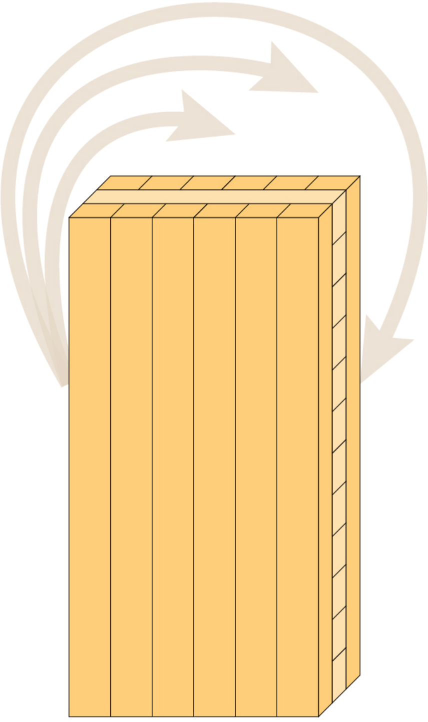

Reuse of structural CLT elements

Assessing the impact of inter-element joint solutions on the reuse potential and environmental impact of a load-bearing wall panel

Master's thesis in Industrial Ecology

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Cover: Illustration of the multi-cycle reuse of a CLT wall panel.

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Abstract

The construction sector is a significant contributor to many of our current environmental challenges. To make the sector more sustainable, it is important to increase the use of renewable materials and implement circular strategies such as the reuse of building components. For reuse to become practically possible, the elements of a building must be easily removable without causing them damage. The joints connecting the building elements are thus vital for enabling reuse. The aim of this study is to assess how the choice of inter-element joint solution affects the reuse potential and environmental impact of reusing a load-bearing CLT wall panel.

A literature review is performed to analyse how joint solutions impact the reuse potential of a structural element. The limited amount of existing research on the topic was found to be too general to be of sufficient relevance for CLT construction, in addition to being inconsistent in including important factors determining reuse potential. A new framework for analysing reuse potential is therefore developed in which joint solutions for a CLT wall panel are categorised according to the direction of removal they enable and whether their removal causes damage to a panel. The reuse potential framework is further used as a basis for developing scenarios for reusing a wall panel over multiple cycles. Two types of reuse are distinguished between in the scenarios: reuse between buildings (disassembly) and reuse within a building (adaption), forming the basis of an LCA of the environmental impact of multiple cycles.

By analysing the direction of removal and potential damage caused to a panel, it is found that common joint solutions for CLT wall panels offer a range of reuse potential when assessed individually. However, there is currently a lack of joint combinations that fully enable reuse of a wall panel both through disassembly and adaption. To ensure more flexibility in how a panel can be reused, it is necessary to opt for other, or develop existing, solutions to increase the overall reuse potential. Additionally, the choice of joint solution affects the number of possible reuse iterations (use cycles) which is a key factor in determining the potential environmental impact reduction of a reused panel compared to the corresponding linear pathway. The largest impact reductions are found in the intermediate use cycles, suggesting that joint solutions enabling many intermediate cycles might create the largest reuse incentive.

Keywords: reuse, reuse potential, CLT, timber structure, joint, direction of removal, Design for Adaption, Design for Disassembly, circular economy, multiple-cycle LCA

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Jonna Ljunge & Helena Nerhed Silfverhjelm, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BAU	Business as usual
CE	Circular economy
CLT	Cross-laminated timber
DfA	Design for Adaption
DfD	Design for Disassembly
EoL	End-of-life
EPD	Environmental product declaration
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life Cycle Assessment
RF	Reference flow
UC	Use cycle
W2F	Wall-to-floor
W2R	Wall-to-roof
W2W	Wall-to-wall

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1

Introduction

The construction industry is responsible for a large share of society's resource consumption and environmental impacts. Approximately a fifth of greenhouse gas (GHG) emissions both globally (Shukla et al., 2022) and in Sweden (Boverket, 2021b) originate from the construction and demolition sector. One way to mitigate and reduce these impacts is to increase the use of renewable and sustainable construction materials such as timber (Balasbaneh & Sher, 2021; Pierobon et al., 2019). The structural elements of a building is of particular interest with respect to impact reduction as they typically account for most of the mass of used materials, and thus embodied impacts, of a building (Brütting et al., 2019). Currently, attempts are being made in several European countries to increase the use of renewable materials which has led to a growing interest in structural elements made of wood (Svenskt trä, n.d.).

In order to replace more traditional building materials such as steel and concrete, new timber-based products have been developed which offer more constructional flexibility as well as improved dimensional stability and load-bearing capacity. Cross-laminated timber (CLT) is an example of a relatively new construction product developed with these characteristics in mind, and it has become increasingly popular on the market (FPInnovations, 2019). However, a growing global demand for timber products has led to a shortage of raw materials, and wood prices are thus increasing as a result (Statistics Sweden, 2022). Between March 2021 and March 2022, the cost of wood products on the Swedish construction market rose by 59.3%. Furthermore, the CLT market is expected to continue to expand; increases of 14.5% and 36% are projected on the global and European markets respectively (Research and Markets, 2022). In addition, an accumulated rising demand for renewable biomaterials across several sectors may ultimately lead to a shortage of wood resources (Jonsson, 2010). Consequently, implementing a more efficient use of timber elements is vital for a sustainable development in the construction sector.

Circular economy (CE) has the potential of reducing the resource consumption and environmental impacts of the construction sector. The concept of CE pertains to changing patterns of production and consumption with the aim of recirculating materials, by for instance recycling or reuse, to reduce waste and decrease the dependency on virgin resources (European Parliament, 2022). CE is currently gaining momentum in the construction sector (Pomponi & Moncaster, 2017), and is typically operationalized through strategies, or approaches, that target different parts of a building's or its constituent elements' life-cycles. Design for Dissassembly (DfD) and Design for Adaption (DfA) are two such approaches which aim to promote reuse in order to increase the circularity of buildings (Eberhardt et al., 2021). By extending the service life of building elements through reuse, DfD and DfA can reduce the environmental pressures associated with timber construction as well as the need for extraction of virgin material. In turn, the reuse of individual elements is highly dependent on the choice of appropriate connections to enable their removal and reinstallation in other locations (Jockwer et al., 2020). In spite of this, the extent to which the choice of joint solution contributes to the reuse potential of a structural element and what the consequences are in terms of environmental impact has not been widely researched. To aid the construction sector in its transition towards a CE, it is thus vital to increase knowledge about the details of reusing building elements and its associated environmental impacts.

1.1 Aim and objectives

The aim of the study is to analyse how the choice of inter-element joint solution affects the reuse potential of a load-bearing inner wall made from CLT. Moreover, the study aims to assess how this reuse potential translates into an effect on environmental impact compared to when there is no reuse. The following research questions guide the study towards fulfilling its aim:

1. How can the reuse potential of a CLT wall panel be assessed based on the choice of inter-element joint solution?
    1.1 Which joint solutions should be prioritized in CLT construction in order to enable reuse of load-bearing inner walls?
2. How is the environmental impact associated with reusing a CLT wall panel affected by the choice of inter-element joint solution?
    2.1 Does the choice of inter-element joint solution for a CLT wall panel have an impact on the incentive to reuse?

A broader objective is to contribute to reducing the environmental impact of the construction sector by supporting the implementation of more reuse within timber construction. The intention is for the results to be used as a guide in early connection design choices to create possibilities for reuse later on in the life cycle of a CLT wall panel. Furthermore, the study outlines the impacts of such design choices in terms of their environmental impact. It is thus the belief of the authors that the outcomes of the study will be of interest to any stakeholder with an interest in circular building practice in relation to CLT.

1.2 Delimitations

As is highlighted by Section 1.1, the scope of the study pertains to individual CLT elements rather than entire structures composed of CLT. More specifically, the aim is to analyse and assess *load-bearing* CLT panels used as *inner walls*. The decision to study load-bearing wall panels is due to the fact that a majority of a building's mass, and thus its environmental impact, is tied to its structural components (Brütting et al., 2019). Furthermore, it was chosen to delimit the study to inner walls since a building's exterior walls are more exposed to wear and damage. The National Board of Housing, Building and Planning (Boverket, 2009) has made an inventory of the Swedish building stock and found that 15–25% of exterior walls suffer from damage or lack of maintenance. The corresponding range for interior surface layers is only 5–15% (Boverket, 2009). Inner walls can thus be assumed to be more fit for multiple cycles of use.

The objective of research question 1 is to assess reuse potential based on the *choice of inter-element joint solution*. Consequently, the analysis excludes any other factor which can be assumed to influence the reuse potential of a CLT wall panel. Such factors include (but are not limited to): accessibility issues, deterioration of functional qualities, and exposure to certain kind of damage. Excluding accessibility from the reuse potential analysis means to not consider the presence and characteristics of adjacent non-CLT building elements. In that sense, it is assumed that access to a CLT wall panel is uninhibited by the placement and mounting technique of e.g., insulation materials, plaster boards, and installations. To exclude issues of accessibility further means that the analysis does not consider panel size in relation to openings in the building. Thus, it is assumed that a wall panel is removed and remounted on the same storey if it is to be reused within a building. Moreover, a lower reuse potential due to the deterioration over time of e.g., a panel's load-bearing capacity is excluded from the analysis. In addition, the analysis does not consider how reuse potential is affected by damage that is not directly correlated to the choice of joint solution. In other words, a panel's exposure to potential sources of wear and damage such as moisture and fire are not included.

Research question 2 formulates the second objective of the study: to assess the environmental impact of varying degrees of reuse potential resulting from choosing different joint solutions. Only fossil carbon impacts will be assessed in the study. This choice is motivated by the need to rapidly reduce GHG emissions originating from the construction sector if it is to reach its own targets of a net-zero emissions level in 2045 (Fossilfritt Sverige, 2018). Lastly, the scope of the study is limited to a Swedish context as it analyses joint solutions relevant to Swedish CLT construction practice and uses Swedish data for the impact calculations.

1.3 Methodology overview

The study comprised of three methodological components: a literature review, a qualitative analysis, and an assessment of environmental impact. The literature review had two purposes. First, it was used as a tool to identify important concepts and form a theoretical background (outlined in Chapter 2). Second, it aimed to inform the reuse potential analysis presented in Chapter 3 by presenting previous efforts in assessing joint solutions based on principles of reuse. The literature review method is described in more detail in Section 2.1. A qualitative analysis was then employed to determine how joint solutions relevant to CLT should be assessed in terms of their ability to enable reuse. Section 3.1 presents the method for the qualitative analysis. Lastly, the environmental assessment (see Section 4.1 for method description) aimed to convert the conclusions from the reuse potential analysis to quantitative results in terms of environmental impact.

2

Background

The following Chapter provides a theoretical framework for the study and puts the aim into context. First, the method for the literature review is presented in Section 2.1, followed by the theoretical framework. Section 2.2 presents the environmental impacts of the construction sector and the standards and regulations for assessing and declaring the environmental impact of the construction sector. Section 2.3 presents the concept of reuse within the sector, how the joint design can enable reuse, and how reuse of building components can be included in impact assessments. Finally, Section 2.4 describes CLT as a construction material, its possibilities and challenges as a renewable material and the challenges of assessing the life cycle impacts of biomaterials.

2.1 Literature review method

The process of finding, selecting, and reviewing written material for the study largely followed the format of a structured literature review. A structured literature review borrows elements from a systematic literature review but is far less time consuming and thus more suitable for master's level theses (Karolinska Institute, 2021). The following six steps constitute a structured review (Karolinska Institute, 2021): (1) Defining a research question and appropriate delimitations, (2) Identifying keywords and using them to construct search blocks, (3) Conducting the search, (4) Reviewing and improving the search strategy, (5) Selection and review of the collected material, and (6) Reporting of the search method.

Since the literature review had two functions in the study (see Section 1.3), the search strategy departed from different questions and delimitations depending on if the purpose of a search was to collect material for the theoretical framework surrounding the study or provide a basis for answering the first research question. In case of the former, it was necessary to spend more time conducting unstructured initial search queries to identify what concepts would be of relevance to the study. According to the Karolinska Institute (2021), such "test searches" are useful when it comes to familiarising with the terminology of a topic and identifying suitable keywords. Once such an aspect had been identified (e.g., 'circularity'), more targeted search questions could be formulated (e.g., What role does a circular economy play in the construction sector?), and key words could be extracted (e.g., 'circular', 'economy', 'construction', 'sector'). The part of the search aimed at collecting material for the reuse potential analysis was narrower and could depart more directly from the formulation of research question 1 in identifying appropriate keywords. Keywords were then organised in search blocks using Boolean operators, which are presented in 2.1.

Table 2.1: Keywords and search blocks used for the different concepts included in literature review.

Concept	Keywords and search blocks
Environmental impacts construction sector	("environmental impacts" OR "fossil GWP" OR emissions OR "resource consumption") AND (building OR construction) AND (assessment OR declaration)
CE in construction sector	(reuse OR reusability OR circular* OR disassembly OR adaption OR adaptation) AND (building OR construction) AND (joint OR joinery OR connection OR connector)
CLT	(CLT OR "cross-laminated timber") AND (possibilities OR challenges OR advantages OR disadvantages OR "biogenic carbon")

The literature search was conducted in two databases (Scopus and Google Scholar) and a search engine (Google) to enable a wider collection of relevant material. The database searches primarily provided material in the form of journal articles, conference papers, and book chapters. As a first selection, search results were assessed based on the relevance of the abstract and introduction. Other criteria that guided the selection of material were the date of publication and number of citations. Relevant keywords were mapped continuously with the purpose of improving the used search strings. Additionally, publications that were considered of particularly high interest were used for reference snowballing. Thus, the final body of analysed literature also included dissertations, e-books, and web pages and documents published by national and international bodies, industry organisations, institutions, and NGOs.

The software NVivo 12 Plus was used for the qualitative review as an aid in structurally gathering and analysing the collected material by a categorisation method called coding. Coding enables collection of information relating to the same topic under a common category (code), so that a particular concept (e.g., 'Design for Adaption') can be analysed across multiple sources. A mixture of an inductive and deductive coding approach was used. The inductive approach develops codes "along the way" based on what is found in the data, which is suitable when there is uncertainty around what concepts are of most importance to a subject (Skjott Linneberg & Korsgaard, 2019). Thus, this data-driven approach was helpful when setting up the theoretical framework of the study presented in this Chapter. On the other hand, the deductive approach is relevant when the important concepts of an issue are already known as it departs from a predefined set of codes for which the collected material is searched (Skjott Linneberg & Korsgaard, 2019). The part of the review targeting research question 1 commenced using a inductive approach but moved towards concept-driven, deductive coding as the analysis progressed.

