WOOD WORKS

Johan Wall | Architecture and Urban Design | Chalmers University of Technology | 2021

© 2021

Johan Wall
hello@johanwall.com

Examiner: Ola Nylander
Supervisor: Jan Larsson

Chalmers University of Technology
Department of Architecture and Civil Engineering
Master's programme of Architecture and Urban design (MPARC)

ABSTRACT

An innovative system of wood connections, originating in state-of-the art circular design principles and traditional joinery craftsmanship, is developed for a structural system of engineered wood products. The joinery system is an architectural exploration aimed at demonstrating how timber structures could be assembled to facilitate easier deconstruction and increase the reuse potential of structural components.

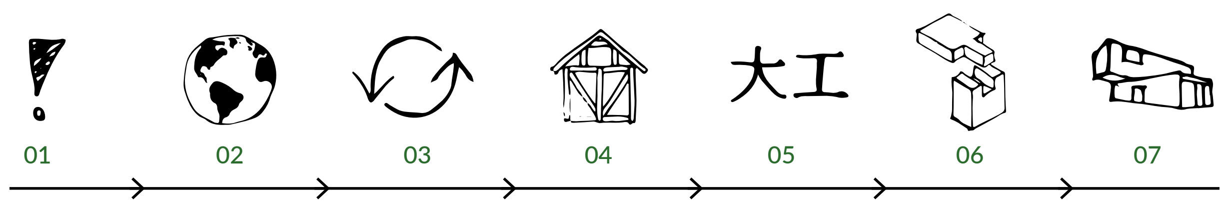
This circular approach to timber design is a response to the building industry's linear and non-disruptive state of affairs which results in significant negative climate impact and geophysical catastrophes as consequences. The linear production process defining the building industry is unsustainable and a direct contradiction to our shared vision of a circular future. These challenges are becoming increasingly recognized around the world, but the building industry is moving slowly, and Sweden is no exception.

The way we use resources for constructing our built environment results in a fine-tuned and highly efficient method for producing unmanageable amounts of greenhouse gas emissions and mountains of waste. We must transition to a circular design process which better utilizes resources – fossil as well as renewable - and enables reuse of processed building components. As being a significant part of the problem, the industry is also a significant part of the solution.

This thesis identifies the climate crisis and related sustainability challenges along with reports on methods for counteracting the current downward spiraling course of action. A substantial design solution is demonstrated which performs according to principles of circularity and utilizes both innovative and traditional technologies for refining wood.

Keywords:

Joints,
Architecture,
Circular Design,
Timber Structures,
Wood Innovations,
Engineered Wood Products,



CONTENT

01. INTRODUCTION

"When I look at a beautiful example of wood construction, I cannot help thinking that the beauty of the architecture derives not only from its design and construction techniques, but also from the very soul of the wood itself."

Seike, 1977, p 13.

THE AUTHOR

Johan Wall
hello@johanwall.com

EXPERIENCE

Architect
Hugo Nils Arkitekter
+ *Residential architecture.*
2020 - present

Architect & Parametric Designer
WALLS
+ *Residential architecture.*
+ *Sustainability consultancy.*
+ *Climate analysis and simulations.*
2017 - present

Intern Architect
Tyréns
+ *Healthcare and industrial architecture.*
+ *Immersive technology implementation.*
+ *BIM workflow automation.*
2018 - 2019

Architect & Project Leader
CTK
2018

Graphic Designer
CHS Promotion
2015 - 2016

EDUCATION

Architecture & Urban Design
Chalmers University of Technology
+ *Additive and subtractive manufacturing*
+ *Building climatology*
+ *Competitions*
+ *Digital fabrication*
+ *Space syntax*
+ *Robotic manufacturing*
+ *Urban planning*
2019-2021

Architecture
Chalmers University of Technology
2015-2018

Civil Engineering
Chalmers University of Technology
2013-2015

AIM AND OBJECTIVES

A

Develop a set of joints for engineered wood products which will enable increased circularity of materials.

B

Explore the architectural potentials of joints in timber structures.

C

Make an addition to the research gap which exists on the topic of architectural potentials for joints for engineered wood products.

The aim of this thesis is to demonstrate how the building industry can accelerate the transition to a sustainable future by improved utilization of our most abundant renewable resource – wood – and the innovations derived from it.

This is demonstrated through the development of a set of wood joints which results in an innovative system for assembling engineered wood products into buildings. The system reduce the need for fossil-based resources and increase the use of bio-based equivalents.

The joints are designed for circularity and enables the building to be disassembled into individual building components, at the end of the buildings life cycle. The components can then be re-used in other buildings, effectively transforming buildings into different 'design iterations' originating from a defined set of original components – successfully looping materials.

The nature of the joints makes them suitable for exposure and the architectural potentials of this feature is explored throughout the thesis.

As the research conducted on timber joints is primarily shifted toward structural engineering, there is a significant gap regarding the architectural potentials. The investigations followed by the research objectives in this thesis will serve as an addition to the field of architectural potentials of wood joints.

METHOD

A research for design method is used throughout the thesis, where a literature review is conducted on the state-of-art in circular design to identify challenges related to sustainability in the building industry and viable solutions for combating such challenges. The literature study serves as framework for the development of a succeeding design proposal, which demonstrates a viable solution in line with circular design principles.

The research phase includes a macro view on sustainability challenges, how they are derived into the building industry and how both modern and traditional construction techniques can assist in the development of a refined building system responding to the identified challenges.

During the design phase a preliminary design for a refined building system is developed, originating in findings from the research phase. The refined system is demonstrated through individual prototypes as well as through applying the system to a building structure.

LIMITATIONS

Sustainability aspects of timber architecture covered in this thesis originates from the Swedish forestry industry and for other regions these aspects may vary greatly. This could render the sustainability of wood in a different light. Similarly, as the character and composition of building industries varies between nations, it should be noted that the results of this thesis are aimed specifically at the Swedish building industry. Regarding the specific design proposals which are to be developed as part of the thesis, architectural qualities will be prioritized, and aspects of engineering will be secondary or not considered.

The development of joints for timber structures considers the connections between complete elements of engineered wood products and will not consider connections within the elements themselves, such as how different timber lamellas within the engineered wood products are adhered to each other. Subsequently, this thesis will not address the potential use of non-sustainable and toxic chemicals in the lamella adhesion process.

The conducted design phase will be of theoretical character, apart from the production of small-scale prototypes. A study of this type would potentially benefit from full-scale prototyping of joints as well as of an entire building, but this is not possible within the boundaries of this thesis.

Lastly, estimating the sustainability of an entire building is a complex task. This thesis will focus on the improvement of timber structures but will not cover the sustainability aspects of other building components, which all have their own sustainability challenges.

02. BACKGROUND

CLIMATE AND CONSTRUCTION

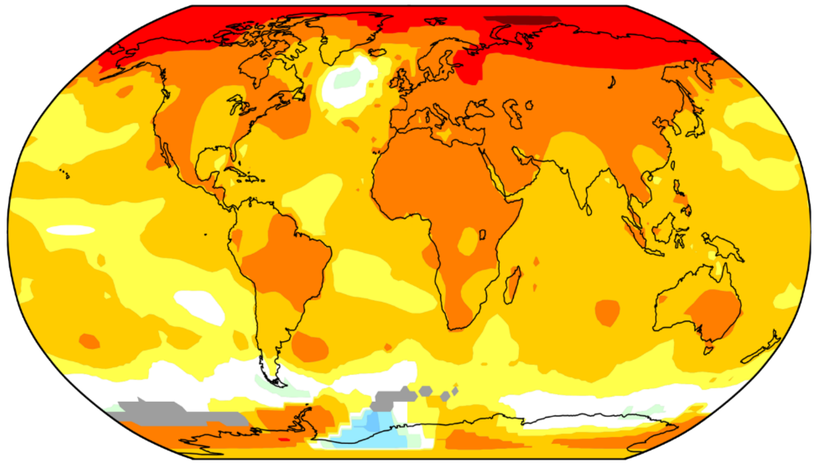


Figure 1:1. Temperature change in the last 50 years.

The climate crisis continues unabated as the global community shies away from the commitment required for its reversal. As reported by the United Nations (UN, 2020), the last completed decade between 2010-2020 was the warmest ever recorded, resulting in droughts, massive wildfires, floods, and other geophysical disasters across continents. The global emissions have not yet peaked and seem to increase even further, with an increased frequency and magnitude of climate disasters. Significant measures are to be taken for the global community to reduce greenhouse gas emissions and reach the global net-zero target by 2050 – a target necessary for limiting the global warming to 1.5 C°, resulting in manageable consequences for the planet. (United Nations [UN], 2020).

+2.0 **2050 limit**
+1.5
+1.0

Figure 1:2. Global temperature target by 2050.

The building industry have a significant negative climate impact worldwide and is being rigorously monitored by the United Nations Environment Programme (UNEP). By the end of 2020, the UNEP (2020) published the 2020 Global Status Report for Buildings and Construction, in which they identify the building industry to be accountable for 10 % of the total energy related CO_2 emissions. With the inclusion of the operation of buildings the share increases to an astonishing 38 %.

For Sweden in particular, Boverket (2021) have estimated the equivalent share to 21 %. Although close to half of the worldwide share, the Swedish building industry have significant climate impact and need to take serious measures to achieve the national goal of net-zero carbon by 2045, set by the Swedish Government (2020).

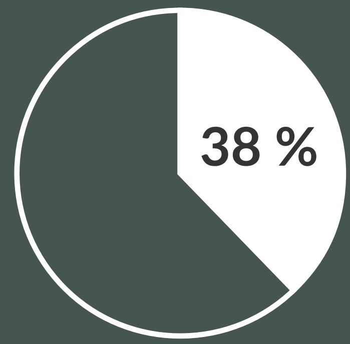


Figure 1:3. Share of global energy related CO_2 emissions caused by the building industry.

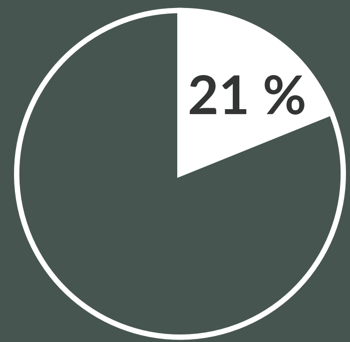


Figure 1:4. Share of Sweden's total energy related CO_2 emissions caused by the Swedish building industry.

CIRCULAR ECONOMY

1. Product maintenance
2. Product re-use/redistribution
3. Product refurbishment
4. Product recycling
5. Reprocessing of technical nutrients

Figure 1:5. Circular economy loops by Beaulieu et al.

- A Reduce
- B Re-use
- C Recycling
- D Energy
- E Incineration
- F Landfill

Figure 1:6. Lansink's ladder - a well-established waste hierarchy concept.

UNEP (2020) recognize the transition to a circular economy as a key factor for accomplishing the necessary reduction in climate impact from the building industry. All actors involved need to evaluate how they can adopt concepts around circular economy to reduce the demand for construction materials and enable nature-based solutions that enhance building resilience. Governments along with public and private organizations are encouraged to develop strategies to support the transition to a sustainable, net-zero carbon building stock.

An established definition of circular economy was made by Beaulieu et al. in 2015, presented as the five value creating loops in circular economy (Figure 1:5). The loop furthest down (reprocessing) generates the lowest value while the most immediate loop (product maintenance) generates the highest value. Industries need to start circulating materials in loops and transition to completely circular business models for the global community to get the most possible value out of our shared limited resources (Research Institutes of Sweden [RISE], 2020)

The five value creating loops in circular economy are directly related to the well-established waste hierarchy concept defined by Lansink in 1979, known as "Lansink's ladder" (Figure 1:6). According to Lansink (2017) and the EU, recycling refers to materials being transformed into new products and incinerating materials into energy is not recycling. Although being energy recovery, it is essentially a form of aero-depositing.

Currently, most of the wood waste from the building industry is incinerated for energy recovery or used as landfill. (Vis et al., 2016). This is a major issue due to the re-depositing of carbon dioxide in the atmosphere. Merely one third of Europe's building industries wood waste is recycled, and when it is recycled it is transformed into lesser products down the value chain, often wood board products.

TRANSFORMING THE INDUSTRY

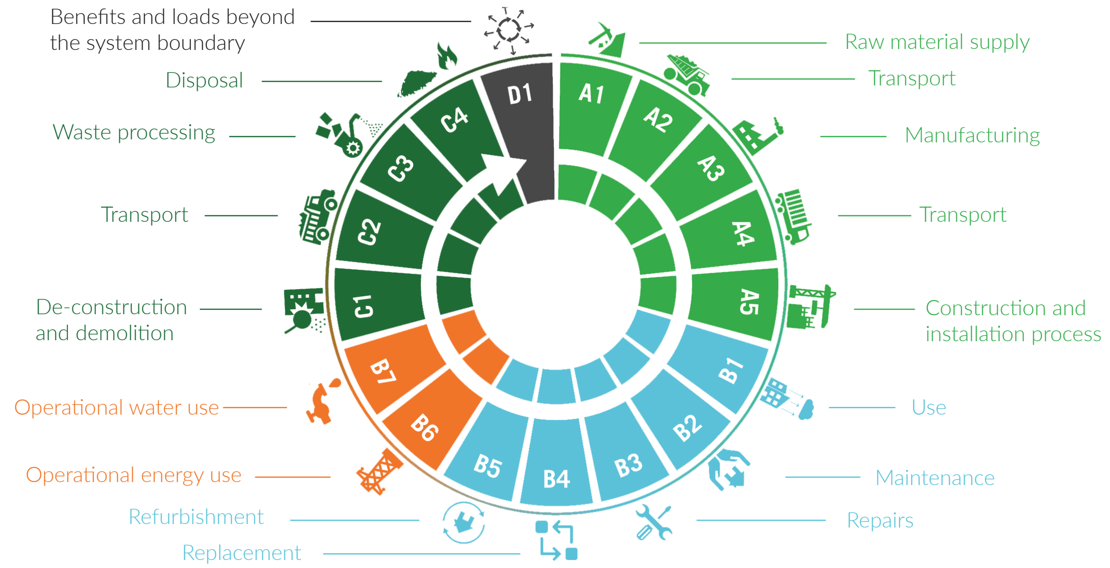


Figure 1:7. A buildings life cycle and its stages.

In line with the UNEP strategy, the Swedish government (Boverket, 2020) have initiated an administrative instrument which will force the building industry to accelerate the transition to a circular building industry. Starting January 1st, 2022, developers will need to submit a climate declaration containing a life cycle analysis of the building and its components. This is the first stage of a more extensive climate declaration and additional requirements to the declaration will follow over the years.

