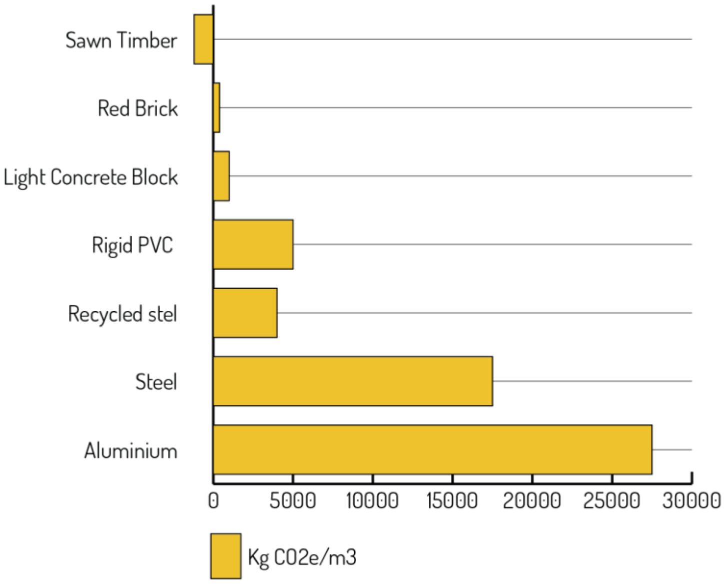
ADHESIVES IN WOOD INDUSTRY

Sawn Timber can be reprocess into structurally optimasied building materials well know as EWP's or engeneired wood products, as seen in the material analysis section. a main advantage of such a composite includes incresing dimensional stability, a more homogenous mechanical property, and greater durability (Yadav & Kumar, 2022) (Ramage et al., 2017). most of this products requited the application of wet adhesives requiting an extensive amount of energy to be produce and applied. As seen in the ghrap bellow, () despited the supirior structural advantages of EWPS is evident the negative impact on the embodied energy burden. Furthermore, glued connections must be performed in a controlled enviroment, limitating their use on-site.

Nevertheless, as (Ramage et al., 2017) expresses, the implementation of such a products make sense in buildings of large spam, while in small structures, a more traditional timber product with smaller cross-sections can be implemented to overcome structural requitments.



Total **non-renewable** primary energy consumption and distribution/installation energy associated with **adhesively bonded engineered timber products** manufactured in the EU.



RE-USE, REDUCE, PRODUCE

The re-use of wood products is a priority after one services unit into the same porpouse or even less demanding purposes after simple reshaping (author). If this products are not quilify for further use, they can be reprocess as fibrous materials to fabricate new wood-base products such as OSB panels. However, if recycle is not possible wood products can still produce energy throught direct cumbustion or conversion to gaseous or liquid fuel before burning. clean wood without harmful substansces are allowed to be burn in normal power stations, while contaminated wood such as painted wood, or chipboards containing adhesives of formaldehyde requited an specific equippment for energy generation. Thus, making the reprocess of adhesive a more expensive and demanding process.

STEEL FASTENERS: NAILS AND SCREWS

Mechanical connections using steel fasteners like screws, blots, nails and dowels achieve afficiencies approximately 20% to 30% without the use of adhesives and can be installed in site (Ramage et al., 2017). Nevertheless, the used of this connectors can lead to material corrosion, prevension of easy dis-assembly and re-assembly, and mainly re-use, as damage may accumulate and the remainig capacity is unknowng, as previous loadin beyong elastic limit causing reduction in the displacment capacity. Modern selft tapping screws for single-use installation. Dspied that can be removed after service life; however, friction and possible fusion between screw thread and timber ofteen prevents disassmbly of screwed joints after longer period in use (Ottenhaus et al., 2023). latest self tapping screws developed for hardwood feature thicker core allowing higher torque. Unfurtunately reinstallation of screws in the same perforation leading to reduce performance/ This issue can be overcome by installing larger screws diameters.

MECHANICAL ASSESEMENT

FLOOR COMPONENTS

DESIGN GUIDLINESS FOR STRUCTURAL ANALYSIS OF FLOOR COMPONENTS

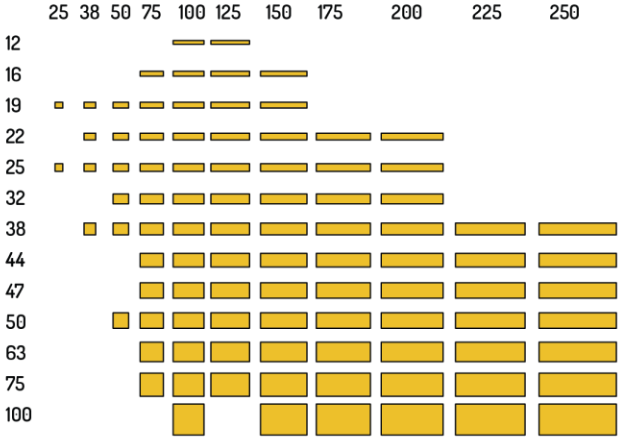
Prior to conducting the mechanical and structural analysis of the floor system, it is essential to establish an understanding of the material capacity. This understanding is grounded in the skeleton structure design, which utilizes the Half Lap Joinery system as explained in the structural analysis section.

In order to grasp the requirements of the floor component, a structural analysis of this particular building section was carried out using Ansys Workbench 2020. This analysis incorporated various considerations to simulate a realistic scenario concerning material and assembly requirements.

DIMENTIONS

Firstly, the span between the skeleton beams, which approximately amounts to 600 mm, was taken into account. This span is depicted in the diagram on the right section, highlighted in yellow.

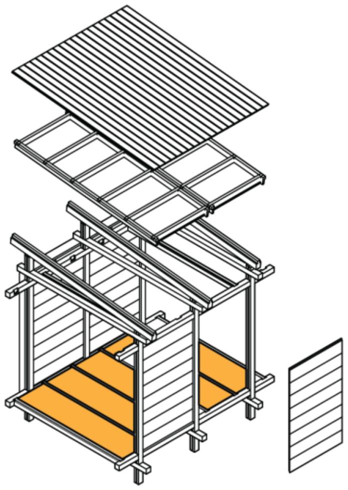
SOFTWOOD COMMON DIMENTIONAL SECTIONS IN MM



	25	38	50	75	100	125	150	175	200	225	250
12					▬	▬					
16				▬	▬	▬	▬				
19	▬	▬	▬	▬	▬	▬	▬				
22		▬	▬	▬	▬	▬	▬	▬	▬		
25	▬	▬	▬	▬	▬	▬	▬	▬	▬		
32			▬	▬	▬	▬	▬	▬	▬		
38		▬	▬	▬	▬	▬	▬	▬	▬	▬	▬
44				▬	▬	▬	▬	▬	▬	▬	▬
47				▬	▬	▬	▬	▬	▬	▬	▬
50			▬	▬	▬	▬	▬	▬	▬	▬	▬
63				▬	▬	▬	▬	▬	▬	▬	▬
75				▬	▬	▬	▬	▬	▬	▬	▬
100					▬		▬	▬	▬	▬	▬

MATERIAL SECTIONING

Secondly, the material thickness was selected in accordance with the standard dimensional section diagram for softwoods commonly used in the wood industry. It is important to remarked that this type of diamentions are implemnted in the softwood types as this material is commonly used. Contrary, hardwood species do not present an standart sectioning system. Therfore,- following a criateria already used it is decided to keep the same sectioning logic.



MATERIAL MECHANICAL CHARACTERISTICS

In general, wood exposed to outdoor environments is more susceptible to gradual decay caused by fungal or insect attacks (Ramage, 2017). Given the specific environmental characteristics and humidity levels in the Colombian territory, a more optimal and locally-sourced material has been chosen to address this concern.

In temperate climates, insect attacks on timber within a building do not pose a significant risk of fungal decay. However, when the moisture content of the wood exceeds approximately 20%, there is a heightened risk of failure. Consequently, the use of softwood materials commonly employed in the European industry is not advisable due to this elevated risk.

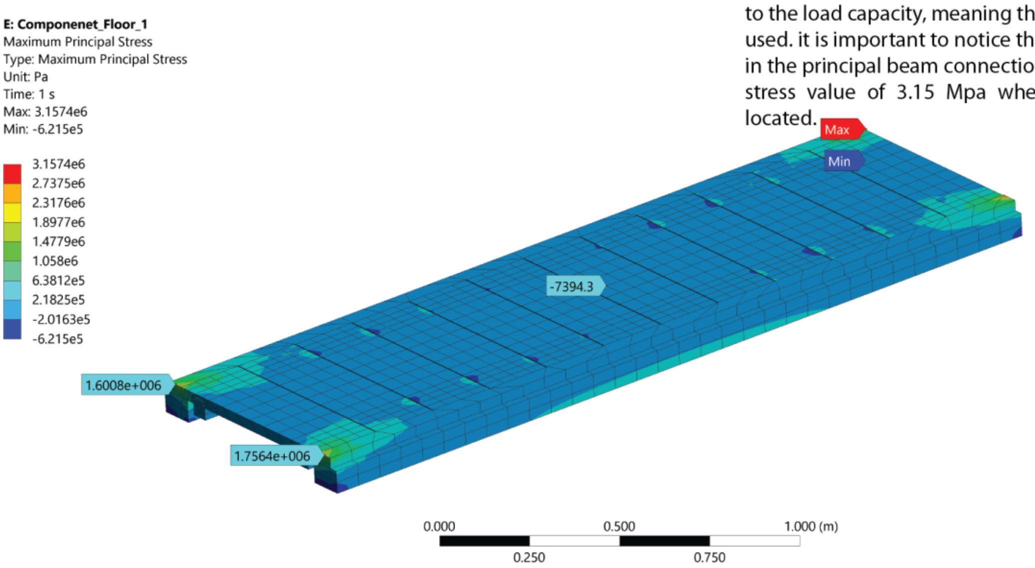
Conversely, hardwood species that are readily available and relatively affordable in the country, such as Oak (flormorado), serve as a more suitable material choice.

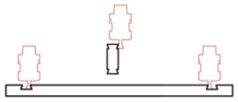
LOAD

Taking into consideration the Euro Code number 5 a design load is assigend to the numerical simulation. This design load takes into consideration the live load, dead load, and safty factore appointed to the European regulations to provide practical an realistic value to the calculation (2350 N). The final objective of this assesment aims to determine the tickens, and configuration of the floor panel to verify design configuratiomns. For the following assesment the most basic design iteration (floor type I) was selected to, as well as the dimentional section of 32 x 200 mm planks, as is the minimum dimention that fits the typE of milling strategy.

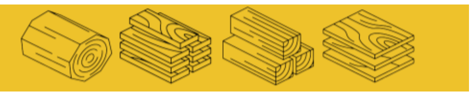
RESULTS

The maximum principal stress shows optimal bending resistant to the load capacity, meaning the tickenss of 32 mm can be saftly used. it is important to notice that the maximum stress is located in the principal beam connection to the overall structure with an stress value of 3.15 Mpa where the Half-Lap connections is located.



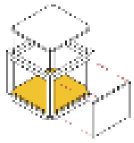


MILLING STRATEGY

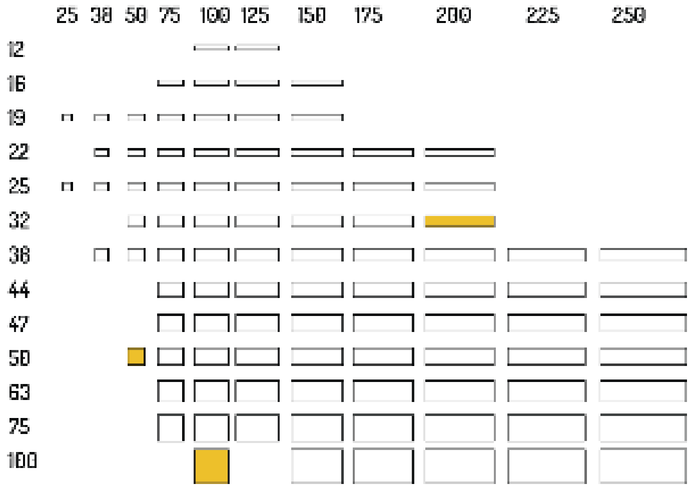


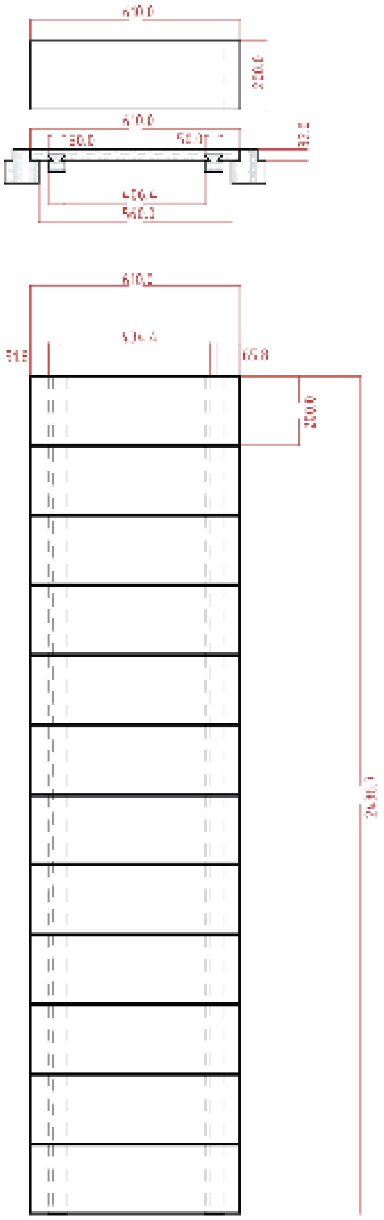
FLOOR BUILDING COMPONENT

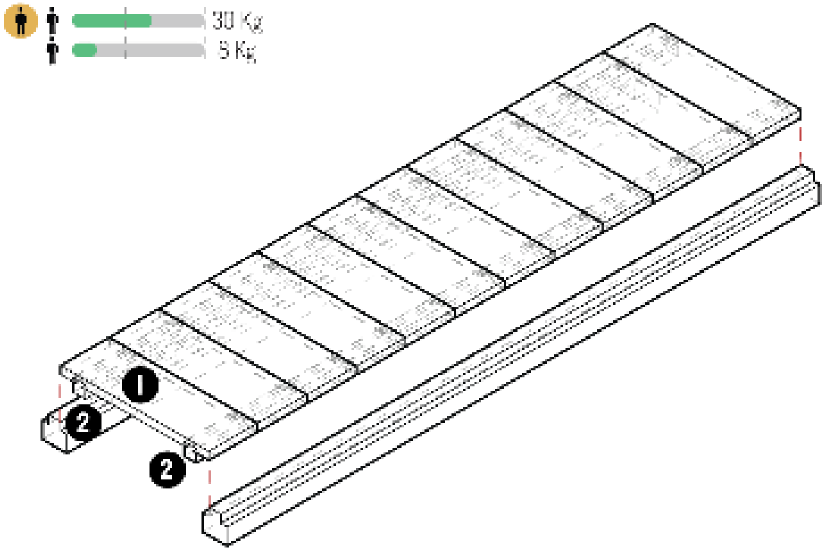
FLOOR TYPE I



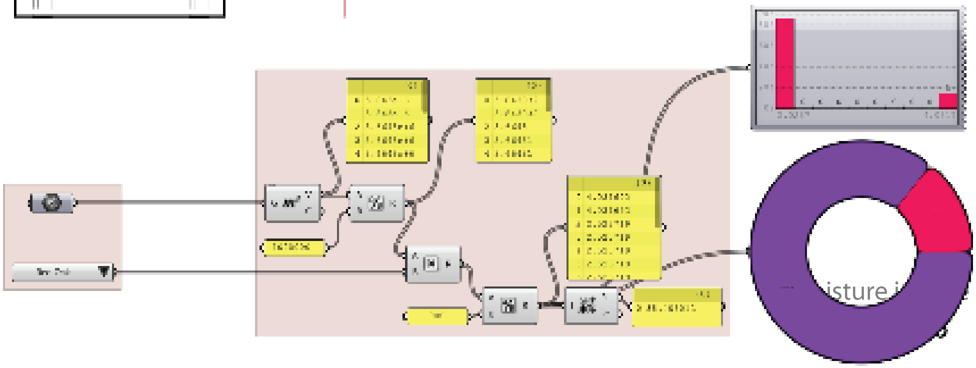
SOFTWOOD COMMON DIMENTIONAL SECTIONS







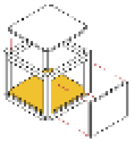
# PARTS NEEDED	MATERIAL	DIMENSIONS	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
1	Red-Oak	610 x 200 x 32 mm	2.5 kg	12	30 kg
2	Red-Oak	50 x 50 X 2440 mm	4.03 kg	2	8.06 kg
			TOTAL WEIGHT		38 kg