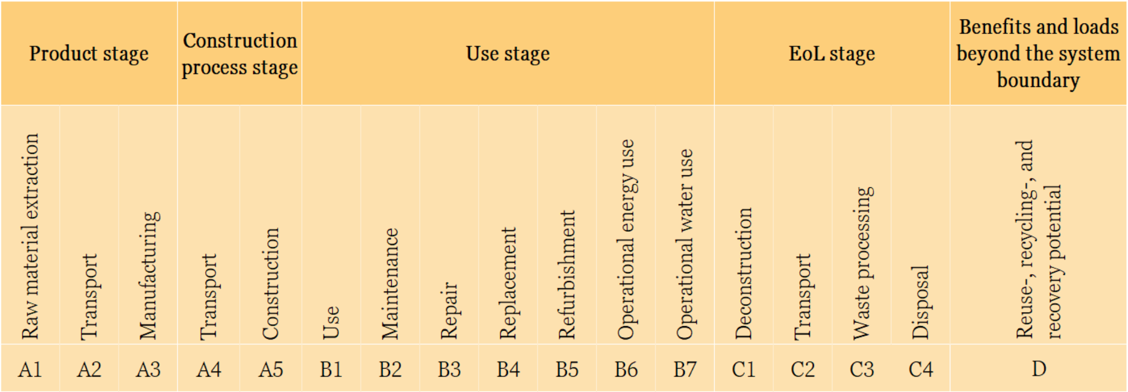
2.2 Environmental impacts of the construction sector

The construction sector accounts for a large amount of the total global anthropogenic GHG emissions. In 2019, its total GHG emissions were 12 $GtCO_2$-eq, corresponding to approximately 20% of the total global anthropogenic GHG emissions that year (Shukla et al., 2022). Correspondingly, the Swedish construction sector accounts for more than one fifth of the total national GHG emissions (Boverket, 2021b). During 2019, there was a large global increase of direct and indirect emissions from buildings driven for instance by population growth and infrastructure buildup in emerging economics. These contributing factors are excepted to continue to increase in the future (Shukla et al., 2022), and are also known drivers of resource consumption (Oberle et al., 2019). Since extraction and processing of natural resources contribute to a large share of the total global GHG emissions, approximately 50% according to Oberle et al. (2019), resource consumption has been identified as one of the major global sustainability challenges included in the United Nation's Sustainable Development Goals (United Nations Statistics Division, n.d.). It is estimated that the construction sector currently consumes 40% of global resources, and further that it generates one of the world's largest waste streams (Cruz Rios et al., 2019). Consequently, if no improvements are made to construction technologies and practices then the production and upgrading of new and existing urban infrastructures may result in a 100% increase of the sector's annual CO_2 emissions and consumption of resources until 2030 (Shukla et al., 2022).

Since construction activities are expected to increase, with increased environmental impacts as a potential consequence, it is critical that the sector transitions to a more efficient way of managing its resources. CE is a concept aimed at extending the life cycle of products by implementing strategies such as reuse, recycling, and repair to reduce waste generation and create value for products after their traditional EoL (European Parliament, 2022). According to Joensuu et al. (2022), a CE has the potential to decouple environmental impacts from economic growth by reducing the use of raw materials while retaining value in building materials and components. Thus, waste generation and GHG emissions can be prevented by extending the service life of buildings and their constituent components.

2.2.1 Assessing and declaring environmental impacts

In order to raise awareness of and reduce the construction sector's environmental impact, developers in Sweden are now obliged to declare the climate impacts of all new buildings requiring a building permit according to the Act on Climate Declarations for Buildings under Construction (Boverket, 2021a). A climate declaration accounts for GHG emissions originating from a selection of construction components (envelope, load-bearing elements, and inner walls) across a limited part of a building's life cycle. The life cycle impacts of a building may be divided into 17 modules (see Figure 2.1) according to the standardised Life Cycle Assessment (LCA) method specified in SS-EN15978:2011 (Swedish Institute for Standards, 2011). The modules describe emissions associated with processes belonging to the various stages of a building's life cycle. Modules A1-A3 and A4-A5 represent impacts from the product and construction stage processes respectively, modules B1-B7 represent impacts from the use stage processes, and modules C1-C4 represent impacts from the EoL stage processes. In addition, there is a D-module to account for potential environmental benefits and loads beyond the system boundary. The Act on Climate Declarations specifies that GHG emissions must be declared for the product and construction stages of new Swedish buildings, i.e., modules A1-A5, which cover processes of raw material extraction (A1), product manufacturing (A3), construction work (A5), and transports (A2, A4).



Product stage			Construction process stage		Use stage							EoL stage				Benefits and loads beyond the system boundary
Raw material extraction	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse-, recycling-, and recovery potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 2.1: Life cycle stages and process modules in a building LCA according to SS-EN15978:2011 (Swedish Institute for Standards, 2011).

Environmental product declarations (EPDs) are important sources of data when conducting LCAs for building climate declarations (Boverket, 2019b). Similar to a building declaration, an EPD employs LCA methods to account for the environmental impacts of a product across parts of its life cycle (e.g., A1-A5) or from cradle (A1) to grave (C4). Producing an EPD for a construction product also follows a standardised process according to SS-EN15804:2012+A2:2019 (Swedish Institute for Standards, 2019) based on a set of product category rules (PCR). The PCR establish guidelines for producing EPDs of specific product groups (e.g., doors) regarding for instance delimitations, methods, and data, and are normally developed in collaboration with industry organisations (Boverket, 2019b). Although it is not mandatory to declare the environmental impacts of construction products through EPDs, the product-specific information they contain forms an important contribution to the process of declaring a building's climate impact.

2.3 Reuse in the construction sector

The European Commission (n.d.) has provided a framework intended to enhance resource efficiency and mitigate the environmental impacts associated with waste generation and management. The framework includes a waste hierarchy to specify which waste management option is favourable in protecting human and environmental health. Waste prevention and reuse are identified as the most preferred options followed by recycling, energy recovery, and disposal (European Commission, n.d.). Based on this directive, several publications focused on building practice emphasize the importance of prioritising reuse of building components over recycling and energy recovery (De Wolf et al., 2020; Eberhardt et al., 2020; Huuhka & Lahdensivu, 2016; Joensuu et al., 2022). The uncertain climate benefits of energy recovery together with the energy-intensive nature of recycling processes are held out as arguments in favour of reuse. However, the sector needs to develop strategies to enable such multi-cycling systems of construction products (Eberhardt et al., 2020; Joensuu et al., 2022).

According to Huuhka and Lahdensivu (2016), buildings can be considered reserves of building materials and components that can be made available both for present and future needs. The authors claim that the value of such products should not solely be based on product performance but also on a potential for adaption and reuse. The application of reuse in the construction sector aims to prolong the service life of building elements and distribute them over multiple building life cycles (De Wolf et al., 2020). Elements can thus be used again with their original features in another building context, preventing the use of virgin materials as well as recycling transformations such as re-manufacturing and downgrading (De Wolf et al., 2020).

There are several existing concepts of circular building design aimed at reducing the environmental impacts of the construction sector by promoting reuse. Two such concepts are DfD and DfA, which are adressed in the following section. Eberhardt et al. (2021) highlight the importance of combining several circular design concepts to maximise building environmental performance and to utilise the full capacity of a component's technical life-time, e.g. by prolonging the use-phase through adaptable design and facilitation of multiple cycles. However, (Eberhardt et al., 2021) emphasize that further research is essential to be able to identify the most efficient combinations of circular design concepts and design parameters.

2.3.1 Concepts of circular building design: DfD and DfA

DfD aims to create buildings whose components can be disassembled easily and, e.g., reused for other purposes at their EoL (Durmisevic, 2019; Guy & Ciarimboli, 2008). Joensuu et al. (2022) emphasize the importance of DfD in extending the service life of buildings and construction elements to achieve a CE. However, there are important barriers relating to market factors and supply chains which inhibit implementation of DfD on a large scale (Joensuu et al., 2022). Additionally, Durmisevic (2019) mention that buildings are traditionally designed for assembly rather than disassembly and that the use of this concept within the sector is thus not yet fully developed.

Throughout this study, DfD denotes 'Design for Disassembly' in accordance to the description above. There is, however, some ambiguity as to what DfD refers to in the literature. The International Organization for Standardization (2016) defines Design for Disassembly as: "A characteristic of a product's design that enables the product to be taken apart at the end of its useful life in such a way that allows components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream". This definition also forms the basis for how Durmisevic (2019) introduces disassembly. However, the European Commission (2020) uses almost exactly this terminology when describing design for deconstruction. Correspondingly, Jockwer et al. (2020) use the abbreviation DfD to denote design for deconstruction and define it as a "dismantlement of building components, specifically for reuse, repurposing, recycling, and waste management. In addition to giving materials a new life cycle, deconstruction has the benefits of minimising landfill waste and to help to lower the need for virgin resource". Thus, it should be noted that the definition and use of 'DfD' varies between publications.

DfA is another circular design concept aimed at extending the service life of buildings. According to Ross et al. (2016), adaption within a building and construction context can be defined as "the ease with which buildings can be physically modified, deconstructed, refurbished, reconfigured, repurposed and/or expanded". An adaptable building can be altered so as to be optimised for the spaces and services required by its users (Densley Tingley & Davison, 2012). Adaptability can thus contribute to prevention of unnecessary demolition, promotion of sustainability, and preservation of investments that have already been made in existing buildings and components (Ross et al., 2016).

According to Jockwer et al. (2020), the difference between DfA and DfD is the stage of a building's life cycle in which the concept is applied. Dismantling processes of a building's elements are of interest both to DfA and DfD. However, DfD focuses on extending the service life of elements whereas DfA aims to extend the service life of buildings. DfD enables elements to be removed and reused at a building's EoL while DfA tries to adapt a building for other purposes than it was originally intended. Another target of DfA is to enable refurbishments, e.g., due to local damages, without creating a need for deconstruction or demolition.

2.3.2 Joint design as an enabler of reuse

According to a definition by International Organization for Standardization (2020) in their vocabulary of building- and civil engineering-related concepts, a joint (or connection) is a "construction formed by the adjacent parts of two or more products, components, or assemblies, when these are put together, fixed, or united". The suitability of a particular joint technique depends on the structural system and materials used in a building. For instance, structural steel elements can be joined using bolts or welding while mortar functions as a connecting substance between bricks. For CLT wall panels, nailing, screwing, and various hidden mountings are examples of common joint solutions according to a handbook published by industry organization Swedish Wood (2019). However, there is unlikely to be a "one size fits all" joint solution across a structure. Rather, joint solutions are tailored for the assembly of different combinations of structural elements such as walls, floors, and roofs.

The importance of well-designed joint solutions as an enabler of reuse is a reoccurring topic in publications revolving around circular building concepts. According to Jockwer et al. (2020), joints are in fact essential to the successful removal and adaption of structural elements, and as such, to the notion of DfA. Within disassembly research, joints have been subject to particular interest as was noted in a recent DfD literature mapping (Ostapska et al., 2021). Guy and Ciarimboli (2008) describe connections as “a large factor of on-site disassembly processes” and point out that connections need to be accessible and readable in order not to obstruct disassembly. On a more general note, De Wolf et al. (2020) mention poorly designed connecting elements as an inhibiting factor to a building’s reusability. Durmisevic (2019) further lists ‘type of connections’ as one of eight key design criteria for reversibility, i.e., a building’s ability to be transformed or its components separated. The same author even holds out that the technique used to assemble elements is more important for the circularity of a building than the permanence of its constituent materials (Durmisevic, 2019).

The ease with which a structural element can be removed and reused (or replaced) can thus be claimed to depend on the careful consideration of what is an appropriate method of connection. For construction timber, this is of particular interest as chipping or energy recovery through incineration are otherwise typical modes of repurposing (Eberhardt et al., 2020). Mapping the relationship between joint solution design and reuse potential of structural elements thus becomes of high relevance.

2.3.3 Assessing the impact of reuse

The promise posed by a wider implementation of reuse in the construction sector lies in a decreased dependence on virgin materials and avoided impacts associated with recycling transformation processes (De Wolf et al., 2020; Densley Tingley & Davison, 2012). Employing reuse as a circular building principle can be a very effective way of reducing the environmental impacts associated with construction. Minunno et al. (2020) report that a modular building prototype designed with disassembly and reuse in mind can reduce global warming potential (GWP) by up to 88% compared to if the materials of the building are recycled or landfilled at EoL. Replacing conventional building elements with circular options results in a considerable decrease of GHG emissions according to Andersen et al. (2020), who find that the largest reductions are indeed achieved by reuse rather than recycling. Furthermore, the number of times an element is reused plays an important role in determining potential impact reductions. A structural system that is reused three times thanks to DfD considerations is able to decrease the impact of a building by a mean value of 60–70% compared to its conventional building equivalent (Eckelman et al., 2018). Cruz Rios et al. (2019) investigate the difference between reusing frames made of steel and wood and observe that the steel needs to be reused two times or more if is to achieve lower embodied emissions than the wood frame.

As the interest grows for reuse as a way of reducing the environmental impacts of construction activities, so does the sector’s confusion regarding how to properly account for such benefits. Recent findings identify important challenges of using established LCA-based methods to evaluate the multiple use cycles signifying circular building practice. Häfliger et al. (2017) identify several ways in which LCA results for buildings demonstrate sensitivity to modelling options of which there is currently no strict consensus. One such crucial parameter is the choice of system boundary, where the inclusion of module D is found to have significant effects on the results, particularly for bio-based building materials. According to Anand and Amor (2017), early assumptions regarding service life and the possibility of deconstruction ahead of the predicted EoL also implies large uncertainties regarding a building's final impact. The original intention of LCA to assess products that are well-defined beforehand in time and space is held out as a barrier to its successful implementation in CE (Eberhardt et al., 2019; Eberhardt et al., 2020). De Wolf et al. (2020) further state that "most current life-cycle assessment (LCA) tools are not appropriate to evaluate the environmental impact of a building when its components originate from prior buildings and/or will be used in future unknown ones". Among else, the authors point to the fact that LCA is unable to account for important qualitative aspects of reuse such as complexity in design and ability to dis- and remount. Lastly, Eberhardt et al. (2020) mention the general difficulties of creating incentives for circular construction as conventional LCA methods lack the systems perspective required to adequately represent benefits created by multi-cycling.

The Swedish Environmental Research Institute (IVL, 2020) has published a guide with the aim of facilitating calculations of reuse within construction to support decision making, communication, and reporting of reuse practice. The guide departs from the SS-EN15978 standard and is developed in accordance with the Act on Climate Declarations for Buildings under Construction (see Section 2.2.1). Two types of reuse are distinguished between in the guide: reuse *within* the system boundary of the studied building, and reuse *outside of* the system boundary of the studied building. The first type of reuse typically occurs during the construction of new buildings where pre-used elements are used, or during remodelling where existing elements are reused within the building. In such cases, the environmental impact associated with the raw material extraction and manufacturing processes of an element (A-modules) are "zeroed", however, there might be additional impacts arising due to reuse processes such as transports, refurbishments, and storage (IVL, 2020). IVL's calculation guide points out that the allocation of such reuse processes across an element's various cycles is not regulated in the standard and thus subject to interpretation.