A buildings life cycle consists of seventeen stages, as defined in the European standard EN 15978 issued by the European Committee for Standardization [CEN], 2011). The standard defines three stages – (A) construction, (B) usage and (C) end of life – along with a supplementary stage (D) concerning factors outside the system boundaries. The Swedish Green Building Council (2021) provides a human-friendly visual representation of these stages (Figure 1:7) and in the introductory 2022 edition of the climate declarations, Boverket (2021) have decided to include stage A1 to A5.

This transition generates possibilities for the architectural profession. Recently, the trade union Architects Sweden (2021) published an action plan for how Swedish architects can contribute to a more sustainable building industry. By taking advantage of this window of opportunity, which the climate declaration strategy enables, Swedish architects may advance their key position in the building design process. Naturally, architects have always played a central part in the design process, but with their expertise in resource efficient solutions, ecosystem services, resilient cities and sustainable design, their position could be given an even greater importance. As architects are often involved in the early design stages, where many decisions regarding process and form are taken, their ability to design circular will have positive impact on the resulting climate declaration.

LESS CONCRETE AND MORE WOOD

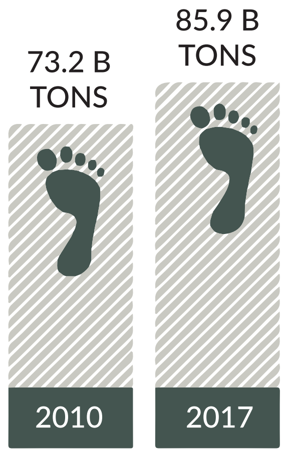


Figure 1:8. Global material footprint in 2010 and 2017.

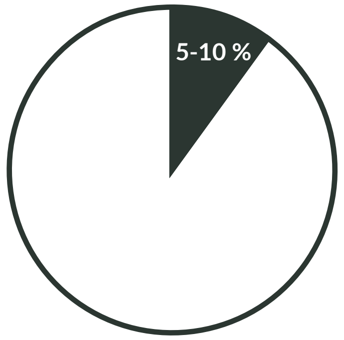


Figure 1:9. Cement production equals to 5-10 % of global CO_2 emissions.

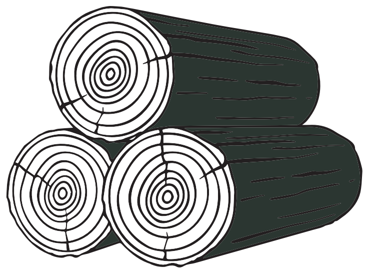


Figure 1:10. Increased timber usage would decrease CO_2 emissions.

The UN (2020) reports that the global material footprint is still increasing. Between 2010 and 2017 the footprint grew 17.4 %, from 73.2 billion metric tons to 85.9 billion metric tons. The footprint expanded for all types of materials, but especially for non-metallic minerals which accounted for about half of the global footprint. This growth is concentrated to the areas of infrastructure and construction, making them areas which can contribute the most to footprint reduction. The infrastructure and construction industries are key consumers of the global concrete production, which also happen to be the most produced material in the world at 4.2 billion tons per year, as stated by the UN in the 2019 Global Sustainable Development Report. The high volume of production makes the global cement industry one of the largest producers of CO_2, accounting for 5-10 % of the global greenhouse gas emissions.

The use of concrete in construction projects is concentrated to emerging and fast-growing economies and is the most feasible alternative in much urban construction. Hence, viable solutions in such contexts need to focus on the reduction of emissions during the cement production (UN, 2019). For the global community to meet UN (2021) sustainability targets other than reducing greenhouse gas emissions and material footprint, such as social challenges and world hunger, the use of concrete in the building industry could be a necessity in specific nations and contexts.

An increased us of timber in the building industry would reduce the carbon dioxide footprint and subsequently also reduce the overall environmental impact of the construction industry. By using timber, the carbon once bound by the trees is retained in the buildings for a long time, essentially end effectively turning timber structures into carbon capturers. (UN, 2019).

TIMBER FOR CARBON CAPTURING

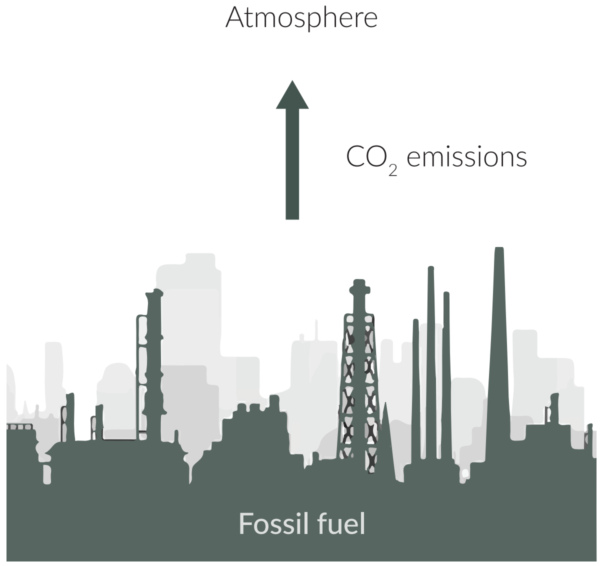


Figure 1:11. Conventional, linear carbon utilization.

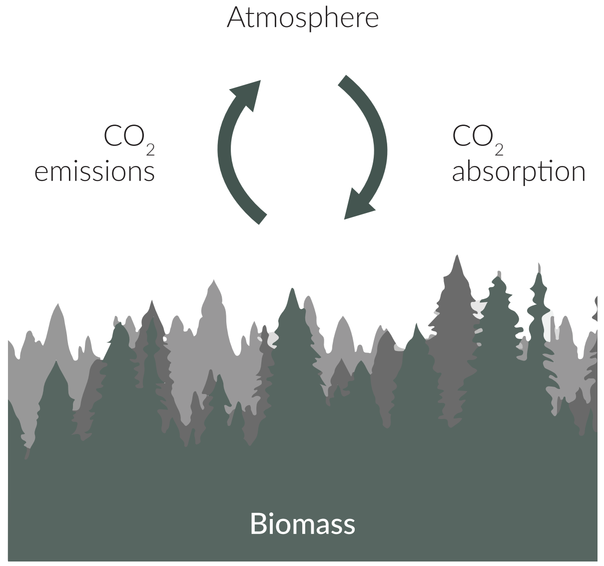


Figure 1:12. Circular carbon cycle.

As trees grow, they absorb carbon dioxide which effectively makes forests large-scale carbon capturers. As this includes emissions from the incineration of timber, a general perception has been that the incineration of wood is not an issue, as this carbon cycle already assure the circularity of wood (RISE, 2020). But this conventional perception is not unproblematic. Such a carbon cycle assumes a one-to-one relationship between forest growth (CO_2 absorption) and timber incineration (CO_2 emission), enabling a closed life cycle (Figure 1:12) and net-zero emissions. But other than emissions from the incineration of timber, trees also absorb CO_2 emitted from the incineration of fossil fuels. All in all, there is a net surplus of carbon dioxide, caused by human activity.

The perception of wood being part of a closed carbon cycle could be abandoned in favor of the perception of forests as global systems for carbon capture and storage (CCS). Such systems could assist in the reduction of the global surplus in greenhouse gas emissions, regardless of origin. (UN, 2019). An increased use of timber in the building industry could increase the demand for raw wood material, which in turn encourages the forest industry to grow even more wood. By harvesting wood for buildings, we effectively turn every timber building – component by component - into a product of carbon capturing and storage.

THE FOREST WILL NOT BE ENOUGH

Figure 1:13. Illustrative forest depletion.

The contemporary building industry has recently realized the significance of increased timber usage. But, as concluded by RISE (2020) in their state-of-the-art-review 'Design for deconstruction and reuse of timber structures', modern timber construction is currently not aligned with circular economy principles. Partly due to buildings complete life cycles rarely being considered. The building industry is slowly transitioning towards a more climate friendly and resource efficient circular economy, originating in bio-based materials, but it is not happening fast enough.

However, this is not without challenges. To achieve a fossil-free Sweden by 2045 (Government Offices in Sweden, 2021), the demand for wood will increase significantly. The amounts which are to be required will not be available, considering that the forestry industry need a to maintain a sustainable forestry management (Mantau et al, 2010). Because of this, it is crucial for the building industry to reconsider the linear applications of wood. It is a material which need to be part of the re-usable material bank. Even though wood is a renewable bio-material, our forests cannot be harvested indefinitely; **the forest will simply not be enough**. (Lundmark, 2020).

We must look ahead onto the next challenge; how to make the most out of our forest and wood supply; essentially how to increase circularity in wood buildings by designing our buildings for deconstruction all from the start. Hence the existence of this thesis and the ambition of pushing circular timber design forward.

03. CIRCULAR DESIGN

THE FUTURE IS CIRCULAR

Multiple incentives exist for transitioning to a circular design approach in the building industry; the UNEP (2020) recognize the transition to a circular economy as a crucial aspect for a sustainable society, RISE (2020) enforce the circular usage of materials and the Government Offices of Sweden is, via Boverket (2020), applying political instruments for pushing the building industry away from linear thinking and towards a life-cycle approach. The transition to circular design is a necessity for achieving a sustainable building industry – and by extension a sustainable society. Architects may have a key role to play and the time for action is now.

In 2020 the Research Institutes of Sweden (RISE) conducted a study on novel design concepts for deconstruction and reuse (DfDR) which could be applicable in modern timber construction. The study was focused on the technical premises for a potential circular use of timber in building construction and was shifted towards applications in northern and central Europe, in nations with a long history of building with timber. This included Sweden, Finland, the UK, Spain, Germany, and Slovenia. The buildings included in the study were designed to exist at one specific site for a limited amount of time, and later deconstructed and reassembled at a different location, without any additional components or replacement of such. From the studied buildings and applications, RISE concluded several key factors of the circular design concept, presented on the right.

These key factors are significant in the development and implementation of a new design concept for reuse and recycling, which is likely to offer substantial potential to the reuse of components from wood structures. (RISE, 2020).

EWP

Innovations in the timber constructions industry have transformed the sector and enabled the production of previously unfeasible buildings. The utilization of engineered wood products [EWP], such as cross-laminated timber [CLT], have made it possible to construct large-scale buildings such as high-rises and office blocks, even though most of the timber constructions remains residential.

PREFABRICATION

The increase in offsite construction and usage of prefabricated components makes timber construction more accurate, material efficient and faster while simultaneously reducing waste.

LARGE COMPONENTS

The reuse potential is directly related to the scale of the reclaimed building components. Larger components are preferred over smaller ones, due to the being more beneficial in terms of greenhouse gas emissions, assembly time and waste reduction.

PLANNED DISASSEMBLY

Building components should be designed in a way that preserves the quality of materials and enables both easy and efficient recycling. The demolition needs to be considered and planned for from the beginning.

MODULARITY

Building components should have a high degree of modularity and be joined together using reversible connections. This will ease a future deconstruction and enable more possible applications of the components.

RISE DESIGN STRATEGIES

DISASSEMBLY EASE			REUSABILITY
Low weights and small sizes for easy transport and dismantling.	D1	R1	Standardize element geometry to maximize repetition and similarity.
High accessibility of joints	D2	R2	Low exposure to deterioration processes.
Separability of subcomponents for easy dismantling.	D3	R3	Insignificant long-term deformations.
Resistance to damage during disassembly.	D4	R4	Manageable remoteness of building location to ease transportability.
		R5	Documentation about design and maintenance

The previously mentioned circular design review published by RISE (2020) reports, along with the key factors, a concise summary on historic and contemporary guidelines for *Design for Adaptability and Deconstruction* (DFAD), aimed at architects and building designers. Originating in previous research, the review identifies a set of general indicators for DFAD in, including *time*, *separability*, *risk and safety*, *simplicity*, and *interchangeability* which can be used to evaluate DFAD properties of design concepts. The report identifies that the feasibility as well as the reuse potential of building components is closely related to the scale of the recovered components. Larger components and assemblies are preferable in terms of greenhouse gas emissions, time, and waste reduction. Moreover, key-features in a circular design project often include modularity of the components along with reversible connections and an inherent flexibility of the floor plans.

The review finds reoccurring patterns in the historic examples and translates these into principles for guidance in future developments of buildings and building components. From the patterns, it is concluded that **the most crucial factors are the easy of disassembly and reusability of structural systems and their connections**. The aspect of reusability includes the repurposing of individual elements and for each of the factors a set of concrete instructions are derived, which are presented above.

HUUHKA'S TEN DESIGN PRINCIPLES

Divide the spatial program into smaller units.	1	6	Define ranges instead of fixed properties.
Divide elements into smaller units.	2	7	Rotate and re-purpose.
Avoid equal spans and dimensions.	3	8	Select the application according to the properties.
Distribute functions for different members.	4	9	Combine creatively.
Use efficient forms for long spans from short pieces.	5	10	Let the patina speak.

To identify obstacles of circular timber design and to postulate solutions, Hradil et al. (2014) studied the reuse potential of timber structures. The difficulties of grading wood quality and evaluating structural properties of reclaimed components was identified as significant obstacles, along with the large variety of geometric indifferences between the components. The research of Hradil et al. (2014) was supplemented by Huuhka (2018) by identifying additional factors which complicated timber reusage: inconsistent quality, inconsistent quantity, difficulty of dimensional coordination and the negative perception of used materials, which are all issues connected to design. To overcome these barriers, Huuhka (2018) defined ten universal design principles for the tectonic use of reclaimed timber components in architectural applications. These ten principles surpass the case-specific context from which they were synthesized and could help architects to prepare for reuse in future design process (Huuhka, 2018).

CIRCULAR DESIGN CONCEPTS

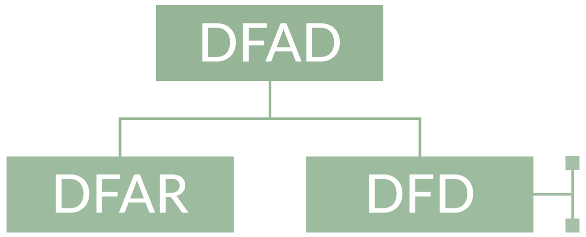


Figure 1:14. Delineation of circular design concepts.