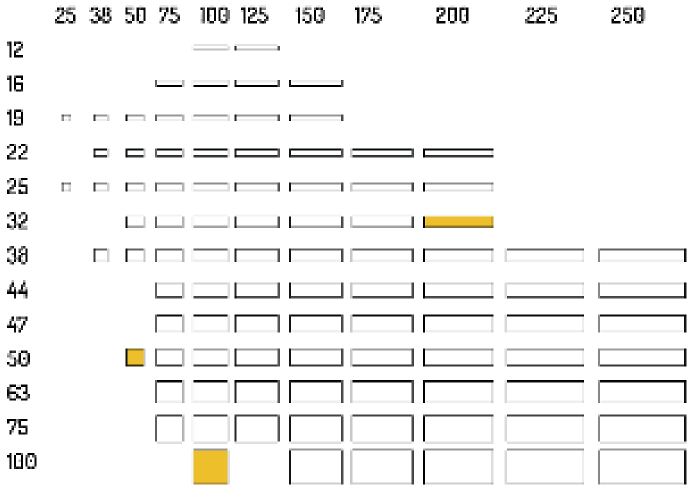


WEIGHT	WEIGHT
Spruce-Pine 34 Kg	Red-Oak 38 Kg
Douglass-pine 24 Kg	Larch 32 Kg

FLOOR BUILDING COMPONENT

FLOOR TYPE 2





SOFTWOOD COMMON DIMENTIONAL SECTIONS

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12					▭	▭					
16				▭	▭	▭	▭				
19	▭	▭	▭	▭	▭	▭	▭				
22		▭	▭	▭	▭	▭	▭	▭	▭		
25	▭	▭	▭	▭	▭	▭	▭	▭	▭		
32			▭	▭	▭	▭	▭	▭	🟨		
38		▭	▭	▭	▭	▭	▭	▭	▭	▭	▭
44				▭	▭	▭	▭	▭	▭	▭	▭
47				▭	▭	▭	▭	▭	▭	▭	▭
50			🟨	▭	▭	▭	▭	▭	▭	▭	▭
63				▭	▭	▭	▭	▭	▭	▭	▭
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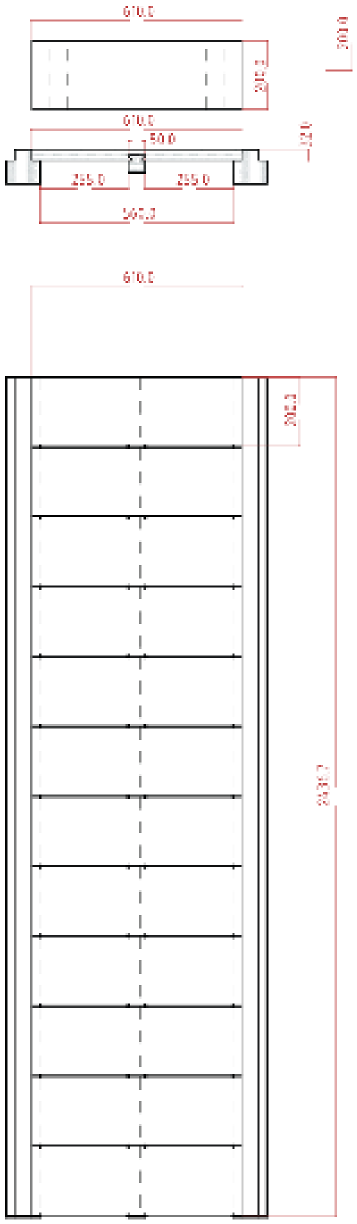
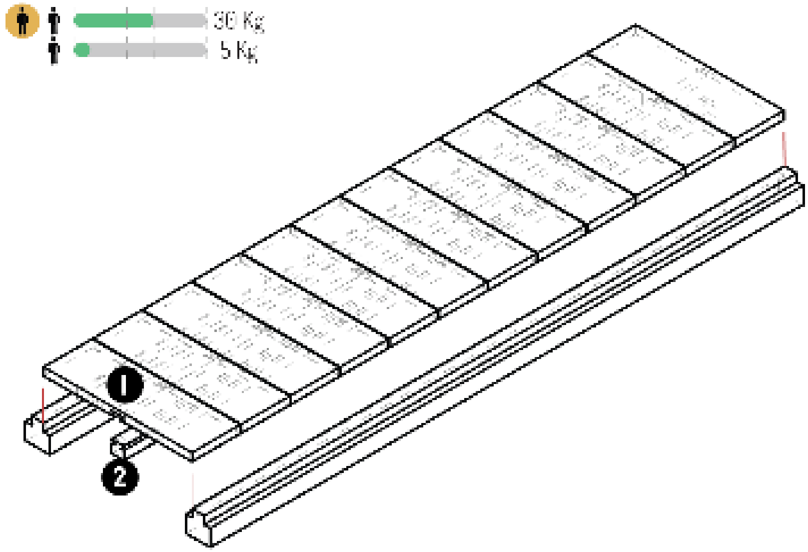
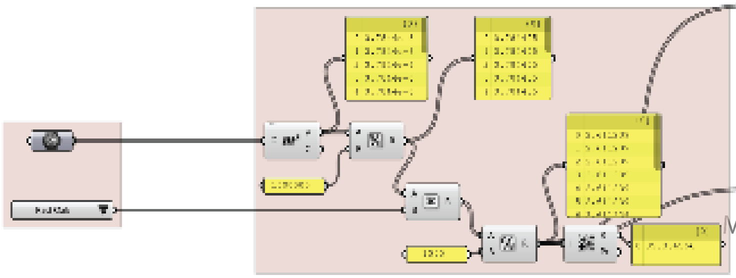
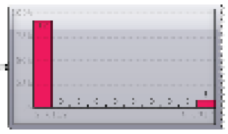


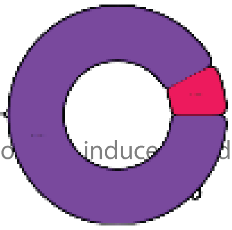


# PARTS NEEDED		MATERIAL	DIMENSIONS	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
❶	5	Red-Oak	610 x 200 x 32 mm	2.5 kg	12	30 kg
❷	4	Red-Oak	50 x 50 X 2440 mm	4.03 kg	1	4.03 kg
				TOTAL WEIGHT		35 kg

WEIGHT	WEIGHT
KG	KG
Spruce-Pine 32 Kg	Red-Oak 35 Kg
WEIGHT	**WEIGHT**
KG	KG
Douglass-pine 22 Kg	Larch 20.5 Kg

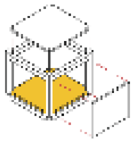




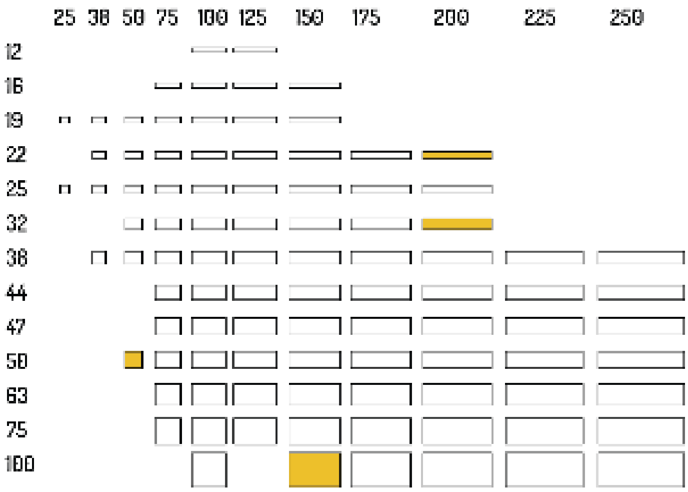


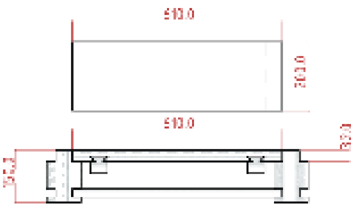
FLOOR BUILDING COMPONENT

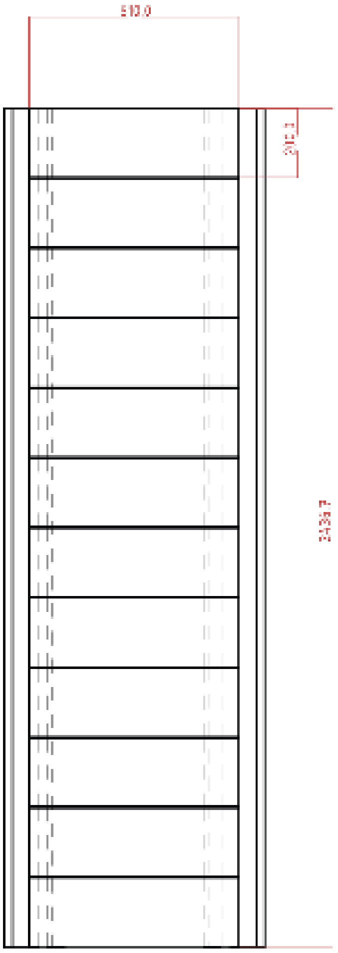
FLOOR TYPE 3

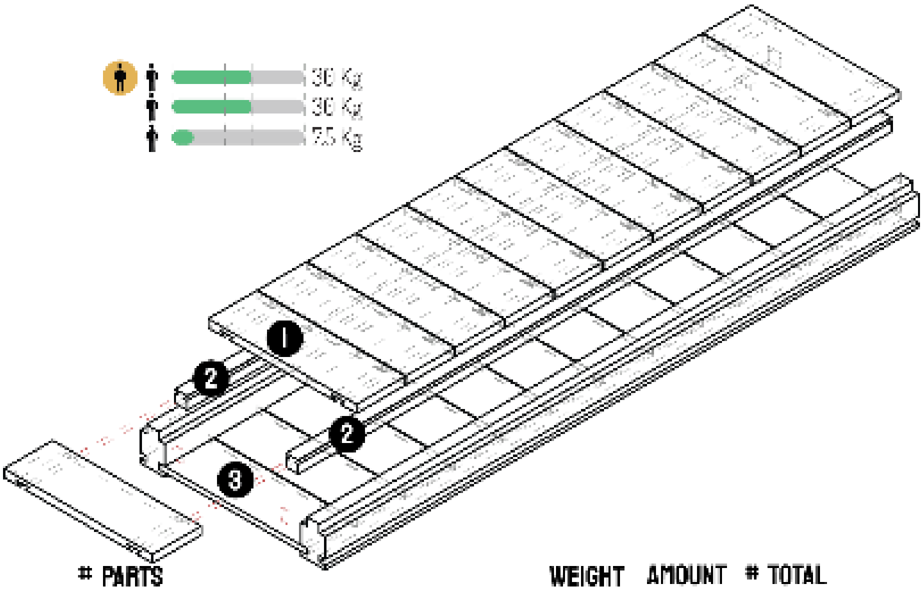


SOFTWOOD COMMON DIMENTIONAL SECTIONS

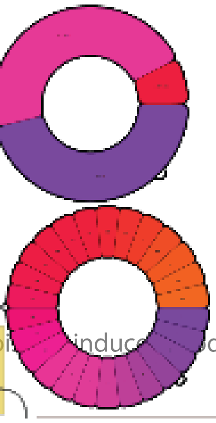






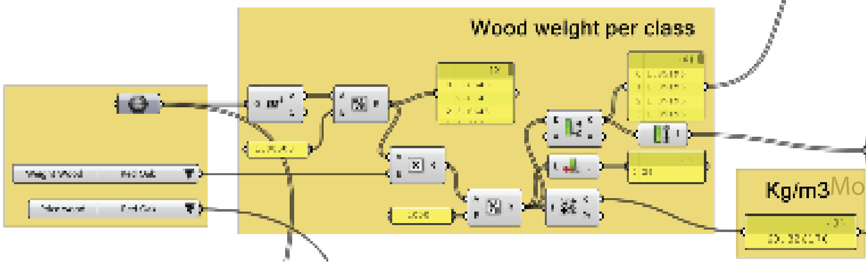


# PARTS NEEDED	MATERIAL	DIMENSIONS	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
❶	Red-Oak	610 x 200 x 32 mm	2.5 kg	12	30 kg
❷	Red-Oak	50 x 50 X 2440 mm	4.03 kg	2	8.06 kg
❸	Red-Oak	610 x 200 x 22 mm	1.85 kg	12	22.2 kg
			TOTAL WEIGHT		60 kg
❹	Cullex	610 x 200 x 22 mm	7.5 kg	1	7.5 kg
			TOTAL WEIGHT		67.5 kg



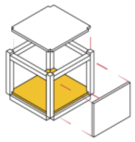
WEIGHT	WEIGHT
Spruce-Pine 54 Kg	Red-Oak 60.3 Kg

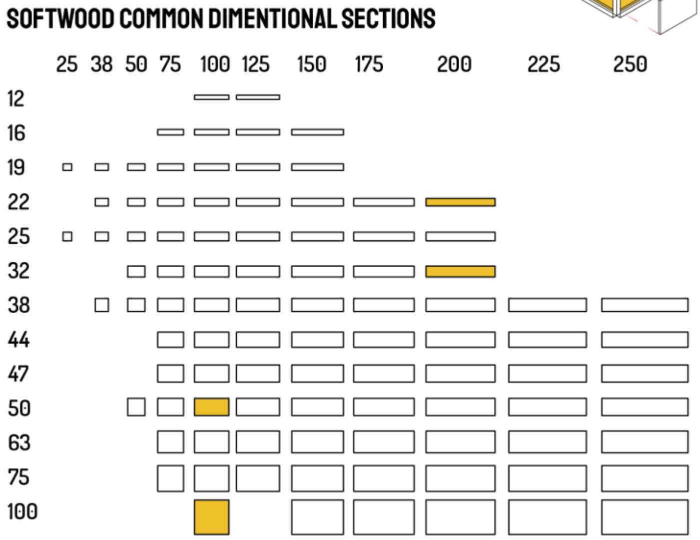
WEIGHT	WEIGHT
Douglass-pine 38 Kg	Larch 50 Kg

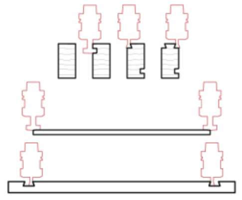


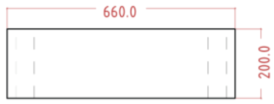
FLOOR BUILDING COMPONENT

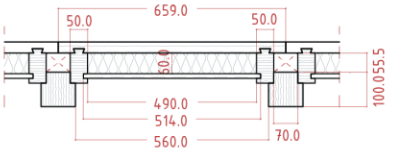
FLOOR TYPE 4

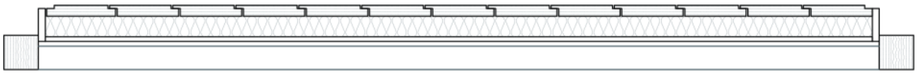


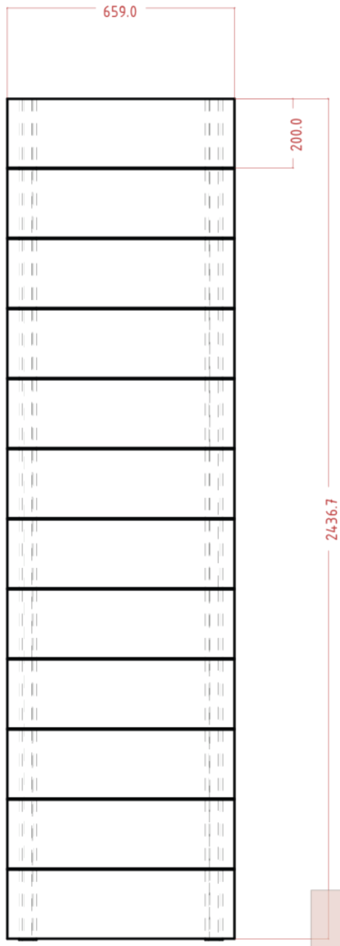


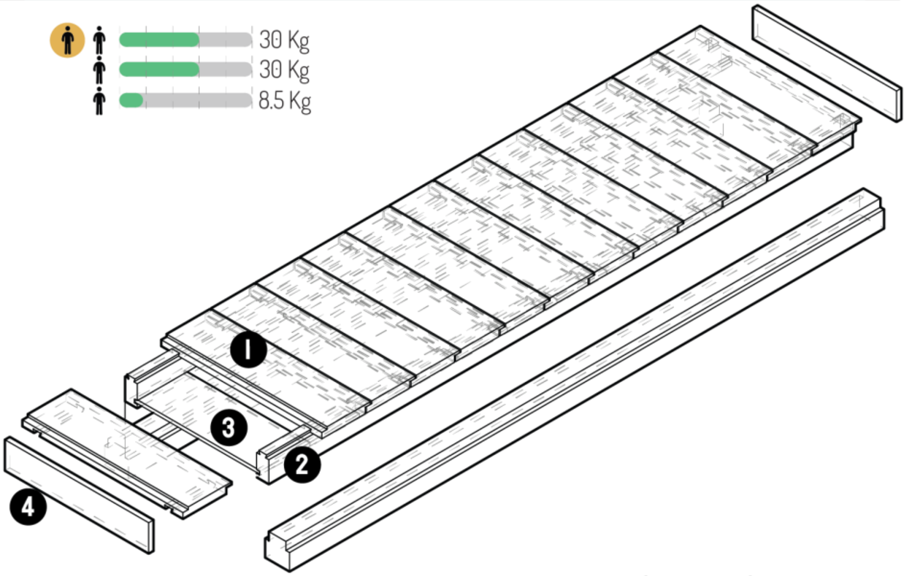






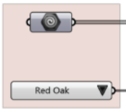


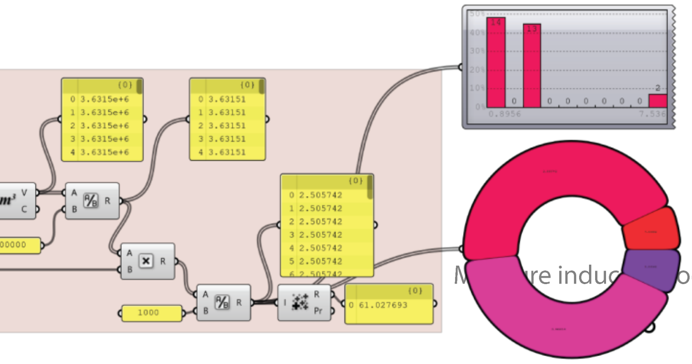




# PARTS NEEDED	MATERIAL	DIMENSIONS	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
1	Red-Oak	610 x 200 x 32 mm	2.5 kg	13	32.5 kg
2	Red-Oak	50 x 100 X 2440 mm	7.53 kg	2	15.06 kg
3	Red-Oak	610 x 200 x 22 mm	0.97 kg	13	12.6 kg
4	Red-Oak	590 x 110 x 22 mm	0.90 kg	2	1.8 kg
			TOTAL WEIGHT		61 kg