Reuse that occurs outside of a building's system boundary typically occurs during remodelling or demolition where elements are sent off to be reused someplace else (IVL, 2020). In such cases, the reuse results in a reduced environmental impact associated with waste management (C-modules) along with certain environmental benefits outside the boundary which are accounted for in module D. Within a framework of reuse, the purpose of module D is to assess the avoided environmental impacts that can be assumed to arise from not opting for a newly produced product. However, there might be additional impacts due to reuse processes similar to when reuse occurs within a building's system boundary. Module D thus compares the environmental impacts from a traditional, linear product life cycle with those of a reused product (IVL, 2020). The data for module D is generally not declared for with as high accuracy as other modules in EPDs for building materials (Meex et al., 2018). Due to uncertainties regarding its exact calculation procedure as well as when and how to use it, module D is thus often excluded from building LCAs (IVL, 2020).

2.4 Possibilities and challenges of CLT

CLT is a construction material composed of planks glued together in layers where each layer is oriented perpendicularly to the other (Swedish Wood, 2019). CLT is most commonly used for structural components such as panels, posts, and beams to form the frame of various types of buildings. CLT has a broad spectrum of applications, however, in Sweden it is most commonly used for walls and floor structures (Swedish Wood, 2019).

The growing awareness of climate change and environmental impacts associated with construction activities has encouraged the industry to try to reduce its impacts, for instance by using more renewable and sustainable materials (Balasbaneh & Sher, 2021; Pierobon et al., 2019). CLT has the benefit of being a renewable construction material as well as having a lower environmental impact than other materials such as steel and concrete. For instance, 1 m^3 of CLT has the ability to prevent 1 tonne of atmospheric carbon from being emitted when compared to the same amount of concrete (Balasbaneh & Sher, 2021). Apart from advantages pertaining to reduced GHG emissions, the increasing interest in wood products such as CLT is also due to the material's structural benefits in terms of, e.g., a high load-bearing capacity and light structural performance (Balasbaneh & Sher, 2021; Pierobon et al., 2019).

The construction sector is not the only industry where the demand for wood is increasing. For instance, the bioenergy sector is contributing to the increasing demand and consumption of wood (Nepal et al., 2019; Sikkema et al., 2017). In 2010, about 460 million m^3 wood was consumed in the EU for wood and paper products production, and the demand is expected to increase by 160 million m^3 in 2030 (Sikkema et al., 2017). However, these estimations do not include additional demand from the developing and growing markets of construction materials such as CLT (Sikkema et al., 2017). Consequently, the demand for wood can be expected to increase even further. Even though wood is a renewable resource, the high demand for the material may lead to an over-exploitation of the forests and other environmental impacts, such as biodiversity loss, deforestation and forest degradation (Nepal et al., 2019; Sikkema et al., 2017). According to Sikkema et al. (2017), one of the main challenges of the growing bioeconomy is to ensure a sustainable and efficient use of wood.

Sikkema et al. (2017) suggest that one way to mitigate the challenges posed by the large demand for wood is to improve the material's EoL options. By improving recovery of wood through reuse and recycling, the amount going to landfill can be reduced. According to Avfall Sverige (2019), the most common waste management methods for wood waste in Sweden is currently either recycling or incineration for energy recovery, depending on whether the wood has been treated with chemicals. Since CLT contains chemical adhesives, the most common waste management for CLT is thus incineration. Reuse and recycling are indeed possible for wooden products such as CLT. However, due to concerns regarding cost-effectiveness, practicality, and quality, recycling rates of CLT remain low (Ijeh, 2015).

2.4.1 Biogenic carbon

Like all biomass, trees use the photosynthesis process to extract CO_2 from the atmosphere, which is then stored in the form of carbon. The carbon remains in the biomass until degradation before being emitted back into the atmosphere. Carbon stored by biological material is referred to as biogenic carbon (Harris et al., 2018). Consequently, when using wood for construction materials such as CLT, the carbon is stored within the building.

Impact evaluation of biomaterials is performed using LCA, in the same way as it is for other construction materials (see Section 2.2.1). However, according to Hoxha et al. (2020), there is a lack of consensus and common method for how to the model biogenic carbon contained in biomaterials used in, e.g., buildings. The main issues are said to be that existing methods either fail to include carbon storage benefits, or that they only include some stages of a biomaterial's life cycle which may result in a negative, and thus misleading, environmental impact (Hoxha et al., 2020). The knowledge gap surrounding how to account for and incorporate biogenic carbon with LCA is highlighted in several studies (Andersen et al., 2020; Erlandsson & Zetterberg, 2017; Hoxha et al., 2020; Pierobon et al., 2019), emphasizing the need for further research into the topic.

3

Reuse potential analysis

The following Chapter targets the first research question and sub-question by analysing how the choice of inter-element joint solution affects the reuse potential of a load-bearing inner wall made from CLT. The Chapter begins with a description of the analysis method in Section 3.1, and a presentation of the analysed joint solutions in Section 3.2. Sections 3.3 and 3.4 then evaluate existing frameworks for assessing the reuse potential implied by connections, and apply such frameworks to joint solutions relevant for CLT wall panels. Lastly, a new framework for reuse potential is defined in Section 3.5, and applied in Section 3.6.

3.1 Analysis method

The reuse potential analysis of joint solutions for CLT wall panels was carried out in five consecutive steps:

i. Selection of relevant joint solutions
ii. Review of existing reuse assessment frameworks
iii. Application of existing frameworks
iv. Construction of new reuse potential framework
v. Application of new framework

Firstly, a selection of joint solutions relevant to current Swedish CLT construction practice was made based on techniques described in *The CLT Handbook* – a document published by the industry organization Swedish Wood (2019). The selection included all joint solutions from the three categories of inter-element connections used for wall panels: wall-to-wall (W2W, both in-plane and perpendicular joint solutions), wall-to-floor (W2F), and wall-to-roof (W2R). Secondly, a structured literature review was employed to source and analyse previous studies where joint solutions are assessed in terms of their associated reuse potential. By reviewing previous works, it was possible to identify joint design parameters that influence the possibility of reusing a building element. The structured literature search was not limited to a particular concept of reuse due to a general scarcity of relevant literature. Instead, any publication where joint solutions were assessed in terms of an ability to enable removal, reuse, or replacement of an element was included. For a more detailed description of the literature review method, refer to Section 2.1.

Once an understanding had been gained of how reuse potential has been defined previously in relation to joint techniques, that theory was applied to the selection made in the first step of the analysis. The outcome was then analysed in terms of how well-suited existing frameworks are for joint solutions relevant to CLT wall panels. A new reuse potential framework was then constructed based on areas of improvement that had been identified in the previous step. Lastly, the CLT wall panel joint solutions were categorised according to the new reuse potential framework.

3.2 Joint solutions for CLT wall panels

The industry organization Swedish Wood (2019) provides a digital handbook with information about CLT as a construction material as well as guides for construction planners to design and build using CLT. The CLT Handbook includes both principle solutions for the execution of construction projects as well as detailed solutions for, e.g., joints and connection details. The joint solutions included in the Handbook are established and common joints on the Swedish market, which is why the analysis in this study is limited to the joints included in the Handbook. In the following sections, the joints are presented in detail and in accordance with the function of the joinery technique, i.e., joints for W2W connections are separated from joints for W2R and W2F connections. Figures presented in Sections 3.2.1, 3.2.2, and 3.2.3 are reprinted with permission from Swedish Wood (2019).

3.2.1 W2W joints

In this section, the W2W joints provided by the CLT Handbook (Swedish Wood, 2019) are presented. First, seven different joints for connecting CLT wall panels in-plane are presented, followed by two different joints for connecting CLT wall panels perpendicularly.

A common joint solution for connecting in-plane wall panels is by using splines, an additional wooden component that is usually made of plywood or laminated veneer lumber. The CLT Handbook presents several different spline solutions for connecting two wall panels. For all spline solutions, the spline is located in between two panels and fixed by screws or nails. For the *internal spline* joint, the spline is located on the inside between two CLT panels (Figure 3.1, elevation view).

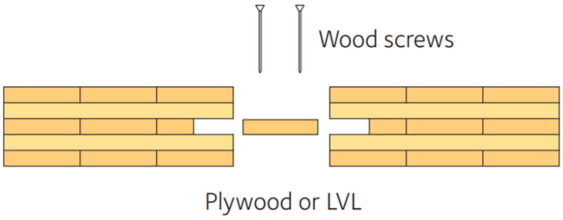


Figure 3.1: In-plane W2W joint: Internal spline. (Swedish Wood, 2019).

Another joint solution by spline is the *single surface spline* (Figure 3.2, elevation view). Compared to the internal spline joint, the spline for this connection is instead located externally.

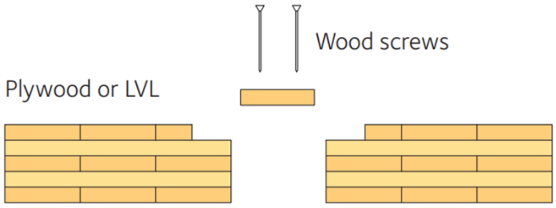


Figure 3.2: In-plane W2W joint: Single surface spline. (Swedish Wood, 2019).

The *single surface spline with skew screw* is another joint where two CLT panels are connected via an external spline (Figure 3.3, elevation view). However, compared to the single surface spline, this joint is reinforced with long self-drilling screws for wood.

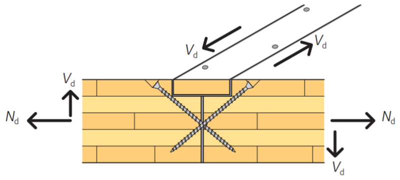


Figure 3.3: In-plane W2W joint: Single surface spline with skew screw. (Swedish Wood, 2019).

The *double surface spline* uses two external splines to connect two CLT panels (Figure 3.4, elevation view). The two splines are fastened to the CLT panels by wood screws.

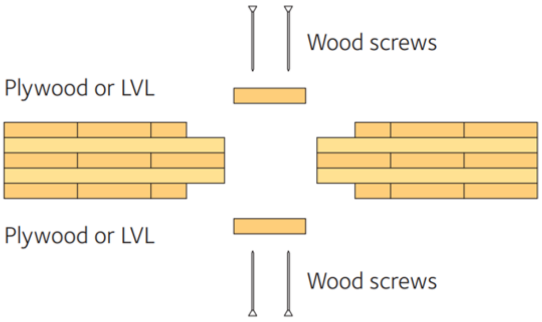


Figure 3.4: In-plane W2W joint: Double surface spline. (Swedish Wood, 2019).

Half-lapped refers to a joint solution in which the edges of the CLT panels are cut so that they can be tightly fitted together by overlapping each other (Figure 3.5, elevation view). The panels are fixed with self-drilling wood screws.

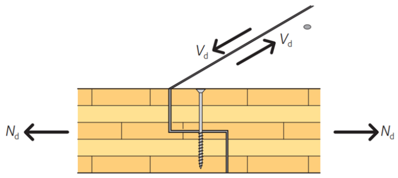


Figure 3.5: In-plane W2W joint: Half-lapped. (Swedish Wood, 2019).

Joint with *bonding steel tube* connects two CLT panels by a steel tube and screws (Figure 3.6). Most commonly, fully threaded, glued-in, or wood screws are used for this joint. The screws are screwed into the edges of the two panels and fix the steel tube, which works as the bonding component that joins the two panels.

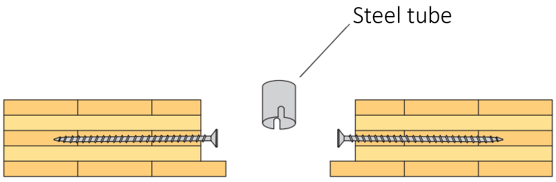


Figure 3.6: In-plane W2W joint: Bonding steel tube. (Swedish Wood, 2019).

Joint with *hooking brackets* refers to a joint solution where the panels are connected through a hooking system (Figure 3.7, elevation view). The hooking system consists of a hooking bracket made of aluminium or steel, that is screwed into the edges of both CLT panels. To be able to join the two panels, one must be lifted so that the hooking brackets hook vertically into each other.

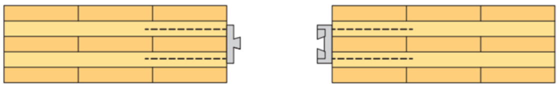


Figure 3.7: In-plane W2W joint: Hooking brackets. (Swedish Wood, 2019).

According to Swedish Wood (2019), *screw* is the most simple joint for perpendicularly connecting two wall panels (Figure 3.8). For this joint, one CLT panel are perpendicularly connected to the surface of another CLT panel with usually self-drilling wood screws (Figure 3.8 to the left, elevation view) or by skew screwing (Figure 3.8 to the right, elevation view).

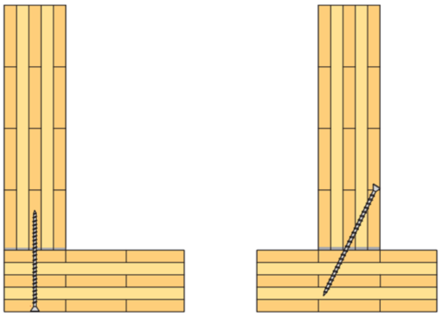


Figure 3.8: Perpendicular W2W joint: Screw. (Swedish Wood, 2019).

Angle brackets is another simple joint for connecting two CLT wall panel perpendicularly (Figure 3.9, elevation view). This joint is connecting the panel by the angle brackets or angled nail plates.

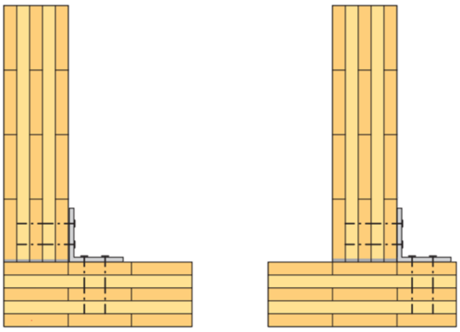


Figure 3.9: Perpendicular W2W joint: Angle brackets. (Swedish Wood, 2019).

3.2.2 W2F joints

According to Swedish Wood (2019), the simplest joint solution for connecting a wall CLT panel with a floor CLT panel is by *screw* (Figure 3.10, plan view). Long self-drilling wood screws connect the floor with the wall below through vertical screws, and the wall above is connected to the floor by skew screwing.

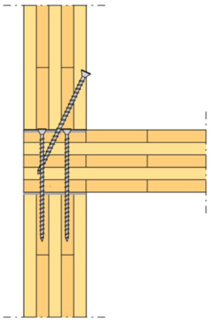


Figure 3.10: W2F joint: Screw. (Swedish Wood, 2019).

Figure 3.11 (plan view) illustrates two examples where the floor and wall is connected with *angle bracket*. The figure to the left shows joint by angle bracket, or sometimes nail plate angled brackets, which is fixated with anchor screws or anchor nails. The figure to the right shows joint by longitudinal angle brackets.