In literature associated with reducing the building industry's environmental footprint through increased reuse and recycling, one finds a variety of terms and phrases to describe key concepts. These terms and phrases often occur as overlapping, conflicting, and even contradictory, leads to confusion and difficulty in understanding the fundamental concepts (Long, 2014). To promote a better understanding of these concepts and reduce terminology clutter, Long defines a refined hierarchy of terms:

> ***Design for Adaptability and Deconstruction*** *(DFAD) represents an umbrella term that includes all things associated with the reuse of buildings, building components, and materials. As an umbrellas term, it includes each approach below:*
>
> *1)* ***Design for Future Adaptive Reuse*** *(DFAR) includes the direct reuse, adaptation, or relocation of an existing building or its structure. This constitutes the highest form of built environment adaptability as it preserves the most embodied energy and has the greatest environmental impact.*
>
> *2)* ***Design for Deconstruction and Disassembly*** *(DFD) represents a broad term which includes multiple topics related to the reuse and recycling of building materials and components, but not buildings themselves. This includes the two following DFD subcategories:*
>
> *a)* ***Design for Deconstruction*** *includes the direct reuse or relocation of building components or assemblies within a new or existing building*
>
> *b)* ***Design for Disassembly*** *involves the recycling of existing building materials into new materials or components. Recycled goods are used as raw material in the manufacture of new products. This approach is the least environmentally friendly as it preserves the smallest amount of embodied energy and requires additional energy to produce new materials. (Long, 2014, p. 2)*

As reuse and recycling are two strategies which are not interchangeable or equally desirable, this delineation is important. The reuse of entire building components requires less energy and resource consumption than material recycling, making Design for Deconstruction more desirable than Design for Disassembly, from a sustainability aspect. But among all concepts, Design for Future Adaptive Reuse is considered the most desirable because it results in greater reductions in energy consumption, in waste production, and it minimizes the demand for virgin natural resources. (Long, 2014). The implementation of circular design concepts could significantly reduce the amount of waste produced by the demolition of buildings (Durmisevic, 2006).

BUILDINGS AS MATERIAL BANKS

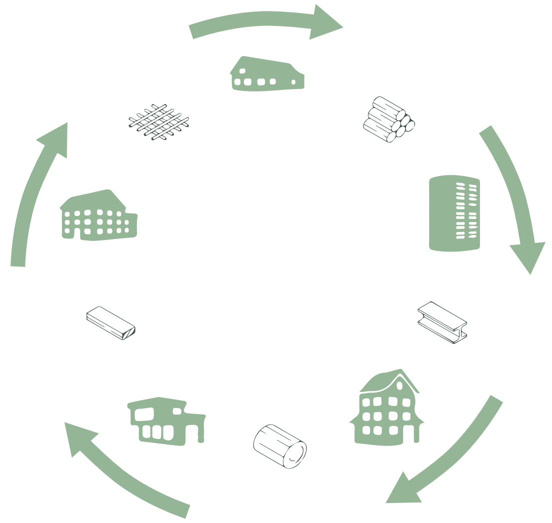


Figure 1:15. Looping materials.

The EU initiated organization Buildings as Material Banks [BAMB] (2021) is conducting research on how circular design concepts could be applied to reduce the amount of waste produced by the demolition of buildings. The idea of BAMB is that buildings should be considered as temporary deposits of valuable materials – as material banks. Such a perspective on our building stock emphasizes that materials can be brought to a site, be 'stored' as a man-made structures and later collected for reuse in a different structure, effectively enabling material loops.

This requires a shift in mindset regarding the lifecycles of building. The conventional linear thinking, that a building starts with design and ends with demolition, must be shifted towards a mindset where a buildings lifecycle consists of (1) demolition, (2) component recovery, (3) design, (4) construction and (5) operation in a continuous cycle. This must be the main strategy for closing material loops in the building industry. (Van der Berg, 2019).

As most of the wood from the demolition of buildings is incinerated for energy recovery (Borzecka, 2018), the application of circular design is a necessity for timber buildings as well (RISE, 2020), despite originating in a renewable and bio-based resource.

04. TIMBER CONSTRUCTION

TIMBER STRUCTURES ON THE RISE

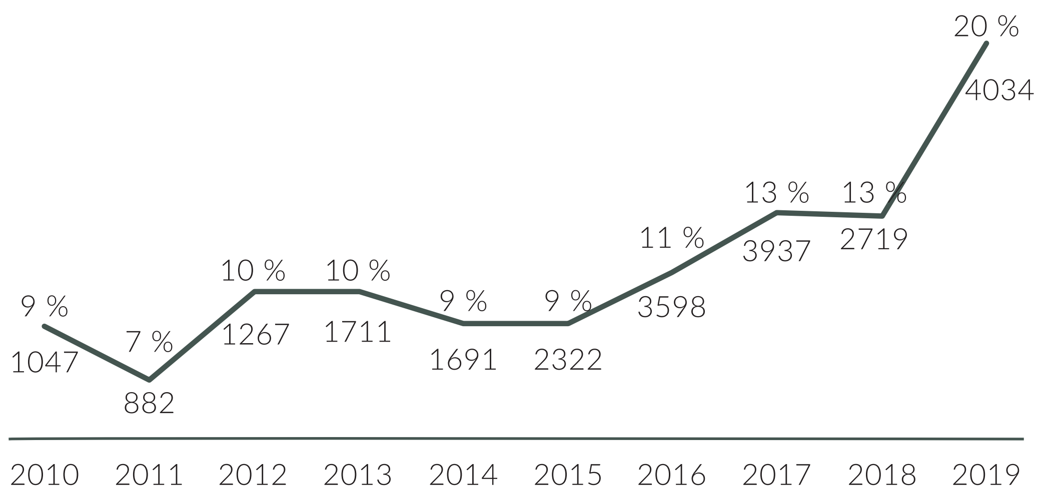


Figure 1:16. Timber construction statistics from TMF.

The Swedish building industry sees a dramatic increase in the construction of timber buildings, as concluded from statistics provided by Statistics Sweden [Swedish: Statistiska Centralbyrån, SCB] on the account of the The Swedish Federation of Wood and Furniture Industry [Swedish: Trä- och möbelföretagen, TMF] (2021). During 2020 a total of 4 485 apartments in multi-family buildings were constructed using a timber structure, which is an increase by 18 % compared to 2019. In 2011 the number of buildings of wood structures was merely 882 which makes the 2021 figure a five-fold increase. However, the statistics reveal that a majority of the buildings produced every year contains concrete structures. The increasing trend of using timber structures could change this ratio.

The international forest industry group Södra (2021) is currently constructing a new factory for cross-laminated timber (CLT) which will increase their production capacity by a factor of ten. These CLT products are aimed for building components – timber structures – and will have a significant impact on the CLT availability. Similarly, the Swedish-Finnish forestry company Stora Enso (2019) is investing in the production of additional CLT factories to increase their capacity. In 2019 they inaugurated their third CLT factory with a capacity of 100 000 m^3 per year – equivalent to 4 500 apartments per year. In 2020 they announced the production of a fourth factory which will increase their total capacity to 390 000 m^3.

The factories currently constructed by Södra (2021) and Stora Enso (2020) respectively will reach completion in 2022 which suitably correlates with the introduction of Boverkets mandatory climate declarations. It can be concluded conclude that public and private incentives favoring sustainable construction using timber are accumulating, generating promising prerequisites for reducing the building industry's negative climate impact.

TIMBER POTENTIALS

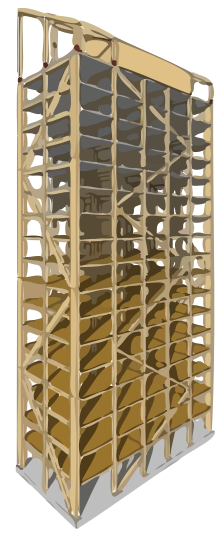


Figure 1:17. Structural system of Mjøstårnet.

The share of timber construction in the building industry is increasing and there are several ways to construct buildings out of wood and engineered wood products – **light-frame** construction using studs or I-joints, **post-and-beams** of prefabricated units and **massive timber** construction have long been among the most common techniques. The different building systems are characterized by several aspects, including the size of the components and elements, level of prefabrication, material usage, and the type of buildings the system is intended for. Along with the increased ambition of wood construction the list of building types for which the systems can be applied to has been extended to range from single-family houses to high-rises, office buildings, school buildings and bridges (Swedish Wood, 2021).

The potentials of timber construction are showcased in *The tower of Lake Mjøsa* (Figure 1:17) in Norway, designed by Voll Architects (2021). It is an 18 story high-rise mixed-use building with a height of 85,6 meters, making it the tallest timber building in the world and one of the most advanced technical achievements in timber construction. Its main load bearing consists of large-scale glulam trusses along the facades accompanied by internal posts and beams, while secondary loads are handled by wall components of CLT.

CONSTRUCTION TECHNIQUES

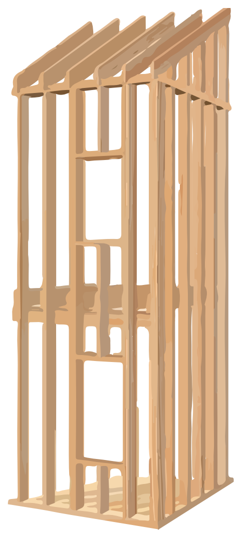


Figure 1:19. Light frame structure (studs).

Figure 1:18. Post and beam construction.

The **light-frame** (Figure 1:19) is an on-site construction technique for buildings which do not require heavy lifting equipment and is typically applied for single-family houses of a few stories, even though multi-story applications occur (RISE, 2020). Ready-cut and light timber elements such as studs or I-joints are assembled on-site by carpenters using screws or nails. Load-bearing exterior walls are often constructed horizontally on a foundation slab and raised into vertical position to be accompanied by vertical studs, potential additional flooring structures and roof trusses. The skeletal framework is covered with a protective roof before the rest of the framework is covered with insulation, boards, and façade covers. The high ratio between structural properties and consumed material makes the light frame technique a resource optimized on-site construction but tend to take longer time than prefabricated systems.

A timber building system of **posts and beams** (Figure 1:18) are made of prefabricated structural units which are assembled on site, usually requiring advanced lifting equipment (RISE, 2020). Similar to the light timber frame it is a material-efficient building system and Swedish Wood (2021) highlights it as the simplest type of all load-bearing timber systems. Although material efficient, for constructions with large spans the system often needs to be supplemented by additional structural members to manage side-loads caused by winds e.g. As wood beams tend to get undesirable thick for large spans it is possible to support them with stays to create trusses and reduce the beam thickness. For a successful design it is essential to study the load-bearing intersections in detail to ensure that such structures are both effective and aesthetically pleasing.

CONSTRUCTION TECHNIQUES

Figure 1:20. Traditional log construction.

Figure 1:21. CLT construction.

Massive timber constructions include traditional log structures (Figure 1:20) and post-and-plank constructions. Mayo (2015) describes the log construction technique as an early and simple form of massive timber structures, where horizontal logs are stacked on top of each other and doubles as both structure and enclosure. Mayo (2015) describes that the closely related technique of post-and-plank utilizes a skeletal massive frame which gaps are covered with planks, but unlike log construction this technique does not rely on vertical stacking of massive exterior walls to create stability. Instead, such structures tend to rely on complex systems of wood joinery for stabilization.

The techniques presented in Figure 1:18, Figure 1:19 and Figure 1:20 could be considered traditional and was accompanied by a fourth technique (Figure 1:21) in the early 1990's with the introduction of a new type of engineered wood product - cross-laminated timber (CLT). The term comprises a variety of sheets, panels, post and beams, which have in common of being made of glued boards or planks layered in parallel or alternately at angles of 45 or 90 degrees (Mayo, 2015). CLT have high structural capacity in relation to their weight and are often used as load-bearing wall and/or slab components.

Despite originating in wood and are material-efficient, RISE (2020) concludes that non modern timber construction techniques in use today are **not aligned with the principles of circular economy**.

CROSS-LAMINATED TIMBER

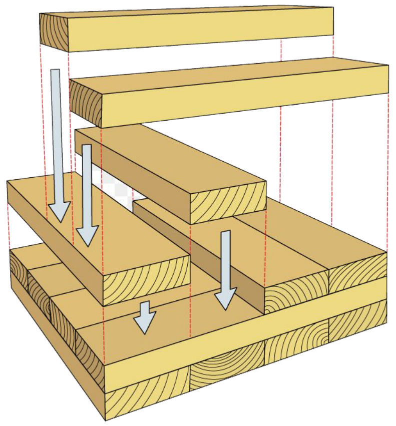


Figure 1:22. Cross-laminated timber is assembled as layers.

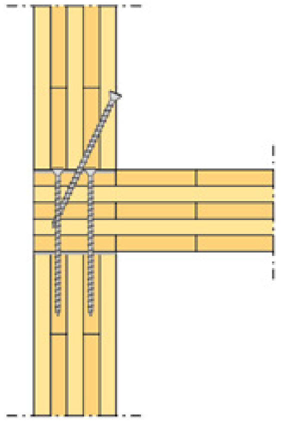


Figure 1:23. Self-drilling screws.

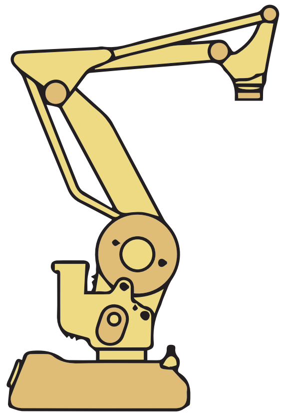


Figure 1:24. Prefabrication encourages innovations.

The concept of *engineered wood products* (EWP) contains a variety of processed products originating in timber, where glue-laminated timber (*glulam*), laminated veneer lumber (*LVL*) and cross laminated timber (*CLT*) are among the most common ones. The characteristics of each product is thoroughly accounted for by Mayo (2015) in *Solid Wood*.

Glulam , LVL and CLT have in common of being made of layered planks or boards which have been glued together. In the case of CLT, each layer is oriented 90 degrees to its neighboring layer as illustrated in Figure 1:22. Unlike traditional massive wood systems which are manufactured from large dimension timbers and generally single directional loading, vertical force resisting only, EWP systems can be used for both vertical and lateral load-bearing and are manufactured from small dimension lumber or other types of wood fibers like veneers or chips. The CLT components are planar structural elements with great load-bearing capacity and can be manufactured in a large variety of dimensions. From large-scale building components up to 16-22 m in length down to thin CLT boards with high-quality finish (Figure 1:25) intented for small-scale products such as furniture and shelf systems.

Current practices for assembling CLT building components rely on long self-drilling screws (Figure 1:23). Apart from being a labor-intense method it is a destructive process as each screw damages the components. A large CLT component could need several hundreds screws which makes a potential deconstruction a tedious process. Also, screws can be easily extracted as long as they are easy to find and have undamaged screw heads, but a simple paint job could practically permanently obstruct a deconstruction. The method of using long self-drilling screws is a symptom of the linear design thinking characterizing the building industry. It prohibits deconstruction and future adaptive reuse.

The nature of EWP is a high level of prefabrication and this enables – almost encourages – further improvements and innovations. This prefab nature goes hand in hand with emergence of digital craftsmanship within architecture.

Figure 1:25. Cross-laminated timber components.

05. JAPANESE JOINERY

CULTURAL CONTEXT

大工

dai-ku

Similar to the Nordic countries, Japan is heavily forested and has a significant historical and cultural relation to wood. The late Kiyosi Seike (1977), who was a Professor of Architecture at the Tokyo institute of Technology, compiled 'The art of Japanese joinery' – an introduction to the unique history and development of Japanese carpentry, which is profoundly intertwined with Japanese architecture.