WEIGHT	WEIGHT
Spruce-Pine 54 Kg	Red-Oak 61 Kg
WEIGHT	WEIGHT
Douglass-pine 38 Kg	Larch 50 Kg





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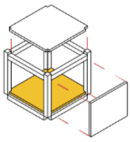
M ure induc od-to-Wood-Joinery

FLOOR BUILDING COMPONENT

FLOOR TYPE 5



SOFTWOOD COMMON DIMENTIONAL SECTIONS

	25	38	50	75	100	125	150	175	200	225	250
12					▭	▭					
16				▭	▭	▭	▭				
19	▭	▭	▭	▭	▭	▭	▭				
22		▭	▭	▭	▭	▭	▭	▭	▭		
25	▭	▭	▭	▭	▭	▭	▭	▭	▭		
32			▭	▭	▭	▭	▭	▭	■		
38		▭	▭	▭	▭	▭	▭	▭	▭	▭	▭
44				▭	▭	▭	▭	▭	▭	▭	▭
47				▭	▭	▭	▭	▭	▭	▭	▭
50			▭	▭	■	▭	▭	▭	▭	▭	▭
63				▭	▭	▭	▭	▭	▭	▭	▭
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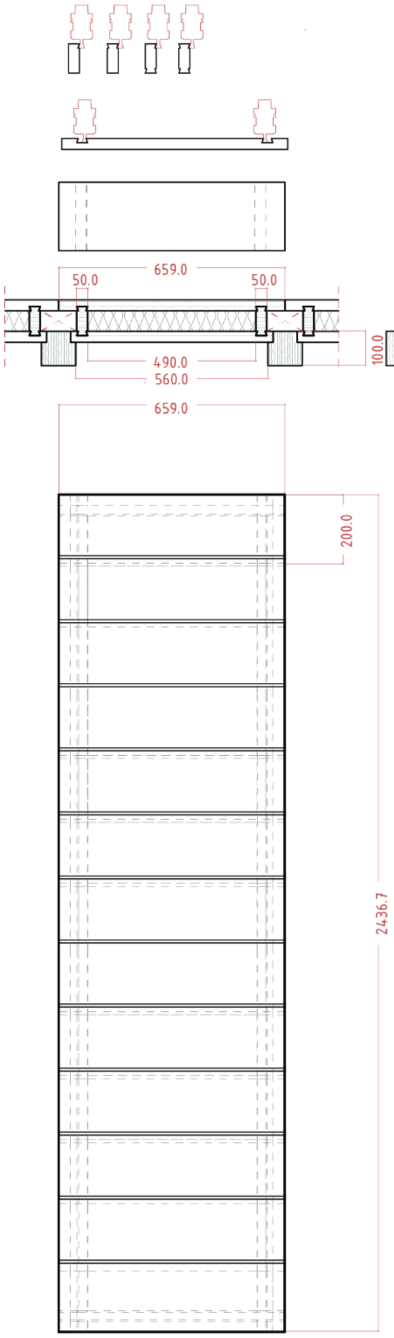
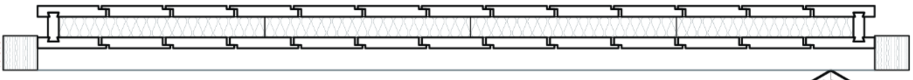
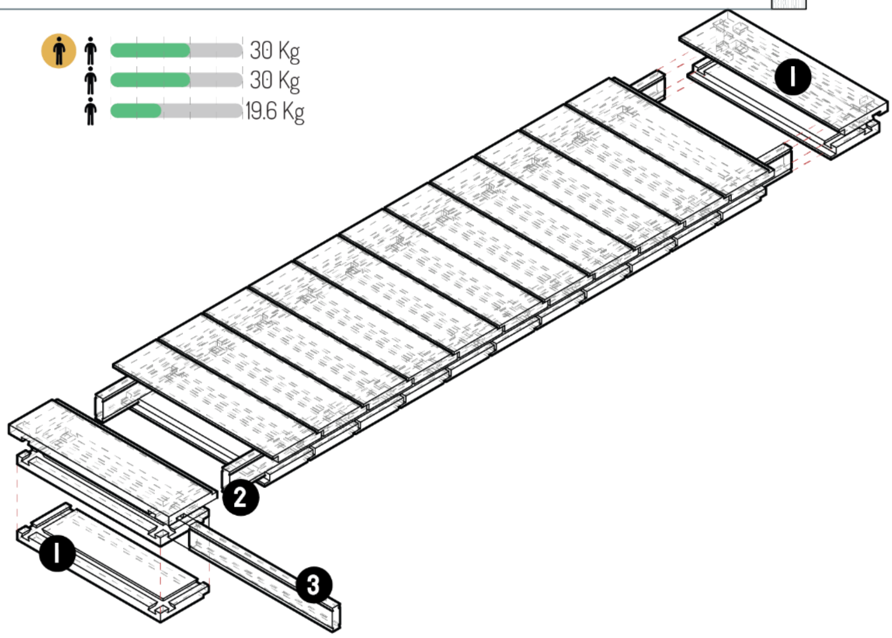
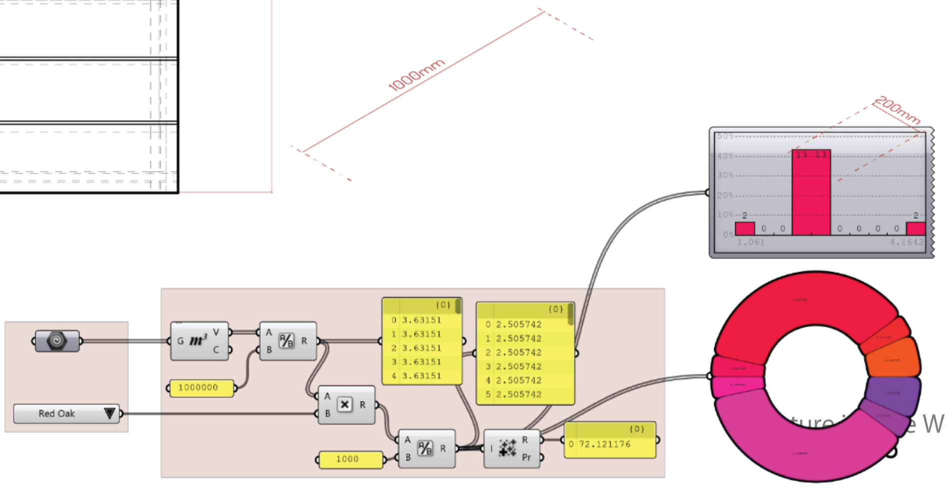
100					▭		▭	▭	▭	▭	▭









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4 2.505742
5 2.505742
```

```
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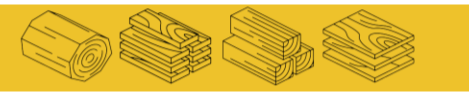
WEIGHT
Spruce-Pine
65 Kg

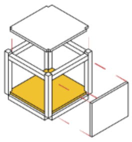
WEIGHT
Red-Oak
72 Kg

WEIGHT
Douglass-pine
45.5 Kg

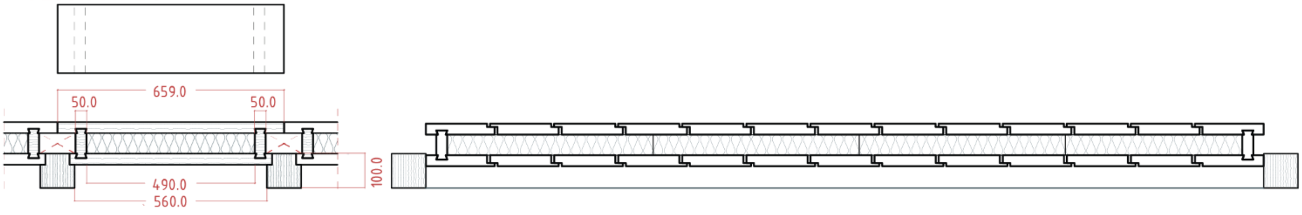
WEIGHT
Larch
60.1 Kg

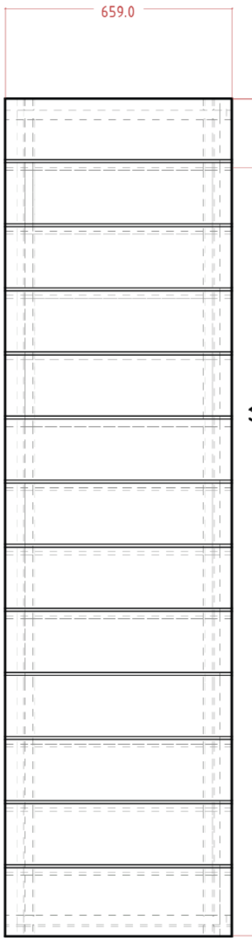


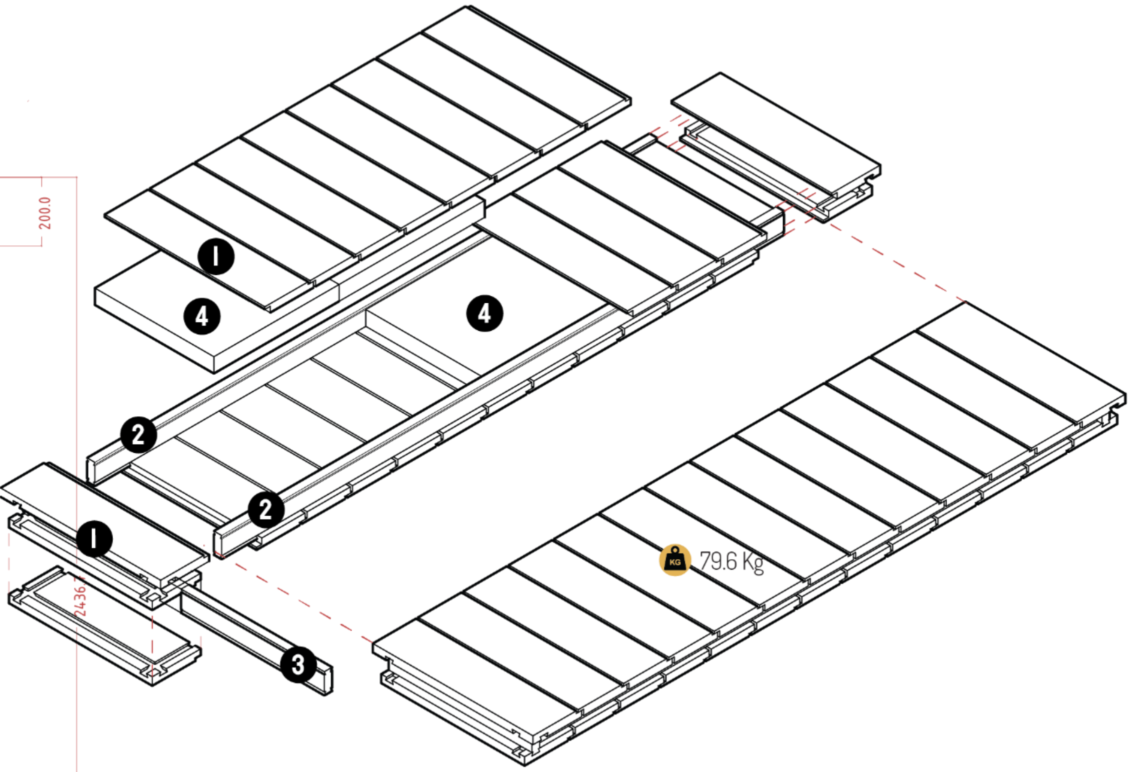
FLOOR BUILDING COMPONENT



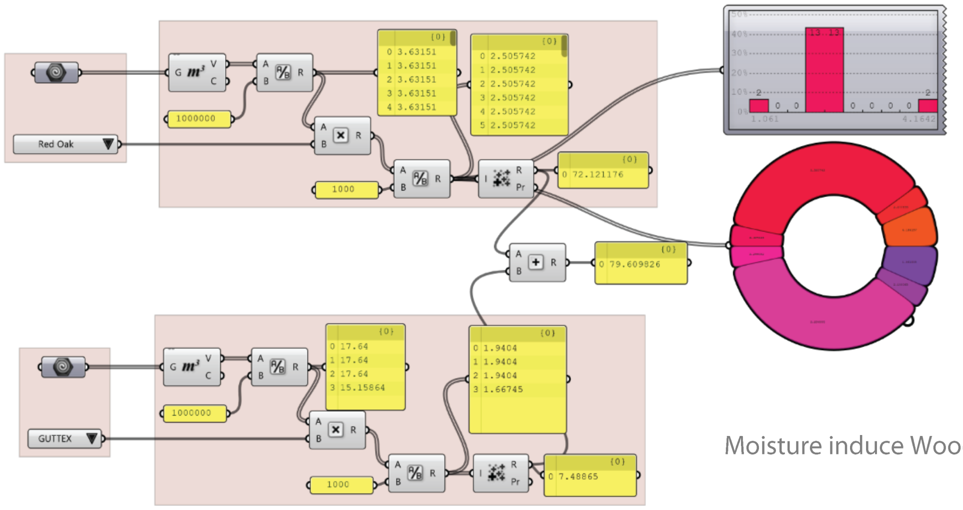
FLOOR TYPE 5







# PARTS NEEDED	MATERIAL	DIMENSIONS	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
1	Red-Oak	610 x 200 x 32 mm	2.5 kg	26	65 kg
2	Red-Oak	32 x 85 X 2440 mm	4.16 kg	2	8.32 kg
3	Red-Oak	590 x 85 x 32 mm	1.1 kg	2	2.2 kg
			TOTAL WOOD		72 kg
4	Guttex	490 x 600 x 60 mm	1.94 kg	4	7.48kg
			TOTAL WEIGHT		79.6 kg



Red Oak

1000000

1000

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4 2.505742
5 2.505742

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{0}
0 79.609826

GUTTEX

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1000

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2 17.64
3 15.15864

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3 1.66745

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0 7.48865

TOTAL WOOD

WEIGHT	WEIGHT
Spruce-Pine 54 Kg	Red-Oak 72 Kg
Douglass-pine 38 Kg	Larch 50 Kg

FLOOR BUILDING COMPONENT

FLOOR TYPE 5

ELEMENT AND COMPONENT WEIGHT STUDY

The outcome of this quick exercise showed the limitation of weight in floor components even with the most simple and aparently lighweight designs. A conclusion of the previous assesment reveals the necesity to subdevide the building compoenets into smaller parts. This desicion allows the integration of two main factores. First, reduce the complexity in transportation, and material handeling due to the size of elements; secondly, the possibility of integration other material that provide a better thermal and acoustic insulation as a result of the smaller blocs and weight.