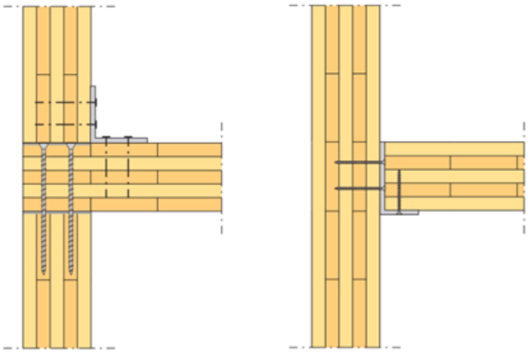


Figure 3.11: W2F joint: Angle bracket. (Swedish Wood, 2019).

Another joint to connect floor to walls is by using *fully threaded rods* (Figure 3.12, plan view). This joint consist of long or short glued-in screws that is located at the end of the wall panels and rods with the length of the wall height, which are connected by thread sleeves.

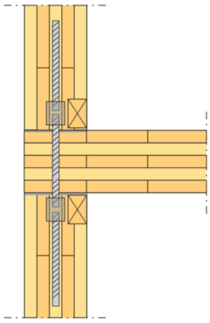


Figure 3.12: W2F joint: Fully threaded rods. (Swedish Wood, 2019).

Inset fixings is another joint used for connecting wall and floor. The *slotted-in steel plates* are screwed into the CLT wall panels, and concealed within it, and fixated with dowels (Figure 3.13, plan view).

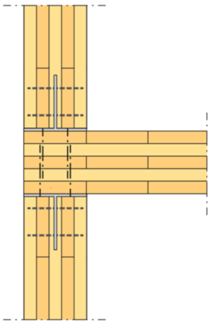


Figure 3.13: W2F joint: Slotted-in steel plates. (Swedish Wood, 2019).

3.2.3 W2R joints

When connecting CLT wall panels to roofs the simplest and most common joint is *screw*, where usually self-drilling wood screws are used (Figure 3.14, plan view).

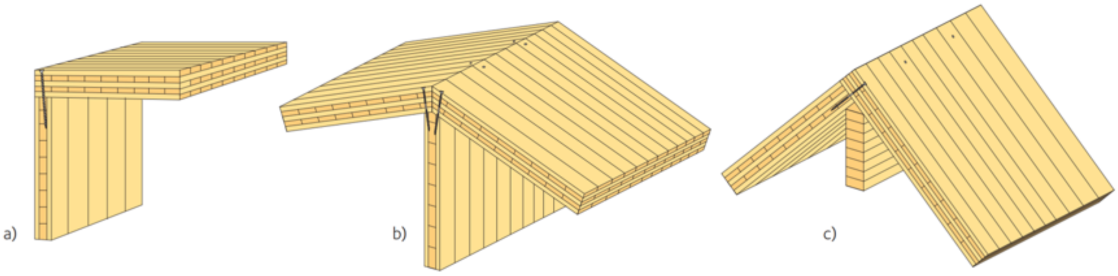


Figure 3.14: W2R joint: Screw. (Swedish Wood, 2019).

3.3 Existing reuse assessment frameworks

A rough classification of joint solutions according to reuse potential can be made based on the geometry of connecting product edges. In the report *Design Strategies for Reversible Buildings*, Durmisevic (2019) makes such a distinction between *interpenetrating* and *open* product edges. The latter is held out as preferable from a disassembly perspective due to the possibility of removal in more than one direction as is demonstrated by Figure 3.15. Furthermore, Durmisevic (2019) classifies connections according to three principal types: *direct* (or integral), *indirect* (or accessory), and *filled*. If the geometry of two product edges overlap or interlock to form a complete connection between product edges, a direct connection is formed. The indirect connection type is characterised by the addition of complementary connective parts that can be either internal (i.e., inserted into an element) or external.

Finally, chemical substances such as adhesives are examples of filled connections. Connection types belonging to the filled category typically offer limited possibilities of reuse due to the risk of element damage during separation (Guy & Ciarimboli, 2008), which becomes of particular importance when handling brittle materials like timber. Figure 3.16 illustrates the difference between the three connections types.

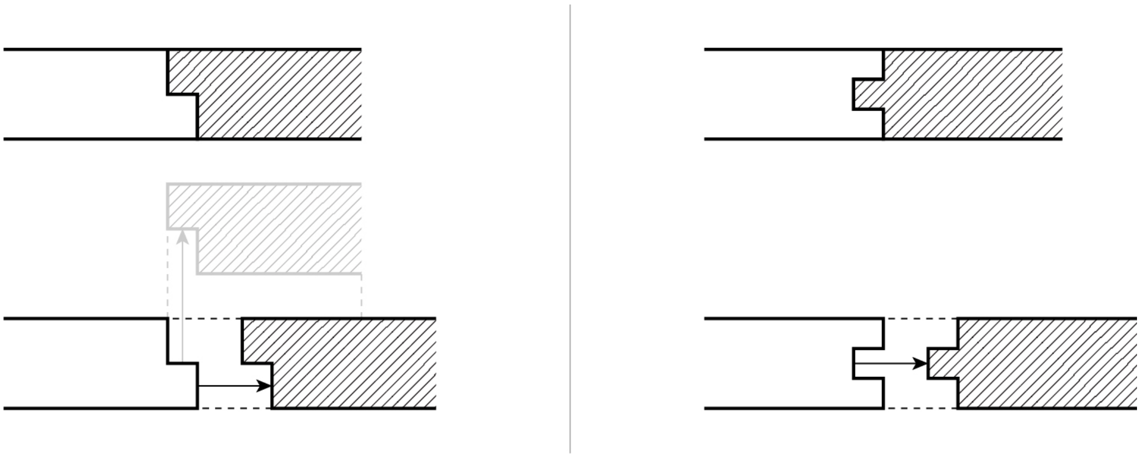


Figure 3.15: Principal dismantling of open (left) and interpenetrating (right) geometry product edges.

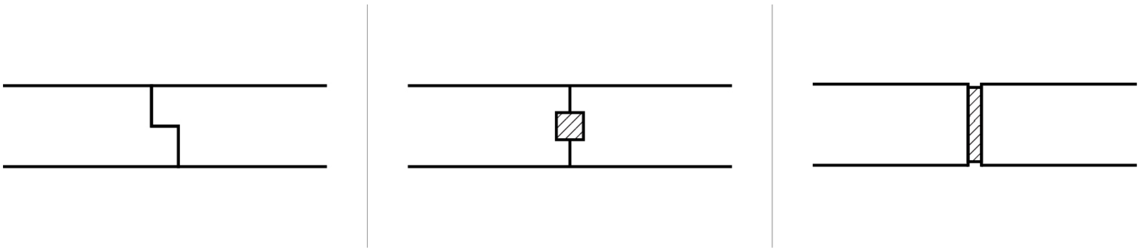


Figure 3.16: Three connection types according to Durmisevic (2019): direct (left), indirect (middle), and filled (right).

According to Durmisevic (2019), joint solutions can be hierarchically sorted according to their *reversibility* potential, i.e., their ability of transforming a building or separating its constituent components. The reversibility hierarchy consists of nine joint Types ranging from direct connections using chemicals (Type I, implying complete non-reusability of the connected elements) to techniques where a connection is formed only by utilizing the force of gravity (Type IX). An overview of the reversibility hierarchy is provided in Table 3.1 (note that the only filled connection, Type I, is termed 'chemical').

Table 3.1: Nine joint types hierarchically sorted from 'fixed' to 'reversible'. Adapted from Durmisevic (2019).

Type	**Joint solution principle**	**Description**
I	Direct chemical connection	A material is permanently fixed to an element by means of a chemical connection. Reuse is not possible
II	Indirect connection, irreversible chemical	Two elements are permanently connected by means of a chemical material that is stronger than the connected elements. Reuse is not possible
III	Direct connection, reversible chemical	Overlapping or interlocking elements are connected by means of a chemical material that is weaker than the connected elements. Reuse is possible by refurbishment
IV	Direct connection, insertion	Overlapping or interlocking elements are fixated by planed insertion of accessories. Reuse is negatively affected since disassembly weakens the element
V	Direct connection, additional mechanical fixation	Overlapping or interlocking elements are connected by an additional mechanical devise. The entire devise needs to be dismantled if one element is to be removed and then reused, however, dismantling can be done without damaging the elements
VI	Indirect connection, dependent third component	Elements are connected by means of assembly-dependent complementary parts. Reuse is determined by elements' position in the assembly sequence, and thus partly possible
VII	Direct connection, interlocking	Elements edges are designed to form an interlocking connection. Can be disassembled without damage, direct reuse is possible
VIII	Indirect connection, independent third component	Elements are connected by means of dry or mechanical complementary connecting parts. Disassembly can be done independently, direct reuse is possible
IX	Connection by gravity	Elements are connected only by means of the force of gravity

The notion of *assembly sequences* (or alternatively, *disassembly sequences*) is an important concept to the reversibility hierarchy. Durmisevic (2019) explains that there are two types of assembly (disassembly) sequences: *sequential* and *parallel.* Sequential sequences create dependencies between elements where they are locked in by each other, resulting in more complicated dismantling processes in cases when single elements need adjustment or replacement. By allowing for parallel sequences where elements are assembled independently, construction work becomes more time efficient while at the same time increasing the flexibility of single elements. Figure 3.17 depicts the implication of product edge geometry on assembly sequences and how the removal of single elements is affected by dependence in disassembly.

According to Wang et al. (2018), the construction sector faces an increasing issue related to the planning of well-functioning assembly sequences to avoid negative effects on cost, safety, and quality of construction. Furthermore, assembly sequence optimisation is claimed to be of particular importance to structures comprised of pre-fabricated elements (Wang et al., 2018), such as CLT panels.

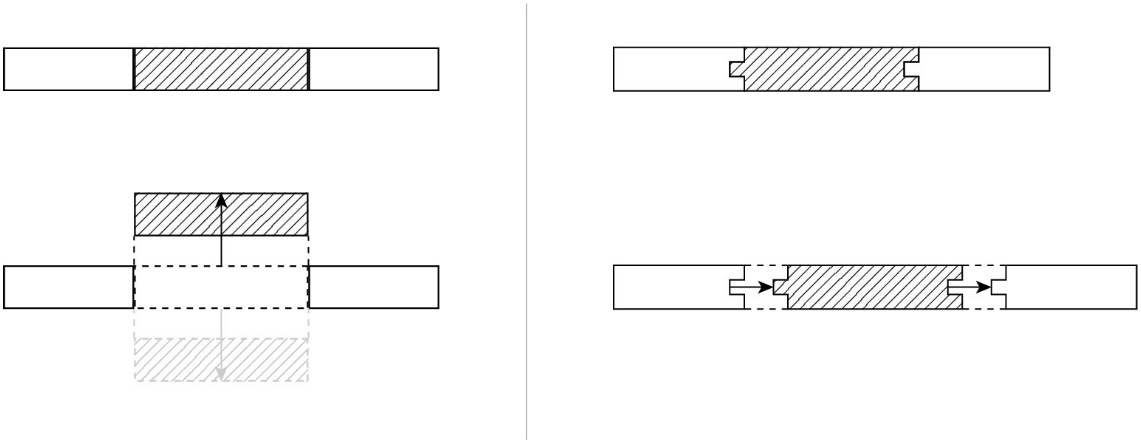


Figure 3.17: Impact of product edge geometry on a disassembly sequence. Left: open product edges creating a parallel sequence. Right: interpenetrating product edges creating a sequential sequence.

The reversibility hierarchy seems to have its origin in Durmisevic's PhD thesis (2006) which departs from the concept of *transformable* structures. The thesis defines a transformable structure as being "designed for reuse, reconfiguration, and recycling" (Durmisevic, 2006), and presents a joint solution hierarchy similar to Durmisevic (2019). However, the earlier hierarchy comprises of seven joint Types instead of nine and ranges between 'fixed' and 'flexible' (see Table 3.2) as opposed to 'fixed' and 'reversible'. Analogous to the reversible building design guide, the flexibility hierarchy (Durmisevic, 2006) classifies direct chemical connections as the most fixed joint option (Type I). However, the most flexible joint solution (Type VII) is an indirect connection using additional fixing devices – corresponding neither to the solution ranked as Type VII in Durmisevic (2019) nor its most reversible option (Type IX).

Table 3.2: Seven joint types hierarchically sorted from 'fixed' to 'flexible'. Adapted from Durmisevic (2006).

Type	**Joint solution principle**	**Description**
I	Direct chemical connection	A material is permanently fixed to an element by means of a chemical connection. Reuse is not possible
II	Direct connection, dependence in assembly	Pre-fabricated elements are connected by means of an interlocking or overlapping principle where there is dependence in assembly/disassembly. Reusing elements is not possible

Continued on next page

Table 3.2 – continued from previous page

Type	Joint solution principle	Description
III	Indirect connection, third chemical material	Two elements are permanently connected by means of a third chemical material. Reuse is not possible
IV	Direct connection, additional fixing device	Two overlapping or interlocking elements are additionally connected by a replaceable fixing devise. The entire devise needs to be dismantled if an element is to be removed and then reused
V	Indirect connection, dependent third component	Two elements are connected by a third, complementary part that is assembly-dependent. Reuse is restricted
VI	Indirect connection, independent third component	Two elements are connected by a third, complementary part where the assembly sequence is partly dependent. Reuse is possible for all elements
VII	Indirect connection, additional fixing device	Elements are connected by an additional fixing device and there is no dependence in assembly/disassembly - any adaption to an element does not effect the others. Reuse is possible for all elements

Several noteworthy observations can be made when comparing Durmisevic's two hierarchy iterations. Type II in the 2006 version is illustrated using two elements forming a "puzzel-piece" interlocking connection (corresponding to the right-hand side of Figure 3.15), exhibiting clear similarities with the illustration of Type VII in the 2019 hierarchy. The former is claimed to not enable reuse due to the inherent dependence in assembly and disassembly caused by the interlocking connection principle. The latter, however, is described in terms of enabling "direct reuse" since there is no risk of damaging the element during disassembly. The 2019 hierarchy also ranks the assembly-dependent Type VII as more reversible than Type VI – an indirect connection where there is also dependence in assembly due to a third component. This might be due to the later hierarchy categorising greater importance to the potential damage caused by certain joint solutions to an element.

Finally, there is a lack of equivalents for some of the joint solution principles, simply because there are more types included in the 2019 hierarchy than in its 2006 predecessor. For instance, the 2006 Type VII (Indirect connection, additional fixing device) lacks an appropriate equivalent in the 2019 hierarchy, which in turn lacks equivalents for Types III (Direct connection, reversible chemical), IV (Direct connection, insertion), and IX (Connection by gravity) in the 2006 version.

On a less principal level than Durmisevic's hierarchies, Morgan and Stevenson (2005) have listed advantages and disadvantages of a range of joint solutions, including their impact on disassembly, in a design guide for deconstruction published by the Scottish Ecological Design Association. As can be seen in Table 3.3, the included joint techniques are not timber specific. However, several more or less common timber construction joint solutions (screws, bolts, nails, friction, and adhesives) are included and assessed in terms of their ability to enable reuse, both of the joint component itself as well as of the building elements it connects.