This intimate relationship between Japanese carpentry and architecture, which has been refined over thousands of years, could be demonstrated through the etymological composition of the Japanese word for carpenter. The characters 大 (Dai, chief) and 工 (Ku, artisan) constructs the word 大工 (dai-ku) and its closest English equivalent is simply "architect". Both etymologically and in terms of responsibility the Japanese carpenter's true Western counterpart is the architect. As one can understand, it is not possible to separate the discussion of Japanese joinery from Japanese architecture, as their history is so intimately bound together. (Seike, 1977)

Seike (1977) elaborates on how the relation to wood and the appreciation of it is deeply rooted in the Japanese culture. Apart from presenting historical references as to why that is, he demonstrates this by presenting his observation of how every Japanese, despite growing up in geophysically dissimilar environments, knows the word 'kodama', literally meaning "the spirit of a tree". This is due to the strong cultural admiration for trees, which is expressed as a substantial appreciation for wood as material, comprehensive reforestation projects and a long and vivid history of wood working. Seike presents himself as a subject to this cultural context, as he describes a most human and universal inclination do ascribe divinity to the mystery of nature that creates beautifully grained wood.

The cultural and historical background, from which the now extensive supply of Japanese wood joints originates, is of fundamental importance for understanding their relevance and architectural qualities. The overview on this topic presented by Seike (1977) is the foundation for the following historical account.

HISTORICAL IMPACT

Throughout history, Japanese architecture and joinery have passed through several paradigm shifts. During the Yayoi period (200 B.C. to 250 A.D.) iron tools were introduced which enabled the production of tenons and mortises. Until then, the architects had been limited by what could be achieved through lasing with vines or rope. This generated a huge leap and buildings advanced from lower ground-level constructions to elevated constructions. Along with the technical improvements two distinct styles emerged: one log-cabin type and a dressed plank-construction. Although most of the buildings constructed with these techniques were storehouses and granaries, some of them could have integrated dwellings.

The relations and contact with the neighboring continent increased during the Asuka period (552-646 A.D.), culminating with the introduction of Buddhism in Japan. Along with the foreign religion came Buddhist carpenters who brought with them innovative technology, complex wood bracketing e.g., and an architectural style entirely different from anything previously seen in Japan. The Japanese carpenters incorporated the foreign technology and adapted it to the indigenous construction methods.

By the end of the seventh century, Buddhist temple architecture was firmly established in Japan, accompanying the already existing Shinto shrine architecture and residential architecture. These architectural styles represent three vastly different structures, each with their own historical background and design and engineering requirements. This variety of context and applications have resulted in a seemingly endless collection of joints, with a combined total of several hundred distinctively different joints. Despite the large supply of joints, only a few are used in all three types of structures and some are reserved for only a single type of structure. However, the selected 48 joints presented by Seike (1977) are for the most part common to all types of Japanese architecture, due to their universal nature enabling versatile applications.

The abundance of wood encouraged an exclusive focus on wood construction. The generous supply was a significant cause as to why wood construction was so overwhelmingly prioritized over other methods and materials. In Europe and China, the art of masonry flourished because of the high availability of stones and clay suitable for brickmaking. But the volcanic soil of Japan offered few materials in favor of masonry construction. Instead, the volcanic soil and the well-tempered climate yielded a seemingly endless variety of trees suitable for many diverse types of wood structures. Most of the available native wood was coniferous – pine, cedar, and Japanese cypress – and the abundance of it encouraged Japanese carpenters to experiment with post and lintel construction, fundamental to wooden architecture.

The extensive use of timber consequently drained the supply of quality timber. It became necessary to use secondary grade timber which was structurally inferior and had previously been passed over. The already established construction techniques relied, to a high extent, on the excellent structural properties of good timber and it became a challenge to construct buildings with the lesser timber. But instead of adapting the buildings and the construction techniques to the lesser material, the material was adapted to satisfy the structural requirements. This led to the creation and development of both new techniques for joining wood and the tools for which to work the joints.

THE BEAUTY OF WOOD

Figure 1:26. Swedish spruce with distinct graining.

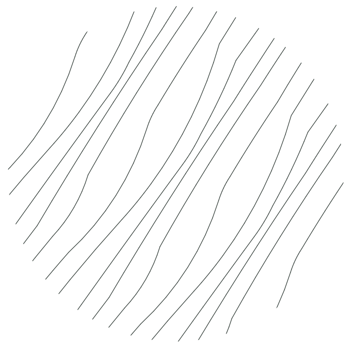


Figure 1:27. Symbolic wood hatch, emphasizing the natural, organic graining.

Wood is a natural material and is responsive to the changes of nature – it absorbs or emits humidity from its surroundings, it contracts or expands with fluctuations in humidity, and Japanese timber have a natural resistance to infestations by bacteria fungi and insects. This property of responsiveness is extended to entire wood constructions and have been of utmost importance as Japan is subject to dramatic geophysical event such as earthquakes and typhoons. As wood structures have a small mass, are light and have an inherent amount of "give", meaning not being as rigid as structures of stones or bricks, they are able to better withstand the forces of nature. Making wood structures resilient both material-wise and construction-wise. (Seike, 1977).

The symbiosis of aesthetics and technical properties is of utmost appreciation by not least Seike (1977) himself who expressed it as; *"when I look at a beautiful example of wood construction, I cannot help thinking that the beauty of the architecture derives not only from its design and construction techniques, but also from the very soul of the wood itself."* (p. 13). Along with this dual nature of wood, perhaps the most important of the special qualities of wood is the ease by with it can be worked and shaped. It is a material which allows processing with the simplest of hand-held tools as well as with cutting-edge robotic machines. This quality has contributed to the widespread preferences for using wood when constructing anything from houses and furniture to aircrafts and ships. Simply put, few other materials are as adaptable as wood. (Seike, 1977).

JOINT TYPES

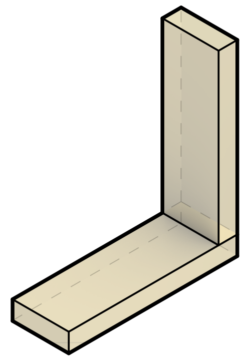


Figure 1:28. Butt joint.

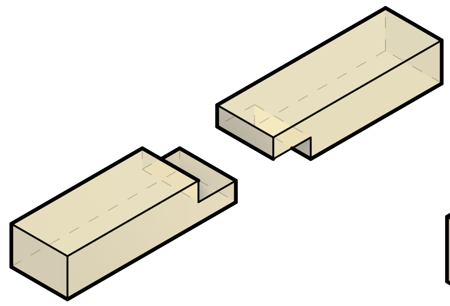


Figure 1:29. Lap joint.

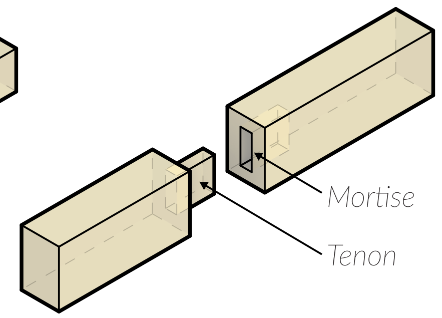


Figure 1:30. Mortise and tenon.

In the West, joints fall into one of two general classes; a joint is either a butt joint (Figure 1:28) or a lap joint (Figure 1:29). This classification originates in how the pieces of wood are joined together, unlike the Japanese tradition of classifying the joints according to their function. A half lap joint used to join two pieces of wood end to end, along a single axis, is classified in Japan as a *tsugite* – a splicing joint. But a half lap joint used to join two pieces of wood orthogonally to each other, at a right angle, is classified as a *shiguchi* – a connecting joint. These joints are, in the West, both simply classified as lap joints.

An inherent property of *tsugite* and *shiguchi* joints, other than serving to splice or connect timber, is that they should contribute to both the strength and the beauty of a building. Japanese carpenters devote a great deal of thought and energy into producing complex joints fulfilling both these aspects, and as a result Japan can enjoy some of the most advanced techniques of wood construction, distinguished from architecture found in many other areas of the world. (Seike, 1977).

The splicing of timber relies on *mortises* and *tenons* (Figure 1:30) which could be described as male and female counterparts. One of the timber components has an extruding part which is inserted in a corresponding void in the other timber component. In general, these should be reinforced with pins, dowels, metal straps and/or adhesives. However, not only the structural properties should be considered, but the appearance of the finished joint should also be taken into consideration. The most elegant solutions eliminate the need for nails, metal straps or adhesives, and solely rely on precisely crafted wood profiles utilizing wood dowels which swells after insertion and thereby tightens the joints. (Seike, 1977).

TSUGITE

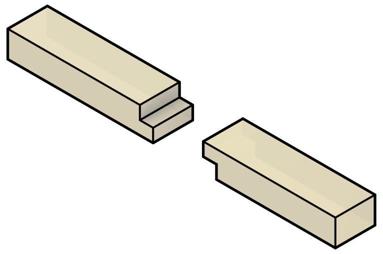


Figure 1:31. Koshikake-tsugi, lap joint.

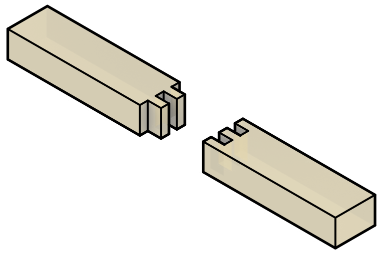


Figure 1:32. Mechigai-tsugi, stub tenon joint

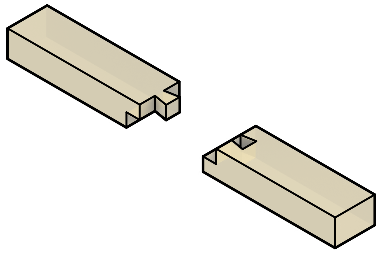


Figure 1:33. Koshikake-are-tsugi, dovetailed lap joint

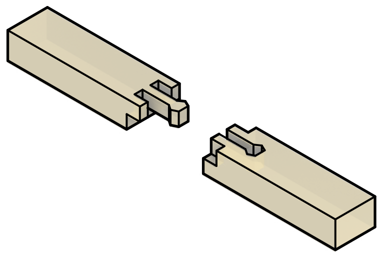


Figure 1:34. Mechigai-koshikake-kama-tsugi, lapped goose-neck joint with stub tenons

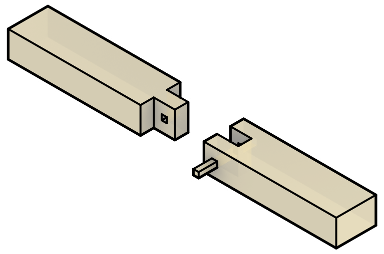


Figure 1:35. Mechigai-tsugi, stub tenon join

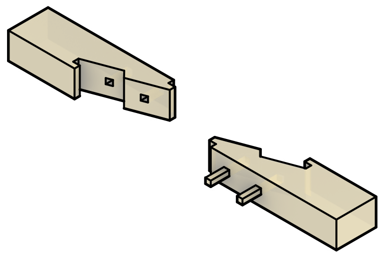


Figure 1:36. Kanawa-tsugi, mortised rabbeted oblique scarf joint

Among the diverse set of *tsugite* joints, the most basic ones are the *koshikake-tsugi* [lap joint] (Figure 1:31) and the *mechigai-tsugi* [stub tenon joint] (Figure 1:32). They rely on simple extrusions and corresponding voids at the end of each component. The simplicity of the joints makes them easy to produce and assemble, but with the drawback of only locking the construction in one dimension. The basic lap joint is dependent on adhesives, nails, screws, or other fasteners to lock it any direction at all.

By adding additional extrusions with chiseled profiles, one can achieve joints which locks the assembly in two dimensions, at the cost of a more complex and time-consuming production. The *koshikake-are-tsugi* (Figure 1:33), which is known as a dovetail joint in the west, exemplifies this. A sibling to the dovetail joint is the goose-neck joint (Figure 1:34), which is characterized by a longer extrusion and a five-sided tenon head.

By detaching the tenon and making it a stand-alone element, the joints become more complex and can obtain the ability to lock an assembly in three dimensions. The joint *mechigai-tsugi* [stub tenon joint] (Figure 1:35) resembles its simpler siblings with stub tenons but have the distinct advantage of locking along an additional dimension. Though ingenious crafting of the end profiles and a by adding detached joints it is possible to produce joints with high locking capacity, at the cost of more time consumed for both production and assembly.

SHIGUCHI

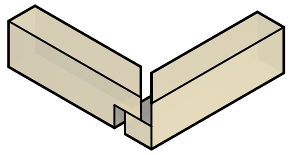


Figure 1:37. Ō-dome, mitered open mortise joint.

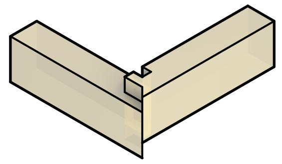


Figure 1:38. Hako-dome, rabbeted tenoned miter joint.

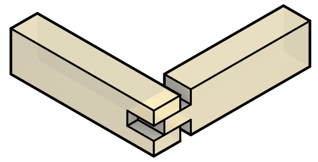


Figure 1:39. Sammai-gumi, open slot mortise joint.

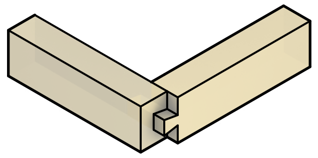


Figure 1:40. Ari-dome, housed dovetail joint.

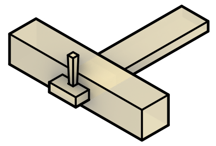


Figure 1:41. Hana-sen, draw pin joint.

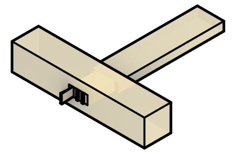


Figure 1:42. Wari-kusabi, split wedge joint.

To join wood elements at an angle, rather than end to end, shiguchi joints are used. The *Ō-dome* [mitered open mortise joint] (Figure 1:37) represents the most basic shiguchi type and could be considered a simple lap joint – in this case presented with a sharp 45-degree angle for the upper half which is not always present. By adding a stub tenon it transforms into the *Hako-dome* [rabbeted tenoned miter joint] (Figure 1:38) which has a more complex profile and demands higher precision during its production. A distinguishing feature of this joint is that the tenon and mortise becomes hidden, which could be desirable.

The *Sammai-gumi* [open slot mortise] (Figure 1:39) corresponds to a stub tenon joint with a single extrusion on one of the elements, fitting into a void in the other element. By reshaping its tenon to a dovetail on obtains the shiguchi version of the common dovetail tsugite joint, called *Ari-dome* [housed dovetail joint] (Figure 1:40).