COMPARISON AMONG DESIGN OPTIONS

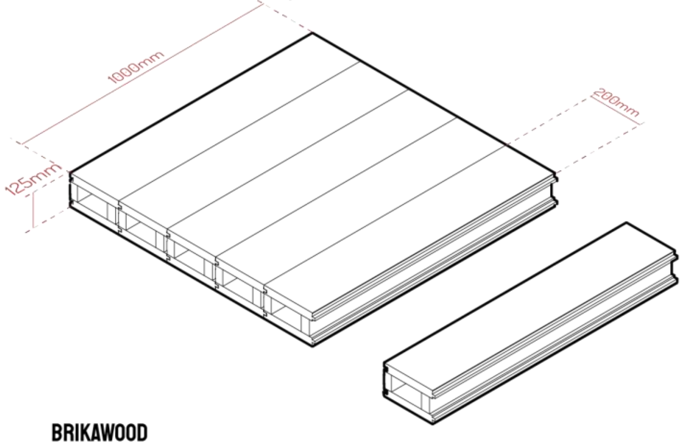
Contrary to Floor type 1, type 5 allows a better material integration. Nevertheless, the component seize and weight makes it difficult to work with, requeting at least 3 people for the possition and assembly process. A fundamental aspect to notice is the milling strategy implemented in all options, this is due to the decision of avoiding extra harware such as screws or bolts. this decision follows the objectives of dis-assembly, and re-useability of wood building components.

SUB-DIVISION OF COMPOENETS - REFERENCE IN THE INDUSTRY

The main design strategy observe from this assesment shows the imperative development of smaller components, thus reducing weight, and increasing building component strategies. Some current building products use this principels in benefit of reducing weight and allowing low expirince workers to be invlove in the building process.

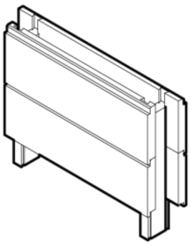
LIGNATUR BOX ELEMENT (LKE)

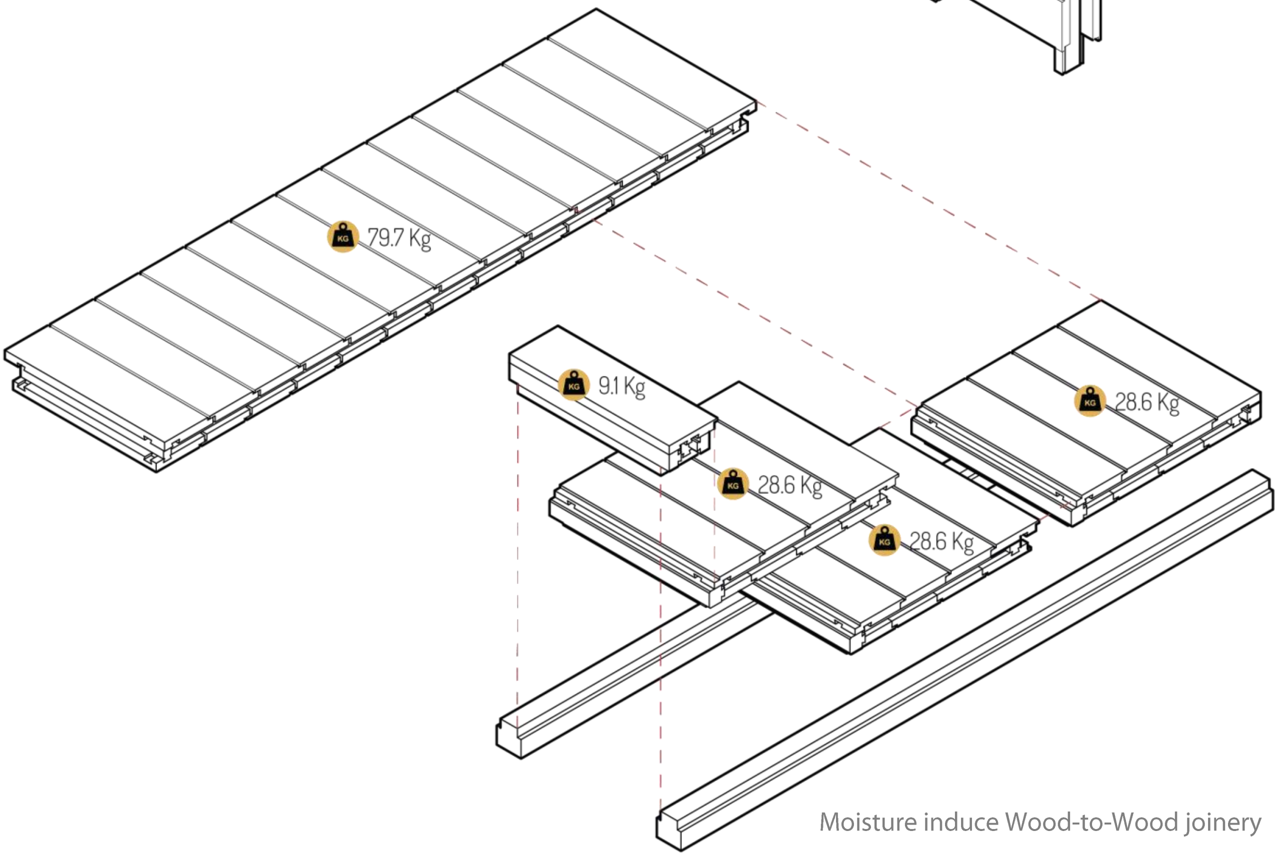
This product have a coverage widht of 200 mm with and a weight of 7Kg for every meter. This building system is particularly suited for manual labor, owing to its lightweight nature. Furthermore, it offers attributes such as fire resistance and superior sound and heat insulation.



BRIKAWOOD

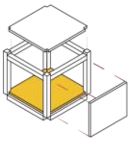
This intuitive system without nails, screws or glue offers a simple assembly logic that follows a repetitive logic. This configuration allows a homogeneity of the wall connection. this porduct is design to ensure comfort in summer and winter as a passive house. The airtight configuration ensures avoiding uncontrolled inner outdeer temperature





FLOOR BUILDING COMPONENT

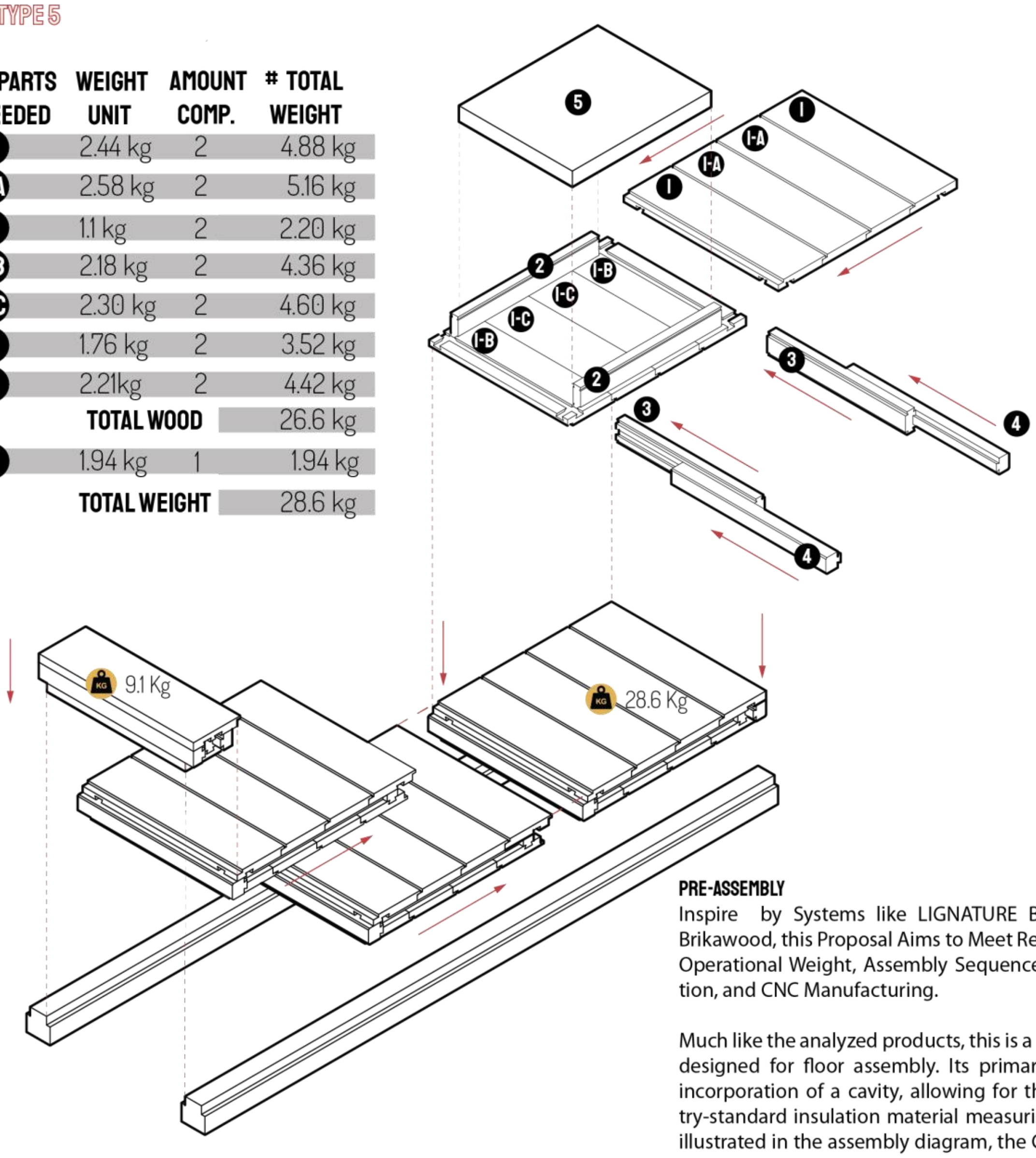
FLOOR TYPE 5



# PARTS NEEDED	WEIGHT UNIT	AMOUNT COMP.	# TOTAL WEIGHT
I	2.44 kg	2	4.88 kg
I-A	2.58 kg	2	5.16 kg
2	1.1 kg	2	2.20 kg
I-B	2.18 kg	2	4.36 kg
I-C	2.30 kg	2	4.60 kg
3	1.76 kg	2	3.52 kg
4	2.21kg	2	4.42 kg
	TOTAL WOOD		26.6 kg
5	1.94 kg	1	1.94 kg
	TOTAL WEIGHT		28.6 kg

TOTAL WOOD WEIGHT

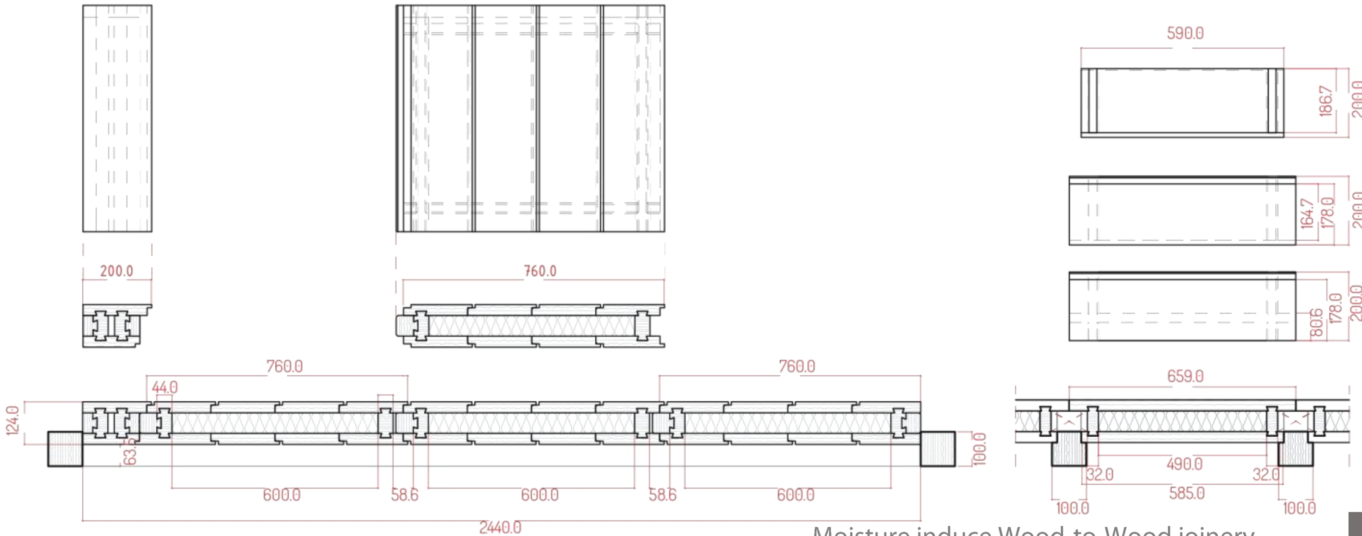
Red-Oak	26.7 Kg
Spruce-Pine	24.2 Kg
Larch	22.3 Kg
Douglass-pine	16.8Kg



PRE-ASSEMBLY

Inspire by Systems like LIGNATURE Box Element (LKE) and Brikawood, this Proposal Aims to Meet Requirements in Line with Operational Weight, Assembly Sequence, Handling, Transportation, and CNC Manufacturing.

Much like the analyzed products, this is a lightweight component designed for floor assembly. Its primary advantage lies in its incorporation of a cavity, allowing for the installation of industry-standard insulation material measuring 600x600x60 mm. As illustrated in the assembly diagram, the CNC manufacturing and assembly approach are geared toward minimizing the need for additional hardware while simplifying the assortment of components required during the assembly stage.



PRICE STUDY

GRASSHOPPER SCRIPT

ASSESMENT OF WOOD PRICE VS COMPONENT CONFIGURATION

Similarly to the protocol of weight study, a Grasshopper integration has been add it to the initial script to understand the desition making of component configuration within the price range. To make an accurate evaluation, the design iterations uses the same type of wood as in the weight assesment (Oak) hardwood. For the price input severals sources were taken into consideration to collect financial information. This includes, small, medium and large companies of the Colombian Forestry industry.

Despite the absence of a standardized price per unit volume (m3) across the region, we have computed an average unit price for wood specimens to mitigate potential variations in the dataset and thereby furnish a more rigorously accurate assessment. This data is tabulated, presenting the cost per m3. It is imperative to notice that within the Colombian industry, a spectrum of dimensions and associated total prices per unit exists. Nevertheless, for the sake of consistency, we have opted to employ a measurement standard commonly found in the market, approximately 150x150x3600mm, for hardwood specimens, serving as the baseline reference for establishing the price per unit volume.

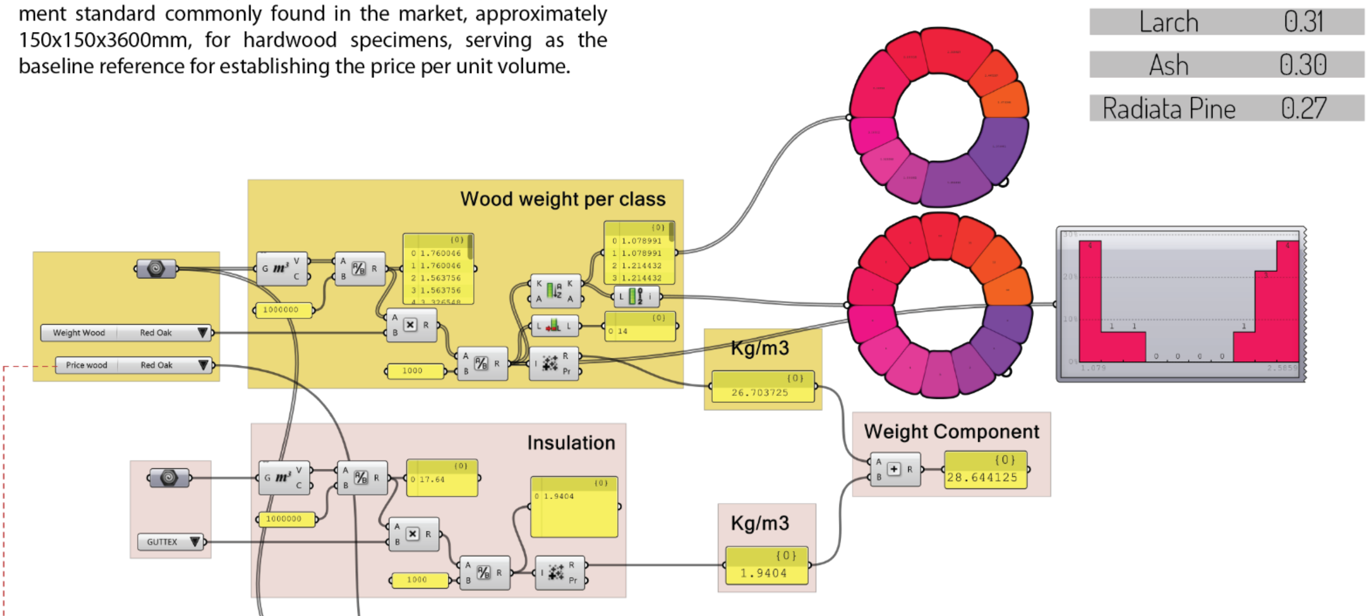
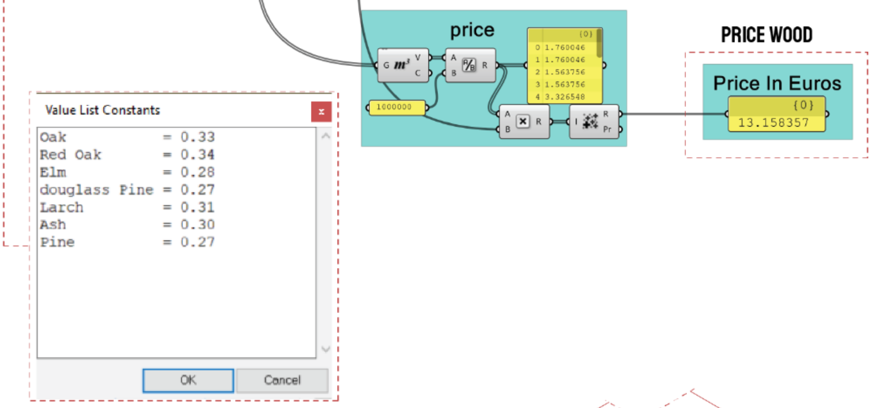
PRICE INPUT