Table 3.3: Advantages and disadvantages of joint solution options for disassembly. Adapted from Morgan and Stevenson (2005).

Joint solution	Advantages	Disadvantages
Screws	Easy to remove	Low reuse potential of both screw and screw hole
Bolts	Multiple reuses possible. Strong, durable connection	Removal can be inhibited due to seizing up, i.e., that bolts become locked into place and are unable to rotate
Nails	Fast construction	Difficult removal that typically results in element damage
Friction	Dismantling does not damage element.	Relatively undeveloped joint solution. Structurally weaker than other alternatives
Mortar	Available in a variety of strengths	Reuse is usually not possible as materials are strongly connected
Resin	Strong connection. Enables complicated connection points	No easy recycling or reuse as layers are more or less impossible to separate
Adhesives	Available in a variety of strengths, can be used for different tasks	No easy recycling or reuse as layers are more or less impossible to separate
Rivets	Fast construction	Difficult removal that typically results in element damage

3.4 Application of existing frameworks to joints for CLT walls

Section 3.3 presented some existing frameworks and analyses where joint solutions are ranked according to characteristics that contribute to determining an element's reuse potential (e.g., reversibility, flexibility). It appears as if these previous efforts tend to discuss joints in relation to reuse potential either on a more conceptual solution level (such as in [Durmisevic, 2019] and [Durmisevic, 2006]), or alternatively across a general, non-timber specific range of techniques (such as in [Morgan and Stevenson, 2005]). However, applying existing frameworks to the joints presented in Section 3.2 can provide an initial understanding of the impact of choosing appropriate joint solutions on the reuse potential of a CLT wall panel. For simplicity, the application of existing frameworks will focus on the joint hierarchy presented in Table 3.1 (Durmisevic, 2019) due to its recent publication date as well as the inclusion of more joint solution types.

Table 3.4 contains an overview of the application of Durmisevic's 2019 framework to the common CLT wall panel joint solutions presented in Section 3.2. The W2W joints can mainly be sorted into the range Type V–VIII in (Durmisevic, 2019). The half-lapped joint solution with its overlapping panel edge geometry can be seen as a typical example of a direct connection where screws provide additional fixation, thus corresponding to Type V, see Figure 3.18. The various other spline connection principles all employ a third component which can be assumed to create dependence in assembly and disassembly to some degree, thus bearing similarity with Type VI (Indirect connection, dependent third component). However, this dependence will be much due to a panel's placement in the sequence and building structure, as well as the nature of the reuse situation. As is demonstrated by Figure 3.19, dependence is avoided if a panel connected by an internal spline is not bounded by other elements at its second edge; in that case, horizontal removal along the panel's own plane is possible. Moreover, if the intention is to reuse the panel at the end of the building's life cycle, step-wise disassembly of superimposed building layers also enables the connection to be undone vertically. Under such circumstances, the spline could be considered an independent third component, classifying it more accurately as Type VIII in (Durmisevic, 2019). The possible *direction of removal* can thus be argued an important factor in determining the possibility of removing a panel for reuse. This factor does not, however, play a crucial role in the existing frameworks.

Table 3.4: Application of reversibility hierarchy by Durmisevic (2019) to CLT wall panel joint solutions. Italicized joint solutions can be paired with multiple Types.

Type	Joint solution principle	Corresponding CLT joint solutions
I	Direct chemical connection	-
II	Indirect connection, irreversible chemical	-
III	Direct connection, reversible chemical	-
IV	Direct connection, insertion	-
V	Direct connection, additional mechanical fixation	Half-lapped (W2W) Screws (W2W, W2F, W2R) Screws with angle bracket (W2W, W2F)
VI	Indirect connection, dependent third component	*Internal spline (W2W)* *Single surface spline (W2W)* *Single surface spline with skew screws (W2W)* *Double surface splines (W2W)* *Bonding steel tube (W2W)*
VII	Direct connection, interlocking	-
VIII	Indirect connection, independent third component	*Internal spline (W2W)* *Single surface spline (W2W)* *Single surface spline with skew screws (W2W)* *Double surface splines (W2W)* *Bonding steel tube (W2W)*

Continued on next page

Table 3.4 – continued from previous page

Type	Joint solution principle	Corresponding CLT joint solutions
IX	Connection by gravity	-
-	No Type equivalent	Hooking brackets (W2W) Fully threaded rods (W2F) Slotted-in steel plates (W2F)

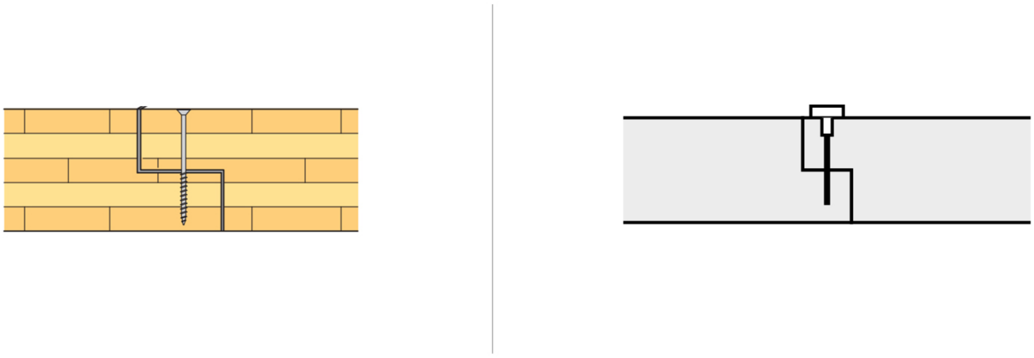


Figure 3.18: Comparison of (left) half-lapped W2W joint solution from Swedish Wood's CLT Handbook (2019), and (right) a Type V connection adapted from Durmisevic (2019).

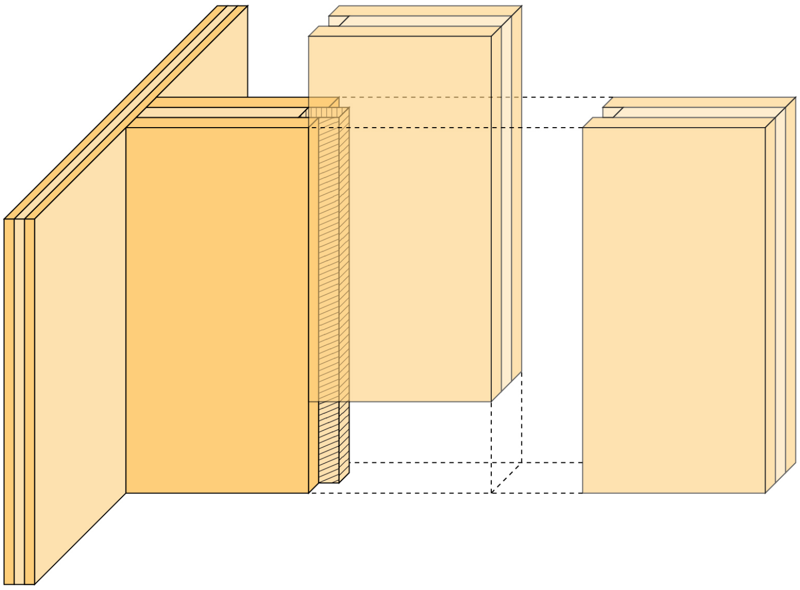


Figure 3.19: Principal removal of the W2W joint solution internal spline in two directions: vertically and in-plane.

Similar to the internal spline, the surface spline solutions (single, single with skew screw, double) provide varying degrees of flexibility depending on which removal direction that is considered. However, for externally accessible third components it is also relevant to discuss whether they should be considered part of the assembly and disassembly sequences. The single surface spline can be used as an example: if the spline is considered part of the sequence then the joint solution must be considered dependent (Type VI) since it is impossible to remove one of the connected panels before the spline is detached. If, on the other hand, the spline is not considered part of the sequence on the same basis as the panels then the joint solution is independent (Type VIII) – the spline can be accessed without moving other elements and a connected wall panel can be removed either perpendicularly or along its own plane (depending on the presence of adjacent elements) after the spline has been detached. The bonding steel tube implies the same ambiguity where the joint solution might be considered either Type VI or Type VIII depending on how the third component (i.e., the steel tube) is viewed.

Application of the reversibility hierarchy to the joint solution employing hooking brackets implies further uncertainties, where the mounting direction of the hooking device will determine the possibility of removing and reusing a panel. A vertical hook mounting, where one element's hooking bracket is lifted onto the bracket of another element, might be assumed for a wall panel since the equivalent horizontal mounting technique would lead to decreased stability in one of the directions perpendicular to the panel's plane. Consequently, the only possible option for reuse is by vertical removal – enabled solely by disassembly of the entire building which suggests a lower reuse potential than for instance the spline solutions discussed above. Moreover, Type VI (one of the possible spline classifications) gathers indirect connections where there is a dependent third component requiring detachment before removal of the connected elements is enabled. In the case of hooking brackets, removal of a panel is not dependent on the detachment of the bracket; rather, the bracket implies dependence for the entire panel. However, such a distinction is not made in (Durmisevic, 2019), and thus no equivalent Type is thus found for the hooking bracket joint solution.

The two remaining W2W joint solutions are the screw joint and the screw joint with angle bracket. In general, screws are perhaps more intuitively thought of as providers of additional fixation rather than constituting joint components themselves. Not considering screws as third components (dependent or independent) supports classifying such joint solutions as direct connections, presumably Type V (Direct connection, additional mechanical fixation). However, this ranks the screw joints below the spline solutions and bonding steel tube in the hierarchy, despite that the same principles apply regarding possible removal directions; screws and angle brackets are readily accessible, and once they are detached the connected panels can be removed both perpendicularly and along their own plane. There is also an additional issue with classifying screws as Type V: according to Durmisevic (2019), such connections do not damage an element during dismantling, which is unlikely when removing screws from a CLT panel.

The W2F screw joints, either with or without angle bracket, are presumably most accurately classified as Type V in accordance with the analysis of the W2W screw solutions above. However, there is an important difference between the W2W and

W2F screw techniques as the latter category employ screws which cross through multiple building layers. There is thus an inherent dependence in assembly and disassembly for the W2F screw joints which is not highlighted by their classification as Type V along with the W2W screw solutions. Fully threaded rods and slotted-in steel plates are further examples of W2F joints where components create dependence by crossing through multiple layers. Similar to the hooking brackets, these joint solutions are difficult to classify according to the reversibility hierarchy since there is a third component which implies dependence for the entire panel, rather than constituting a dependent element itself.

As Table 3.4 demonstrates, the application of an existing framework (i.e., the reversibility hierarchy by Durmisevic [2019]) results in an uncertain and partly incomplete reuse potential analysis of the wall panel joint solutions listed in Swedish Wood's (2019) CLT Handbook. Only three out of nine Types (V, VI, and VIII) are of relevance to the CLT wall panel joints, with the classification into either Type VI or VIII being subject to interpretation. Three analysed joint solutions (hooking brackets, fully threaded rods, and slotted-in steel plates) lack appropriate Type equivalents in the hierarchy, and some joint solutions might actually provide more possibilities for flexible removal, and thus reuse, than their position in the hierarchy suggests. It is for instance debatable whether the W2W and W2R screw joints should rank lower than the other solutions, even if the connection principle itself aligns well with the notion of a direct connection with added mechanical fixation (Type V). Finally, the existing frameworks do not seem to distinguish between reuse *between* buildings, enabled through vertical removal during disassembly, and reuse *within* a building, enabled through horizontal removal where superimposed layers are unaffected.

3.5 Development of a new reuse potential framework

As presented in Section 3.4, previous studies lack a direct correlation between reuse potential and the choice of joint solution for CLT wall panels. Even though previous studies have addressed different types of joints, these frameworks are not applicable to all joints solutions relevant to CLT wall panels presented in Section 3.2, nor the concept of reuse within a building. The analysis further indicates that the reuse potential and the feasibility of reusing a wall panel are dependent on the joint solution and the direction of removal it enables. However, the current frameworks lack sufficient consideration of how this affect the potential of reusing a CLT wall. Therefore, a new framework is constructed where this is taken into consideration.

The direction in which a panel can be disassembled is important for the adaptability of a building. DfA is based on the idea that a building can be adapted without affecting or dismantling other panels or parts of the building. Hence, when adaption is applied to a building where a wall panel has to be moved, it is assumed that all surrounding elements, i.e., walls, floors, and ceilings, are fixed. On the contrary, DfD is based on the idea that the whole building should be easily disassembled upon deconstruction, so that its elements can be reused for other purposes. Disassembly is thus not limited by the building construction itself when elements are to be disassembled. Consequently, adaption is more dependent on the direction in which the panel can be disassembled than disassembly is.

The aim of DfA is to prolong the life of a building by making adaptions. Components can thus either be reused within a building, e.g. due to a need for a different floor plan, or be replaced by other components, e.g. due to damage. Since this study aims to assess the reuse of a CLT wall panel, DfA will be defined solely as the former description throughout the whole study. Thus, when adaption is applied, a wall panel will be used on the same floor of a building, with the aim of changing the floor plan and thus prolonging the life of the building. On the contrary, since the concept of disassembly can only be used when a building is being demolished, DfD intends to prolong the life of a component. Therefore, when disassembly is applied in this study, it is assumed that the CLT wall panel will be reused in another building.

The new framework consists of three joint Groups developed based on the direction in which a wall panel can be removed in a building. For a wall panel to be considered removable (in any direction), it is assumed that the panel can be moved without having to relocate adjacent elements. Note that this framework is aimed at assessing how the reuse potential of a CLT wall panel is affected by the joint solution itself and its enabled direction of removal. Thus, it is independent of specific building design and the arrangements of other elements. The Groups in the new framework are as follows:

- Group V: Removal possible along vertical axis, enabling reuse through disassembly
- Group VH: Removal possible along vertical axis, enabling reuse through disassembly. In addition, removal is also possible along one horizontal axis, enabling restricted reuse through adaption
- Group VHH: Removal possible along both horizontal axes, enabling reuse through disassembly and adaption

Group V includes joints that only enable vertical removal of a CLT wall panel, see Figure 3.20. The removal of a wall panel with Group V joints is thus limited by the joint itself or its location, either separately or in combination with each other. For instance, a joint that is located internally of a wall panel will inhibit removal of the panel without damaging the panel or moving the adjacent elements. Additionally, the joint might be interpenetrating, and connecting several adjacent elements, making disassembly dependent on the surrounding elements. If one wall panel is to be removed with this type of joint, the slab above has to be removed first, before the wall panel can be lifted vertically for removal. Consequently, since removal of the wall panel is restricted by the joint and the superimposed floor, removal is solely possible upon deconstruction of the building. Group V joints are thus compatible with reuse through disassembly but not with adaption.