A mutual property of the joints shown in Figure 1:37 - Figure 1:40 is that they only lock the assembly along two dimensions and additional mechanical fasteners or adhesives are required to achieve a three-dimensional fixture. Like the tsugite types, the introduction of a detached tenon is necessary to lock the assembly along the full three dimensions. The *Hana-sen* [draw pin joint] (Figure 1:41) relies on a piercing locking pin, while the *Wari-kusabi* [split wedge joint] (Figure 1:42) make use of a set of wedges pushed into corresponding slots at the end of the male component, effectively locking the assembly.

JOINTS FOR CIRCULAR DESIGN

The presented joints compose a representative selection of a practically innumerable supply of existing joints. But from these representative sets of tsugite and shiguchi joints, it is possible to conclude which are more stuiabel for circular design and engineered wood products that others. As concluded from the previously presented circular design concepts, "the most crucial factors are the ease of disassembly and the reusability of structural systems and their connections". The joints should be reversible, and the reversion process should be non-destructive.

Japanese joinery have the inherent property of generally being of non-destructive nature, but some joints rely on adhesives and/or nails for fixation, which obstructs future disassembly. It is mechanically possible to extract nails from the joint members, but it is a far more difficult to disconnect joint members which have been adhered together – without breaking them. As a result, any type of joint using these types of supplementary fasteners should be avoided and it implies that only joints using a detached tenon qualifies for circular design. This conclusion on reversibility correlates with the structural ability of locking motion in three dimensions.

Practical assembly aspects of CLT construction eliminates the joints with more complex profiles from the equation. The *mechigai-koshikake-kama-tsugi* (Figure 1:34), the *kanawa-tsugi* (Figure 1:36) and the *hako-dome* (Figure 1:38) have more elaborated profiles and are examples of excellent wood craftmanship, but they are because of this not suitable for CLT construction. The CLT components are often large and heavy, making it a necessity to use heavy lifting equipment to assemble the structure. Adding the sub-operation of sliding the components into elaborative slot profile to the construction process is simple not viable. A more productive approach is to use less complicated profiles, but which still meet the other criteria.

It can be concluded that the joints should have **detached tenons, reversible fasteners, lock motions in three dimensions and have simple profiles** for easier on-site assembly. Among the representative selection of joints presented, the *mechigai-tsugi* (Figure 1:35) and the *hana-sen* (Figure 1:41) best meet these requirements. These joints will serve as a foundation for the development of a new set of wood joints intended for circular design of CLT construction.

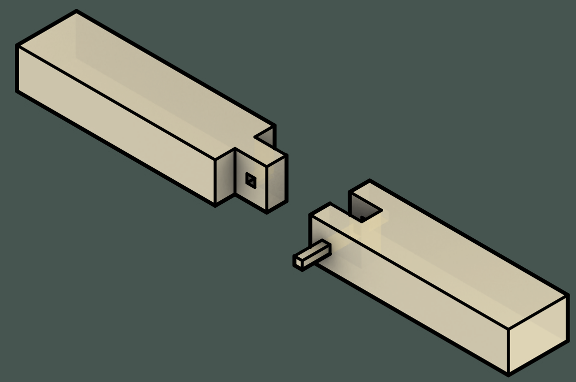


Figure 1:43. Mechigai-tsugi, suitable for circular design.

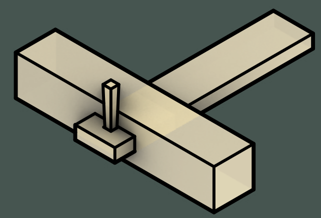


Figure 1:44. Hana-sen, suitable for circular design.

06. JOINT DEVELOPMENT

UNIVERSAL CLT JOINTS

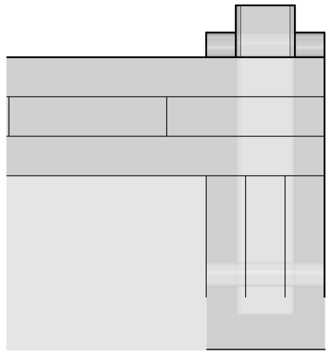


Figure 1:45. Joint A, shiguchi joint for CLT components.

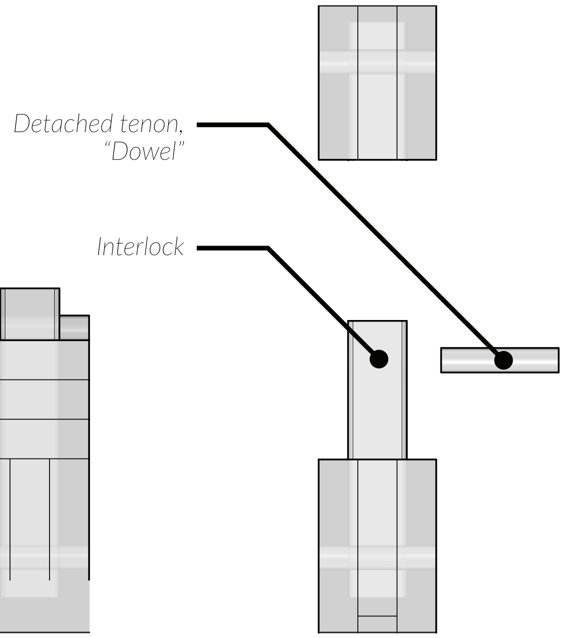


Figure 1:46. Joint B, tsugite joint for CLT components.

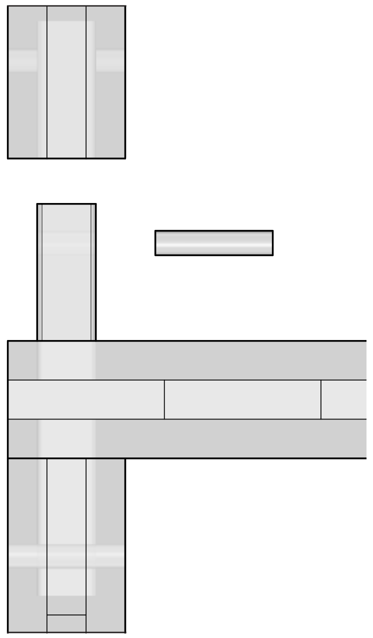


Figure 1:47. Joint B, tsugite joint for CLT components.

Huuhka's ten universal design principles and the guidelines from RISE provide a foundation for circular design. The ten principles defined by Huuhka considers the architectural tectonics and refers to the building as a whole, as its overall spatial programme and physical proportions between different functions. They do not specifically refer to how to approach designing the connections between individual building components, unlike the guidelines identified by RISE. These guidelines are more specific on what to consider when designing individual building elements and their respective connections, making these guidelines more relevant for the development of wood joints.

Originating in these guidelines and inspired by the traditional Japanese joinery, a set of universal wood connections for planar building components of cross-laminated timber have been developed as part of this thesis. The ambition has been to develop joints which meet the identified requirements for DFAR with the end result of enabling timber structures to be disassembled and its components to be reused in other contexts and buildings.

The set of developed joints for engineered wood products (CLT e.g.) is composed of three distinct types - A, B and C shown above and to the right. All three types utilized a universally shaped interlocking piece which is locked in place with two detached tenons, also known as "dowels" (Figure 1:46). In the semi-transparent illustrations above it is possible to see how far the interlocking is inserted into each CLT component and the depth of each corresponding void.

Joint type A (Figure 1:45 and Figure 1:48) is a corner joint, or a *shiguchi* by Japanese terminology. While both type B (Figure 1:46 and Figure 1:49) and type C (Figure 1:47 and Figure 1:50) are interim joints, or *tsugite*. The design of the interlocks and their associated dowels enables a high degree of universality and flexibility of the system.

UNIVERSAL CLT JOINTS

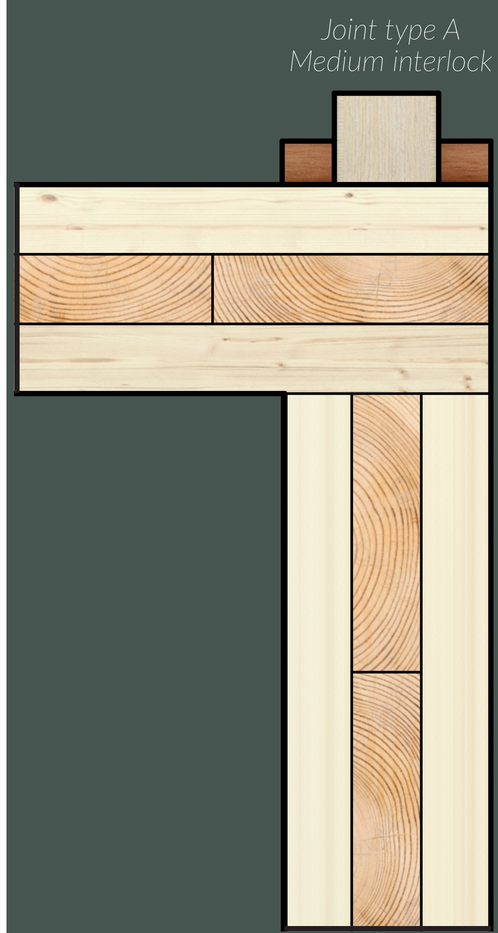


Figure 1:48. Joint A, shiguchi joint for CLT components.

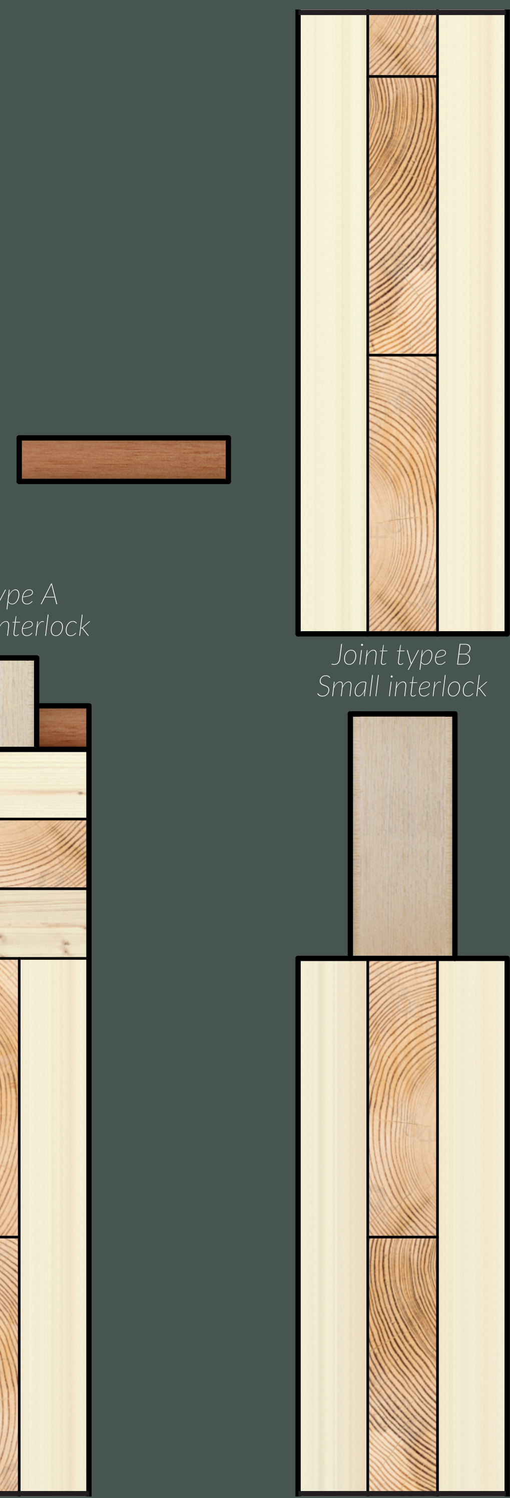


Figure 1:49. Joint B, tsugite joint for CLT components.

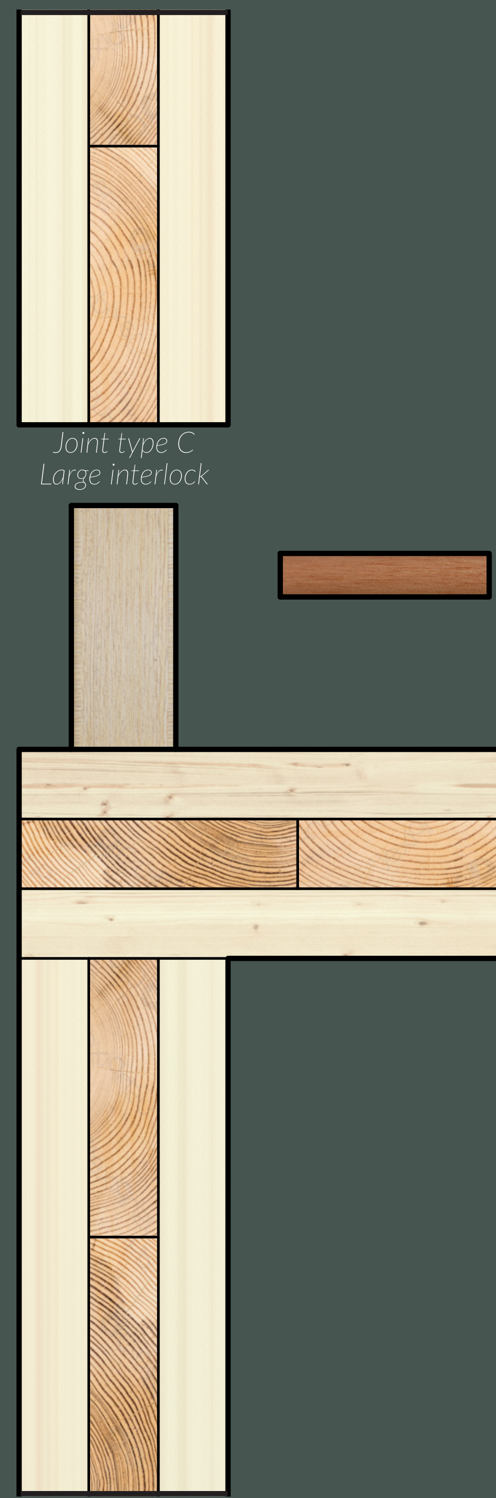


Figure 1:50. Joint B, tsugite joint for CLT components.

INTERLOCKS AND DOWELS

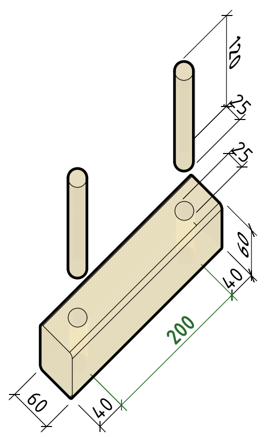


Figure 1:51. Small interlock piece with extracted dowels.