The table displays prices in Euros for the convenience of the reader, as it is a widely recognized currency. However, it's important to note that the industry primarily operates in the local currency: Colombian Peso COP

DIMENTION	UNIT PRICE	PRICE
0.15m x 0.15m x 3.6 m = 0.081 m3	0.34 Eu x1000	27.54 Eu

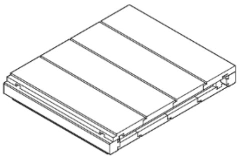
PRICE EURO	PRICE COP	COLOMBIAN MINIMUM SALARY	CONVERTION
27.54 Eu	57.100 Cop	1.160.000 Cop	264 Eu

TYPE	PRICE UNIT CENT EU
Oak	0.34
Elm	0.28
Douglass Pine	0.27
Larch	0.31
Ash	0.30
Radiata Pine	0.27

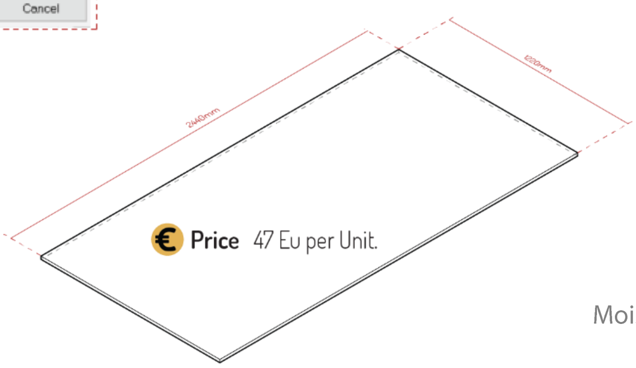



Value List Constants

```
Oak          = 0.33
Red Oak      = 0.34
Elm          = 0.28
douglass Pine = 0.27
Larch        = 0.31
Ash          = 0.30
Pine         = 0.27
```



€ **Price** 13 Eu per Comp.

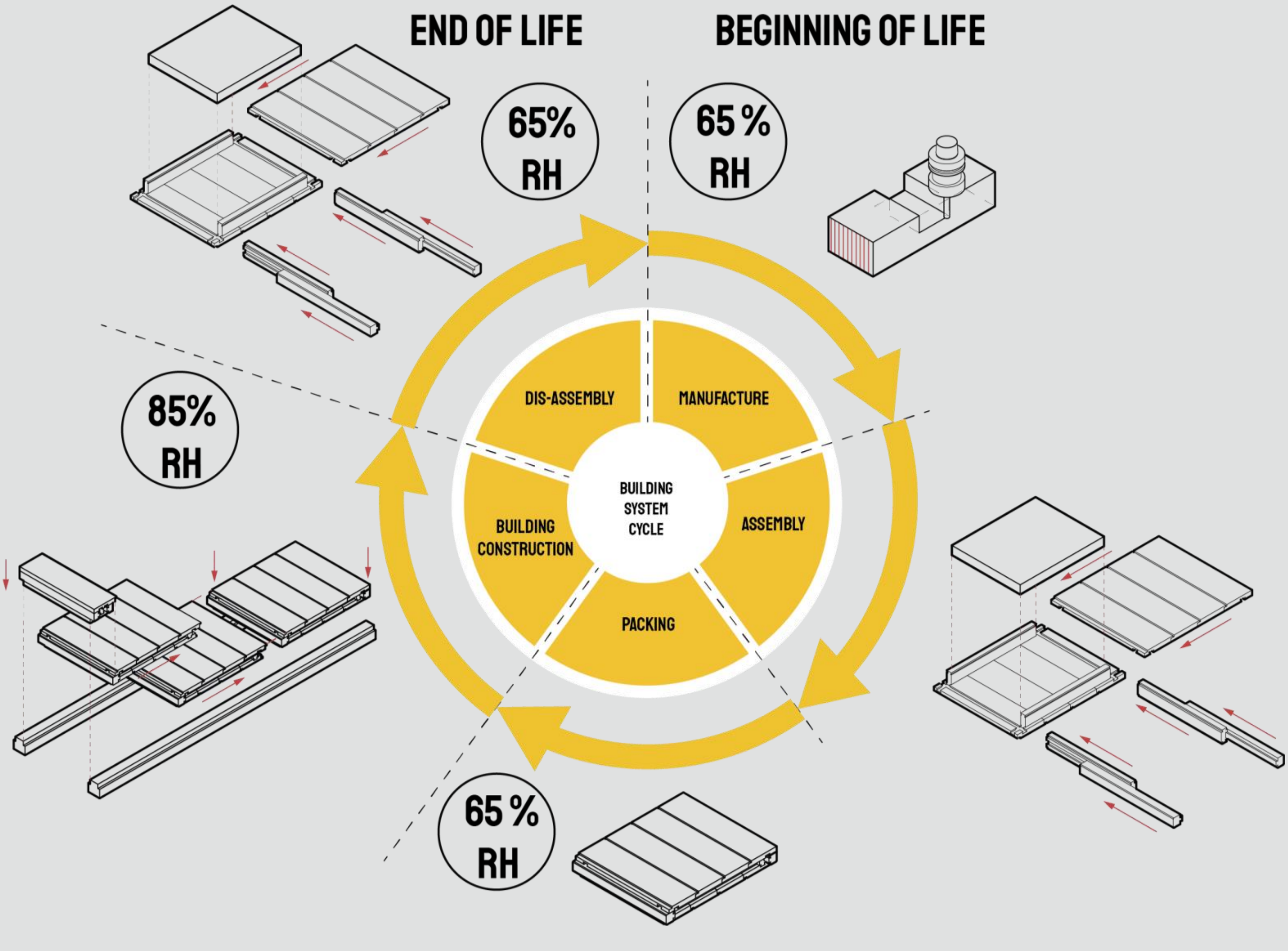


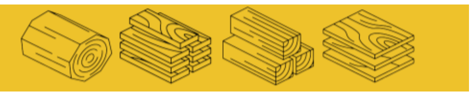
€ **Price** 47 Eu per Unit.

EWP'S

As previously detailed in earlier chapters, engineered wood products (EWPs), including structural boards and plywood panels, are manufactured overseas. Consequently, the unit price is considerably elevated, rendering their use financially unfeasible for our project. Additionally, these materials exhibit poor performance in terms of resistance to humidity and susceptibility to fungal decay due to their foreign production as well as wet adhesives.

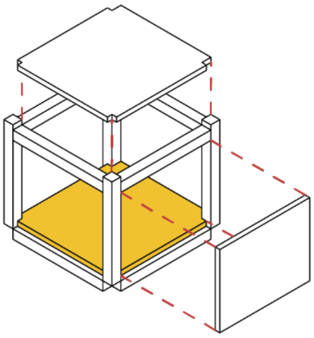
REPURPOSE


END OF LIFE
BEGINNING OF LIFE
65%
RH
65 %
RH
85%
RH
DIS-ASSEMBLY
MANUFACTURE
BUILDING
SYSTEM
CYCLE
BUILDING
CONSTRUCTION
ASSEMBLY
PACKING
65 %
RH



ANALYSIS OF FLOOR BUILDING COMPONENT

STRUCTURAL MODULE



WEIGHT

MATERIAL

Component weight	●●●
Material	●●
Workers requited	●●●

CRITERIA

Max. Weight person	🧍 30 Kg Max.
Material	Quercus Robur - Oak
Max. staff requited	🧍 🧍🧍
Max. Component	60 Kg Max.

COST

MATERIAL PRICE

Dis-Assemblly	●●●
Herarchy	●●
Modularity	●●●
Weight	●●●

€ **Price** Colombian Wood in Euros m3

ASSEMBLY DIS+ASSEMBLY

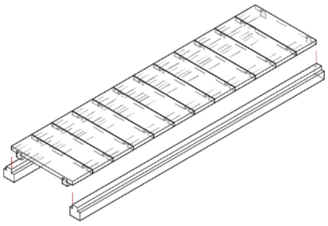
ASSEMBLY

Speed	●●●
Simplycity	●●●
Unexpirience Labour	●●●
Herarchy	●●
Modularity	●●●
Design Freedom	●●

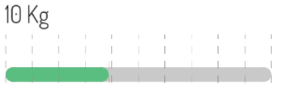
DIS-ASSEMBLY

Speed	●●
Simplycity	●●●
Unexpirience Labour	●●
Herarchy	●●●
Modularity	●●

FLOOR COMPONENT TYPE I



ASSESSMENT



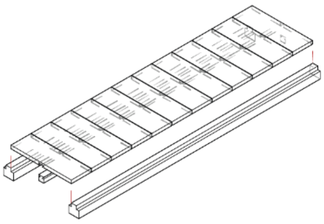
Oak 38 Kg

Insulation 0 Kg

🧍 🧍🧍

€ **Price** 18 Eu

FLOOR COMPONENT TYPE 2



ASSESSMENT

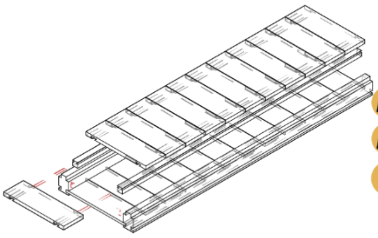
Oak 35 Kg

Insulation 0 Kg

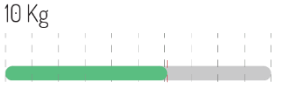
🧍 🧍🧍 35 Kg

€ **Price** 17.4 Eu

FLOOR COMPONENT TYPE 3



ASSESSMENT



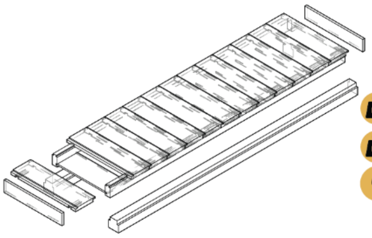
Oak 60 Kg

Insulation Guttex 7.5 Kg

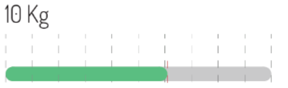
🧍 🧍🧍🧍 67.5 Kg

€ **Price** 29.7 Eu

FLOOR COMPONENT TYPE 4



ASSESSMENT

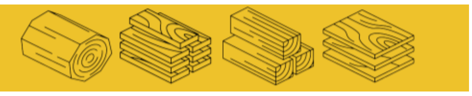


Oak 61 Kg

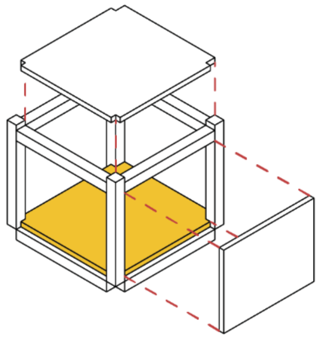
Insulation Guttex 7.5 Kg

🧍 🧍🧍🧍 68.5 Kg

€ **Price** 30 Eu



STRUCTURAL MODULE



WEIGHT

MATERIAL

Component weight	●●●
Material	●●
Waste	●●●

CRITERIA

Max. Weight person	🧍 30 Kg Max.
Material	Quercus Robur - Oak
Max. staff requited	🧍 🧍🧍
Max. Component	KG 60 Kg Max.

COST

MATERIAL PRICE

Dis-Assemblly	●●●
Herarchy	●●
Modularity	●●●
Weight	●●●

€ **Price** Colombian Wood in Euros m3

ASSEMBLY DIS+ASSEMBLY

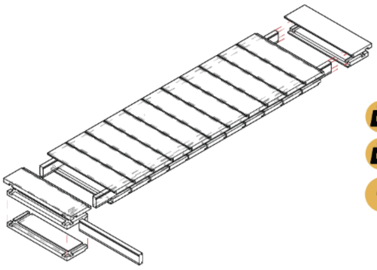
ASSEMBLY

Speed	●●●
Simplycity	●●●
Unexpirience Labour	●●●
Herarchy	●●
Modularity	●●●
Design Freedom	●●

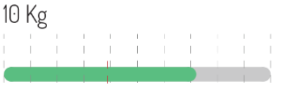
DIS-ASSEMBLY

Speed	●●
Simplycity	●●●
Unexpirience Labour	●●
Herarchy	●●●
Modularity	●●

FLOOR COMPONENT TYPE 5



ASSESSMENT



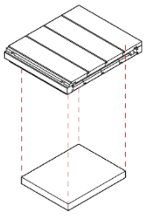
KG **Oak** 72 Kg

KG **Insulation Guttex** 7.5 Kg

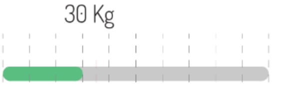
🧍 🧍🧍🧍 80 Kg

€ **Price** 35 Eu

FLOOR COMPONENT TYPE 6



ASSESSMENT



KG **Oak** 26.7 Kg

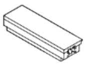
KG **Insulation Guttex** 1.94 Kg

🧍 🧍 28.6 Kg

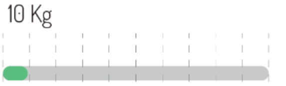
€ **Price** 13 Eu per Comp. **x3**

€ **Price** 39 Eu

FLOOR CONNECTOR COMPONENT



ASSESSMENT



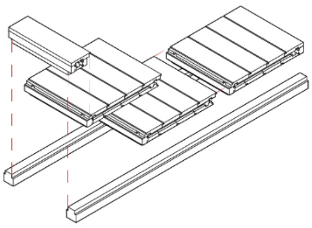
KG **Oak** 9 Kg

KG **Insulation Guttex** 0 Kg

🧍 🧍

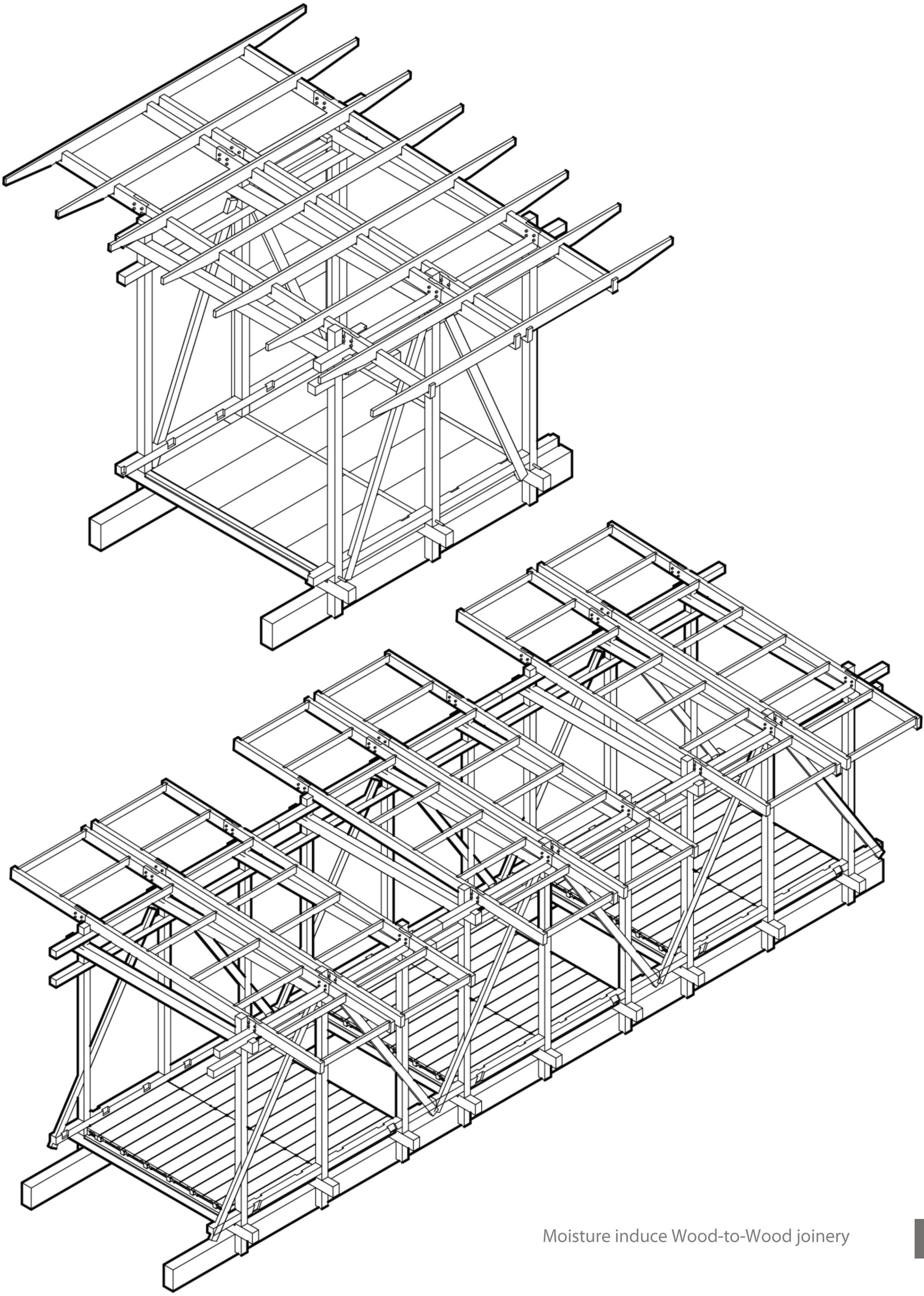
€ **Price** 4.5 Eu per Comp.