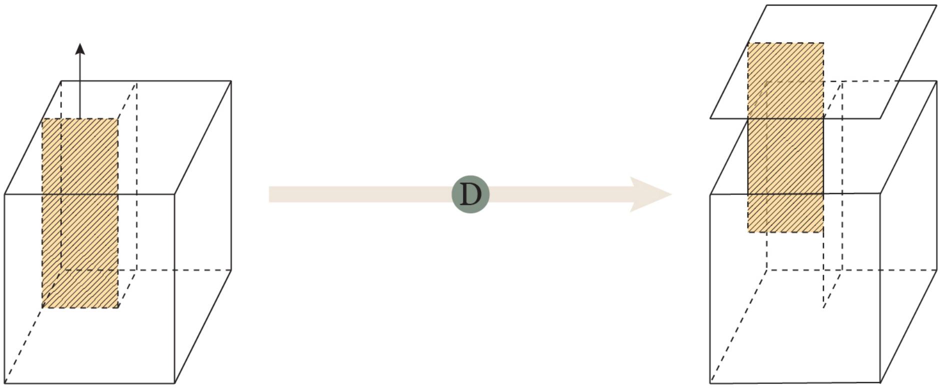


Figure 3.20: Removal options for a wall panel connected by a Group V joint solution. Arrow marked 'D' indicates that reuse is enabled by disassembly.

Group VH includes joints that enable removal of a wall panel along its vertical and one of its horizontal axes (along or perpendicular to its own plane), see Figure 3.21. The removal of a wall panel employing Group VH joints is partly limited by the joint itself or its location, either separately or in combination. For instance, a Group VH joint may be located partly internally and partly externally, making disassembly dependent on the joint itself so that it has to be carried out step-wise. On the other hand, if the external parts of the joint can be undone easily and the internal parts are not fixating, then the removal of a panel is possible along two axes. Thus, Group VH joints are compatible with reuse through disassembly and limited adaption.

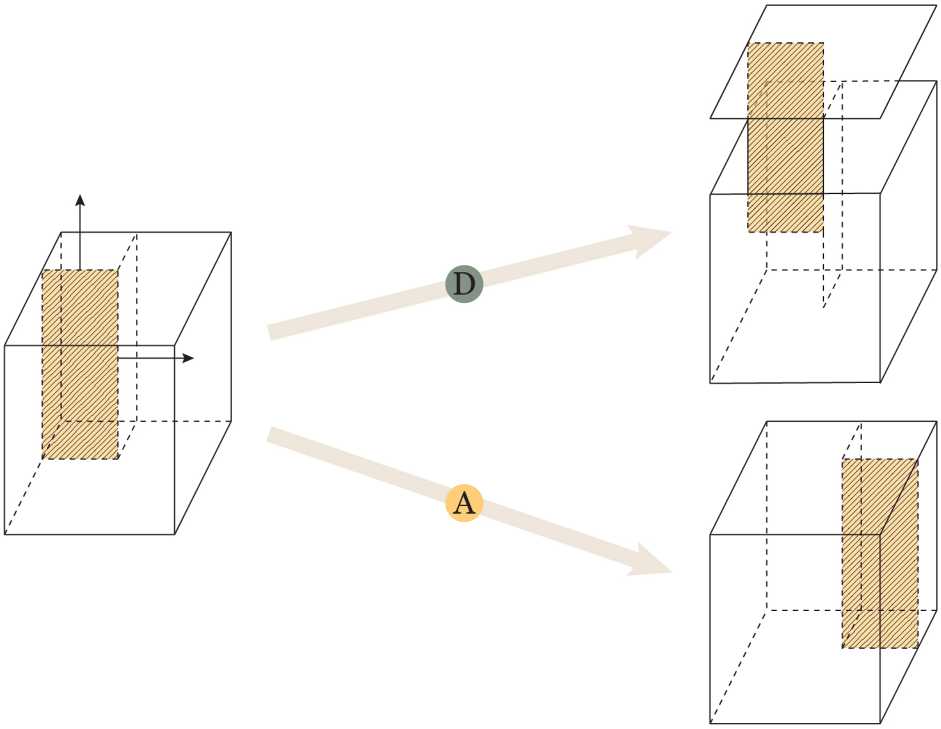


Figure 3.21: Removal options for a wall panel connected by a Group VH joint solution. Arrow marked 'D' indicates that reuse is enabled by disassembly. Arrow marked 'A' indicates that reuse is enabled by adaption.

Group VHH includes joints that enable removal along all axes, i.e., along the vertical axis and both horizontal axes. Unlike the previously presented joint Groups, the removal of the Group VHH joints is not limited by the joint itself nor its location. The wall panel can be removed without having to remove adjacent elements. The joint thus does not restrict the possibility of removing the panel in any direction. Group VHH joints can easily be separated externally from the panel before removal, i.e., there is no internal component of the joint that limits a perpendicular removal of the panel. Therefore, the Group VHH joints are fully compatible with both reuse through disassembly and adaption.

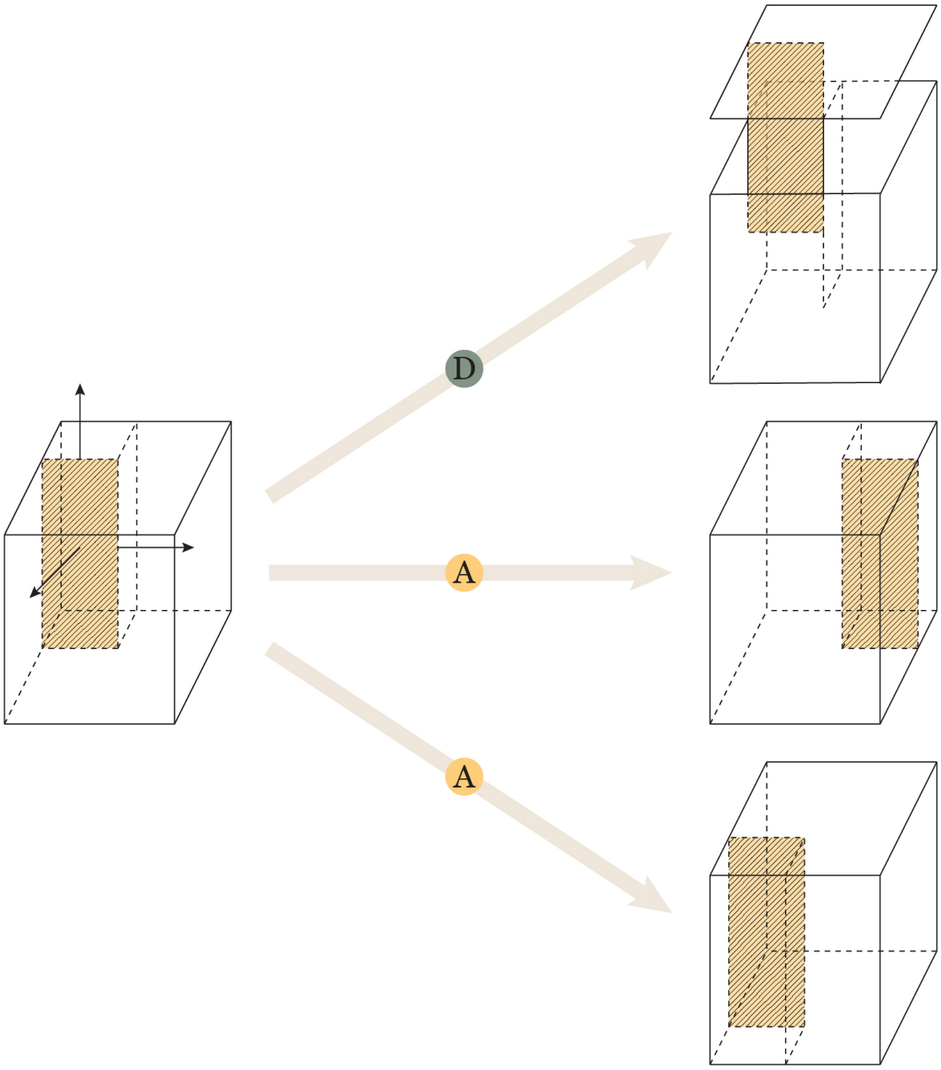


Figure 3.22: Removal options for a wall panel connected by a Group VHH joint solution. Arrow marked 'D' indicates that reuse is enabled by disassembly. Arrows marked 'A' indicate that reuse is enabled by adaption.

The reuse potential of a CLT wall panel can also be affected by if and how a joint will damage the panel upon removal. If the joint is to some extent causing damage to the panel when it is disassembled, the number of cycles it can be used is most likely reduced. This aspect is also included in the framework and defines whether the risk of damage is high (implying low reuse potential [–]) or low (implying high reuse potential [+]). To clarify, a joint can be categorised as a Group VH[–] joint based on that the panel is possible to remove in two directions, but is still considered to have a lower reuse potential compared to Group VH[+]. This can, for instance, be due to that the joint affects the durability of a CLT wall panel for multiple life cycles, since the panel has to some extent been damaged, e.g. by screw holes, since the previous life cycle.

3.6 Application of new framework

The analysis of how joint solutions affect the reuse potential of a CLT wall panel resulted in the development of a new framework based on the direction of removal and potential damage caused upon removal. In this Section, the new framework is applied to the joint solutions for CLT wall panels presented in Section 3.2. Table 3.5 presents how these joints are categorised according to the Groups outlined in Section 3.5.

Table 3.5: Results of applying the new reuse potential framework to Swedish Wood's (2019) joint solutions for load-bearing CLT wall panels.

	Group V		**Group VH**		**Group VHH**	
	[–]	[+]	[–]	[+]	[–]	[+]
In-plane W2W joints						
Internal spline			×			
Single surface spline					×	
Single surface spline with skew screw					×	
Double surface spline					×	
Half-lapped					×	
Bonding steel tube						×
Hooking brackets		×				
Perpendicular W2W joints						
Screw					×	
Angle bracket					×	
W2F joints						
Screw	×					
Angle bracket	×					
Fully threaded rods		×				
Slotted-in steel plates		×				
W2R joints						
Screw					×	

The solutions categorised as Group V are the W2W hooking brackets and the W2F joints screw, angle bracket, fully threaded rods, and slotted-steel plates. All these five joint solutions thus solely enable vertical removal of a wall panel. The joints are partly or fully located internally, making them poorly accessible from the outside. Thus, the disassembly of the panel is dependent on the adjacent elements. For instance, fully threaded rods connect a wall panel with the above slab and a wall panel on the next floor (as illustrated in Figure 3.12). Since the same joint interpenetrates all three components, the removal of the below wall panel will be dependent on the above elements. I.e., all the above wall panels and slabs have to be disassembled vertically in order to be able to disassemble the below wall panel for reuse. Moreover, only the screw and angle bracket W2F joints will to some extent damage the wall panel upon disassembly, since these two joints will leave screw holes on the panel, which is why they are categorised to Group V[–]. The other Group V joints (W2W hooking brackets, W2F fully threaded rods, and W2F slotted-in steel plates) do not cause any damage to the panel upon disassembly and are thus categorised Group V[+].

For Group VH, only the W2W joint internal spline is categorised. The internal spline joint is not completely accessible externally, making removal horizontally restricted. However, the joint consists of both the internal spline and the external screws, which fixate the panel to another one (see Figure 3.1). Since the screws are accessible externally, removal of the wall panel is solely dependent on the internal spline. Thus, when the screws are removed, the wall panel can either be moved horizontally or vertically. Furthermore, since the screws will leave screw holes on the wall panel, the internal spline is categorised as a VH[–] joint.

The solutions categorised as Group VHH are the W2W joints single surface spline, single surface spline with skew screw, double surface spline, half-lapped, bonding steel tube, screw, and angle brackets, together with the W2R screw joint. For all these, the joints are located externally, making the removal of the joint and detachment of the wall panel easy. For instance, the bonding steel tube consists of screws that are screwed into the edge of the two wall panels and the steel tube that connects the panels. However, to be able to move a wall panel from or within the building, only the steel tube has to be removed. If the wall is to be reused, the screws can stay in place and the steel tube can be put back in place. Therefore, the joint bonding steel tube does not damage the panel upon disassembly and is categorised as Group VHH[+]. The remaining Group VHH joints can be assumed to cause some damage to the wall panel due to screw holes, and are thus categorised as VHH[–] joints.

A final observation from the application of the new framework is that when all connecting sides of a panel (W2W, W2F, W2R) are considered, the joint solution enabling the lowest reuse potential can be assumed to dictate the potential of the entire panel. For example, if the W2W solution enables removal in all directions (VHH) but the W2F solution only enables vertical removal (V), only vertical removal will be possible for the panel as a whole. The W2F joint solutions are particularly critical in this regard as there are no solutions for the connection between wall and floor which enable horizontal removal. It can thus be argued that other W2F joints than the ones included in Swedish Wood's Handbook should be employed to provide more flexibility and increase the possibility for reuse of a wall panel within the life cycle of a building.

4

Environmental impact assessment

The aim of the following Chapter is to assess the environmental impact associated with reusing a CLT panel intended for use as a load-bearing inner wall. The assessment departs from the notion that a panel's reuse potential is determined by the choice of inter-element joint solution, which is analysed in Chapter 3. The Chapter starts by describing the assessment method in Section 4.1 before presenting the results in Section 4.2.

4.1 Assessment method

The following Section presents the method used for the environmental assessment. Section 4.1.1 outlines the process of developing a set of scenarios aimed to represent possible life cycle pathways of a panel depending on its reuse potential. Section 4.1.2 then describes the simplified LCA method based on the standardised procedures specified by SS-EN15978 and SS-EN15804 which was used to evaluate environmental impacts. The scope and system boundary are defined before presenting what data and assumptions were used as well as how the impact assessment was conducted.

4.1.1 Development of reuse scenarios

The environmental impact assessment departed from the creation of a set of scenarios aimed to represent possible life cycle pathways of a CLT wall panel. The life cycle pathways were derived based on a panel's reuse potential as it is defined in Section 3.6, i.e., according to the choice of joint solution. More specifically, it was decided to define reuse scenarios based on the choice of W2W joint Group since this category of joint solutions demonstrates the largest variety in terms of reuse potential (see Table 3.5). The analysed W2F and W2R joints only categorise into one joint Group (V and VHH, respectively) and thus would not create differentiated scenarios. Consequently, the same W2F and W2R joint solutions were assumed for all reuse scenarios while varying the choice of W2W solution.

The reuse potential analysis includes one W2R joint solution which categorises as Group VHH. Consequently, all reuse scenarios were assumed to employ a Group VHH joint for the W2R panel connection. Furthermore, the analysis demonstrates that the W2F joints contained in Swedish Wood's Handbook (2019) all categorise as

Group V which implies that a panel's floor connection only enables vertical removal. As is described in Section 3.6, the reuse potential of a wall panel employing joint solutions from different Groups will be determined by the joint demonstrating the lowest reuse potential. It is thus argued that other W2F joints should be explored to provide more flexibility in how a CLT wall panel can be reused. An example of such a W2F solution can be found in a Canadian CLT Handbook (FPInnovations, 2019). Figure 4.1 demonstrates that this Canadian W2F joint resembles Swedish Wood's solution using screws and angle bracket, however, there is no vertical dependence created since the screws do not cross through multiple layers. Thus, it was decided to assume the Canadian W2F solution for all scenarios in order to prevent the floor connection from restricting the reuse potential of the entire wall panel. Moreover, the Canadian W2F joint was categorised as VHH[–] due to the use of screws that are assumed to damage a panel upon removal.