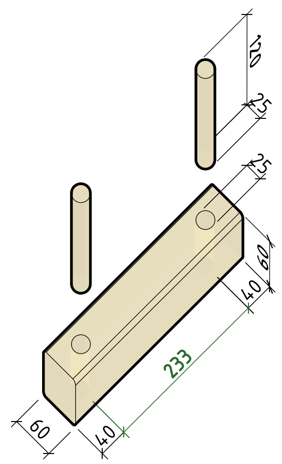


Figure 1:52. Medium interlock piece with extracted dowels

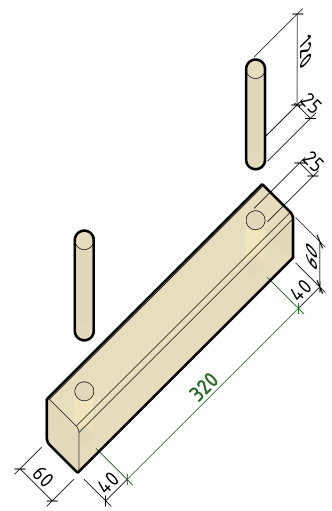


Figure 1:53. Large interlock piece with extracted dowels

The new set joint types A, B and C are associated with three filleted cubic interlocking pieces and each with a pair of wood rods, or "dowels". The universal nature of the joints makes them just as suitable to be produced by cross-laminated timber as by softwoods or hardwoods. As the dowels punctuates both the interlocking piece and the CLT building component they are visible on both the interior and the exterior side. If the interior side is left uncovered the dowels will be exposed as architectural artifacts, making them subjects to special care. Hence, the dowels could preferably be made from hardwood (Figure 1:54) which harmonize with the CLT building component and swells once inserted, effectively locking the assembly in place. At the same time, this would be in line with the circular design principle of making joints as accessible as possible.

The refined system of joints is universal, meaning that the size of the joints and the corresponding insertion holes in the CLT elements share physical dimensions, as shown in Figure 1:51, Figure 1:52 and Figure 1:53. The small, medium and large interlock are interchangeable, making it possible to connect CLT slabs and walls in endless combinations.

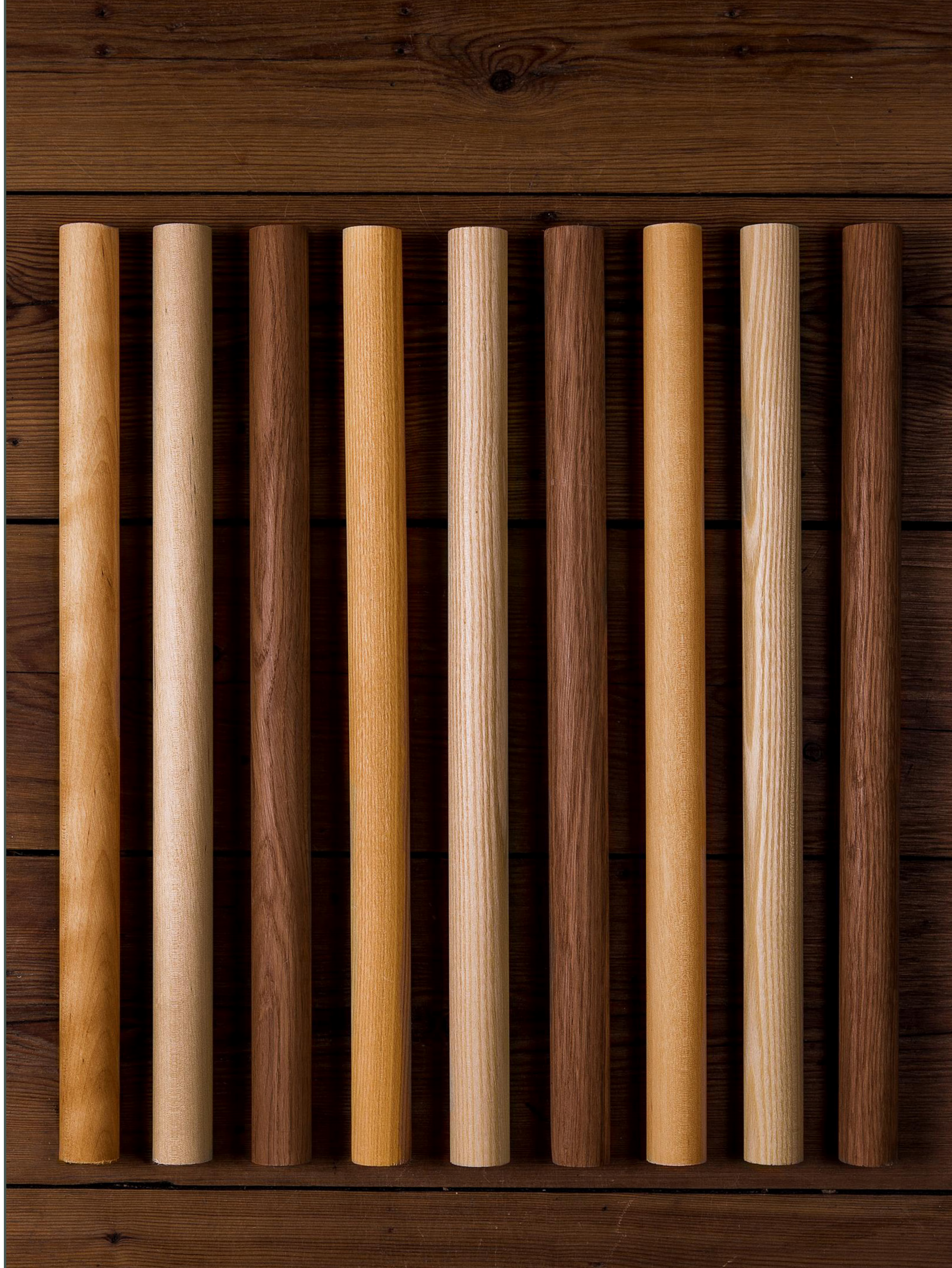


Figure 1:54. Dowels made out of hardwood.

JOINT TYPE A - CLT SHIGUCHI

Scale 1:10

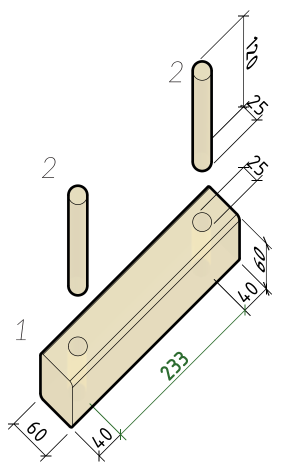


Figure 1:55. Medium interlock, axon view.

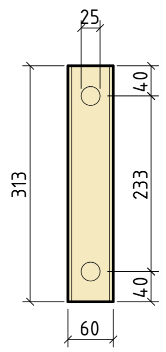


Figure 1:56. Medium interlock, top view.

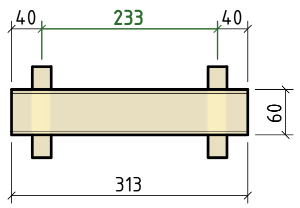


Figure 1:57. Medium interlock, side view.

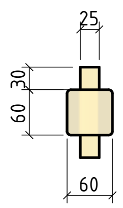
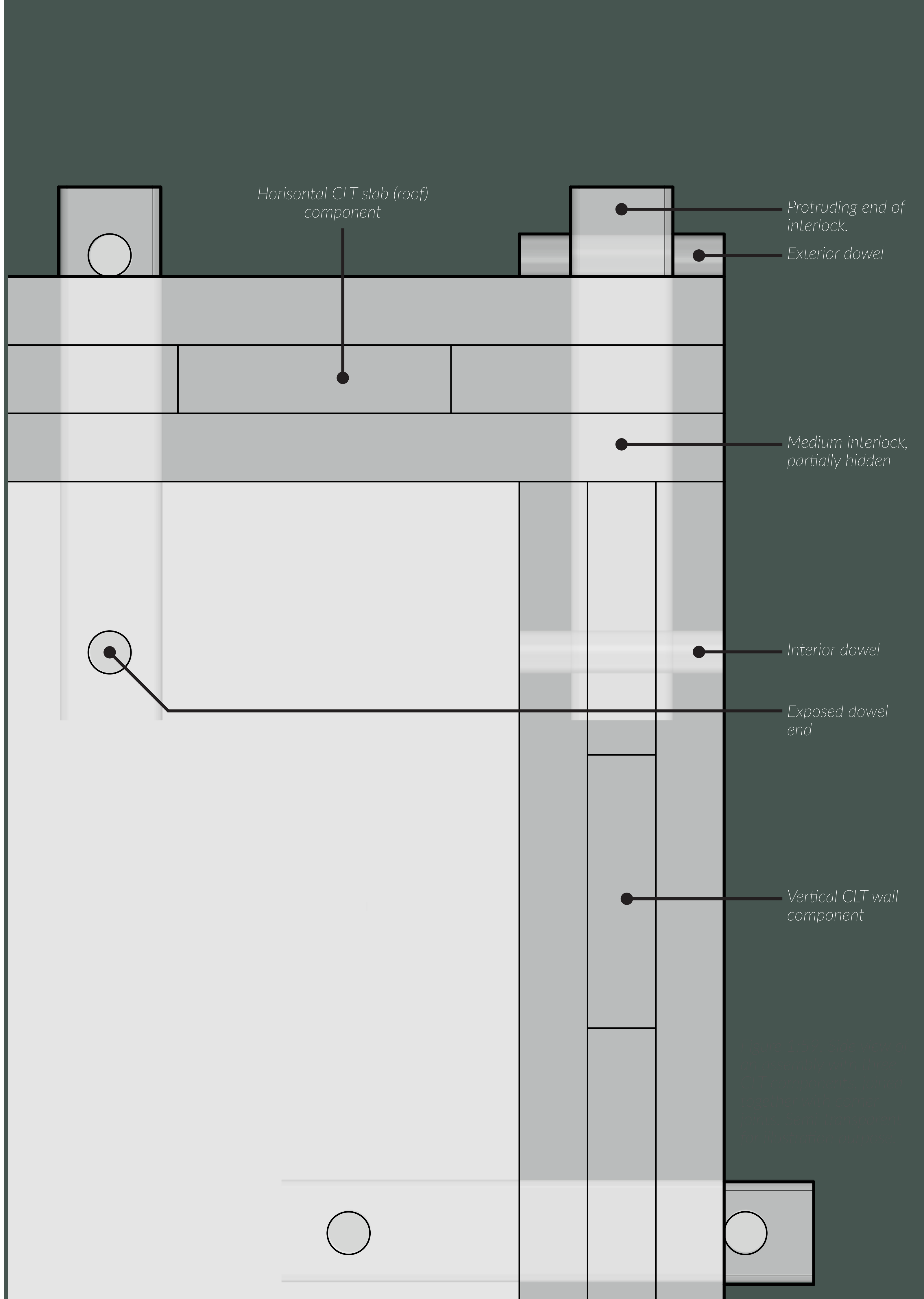


Figure 1:58. Medium interlock, profile view.

A corner joint – *shiguchi* – have been developed for assembling CLT components orthogonally to each other. The joint consists of an (1) interlock and (2) two detached tenons - or *dowels* - illustrated in Figure 1:55. The interlocking piece is inserted into the CLT components and becomes hidden, followed by the insertion of the two dowels to lock the joint in place. Once inserted, the dowel ends are visible on each side of the CLT component and allow for easy and non-destructive extraction of both the interlock and the dowels, resulting in a reversible joint aligning with the principles of circular design.

Figure 1:59 illustrates a side view of an assembly with three CLT components joined together with three corner joints. The semi-transparency of the illustration reveals how the interlocks have been locked in place by the dowels – one exterior and one interior – and how the interlock has been partially hidden once inserted into the CLT components. The *exterior dowel* is inserted into the protruding part of the interlock and becomes an exposed element. The *interior dowel* is inserted into the hidden part of the interlock, rendering the *interior dowel* hidden as well, only exposing its ends on respective side of the CLT component.



JOINT TYPE A - CLT SHIGUCHI

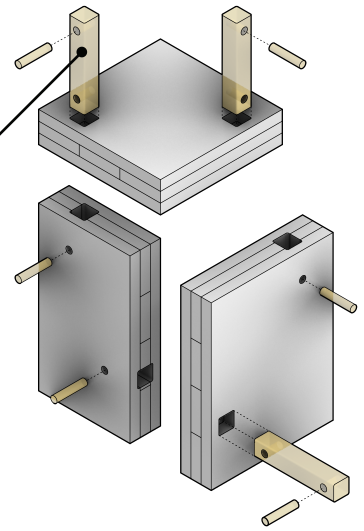


Figure 1:60. Exploded isometric view of joitn type C (medium interlock)

The design of the corner joints makes the *protruding interlock*, the *external dowel* and the *interior dowel ends* subjects to exposure and degradable wear and tear. Hence, it is important to cover these joints with a shield structures on the exterior surface to protect them the effects of nature – precipitation e.g. In conventional CLT construction where the components are applied as exterior walls it is common dress the exterior side of the component with supplementary stud-fames filled with insulation and clad with façade covers. This makes it possible to integrate and hide the protruding interlocks within the exterior stud-frame, behind the façade cladding. This is beneficial as the exterior structure and the insulation is easy to remove during a disassembly process, exposing the *exterior dowels* once again enabling extraction.

On the interior side, where the joints are not exposed to the degradable effects of nature, it is possible to leave both the protruding interlocks and the dowels exposed. Apart from aligning with the circular design principles of easily accessible joints, this could be used as an aesthetic advantage by exposing the joints as architectural artifacts. The hardwood dowels could be used as delicate wood detailing in a design of otherwise exposed CLT structures which are made of spruce or pine.

JOINT TYPE B AND C - CLT TSUGITE

Scale 1:10

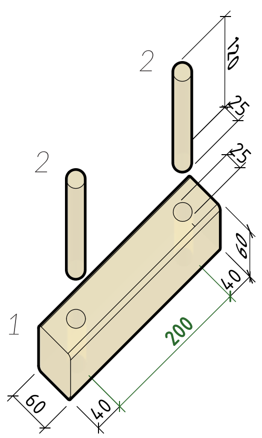


Figure 1:61. Small interlock, axon view.

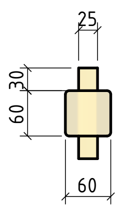


Figure 1:62. Small interlock, profile view.

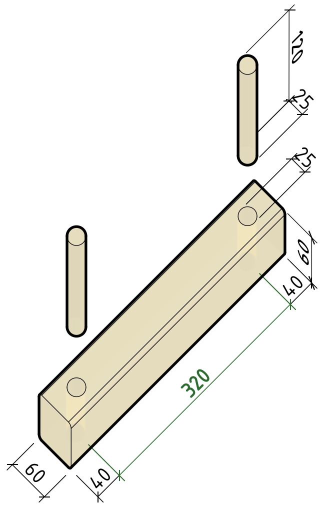


Figure 1:63. Large interlock, axon view.