€ **Price** 43.5 Eu



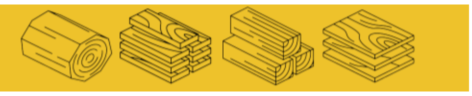
PARTS & OPERATIONS

STRUCTURAL MODULE



REFLECTION

ASSESMENT OF THE RESULT AND THE FUTURE APPLICATIONS



REFLECTION

THE RESEARCH STRUCTURE AND THE RESULTS:

The Big picture:

DOCUMENT STRUCTURE

This research embarks on an exploration of the potential integration of climatic conditions, particularly humidity variations, in the context of developing an alternative prefabricated wood housing system tailored to the unique geographical, climatological, and socio-economic conditions prevailing in Colombia. The research unfolds through several key phases, each of which contributes to a holistic understanding of this multi-layered work.

The ultimate goal of this study is to create an affordable and sustainable solution addressing the social housing crisis in Colombia. It aims to develop a wood-to-wood connection system that harnesses the material's properties, digital manufacturing technology, and structural performance. This system is designed to simplify the construction process, especially for inexperienced users, by leveraging the material's ability to swell in response to environmental humidity.

To assess the viability and impact of this innovative approach, the research was divided into four distinct branches. Each of these phases allowed for an in-depth exploration of the system, starting from specific aspects such as the material properties and progressing to the practical implementation of a housing unit within the Colombian context. The ultimate objective is to revolutionize the construction industry and positively influence the social conditions of vulnerable populations in Colombia.

This research project followed a structured approach that consisted of four main phases:

Wood Industry Assessment: This phase involved a rapid evaluation of the wood industry in Colombia to identify the types of wood products available for use in the study.

Material Science and Properties: The second phase focused on understanding the properties of wood, particularly how it responds to changes in humidity. This knowledge was essential for integrating the material's behavior into the construction process.

CNC Manufacturing Assessment: The third phase revolved around evaluating the potential of CNC (Computer Numerical Control) manufacturing technology, considering the materials available in the Colombian context. This phase also explored the most effective wood joint connections for manufacturing.

Structural Assessment: In the final phase, the study examined various wood joints and structural elements like beams and columns. This analysis aimed to determine the optimal sizes, weight, and construction implications in relation to the material properties.

The findings from each of these four branches were integrated to propose a comprehensive building system. This system, driven by the ability of wood to interlock itself in response to humidity, eliminates the need for screws and glue, making construction more sustainable and efficient.

RESEARCH PROCESS DEVELOPMENT - CLIMATE

A clear understanding of climate and regions in need of this technical solution established the principal boundary conditions of CNC manufacture, and material evaluation to the building assembly constrains:

Boundary conditions:

3. Average relative Humidity of populations in need 80%-85%, as great part of the country.
4. Average relative humidity of CNC machinery locations: 60% - 65%
5. Temperature ranges 23 to 27 degrees Celsius, as 86% is restrained to these conditions.

These boundary conditions were used to study the hygroscopic properties of wood, the primary intension was to identify the ideal specimen for the experimental construction process.

Methodology – Material selection

Due to a wide range of material sub species, as well as limited access to tropical specimens. The study commences by selected the most common and similar samples, intending to homologate material behavior in the Colombian Context. Thus, Douglas Pine, Larch, Ash, Oak Quercus Robur, Meranti, and

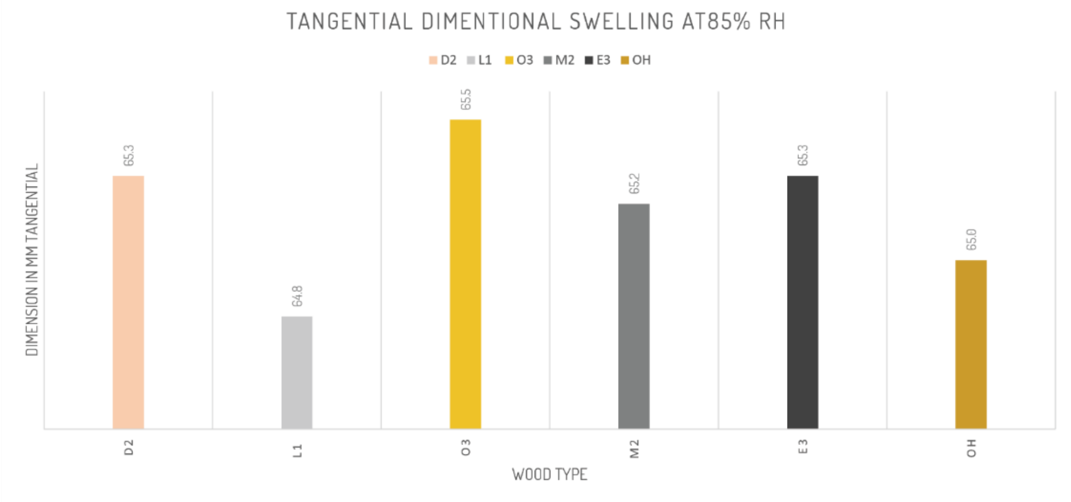


Figure 137 Final dimensional change in tangential fiber direction after 30 days

Elm were under close evaluation to find the most appropriate material to implement principles of volumetric change due to changes in Relative humidity.

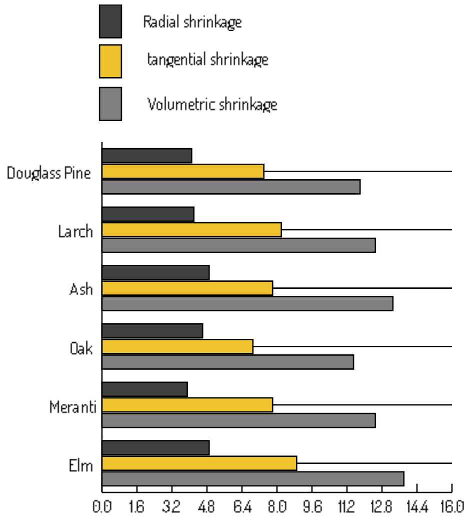


Figure 138. Tangential, radial and longitudinal Shrinkage of several wood spicies

Methodology – Material experimentation.

Figure 139 Wood samples for experimentation

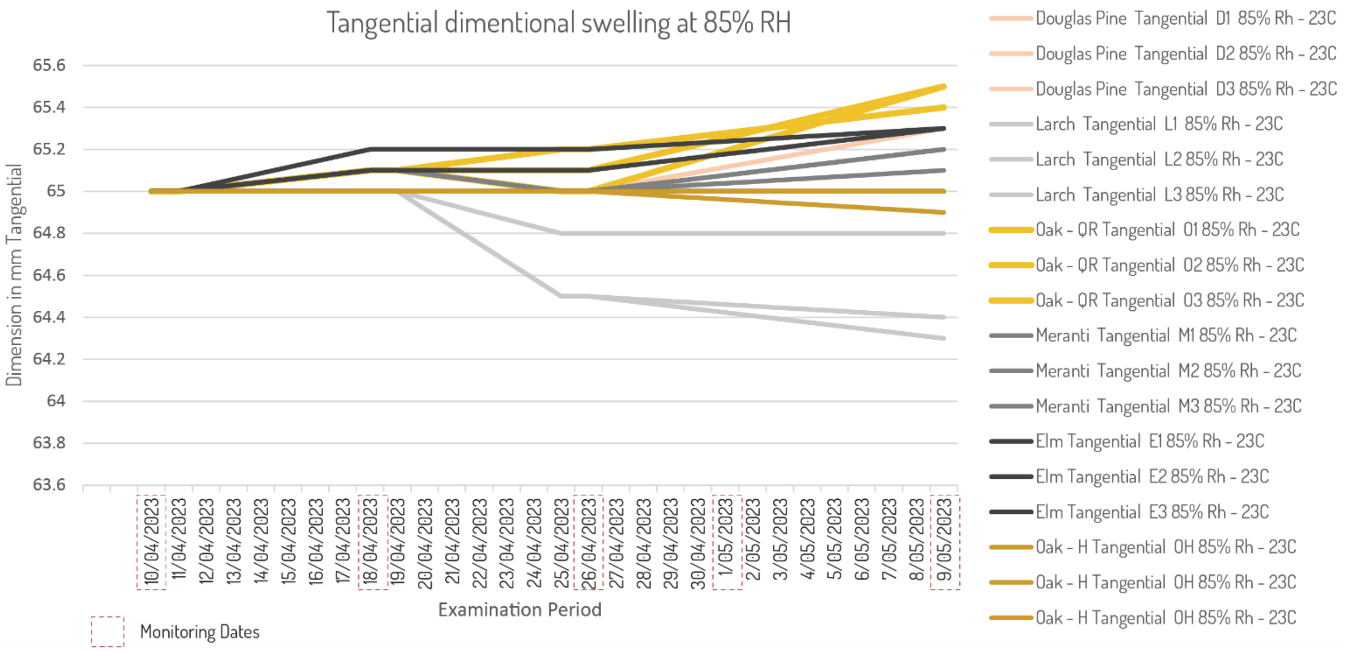
Based on this selection, batches of material samples with similar conditions were under constant monitoring, several material iterations were created to compare and demonstrate results. After a thrilling experimentation phase the Oak Hardwood Quercus Robur shows a consistent and outstanding performance to explore the integration of swelling effects into wood-to-wood connection with interlocking capabilities due to moisture change.

Results

The results observed in figure 108 demonstrate three fundamental research outcomes.

Material Performance

This experiment finds Oak Quercus Robur hardwood as the most suitable specimen for exploration into the applications of Moisture change in interlocking process of wood-to-wood Connections. Nevertheless, other potential species



such as Douglas Pine and Larch wood types show swelling capabilities into the wood-to-wood interlocking systems. Further research into these alternatives is necessary as this type of material offers a more affordable solution.

Time Frame

Some literature research mentioned the time required for the material to reach (FSP) Fiber saturation point up to 60 days, in other words, maximum fiber direction change. Nevertheless, this rigorous study is possible to demonstrate that after a 30 day process, wood specimens reach maximum physical change performance. This data is taken into consideration to formulate a manufacturing and assembly process to create optimal construction workflows.

Joinery Tolerances

wood dimensional changes from initial state to fully dimensional change was identified. After constant 30-day humidity exposure the wood samples of Quercus Robur reach an additional + 1.5 mm material swelling. This process was conducted from a material Moisture content of 9.30% up to 15% MC.

Methodology evaluation,

The scientific experimentation based on literature research gave the ideal framework to demonstrate material capabilities. Following the study of (Karagüler & Kaya, 2017) a research methodology was stablish an set in practice to evaluate material conditions. Due to the effectiveness of the process, which created a close experimental environment was possible to isolate the climate conditions desired for evaluation. Therefore, this rigorous reduces results errors, and creates an effective process.

Figure 140 taken from the research paper of (Karagüler & Kaya, 2017) effects of relative humidity and moisture in durability of spraude and laminated timber.

Material Methodology success

Due to the success of the first stage of experimentation, this methodology was repeated in further stages, such as the implications of the material into the wood-to-wood joints as a mean to demonstrate the structural capabilities of the proposed building system.

This consistent evaluation strongly demonstrates the effectiveness of this specific theory. Moreover, aiming to answer the main question as follows:

Main Research Question:

To what extent can 3-axis CNC milling, a digital manufacturing technology, be utilized to fabricate wood-to-wood connections in sawn timber structures for low-cost housing in Colombia while adhering to Design for Manufacture and Assembly (DfMA) principles?

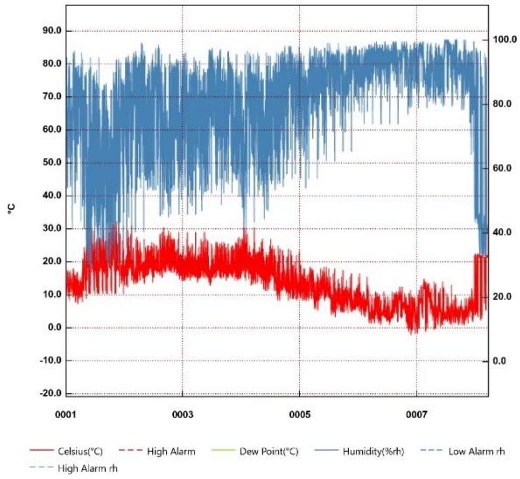
This methodology allowed for the study through each development stage to include more variables. For instance, the first experimentation which can be seen in the material exploration chapter starts from using small 65x65x65 mm samples. By the end of this research, it was possible to compare complex manufacture wood joints, keeping the same experimental conditions.

Extend of the study: Drastic Relative humidity environment change

During the stabilization process, wood tends to warp, and bend following the fiber direction in the process s of moisture release or absorption. Due to the size of the specimens as well as impossibilities to test the structural samples under constant load is not possible to demonstrate the repercussion of this mechanism of assembly in long term effect. Thus, a branch of this research can be originated from this absence. Despite aiming to propose a fully functional building system, a rather complex task means demonstrating each and one of the specific topics that can be generated in the development of the research.

Time frame and planning

As observed, the experimentation timetable required a long prosses of monitoring to produce reliable data. Additional laboratory equipment was implemented to keep records of such a detailed study. For instance, equipment such as the moisture sensor proves efficient to maintain and demonstrate ideal experimental values. The fluctuations in the graph can be seen due to the monitoring of the specimen ever week, which had to be taken out of the close environment, momentarily reduction climatological conditions.



Mathematical research

A valuable approach of the material was the understanding of the mathematical theory behind the volumetric change:

An outcome of this study can be referred to the understanding of the close relation between material Density, and fiber volumetric change, which is confirm by an extend literature research, point at the tangential fiber direction as the characteristic that shows bigger changes.

The numerical values were constant, nevertheless there are some discrepancies in data source regarding physical properties of the wood, such as shrinkage ratios, which differ from source to source.

$$FSP = S_v \cdot G_{H_2O} / G_0$$

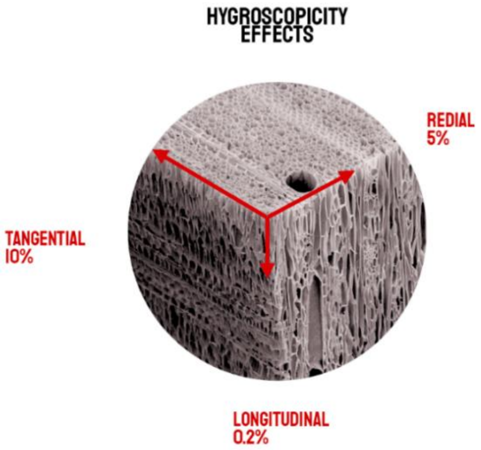


Figure 141 Fiber direction shrinkage ratio taken from PhD candidate Max Salzberger.

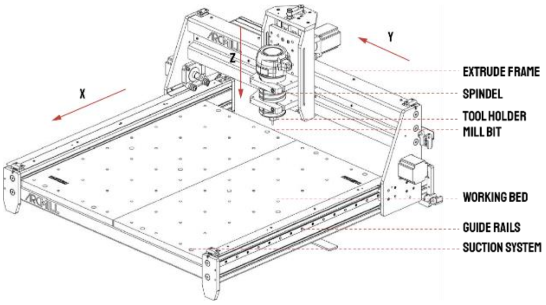
CNC ASSESSMENT

Considerations for design

The big Picture

The primary objective of the manufacturing study is to gain a comprehensive understanding of the capabilities and limitations of CNC (Computer Numerical Control) technology in fabricating traditional joinery connections using sawn timber. This study explores the feasibility of employing non-conventional wood products, specifically sawn timber, in a manufacturing setup, with the aim of assessing its potential applicability in the Colombian context where CNC technology is readily available.

The research encompasses a thorough investigation of various aspects, including working areas, anchorage points, material positioning, precision, production time, material hardness, and other critical factors. These evaluations are pivotal in determining the efficiency and effectiveness of the CNC manufacturing process in the context of different wood-to-wood connections, with broader applications in the research and construction domains.