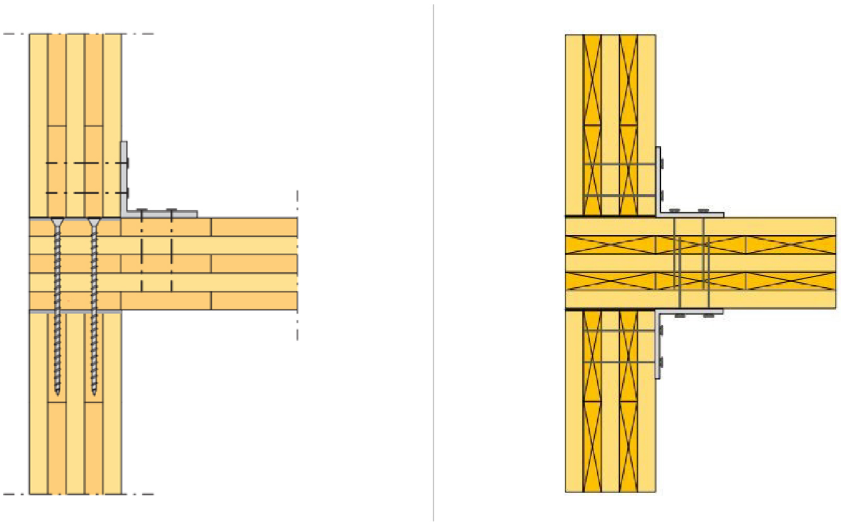


Figure 4.1: W2F joint solutions with screws and angle brackets. Left: option from Swedish Wood's CLT Handbook (2019). Right: option from Canadian CLT Handbook (Figure 23 in Chapter 5 of [FPInnovations, 2019]). Both are reprinted with permission.

To apply Group VHH[–] W2R and W2F joint solutions across all scenarios implied that removing a panel could be assumed to result in damage along the two horizontal (upper and lower) edges. On the other hand, damage along the two vertical (left and right) panel edges could be assumed to depend on whether the choice of W2W joint solution for a particular scenario categorised as [+] (no damage) or [–] (damage). Consequently, two possible levels of modification requirements could be derived for the scenarios as is illustrated by Figure 4.2. Either, the choice of W2W joint implied that the panel would require modification only along its horizontal edges (W2R and W2F are [–]; W2W is [+]), or along both its horizontal and vertical edges (W2R, W2F, and W2W are all [–]). Scenarios where the former applied were annotated [–] in addition to the scenario name, and scenarios where the latter applied were annotated [– –] in addition to the scenario name. The modification was modelled as a 10 cm cut-off along the affected edges of a panel where the waste material was assumed to go to incineration. Note that no modification requirements were assumed for reuse within buildings.

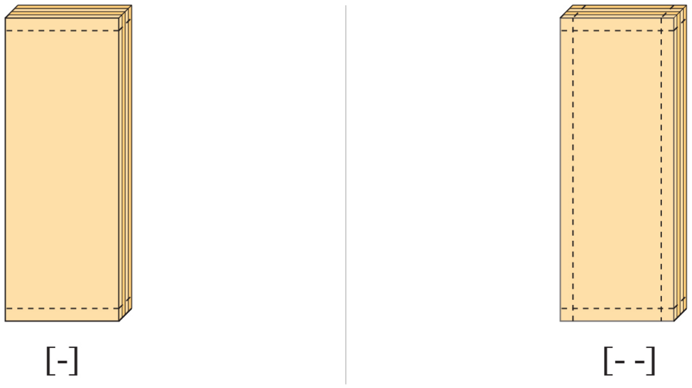


Figure 4.2: Two levels of panel modification requirements. Left: [–] modification affecting the horizontal edges. Right: [– –] modification affecting the horizontal and vertical edges.

The next step of the scenario construction process was to make assumptions regarding the service life of a CLT panel intended for use as a load-bearing inner wall as well as the building(s) where it would be located. According to the EPD used in the impact assessment (see Section 4.1.2.2), wood products belonging to service class 1 and 2 (e.g., CLT) have the capacity of lasting over 100 years according to EN1995-1-1. Swedish Wood (2017) states that it is typically recommended for load-bearing structures of glued laminated timber to be dimensioned for a permanence of 50 years. Moreover, a building service life of 50 years is in accordance with prescripts formulated by the National Board of Housing, Building and Planning (Boverket, 2019a). Consequently, a service life of 100 years was assumed for a CLT wall panel, and 50 years was assumed for buildings where CLT components make up the load-bearing structure. For convenience, it was further assumed for the service life of a panel or building to be equal to its life cycle length, i.e., the length of other life cycle phases was assumed to be negligible compared to the length of the use phase.

Following the assumptions outlined above, a set of possible scenario pathways were derived for the reuse of a CLT wall panel. The scenario development is illustrated by Figure 4.3, where the term *use cycle* (UC) is introduced to delimit a panel's service life in one building from another. The UCs of a panel also distinguish the sub-cycles formed by multiple iterations of reuse from the overarching life cycle of a panel which includes all processes from raw material extraction to EoL waste management. The number of enabled UCs during the life cycle of a wall panel was assumed based on the level of flexibility provided by the chosen W2W joint solution as well as the assumed service life duration. A panel connected by a Group V joint solution was assumed to only be accessible for reuse at the time of a building's disassembly, i.e., when a building reaches the end of its service life of 50 years. The panel was then assumed to be reinstalled in another building for 50 additional years before reaching the end of its service life of 100 years. In other words, a maximum of 2 UCs was assumed for scenarios modelling the Group V joint solutions. Alternate pathways were introduced for scenarios modelling VH and VHH joints to enable an additional

UC of 25 years within the 50 years of a building's service life. This additional UC was activated once per 100 years of panel service life in scenarios modelling the Group VH joints, resulting in a potential maximum of 3 UCs. For scenarios modelling the Group VHH joints, the additional UC was activated twice per 100 years of panel service life resulting in a potential maximum of 4 UCs.

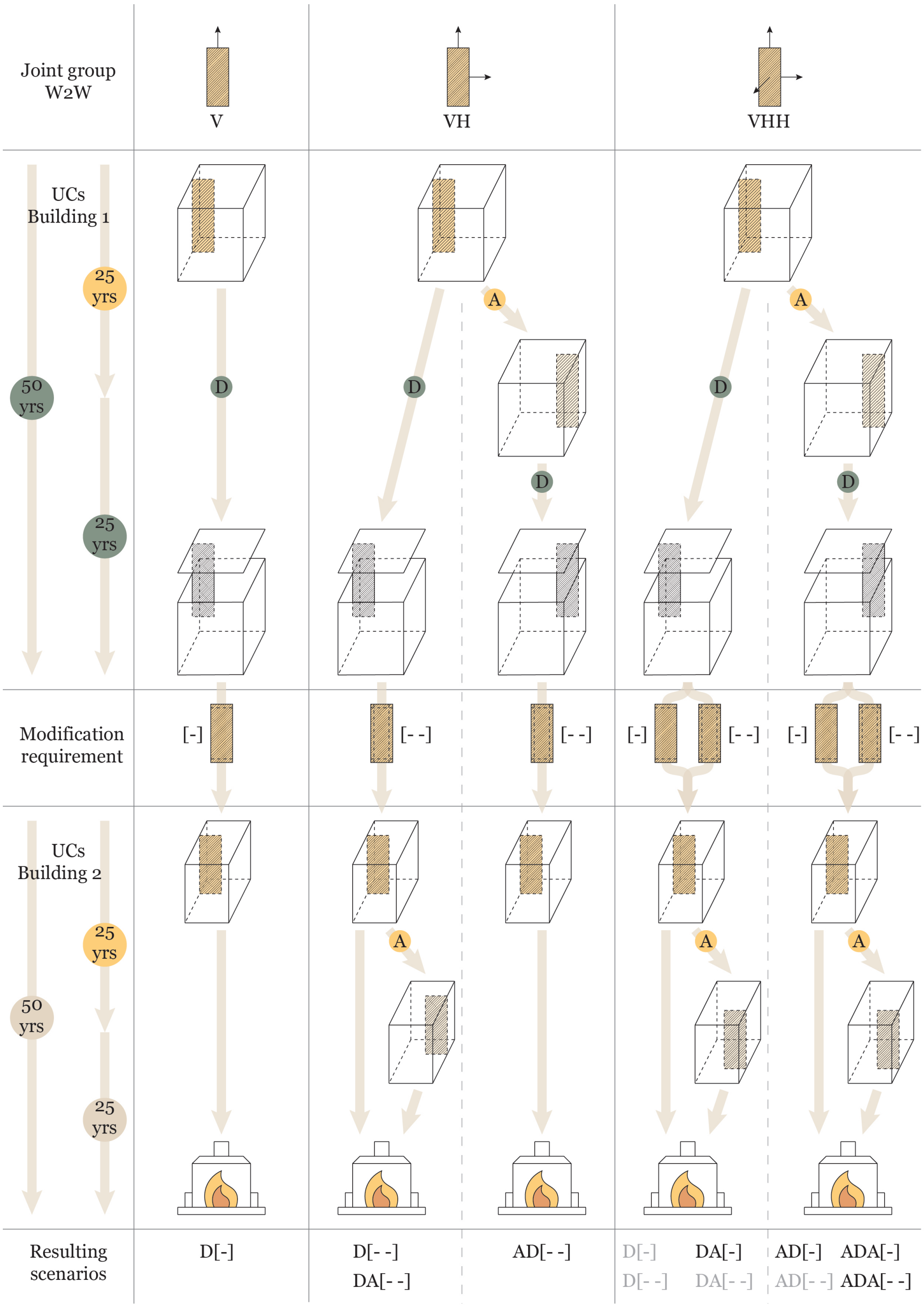


Figure 4.3: Illustration of the development of reuse scenarios. 'D' arrows indicate reuse by disassembly at the end of a UC. 'A' arrows indicate reuse by adaption at the end of a UC. The resulting unique scenarios are denoted in black text at the bottom of the figure.

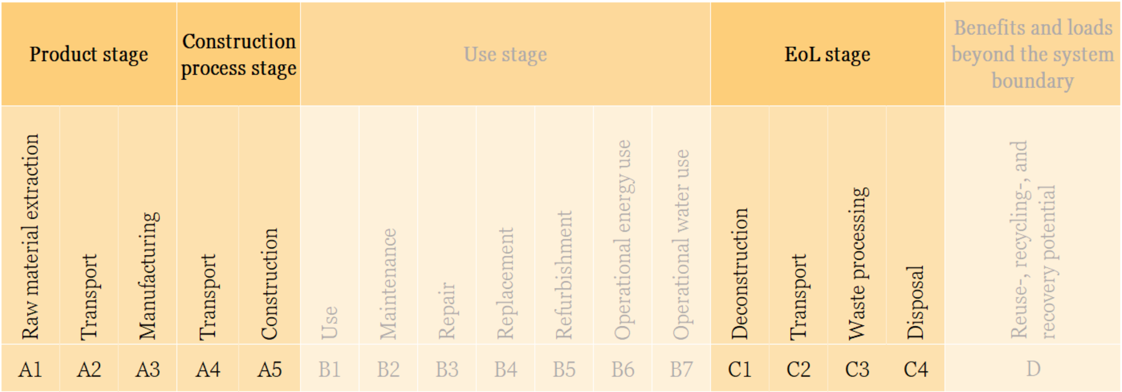
Figure 4.3 illustrates the development of 8 unique reuse scenarios: D[–], D[– –], DA[– –], AD[– –], DA[–], AD[–], ADA[–], and ADA[– –]. Some scenarios were enabled by more than one joint Group; for instance, D[–] was possible both for a panel connected by V[–] as well as VHH[–] joints. Moreover, the number of letters in the scenario acronym corresponds to the number of times the wall panel is assumed to be reused and brought into a new UC. One letter (e.g., D[–]) implies one reuse and thus 2 UCs, two letters (e.g., DA [– –]) implies that reuse occurs twice yielding 3 UCs, and so on. The modification requirements of a particular scenario was determined by the joint solutions included in the relevant joint Group. For instance, Group V does not include any W2W joint solutions that are assumed to damage the panel edges, so the modification requirement could be set to [–] for all scenarios based on Group V. On the other hand, Group VH only includes W2W joint solutions that are assumed to damage the panel edges so the modification requirement could be set to [– –] for all such scenarios. Finally, incineration was modelled for EoL of all scenarios as this is the typical mode of waste management for wood products containing chemicals (Avfall Sverige, 2019). Appendix A contains a detailed overview of the developed scenarios, including the specific steps of each pathway.

4.1.2 LCA

In order to assess the environmental impact associated with the reuse scenarios defined in Section 4.1.1, a simplified LCA was performed based on the standardised procedures specified by SS-EN15978 and SS-EN15804. The following Sections outline the LCA method according to the goal, scope and functional unit (Section 4.1.2.1), data and assumptions (Section 4.1.2.2), and impact assessment (Section 4.1.2.3).

4.1.2.1 Goal, scope, and functional unit

The goal of the LCA was to quantify the environmental impact of a CLT wall panel for which various degrees of reuse potential is enabled by the choice of joint solution. The functional unit (FU) was set to *1 CLT wall panel* since the assessment focused on effects on an element (not building) level. The FU also enabled accounting for changes of the panel dimensions due to the modification requirements described in Section 4.1.1. Figure 4.4 illustrates that the scope included the product stage modules (A1-A3), the construction process stage modules (A4-A5), and the EoL stage modules (C1-C4). The modules belonging to the use stage (B1-B7) were considered negligible for an element-level assessment. In the case of timber products, module D intends to account for the biogenic carbon benefits of wood materials. However, such calculations yet lack a common methodological approach (see Section 2.4.1). Thus, it was decided to exclude module D and account for reuse benefits by considering multiple UCs as parts of a wall panel's overarching life cycle. Benefits due to avoided energy production as a result of EoL incineration of a panel 100 years into the future were also considered too uncertain.



Product stage			Construction process stage		Use stage							EoL stage				Benefits and loads beyond the system boundary
Raw material extraction	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse-, recycling-, and recovery potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 4.4: System boundary of the LCA, represented by life-cycle stages according to SS-EN15978. Faded modules are excluded from the assessment.