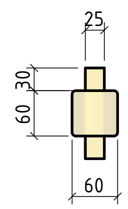


Figure 1:64. Large interlock, profile view.

To assemble CLT components at ends along their length or height directions two interim joints have been developed - *tsugite*. Similar to the corner joint they each consist of one (1) interlocking piece and (2) two associated dowels, exemplified in Figure 1:61. As the corner joint and the interim joints are part of the same universal set, they share several physical dimensions, making it possible interchange the positions of them. This is a key feature of the developed joints, as the three interlocking pieces (small, medium and large) enables three types of connections (type A, B and C).

The small interlock is used to connect CLT components to each others ends as illustrated in Figure 1:65, creating joint type B. With type B it is possible to connect vertical CLT wall components in top of each other and to connect horizontal CLT components next to each other.

By replacing the small interlock with the large interlock, the interlock extrudes further from the CLT component and enables the insertion of a orthogonal CLT component in-between, creating joint type C. This assembly is illustrated in Figure 1:66 with a horizontal CLT slab component fitted in-between the two vertical CLT wall components. The interim interlocks and their associated dowels effectively lock the assemblies together.

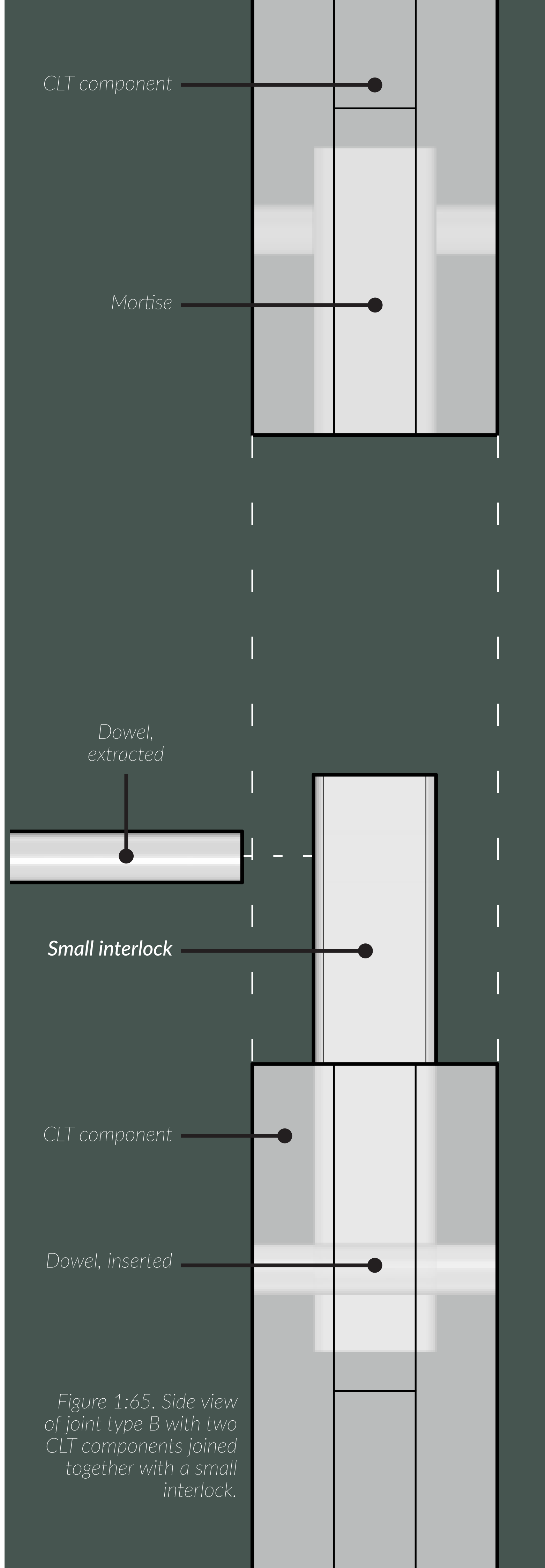


Figure 1:65. Side view of joint type B with two CLT components joined together with a small interlock.

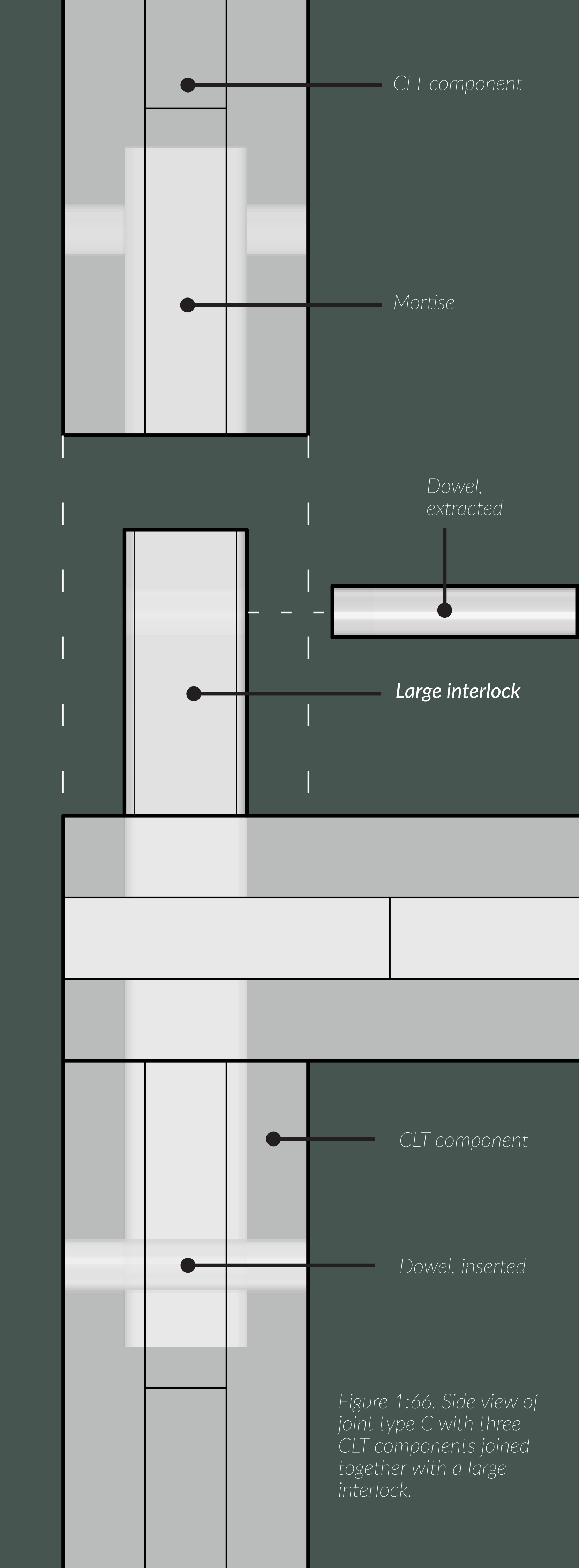


Figure 1:66. Side view of joint type C with three CLT components joined together with a large interlock.

JOINT TYPE B AND C - CLT TSUGITE

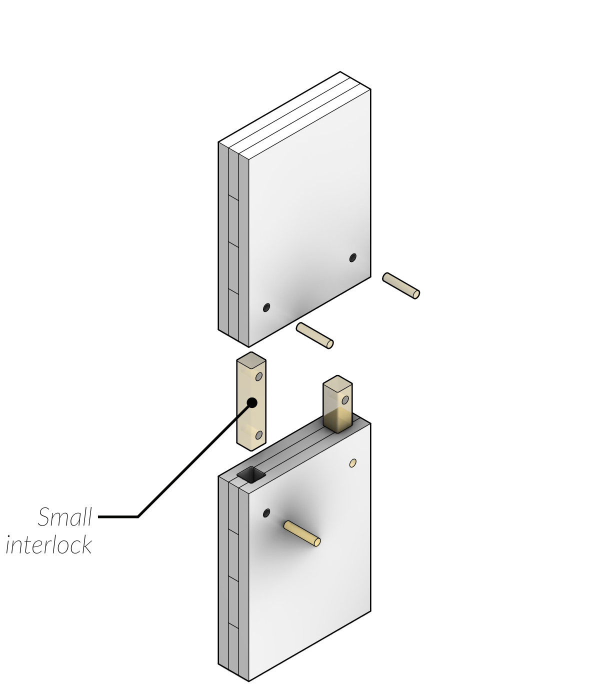


Figure 1:67. Exploded isometric view of joint type B (small interlock).

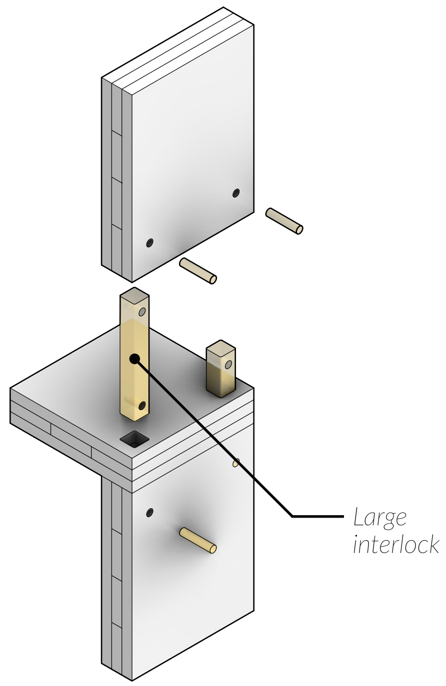


Figure 1:68. Exploded isometric view of joint type C (large interlock).

Joint type B use the small interlock and joint type C use the large interlock, as illustrated in Figure 1:67 and Figure 1:68 respectively. The joint type B can be used to connect vertical components on top of each other as well as to connect horizontal CLT components next to each other. The large interlock is long enough for a orthogonal CLT component to fit in-between, creating wall-slab-wall assembly e.g.

The design of the interlocks and the generated joints B and C makes the interlocks hidden inside the CLT components and only leave the tip of the dowels visible. The result of these assemblies is visualized in Figure 1:69, where the dowel tips can bee seen as distinct but yet subtle architectural artifacts. If made out of darker hardwood, as in the visualization, the dowels could almost be mistaken for wood knots if it were not for the repetitive pattern - which is an inherent property of the joinery system.

As mentioned, the dowels are preferably made from hardwood which harmonize with the CLT building component of spruce or pine. But this also enables the system of dowels to swell once inserted, effectively locking the assembly in place. At the same time, this is line with the circular design principle of making joints as accessible as possible.

The three interlocks enables an equal number of joints - creating the new CLT joint set. When used in conjunction it would be possible to connect entire structural systems and result in complete buildings.

Figure 1:69. Visualization of interior room created with joint type B and C.

07. JOINT APPLICATION

DEMONSTRATION CONTEXT

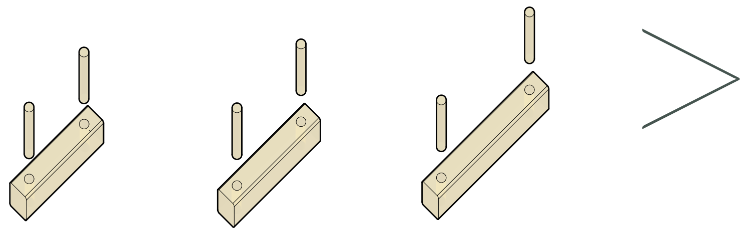


Figure 1:70. Joint interlocks to be applied to a building.

Figure 1:71. Frostaliden by White Arkitekter, subject for joinery re-design.

To showcase the potentials, the universality and the circularity of the developed joints and the joinery system they compose, the joints are showcased in a building design proposal. An existing multi-family building with a structure of CLT has been selected and the joinery system has been applied to its structural CLT components. With the applied joinery system, the building will be possible to deconstruct into its sub-components and by cataloging these components they can be reused in other buildings. Due to the innovative joinery system, this circle of reuse can continue until wear and tear has damaged CLT components to such an extent that their structural or aesthetic properties no longer can serve their purpose.

A remodel with the purpose of applying the joinery system to an existing building postulates certain reservation. An existing building which has already been designed with a specific structural system has achieved specific set dimensions which might not correspond perfectly to the theoretical framework of the joints. Combined with an incomplete knowledge of the structural systems combination, some architectural design freedom has been taken during the application of the joints.

STRUCTURAL SYSTEM

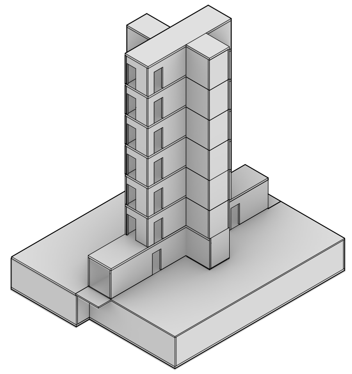


Figure 1:72. Frostaliden, concrete core.

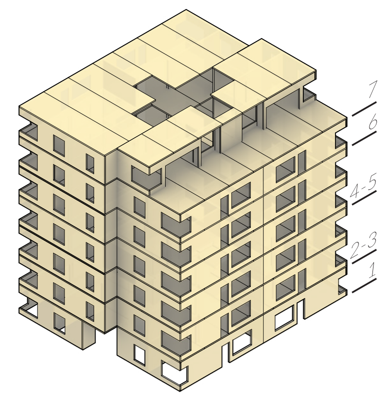


Figure 1:73. Frostaliden, CLT structure.

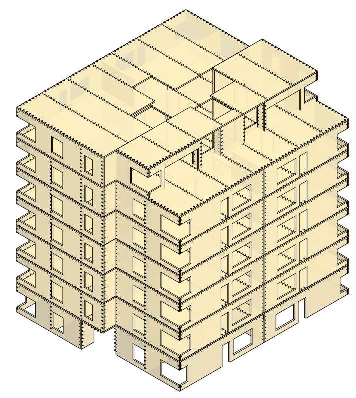


Figure 1:74. Frostaliden, joinery remodel.

The selected building is the multi-story residential building Frostaliden in Skövde, designed by White Arkitekter. Frostaliden is a pair of low-rise tower blocks, but as the towers are identical only one of them has been selected for the joinery application. The tower is eight stories high, and a large proportion of the structural system is made of CLT components. The foundation, the cellar walls, the cellar slab and the core with elevators and stairs are made of concrete, but all the remaining load-bearing walls are made of CLT. These CLT components are the subjects of the re-design with joints.

In a CLT structure the general thickness of the CLT wall components correlates with the height at which they are placed. The thickness of the wall components on the lower floors are overall thinner than the corresponding wall components on floors above, as the walls higher up does not need to carry as much load as the lower walls. In the re-design this has been translated to five different floor plan types, divided into 1, 2-3, 4-5, 6 and 7, as illustrated in Figure 1:73 which shows the remodeled CLT structure of Frostaliden.