In light of the insights gained during the prototyping stage, a set of constraints has been established. These constraints serve as general guidelines for the production of traditional wood joinery connections using a CNC machine and sawn timber elements. They encompass the following key considerations:

Cross section

The following machine conditions provide clear limitations and requirements of the design. As can be seen, the cross sections of the elements cannot reach 100 mm in the Z-Axis. Disregarded structural requirements, the design needs to be adjusted to this limit.

Length

As mentioned in the CNC evaluation sections, a limit length of 3000 mm is taken as most of the machinery presents an average maximum length around this dimension.

17. Z-Axis Working height limit 100 mm
18. Y-Axis Dimensional limit 1200 mm
19. X-Axis dimensional limit 3000 mm

Tooling limitation

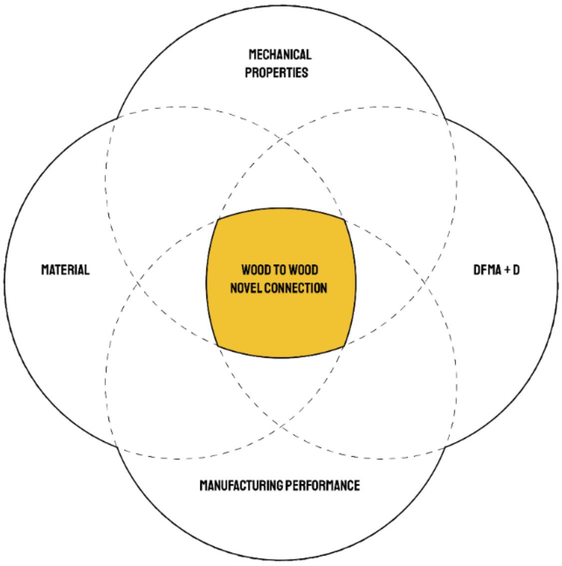
The tooling limitation drastically altered the decision making towards choosing the wood-to-wood joint. As follows you can see a detailed characteristic condition of the milling performance studied at TU Delft University.

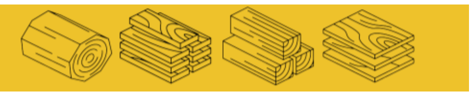
20. Maximum Mill bit Diameter 10 mm
21. Maximum Mill bit high 60 mm
22. Free movement limit after material 5 mm
23. Feed rate conditions: 600 mm/min
24. Step Down layer conditions: 2.0 mm

THE GOAL - FOUR FUNCTIONS

As elaborated in the CNC study, the manufacturing perspective of this research project was guided by four primary objectives. Firstly, the selection of the material was based on the outcomes of the experimental stage, leading to the choice of Oak Hardwood as the preferred material. Secondly, careful consideration was given to the fiber direction of the elements. This was essential to design components that could maximize the tight-fitting effects, particularly in response to variations in relative humidity over time.

The third objective centered on achieving optimal structural performance in the joinery connections by focusing on the mechanical properties. Lastly, each joint design was meticulously crafted in accordance with the principles of DFMA (Design for Manufacture, Assembly, and Disassembly). These elements were integral in shaping the final decisions made within the research project.





LIMITATIONS

Due to machinery restrictions at TU Delft University regarding material hardness, it was not possible to produce a continuous research process. This set back opened the opportunity to conduct a deeper analysis in Koln, Germany, were thanks to the support of my third mentor Max Salzberger, a fully experimental study was developed to demonstrate manufacturing performance.

RESULTS

JOINERY ASSESSMENT

Mortise and Tenon

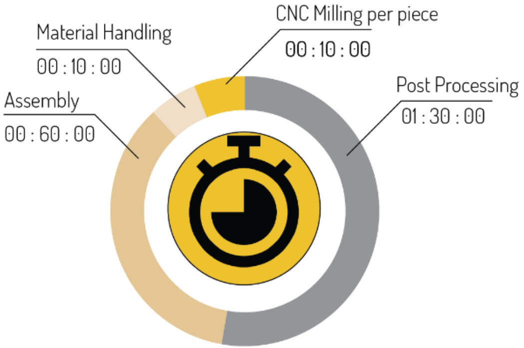


Figure 142 Mortise and tenon CNC assessment

T- Joint

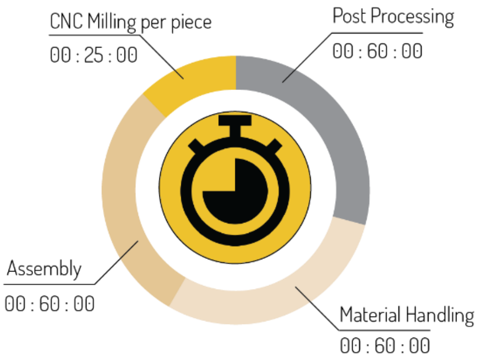
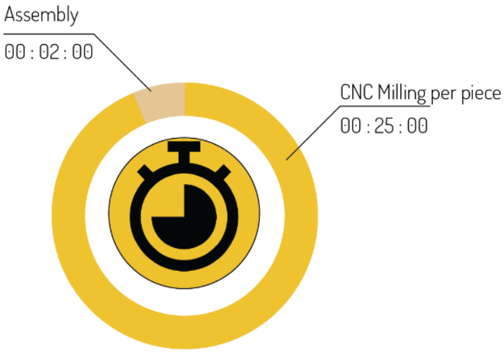


Figure 143 T-Joint CNC Assessment

Cross-Half lap

Figure 144 Cross-Halft Lap CNC Assessment



CONCLUSION OF CNC JOINTS

CNC milling

First and foremost, it is important to note that manufacturing traditional joinery connections like mortise and tenon or T-joints using this type of technology isn't well-suited. The manufacturing process is designed around a 2D strategy for panel production, and attempting to create complex geometry requires additional manual labor, which can quickly diminish the quality and production efficiency of wood elements. This often leads to the necessity of post-production steps to correct any misalignments, essentially reverting to more traditional carpentry craftsmanship.

THE SELECTED JOINT

Contrary to the negative repercussion on the previous two joint examples, the Cross-Half lap joint presents an outstanding performance in manufacturing as well as assembly. From the CNC milling time overview, despite showing a higher production time, this detail achieved excellent precision resulting in time savings of about 150 minutes compared to the Mortise and Tenon, and T-joint connections.

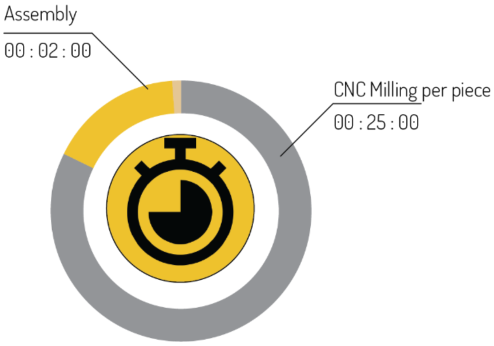


Figure 145 time saving Cross-Half Lap

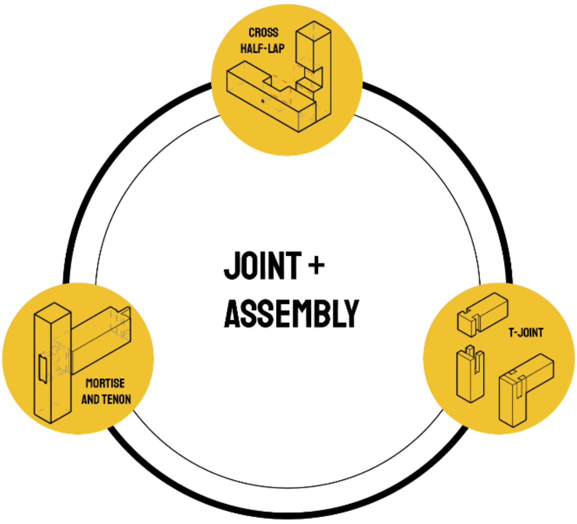
SUB-QUESTION:

How can the advantages of assembly efficiency achieved through digital manufacturing be extended to materials of lower precision, such as locally sawn timber available in the Colombian forestry industry?

There is not a simple answer for this question but a rather complex set of considerations and findings that were identify in the potential of this technology:

Material:

Sawn timber is by nature an irregular element in the building industry. Contrary to EWP’s plates, beams derive directly from the trunk presents nonhomogeneous characteristics, such as fiber direction of the grain, number of nodes present in the pieces, grain orientation, cross-section related to the drying process, among other characteristics that will influence the movement of wood in the drying process. These natural changes of the material have to be tackled in the pre-manufacturing process by aligning the face of the beams into a perfect 90-degree angle. Understanding that the used of any sawn timber element requited additional reprocess to increase the precision of the machine. As you maybe see in the CNC chapter, the prototypes produced without this preparation clearly show a negative impact in the joinery connections.



Working area

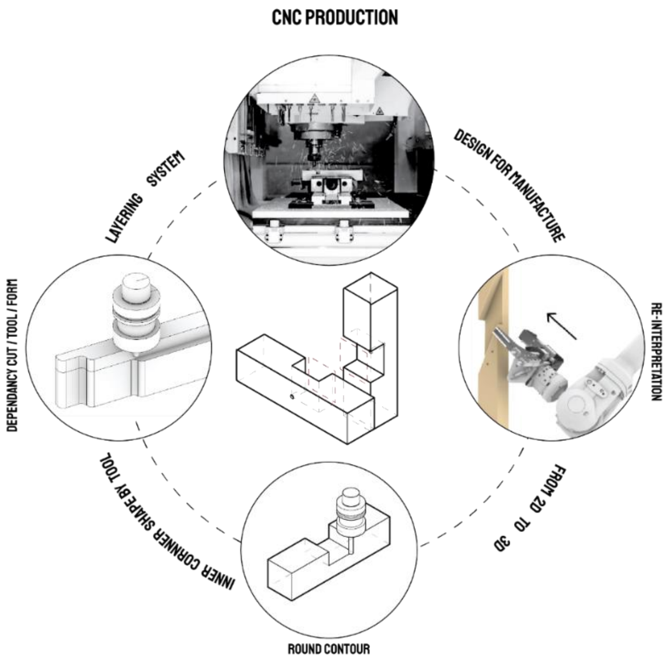
The CNC machine's working areas are notably constrained, especially when compared to conventional Engineered Wood Products (EWP) dimensions, which typically measure 1220 x 2400 x 18 mm. This significant disparity between the CNC machine's capabilities and the industry standards creates challenges in transitioning from design to the actual implementation of timber elements using this equipment.

Furthermore, there is a clear limitation in terms of cross-sectional dimensions, particularly with a maximum limit of 100 mm. This constraint poses a significant challenge if solid wood is intended to be used for constructing larger spans. As a result, the application of this technology is best suited for lower rise building scales, and its effectiveness diminishes when dealing with larger and more substantial structural elements.

CONSIDERATIONS FOR FUTURE RESEARCH

After a meticulous assessment of CNC possibilities and the development of strategies aimed at achieving a more sustainable manufacturing process from an efficiency perspective, it becomes evident that this equipment is not ideally suited for this type of building system. The mechanics of the apparatus are rather constraining and challenging to control, resulting in numerous problems affecting the quality of the produced joints. Most of the equipment used in this research was primarily focused on academic production, and as such, the manufacture format appears inefficient and entirely unrelated to the cross-sections and dimensions of the sawn timber. A more conventional production process aligned with this building system would likely lead to decreased production times and improved efficiency.

Nevertheless, the cross-Half lap joint is rather flexible in the manufacturing constraints. This decision benefit further implementations of the system into a high-end process, where topics of manufacture for high productivity, and supply chain could be integrated into the study. Moreover, their results observed in the assembly, and manufacturing assessment reveal the potential that this simple joints could play into modern constructions.



WHAT'S MISSING?

Model to production digital workflow

The parametric model is an essential component for assessing the joint capacity within the context of the entire skeleton structure. In the initial stages, a Grasshopper script was created to facilitate structural analysis. While this tool is partially resolved, there is room for improvement by developing a script for more automated and efficient analysis.

With a fully automated system in place, the model can quickly assess the structural capabilities in relation to the joint capacity. This level of automation allows for easier adjustments in the fabrication process and streamlines the overall workflow. It enhances the model's ability to adapt to changes and optimizes the fabrication process based on structural requirements.

Robotics in the research

This branch of research draws partial inspiration from the Gramazio Kohler Institute, which has explored wood-to-wood connections in digital manufacturing with a focus on assembly mechanics using robotic systems. However, this master's thesis research takes a distinct approach by examining the application of high-tech solutions in a Latin American context. This context is characterized by specific limitations in technology, available materials, and assembly processes, which have influenced the decision-making process in manufacturing and joinery.

While robotics is not a primary focus of this research, the core topic centers on understanding how wood, when combined with the precision offered by digital manufacturing tools, can be leveraged to create a more user-friendly assembly process. This approach aims to enhance assembly efficiency, reduce reliance on other materials that are less environmentally friendly and challenging to recycle, and ultimately develop a solution that is accessible to individuals who seek to construct their own homes.

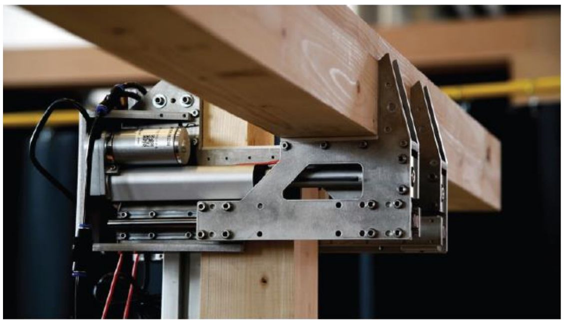


Figure 146 Gramazio kohler institu - Timber assembly with distributed architectural robotics 2018 – 2022

MECHANICAL PERFORMANCE VS MOISTURE INDUCE EFFECTIVENESS

CONCLUSIONS

From the mathematical and numerical analysis, it can be concluded that the Cross-Half Lap connection shows superior structural ultimate bending moment performance with (2.45 kN/m). In contrast, the Mortise and Tenon joint presents almost half of the structural performance with (1.74 kN/m). Lastly, the T-joint connection appears to be the least optimal for housing structural applications (1.54 kN/m). Thus, according to the data, the Cross-Half Lap Joint presents itself as the most structurally optimal choice.

Based on the previous numerical analysis, the T-joint will be excluded from further research consideration as its overall CNC manufacturing performance, assembly, and structural capacity seem inefficient for any application.

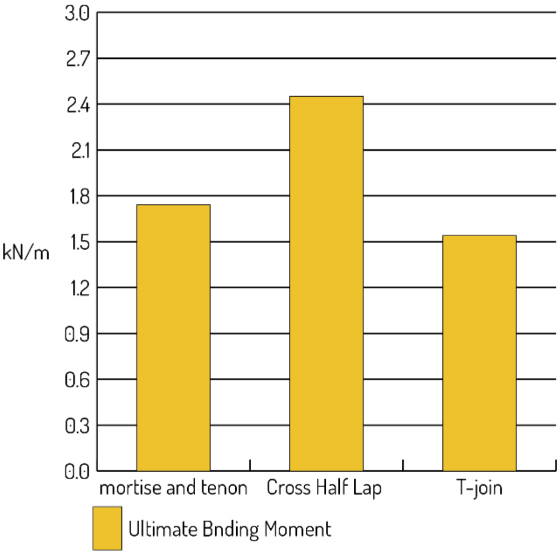


Figure 147 Ultimate Bending Moment Capacity

METHODOLOGY

The structural analysis of wood-to-wood connections, despite involving the same quantity of wood, the same cross-sectional dimensions, and the same wood types, reveals a notably superior performance of the Cross-Half Lap joint. The process of mathematical analysis and assessment was complex, primarily due to the limited existing research on wood-to-wood connections in the academic field.

To address this limitation, this research employed a three-stage approach to verify and establish the structural performance of the connections. Firstly, a mathematical characterization of the wood joints was developed based on a comprehensive literature review. Various calculation methods were tested and proven to be effective in comparing different joint types, marking the initial phase of the analysis. Following this, a numerical analysis was conducted using Ansys Workbench, which served to validate the data obtained from the mathematical calculations.

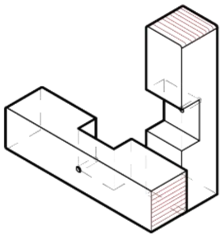
However, the most tangible evidence of this research's findings came from the practical mechanical testing of real wood-to-wood prototypes subjected to compression and tension stress. This final stage of experimentation not only confirmed the results obtained from the previous calculations but also provided a clear understanding of the relationship between joint geometry and structural performance.