The continuous changes in wall thickness becomes a challenge for the joinery applications as the placement of mortises will vary with each thickness of the components. However, as the developed joints are of universal nature it is still possible to achieve a high flexibility and component interchangeability.

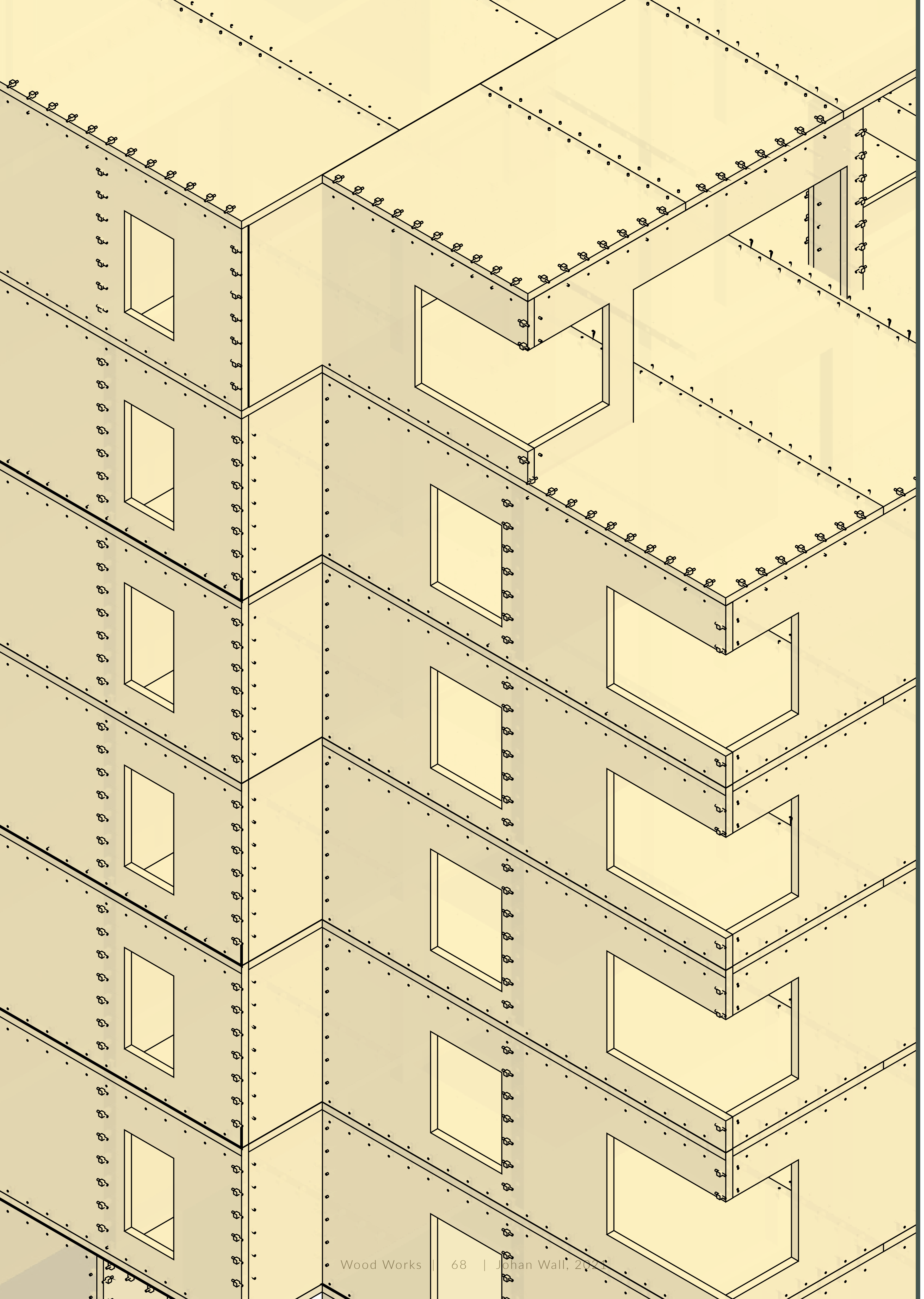


Figure 1:75. Left: close-up of joint types A, B and C applied to Frostliden.

COMPONENT RECOVERY

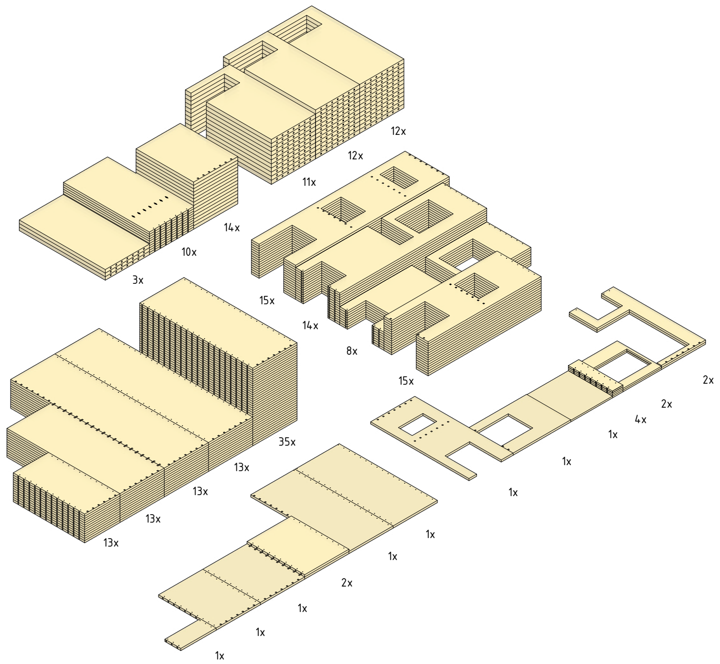


Figure 1:76. Recovered CLT components.

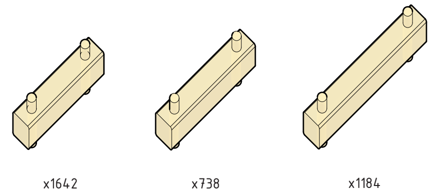


Figure 1:77. Recovered interlocks.

With the joinery system applied to the multi-family housing Frostaliden, it would be possible do deconstruct the building into its sub-components. With careful recovery and by cataloging the many components it would be possible to reuse them in other context. The same building could be re-erected at another location or, more relevant, the components could be used to create other types of buildings - single-family homes, offices, summer houses and more.

A recovery of the CLT components in the remodeled Frostaliden would result in the quantities shown in Figure 1:76. The remodel process generated a simplified set of components compared to the real-world case, but the demonstration illustrates the potentials of the refined joinery system.

The many joints for type A, B and C needed to connect the CLT components would rely on approximately 3 500 interlocks (Figure 1:77). These interlocks and their associated dowels are to be recovered to as high extent as possible, but the risk of damaging the interlocks and the dowels during a deconstruction process would likely result in the disposal of several of them. A relevant approach would be to regard the interlocks and the dowels as disposable elements and instead consider any recovery of them as a bonus. After all, it is the CLT components which embodies the most energy, biomass and carbon dioxide and therefore are the prioritized subjects of reuse.

With the innovative joinery system applied to a CLT structure, the circle of reuse can continue until wear and tear has damaged the CLT components to such an extent that their structural or aesthetic properties no longer can serve their purpose. It is a joinery system derived from both traditional wood working and modern engineered wood products to form an circular design approach for buildings to come.

08. REFLECTION

REFLECTION

The climate crisis requires action, and the building industry must reconsider current linear processes and transition to circular construction. This thesis identifies urgent sustainability challenges, tools for combating them, and present an innovative system of joints responding to the challenges. It is a journey from a macro challenge – the climate crisis – down to a micro solution – the wood joints. It is a journey from a macro perspective to a micro perspective as a solution to the global climate crisis is concretized into small, physical wood joints.

The implementation of the joinery system is fairly simple for smaller structures such as single-family homes of one to two stories, as they depend on a small set of structural wood components relying on a limited variety of associated joints. But larger buildings utilize structural components of greater variety in dimensions and a vast set of joints harder to oversee. Hance, the design of larger buildings would rely heavily on parametric approaches to define, place, evaluate and catalogue the many components and joints. Regardless of using a parametric approach or a more "manual" modeling approach, the developed models could serve as foundations in the fabrication of the structural components. This favors close collaboration between architects, structural engineers and EWP producers. In a larger perspective this approach to architectural, parameterized designs in conjunction with high-level prefabricated components goes hand-in-hand with the emergence of digital craftsmanship within architecture.

The aspect of digital craftsmanship related to the developed joints would benefit greatly from further explorations with large-scale prototyping. With CNC milling and robotic manufacturing of proper CLT components one could possibly refine architectural qualities, structural properties, and real-world assembly strategies. Any receiver of this thesis who finds the aspect of digital craftsmanship thrilling is encouraged to carry on the ideas initiated.

I welcome further research and exploration originating in the ideas initated by this thesis. Feel free to reach out and discuss on how I can assist you in such a feat. Talk to you soon.

hello@johanwall.com

09. BIBLIOGRAPHY

BIBLIOGRAPHY

Beaulieu, L., Durme, G. V., and Arpin, M. L. (2015). Circular Economy: A Critical Literature Review of Concepts. Montréal: International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG). https://ciraig.org/index.php/project/circular-economy-a-critical-literature-review-of-concepts/

Borzecka, M. (2018). European wood waste statistics report for recipient and model regions. Report D1.1. Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB). https://www.bioreg.eu/assets/delivrables/BIOREG%20D1.1%20EU%20Wood%20Waste%20Statistics%20Report.pdf

Boverket. (2020). Utveckling av regler om klimatdeklaration av byggnader (eng. Regulation on climate declarations for buildings). https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2020/utveckling-av-regler-om-klimatdeklaration-av-byggnader/

Boverket. (2021, March 13). Utsläpp av växthusgaser från bygg- och fastighetssektorn (eng. Greenhouse gas emissions in the building industry). https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/vaxthusgaser/

Buildings as Material Banks [BAMB]. (2021, February 26). About BAMB. https://www.bamb2020.eu/about-bamb/

Durmisevic, E. (2006). Transformable building structures, design for disassembly as a way to introduce sustainable engineering to building design & construction. [Doctoral thesis, Delft University of Technology]. http://resolver.tudelft.nl/uuid:9d2406e5-0cce-4788-8ee0-c19cbf38ea9a

European Committee for Standardization. (2011). Sustainability of construction works - Assessment of environmental performance of buildings – Calculation method. https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSPPROJECT:31325&cs=16BA443169318FC086C4652D797E50C47

Gustafsson, A. (2019). The CLT Handbook. The Swedish Forest Industries Foundation: Swedish Wood. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-handbook-2019-eng-m-svensk-standard-2019.pdf

Government Offices of Sweden. (2021, March 11). Sweden's climate policy framework. https://www.government.se/articles/2021/03/swedens-climate-policy-framework/

Kuzman M. K., Sandberg, D. (2017). Comparison of timber-house technologies and initiatives supporting use of timber in Slovenia and in Sweden - the state of the art. iForest 10, 930-938. https://doi.org/10.3832/ifor2397-010

Long, P.W. (2014). Architectural Design for Adaptability and Disassembly. https://www.academia.edu/35804830/Architectural_Design_for_Adaptability_and_Disassembly

Lansink, A. (2017). Challenging changes: Connecting waste hierarchy and circular economy. Nijmegen. https://doi.org/10.1177%2F0734242X18795600

Lundmark, T. (2020). The forest is not enough - how should we prioritize? (swe. Skogen räcker inte - hur ska vi prioritera?) Future Forests Report 2020:4., Swedish Agricultural University (SLU), Umeå. https://www.slu.se/globalassets/ew/org/centrb/f-for/pdf/ffrapport_skogen-racker-inte_20200915_vers2.pdf. (Last access: 2021-02-26).

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

BIBLIOGRAPHY

Research Institutes of Sweden [RISE]. (2020). Design for deconstruction and reuse of timber structures – state of the art review. Report 2020:05. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1527414&dswid=-4593

Sato, H., and Nakahara, Y. (1995). The complete Japanese joinery. Hartley & Marks Publishers Inv.

Seike, K. (1977). The art of Japanese Joinery. Weatherhill: Shambhala Publications, Inc.

Stora Enso. (2019, May 28). Stora Ensos nya produktionslinje för korslimmat trä vid Gruvöns sågverk är invigd. https://www.storaenso.com/sv-se/newsroom/press-releases/2019/5/stora-ensos-nya-produktionslinje-for-korslimmat-tra-vid-gruvons-sagverk-ar-invigd

Stora Enso. (2020, September 7). Stora Enso investerar i produktion av korslimmat trä (CLT) i Tjeckien. https://www.storaenso.com/sv-se/newsroom/regulatory-and-investor-releases/2020/9/stora-enso-investerar-i-produktion-av-korslimmat-tra-clt-i-tjeckien

Swedish Wood. (2021, May 8). A variety of wooden structures. https://www.swedishwood.com/building-with-wood/construction/A_variety_of_wooden_structures/Large_load-bearing_structures_in_wood/

Södra. (2021, March 23). Södras nya fabrik för KL-trä närmar sig – ökar kapaciteten med tio gånger. https://www.sodra.com/sv/se/om-sodra/pressrum/pressmeddelanden/sodras-nya-fabrik-for-kl-tra-narmar-sig--okar-kapaciteten-med-tio-ganger/

The Swedish Federation of Wood and Furniture Industry [Swedish: Trä- och möbelföretagen, TMF]. (2020, November 24). Flerbostadshus. https://www.tmf.se/statistik/branschstatistik/trahusstatistik/flerbostadshus/

United Nations. (2019). Global Sustainable Development Report 2019 – The future is now: Science for Achieving Sustainable Development. Department of Economic and Social Affairs. https://sustainabledevelopment.un.org/gsdr2019

United Nations. (2020). The Sustainable Development Goals Report 2020. Department of Economic and Social Affairs. https://unstats.un.org/sdgs/report/2020/

United Nations. (2021, March 13). Sustainable Development: The 17 goals. https://sdgs.un.org/goals

Van den Berg, M. (2019). Managing Circular Building Projects. [Dissertation, University of Twente]. https://research.utwente.nl/en/publications/managing-circular-building-projects

Vis, M., U. Mantau, B.Allem (Eds.). (2016). Study on the optimised cascading use of wood. No 394/PP/ENT/RCH/14/7689. Finarl report. Brussels 2016. 337 p.

Voll Arkitekter. (2021, May 9). Mjøstårnet – Verldens høyeste trehus. http://vollark.no/portfolio_page/mjostarnet/