Figure 148 Compression test Laboratory of Mechanics-3ME faculty TU Delft University

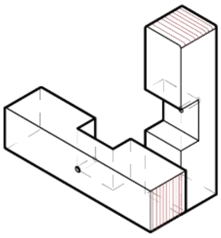
PROVING THE EFFECTIVENESS OF MOISTURE INDUCE JOINTS TO TENSILE STRESS

The experimental testing conducted on the Cross-Half Lap joint, as described in the structural characterization section, has effectively demonstrated the significant impact of relative humidity (RH) on wood-to-wood connections. This revelation opens up exciting possibilities for its application in the construction industry. Through a meticulously designed experimental methodology, several critical points can be argued:

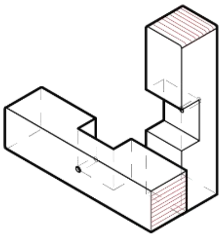
RED -3-4-65%



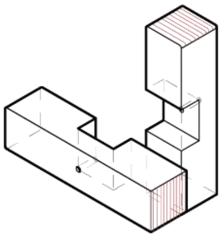
RED -5-6-65%



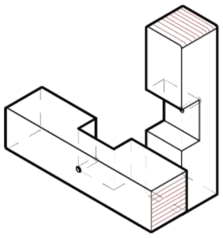
RED -1-2-85%



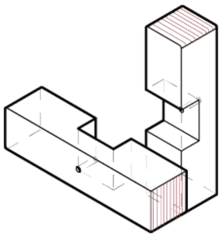
RED -7-8-85%



BLUE -3-4-65%



BLUE -7-8-85%



CNC MANUFACTURING PRECISION: The study underscores the importance of CNC manufacturing methods in elevating production quality and precision, especially in wood-to-wood connections. It clearly establishes the superiority of CNC manufacturing when compared to less precise specimens. This precision is vital for achieving strong and reliable connections.

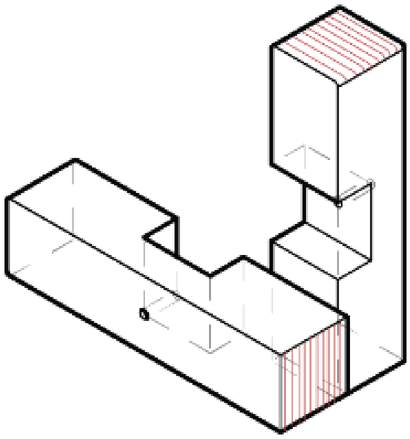
TANGENTIAL GRAIN DIRECTION: The assembly method using the Cross-Half Lap joint showcases an exceptional structural performance, particularly when the tangential grain direction is maintained. This approach ensures optimal interlocking between elements, resulting in superior structural integrity. The graph provided illustrates this advantage.

EFFECTIVENESS OF MOISTURE INDUCTION: The experiment involving different RH levels reveals the remarkable effectiveness of moisture induction in enhancing the joint's performance. The specimen labeled "RED-7-8-85%" demonstrates an outstanding tensile force of 3000 N, thanks to the environmental RH acting as a slow interlocking mechanism. In stark contrast, the specimen "RED-5-6-65%" with identical characteristics but without moisture induction exhibits a significantly lower tensile resistance of about 1600 N. Both specimens share the same material configurations, machining processes, and milling, highlighting the pivotal role of RH in enhancing the joint's properties.

This research not only sheds light on the critical role of CNC manufacturing and grain direction but also underscores the potential benefits of leveraging environmental factors, such as relative humidity, to optimize wood-to-wood connections. These findings hold promise for advancing construction techniques and materials, offering more robust and reliable solutions for the industry.

The tangential grain direction assembly method archived with the Cross – Half Lap joint reveals a superior structural performance using this particularity as part of the design integration.

RED -7-8-85%



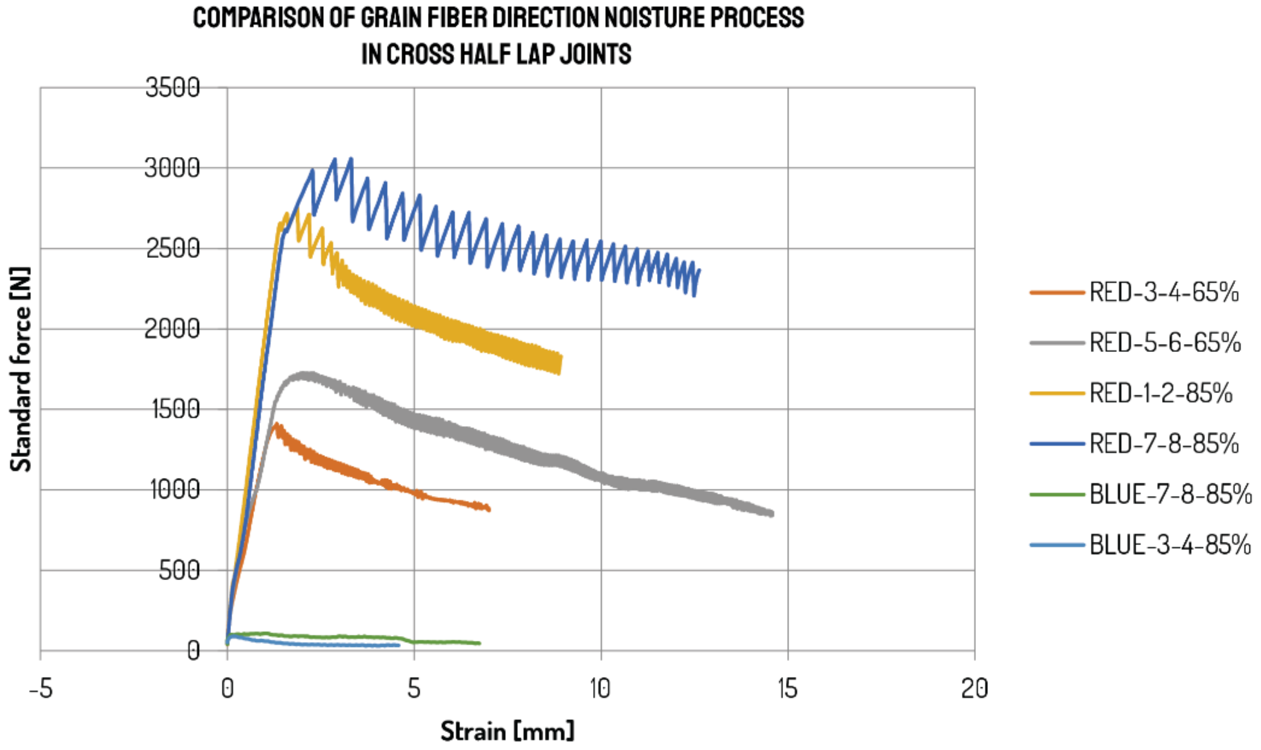


Figure 149 Tensile Test Result of moisture induce Cross Half Lap joints

LOOKING AHEAD

Effectivity in Real Scenarios:

Evaluating the effectiveness of the system in real-world scenarios is crucial. Consider factors like ease of transportation, adaptability to different locations, and how it compares to other construction methods. If lab results indicate limitations in applying the same system in certain conditions, it's essential to outline those limitations clearly. This research has proven the benefits of Relative humidity integration as part of the design of structural elements to maximize assembly process in a short-term scope. Further research into long term effect of these joints is fundamental to evaluate the effectiveness of the structure.

Financial Aspects:

Assessing the financial feasibility of the system is fundamental for this project. As seen in the design analysis of price per component, Oak is considerably more expensive than other rather more affordable materials.

It is important to determine whether this building system is suitable for social housing applications or if it's more appropriate for higher-income populations. The cost of the overall structure represents a large investment, as Oak is one of the most expensive wood products in the construction market.

System Downsides:

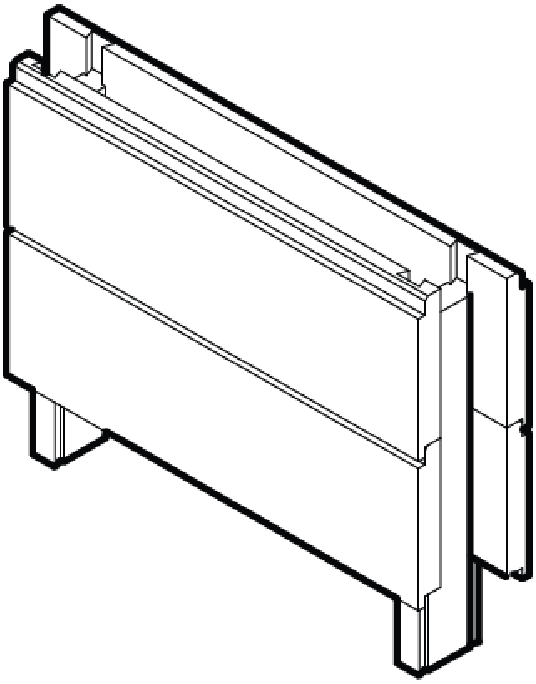
The drawbacks of the system at various stages, from wood processing to CNC milling and assembly showed optimal material waste, production time, and simplicity of assembly. One methodology that is rather not examined is the assembly of elements on site. As the effectiveness of this building process work with a tight-fitting assembly method that requited high pressure of installation. A big question is what speed performance would be counting with the proper tool.

Time Gap Between Milling and Assembly:

Is an interesting aspect of the research. As proved in the Material experimentation, there is a 30 window until the elements are fully saturated. Nevertheless, a negative possible outcome is the transportation of parts, and not immediate assembly on site. The tolerance of the system will dramatically affect the building process in later stages.

Positive Aspects – sustainability outcome:

A significant contribution to both science and society is the positive sustainability impact of this research, as demonstrated throughout the study. This research has successfully developed a structural system that eliminates the need for glue or steel hardware. By utilizing material pressure in combination with traditional joinery methods, it proposes a manufacturing and assembly approach that removes the dependency on glue and screws. This not only simplifies remanufacturing and repurposing processes but also offers the advantage of adaptability. The wood elements can be used in various configurations, including smaller building components, making them easier to transport, handle, and reprocess in later stages.



IMPROVEMENTS AND REPLACEMENTS:

Although the research has provided valuable insights, it's important to acknowledge that due to prototyping limitations, the entire building sequence has not been fully tested. While each independent joint was studied, engineered, and assembled successfully, further development of the entire system is essential to fully comprehend the effectiveness of the proposed construction method Suggest areas where the system can be improved or where alternative materials or processes might be considered. This demonstrates a forward-thinking approach to system enhancement.

Disassembly process – UN-successful outcome.

A significant challenge highlighted by this study is the difficulty of disassembly within the proposed system. The tight-fitting process, optimized through material swelling, presents obstacles to effective disassembly. As demonstrated in the CNC chapter, a substantial amount of pressure is required to position the joints, making disassembly a complex task. This issue raises critical questions for the research:

User-Friendly Disassembly: Exploring methods to make disassembly more user-friendly should be a priority. Designing a system that allows components to be easily detached without the need for excessive force or tools is essential.

Environmental Impact: One approach could involve transporting the structure to an environment with lower relative humidity (RH). In such conditions, the natural reduction in material swelling could lead to automatic disassembly of components. However, the logistics of moving entire structures pose significant challenges.

Permanent Structures: Alternatively, it's worth reconsidering the implications of disassembly in the context of more permanent structures. In situations where the intended use of the building is long-term, disassembly may be a less critical factor. The focus could shift toward optimizing the assembly process for stability and longevity.

Material Selection: Evaluating the impact of different wood types on material swelling and disassembly could be a valuable avenue. Some woods may exhibit less swelling, making disassembly easier, while still providing the desired structural properties.

Mechanical Solutions: Investigating mechanical solutions to facilitate disassembly, such as innovative joint designs or mechanisms that release pressure when needed, should be explored.

Community Involvement: Engaging with local communities and potential users can provide insights into their specific needs and preferences regarding disassembly and reassembly. This feedback can guide the development of user-friendly solutions.

Addressing the challenges of disassembly is crucial, as it not only impacts the practicality of the system but also influences the sustainability and adaptability of the structures. By considering these options, the research can work towards a more well-rounded and comprehensive solution for building construction and deconstruction.

Scientific Contribution:

During the Literature Research it was possible to notice the scarcity of this specific research topic. Some similar findings revel the applications of compress hardwood dowels with moisture difference. (Mehra et al., 2021) This research finding reveals the configuration of structural elements base on their on-material moisture behavior and the interaction with the environment.

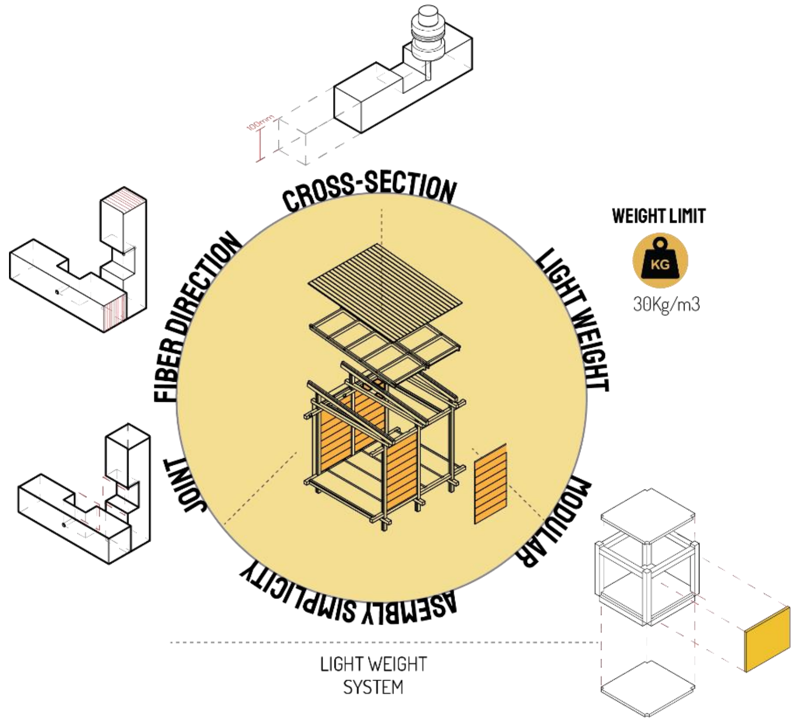
THE RELEVANCE IN SOCIETY AND TECHNOLOGY – BT MASTER TRACK

Building technology Master Track

The primary motivation for pursuing the master's track in Building Technology is rooted in a deep desire to contribute to the advancement and improvement of the social conditions in my home country, Colombia. The principal goal of this research is to serve as an inspiration for future technical advancements that can play a crucial role in rebuilding societies affected by conflicts. For instance, the research aspires to offer an innovative and rapid construction system that could be invaluable in addressing a conflict that has persisted for the past half-century.

This comprehensive research journey encompasses a wide range of subjects, including material science, digital manufacturing, and the structural assessment of wood-based constructions. However, the ultimate vision for this research and development effort extends beyond these individual components. It seeks to create a technical solution that is accessible to everyone, providing opportunities for dignified housing and significantly improving the lives of those it serves.

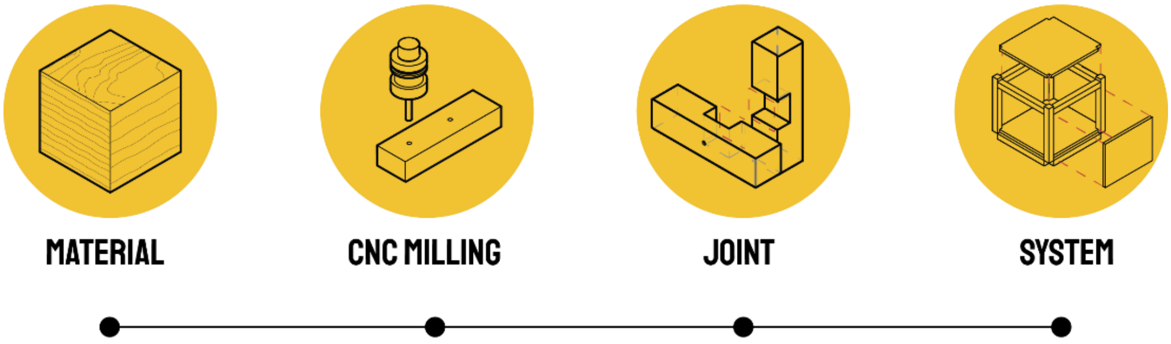
THE INFLUENCE OF RESEARCH IN THE DESIGN / DESIGN IN THE RESEARCH



This research project follows a well-defined path, with a strong emphasis on three key aspects that significantly impact the final system. Importantly, each of these aspects informs the subsequent stage of the research, creating a coherent and interconnected framework. As a result, the progressive studies of the material, CNC manufacturing, and, ultimately, the wood joint continuously shape various elements of the system, including its size, weight, structural performance, and more. One of the most significant outcomes of this research project is the profound understanding of how the expansion of the material harmoniously interacts with the geometry of the joints. Furthermore, it delves into how these joints are produced through CNC technology and, ultimately, how all these elements cohesively form a congruent system that functions in collaboration at every stage of the process.

The research approach employed here serves as an effective model for demonstrating the advantages and drawbacks of each design decision. While this approach involved an extensive study of various topics, it simplified the decision-making process. It made it easier to visualize the options available, as the most favorable and least favorable choices were clearly identified. Moreover, it emphasized how each aspect could inform and influence the final design.

RESEARCH STRUCTURE



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