4.1.2.2 Data and assumptions

The LCA used data from an EPD of CLT produced by Swedish manufacturer Stora Enso (2020). The EPD has been produced in accordance with SS-EN15804 following the European standard EN15804 for LCA-based EPDs in construction. The system boundary of the EPD includes all life cycle stages of Stora Enso's CLT: production (A1-A3), construction (A4-A5), use (B1-B7), and EoL (C1-C4), together with loads and benefits outside the boundary (D). The production modules include extraction and processing of raw materials (A1), transport of raw materials to the mill and fuels for internal transportation (A2), and production of the CLT and by-products (A3). The construction modules include transport of the CLT to a construction site (A4) and construction processes related to the installation of CLT in a building (A5). Modules B1-B7 were not included in the scope of the assessment, and are set to zero in the EPD as the use phase of the CLT is not expected to cause any environmental impacts (Stora Enso, 2020). The EoL modules include deconstruction of the building (C1), transport of the CLT to a sorting facility (C2), waste treatment (C3), and disposal of the CLT (C4). The EPD provides four alternative waste management data sets in module C3: reuse, recycling, incineration, or landfilling. In accordance with the scenario pathways of a wall panel as defined in Section 4.1.1, only the reuse and incineration data were used in the calculations. The EPD also contains four corresponding data sets for module D depending on the waste management option chosen in C3. However, module D was excluded from the assessment due to uncertainties addressed in Section 4.1.2.1.

The EPD contains data for several impact categories, however, only data for fossil GWP expressed in [kg CO_2-eq per m^3] were included in accordance with the delimitations of the study. Reference flows (RFs) in [m^3 per FU] were required to connect impact data to the FU of 1 CLT wall panel. There were three RFs used in the assessment: one RF based on the dimensions of a new panel (RF_N), and two RFs based on the resulting panel dimensions after modification ($RF_{[-]}$ or $RF_{[--]}$). The panel dimensions were assumed based on standard CLT wall panel designs and maximum dimensions according to Stora Enso. According to the manufacturer's technical brochure (Stora Enso, n.d.), a standard panel design consists of five layers of cross-laminated timber with a total thickness of 120 mm (30 mm + 20 mm + 20 mm + 20 mm + 30 mm). Thus, the panel thickness (T) was set to 120 mm across all scenarios. Furthermore, the maximum panel length and height are 16 and 3.5 meters, respectively, according to the EPD (Stora Enso, 2020). The length was thus assumed to be 4 meters for new panels (L_N), and 3.8 meters for subsequent UCs where a vertical 10 cm cut-off is required following disassembly ($L_{[--]}$).

Panel heights were assumed based on technical property requirements for buildings of different purposes. The minimum ceiling height in a building intended for housing or work spaces is 2.4 meters, while the minimum height in a building intended for public premises, teaching premises, or other work premises intended for a large number of people is 2.7 meters (Boverket, 2019a). A height of 2.7 meters was thus assumed for new panels (H_N) to enable assessing reuse between different building types. The panel height was reduced to 2.5 meters for subsequent UCs where a horizontal 10 cm cut-off is required ($H_{[-]}$ and $H_{[--]}$). The resulting three RFs were calculated according to Equations 4.1, 4.2, and 4.2. Note that since reuse by adaption was assumed to create no need for modification between UCs, the RF for such UCs was set to RF_N.

$$RF_N = \frac{T \times L_N \times H_N}{FU} \tag{4.1}$$

$$RF_{[-]} = \frac{T \times L_N \times H_{[-]}}{FU} \tag{4.2}$$

$$RF_{[--]} = \frac{T \times L_{[--]} \times H_{[--]}}{FU} \tag{4.3}$$

The data were used without alterations and additions, and therefore, any assumptions contained in the EPD also apply to the LCA. For instance, allocation in the EPD is performed according to EN15804 with a 1% cut-off (Stora Enso, 2020). An overview of relevant assumptions presented in the EPD together with additional assumptions required to model the multiple UCs constituting the reuse scenarios is available in Appendix B. Additional assumptions primarily revolved around transport and construction impacts as these depend specifically on whether reuse is enabled by adaption or disassembly. For reuse within a building (adaption), transports to the sorting facility (C2) were excluded from the first UC and transports to the construction site (A4) were excluded from the subsequent UC. It was assumed that remounting a wall panel on the same floor would have the same impact as dismounting it during deconstruction, i.e., that module A5 was equal to module C2 in the case of adaption. For reuse between buildings (disassembly), a wall panel requires transport from one building to a sorting facility, and from the sorting facility to a new building. The distance from the first building to the sorting facility was assumed to be equal to the distance from the facility to the second building, implying local reuse of the CLT panel. This was expressed through setting A4 equal to C2 for the subsequent UC.

4.1.2.3 Impact assessment

The environmental impact assessment of multiple UCs largely followed the procedure outlined by IVL's (2020) guide on accounting for reuse based on SS-EN15978 (see Section 2.3.3). Since the scenarios were modelled so as to account for all UCs included in the overarching life cycle of a panel, it was decided to account for the benefits of reuse by "zeroing" the A-modules in a subsequent UC instead of including module D. This approach corresponds to the first type of reuse defined by IVL, i.e., reuse within the studied system boundary. Since SS-EN15978 does not specify where to declare impacts arising specifically due to reuse (IVL, 2020), panel edge modification was treated as an EoL process replacing other waste processes. In other words, additional impacts due to reuse were accounted for in the same UC as the potential damage was assumed to occur. The impact assessment of the possible life cycle pathways of a CLT wall panel was calculated according to Equations 4.4, 4.5, and 4.6.

$$I_{UC,\,S}^{M} = FU \times RF_{UC,\,S} \times m_{UC,\,S}^{M} \tag{4.4}$$

$$I_{UC,\,S} = \sum_{M=A1}^{M=A3} m_{UC,\,S}^{M} + \sum_{M=A4}^{M=A5} m_{UC,\,S}^{M} + \sum_{M=C1}^{M=C4} m_{UC,\,S}^{M} \tag{4.5}$$

$$I_{S} = \sum_{UC=1}^{n} I_{UC,\,S} \tag{4.6}$$

where I denotes fossil GWP in [kg CO_2-eq]. $I_{UC,\,S}^{M}$ is the impact of a module M in cycle UC belonging to scenario S, $I_{UC,\,S}$ is the total impact for all modules in cycle UC in scenario S, and I_S is the total life cycle impact of a scenario S. FU denotes the functional unit [1 CLT wall panel] and $RF_{UC,\,S}$ denotes the relevant reference flow in [m^3 per FU] for cycle UC in scenario S (either Equation 4.1, 4.2, or 4.3). $m_{UC,\,S}^{M}$ denotes the impact data corresponding to module M in cycle UC of scenario S. The inclusion of a module M in a scenario S depended on the number of enabled UCs n in a scenario and whether reuse was enabled by adaption or disassembly between cycles. If a panel is reused within a building (adaption), no transportation is required so that modules C2 from the first UC and A4 from the subsequent UC were excluded. Reuse by adaption also implies that no modification, and thus cut-off to incineration, is required so that modules C3 and C4 were excluded from the UC.

4.1.3 Additional scenarios for comparison

A set of *Business As Usual* (BAU) scenarios were developed to enable comparison of the impacts associated with the reuse scenarios defined in Section 4.1.1 to conventional, non-circular pathways of a CLT wall panel. For the reuse scenarios enabling two UCs, the corresponding BAU scenario included two sets of the modules A1-A3, A4-A5, and C1-C4, representing two new CLT wall panels being produced, transported, installed in a building, and managed at EoL. Correspondingly, the reuse scenarios enabling three UCs were compared to a BAU scenario representing the production, transport, installation, and EoL of three new panels, and the reuse scenarios enabling four UCs were compared to a BAU scenario representing four new panels.

4.2 Assessment results

The following section presents the results of the environmental assessment. Section 4.2.1) contains a comparison of the impact distribution across UCs, and Section 4.2.2 presents the total impact associated with the different scenarios. Additionally, an analysis of how an increased number of UCs affects the life cycle fossil GWP of a CLT wall panel is presented in Section 4.2.3.

4.2.1 Impact distribution across UCs

To illustrate how the fossil GWP differs for the developed scenarios, a comparison of how the impact is distributed across UCs is presented in Figure 4.5. The graphs are structured according to the number of UCs enabled by the scenarios (by columns) and the UCs in which impacts occur (by rows). For instance, impacts of the scenarios enabling two UCs are presented in the left column while impacts of the first UC for all scenarios are presented in the top row. Each graph presents the impacts of either UC 1, UC 2, UC 3, or UC 4 for scenarios that enable the same number of UCs (either two UC scenarios, three UC scenarios, or four UC scenarios). The impact of the BAU scenario is 184,5 CO_2-eq across all UCs since it represents a new wall panel being produced at the beginning and incinerated at the end of every UC. In the reuse scenarios, each UC inhibits the production of a new panel and the impact of the reused panel is instead distributed across several UCs. As Figure 4.5 demonstrates, this results in a reduced environmental impact compared to the BAU scenario in each UC.

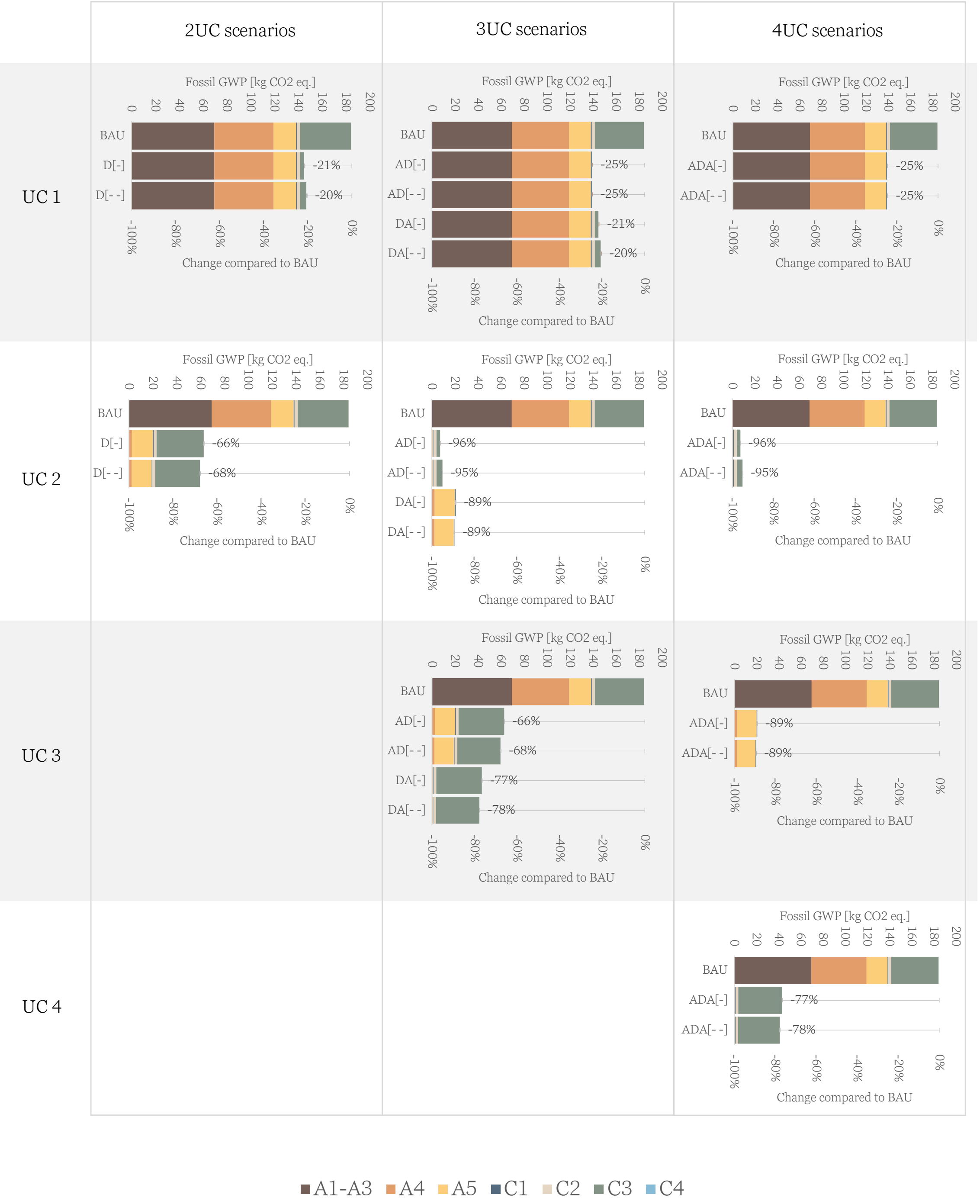


Figure 4.5: Fossil GWP per UC, displayed horizontally. Impacts for scenarios enabling the same number of UCs are sorted vertically.

The UC impact distribution shows negligible differences between scenarios enabling two and four UCs; scenarios D[–] and D[– –] differ by approximately 1–2%, and scenarios ADA[–] and ADA[– –] by 0–1%. However, there is a more noticeable difference between scenarios enabling three UCs depending on when reuse by adaption and disassembly occurs in a panel's life cycle. For instance, when reuse by disassembly is applied early in the life cycle (scenarios DA[–] and DA[– –]), there will be a higher impact distributed to UC 1 and UC 2 compared to scenarios where there is early reuse by adaption (AD[–] and AD[– –]). In contrast, scenarios with early reuse by disassembly perform worse than scenarios with early reuse by adaption in UC 3. This is due to the fact that where disassembly is applied in the life cycle there will be additional impacts arising from modification and transportation processes. On the other hand, when there is reuse by adaption between cycles, the same impacts will instead be distributed to other UCs.

The results for the scenarios enabling three UCs indicate that what type of reuse occurs when in the life cycle of a wall panel has a larger effect on the environmental impact distribution than the level of panel modification. Different modification requirements are the only practical differences between scenarios D[–] and D[– –], and between ADA[–] and ADA [– –]), for which impact differences are negligible at best. Consequently, the results imply that the level of modification is not a significant factor in determining a wall panel's fossil GWP distribution.

Finally, it can be observed from Figure 4.5 that the intermediate UCs, i.e., the UCs in which there are no impacts due to production or EoL processes, display the largest impact reductions compared to BAU. For instance, when UC 2 is the last cycle it achieves an impact reduction of 66–68% (two UC scenarios) while a 95–96% reduction can be achieved when UC 2 is an intermediate cycle (four UC scenarios). The intermediate UCs thus demonstrate the largest benefits in terms of impact reduction when a reusing a CLT wall panel across multiple cycles. The first and final user of the panel will be responsible for a larger share of the total environmental impact than the intermediate user or users, suggesting that the largest incentive for reuse occurs when the next UC is an intermediate cycle.

4.2.2 Total life cycle impacts

Section 4.2.1 demonstrated that scenarios enabling the same number of UCs can vary in the distribution of their associated impacts across UCs, depending on whether there is reuse by disassembly or adaption. However, scenarios enabling the same number of UCs do not differ in terms of their total (life cycle) fossil GWP as can be seen in Figure 4.6. There is a 44% reduction of environmental impact compared to BAU for the scenarios enabling two UCs, a 62% reduction for the three UC scenarios, and a 71–72% reduction for the four UC scenarios. In other words, the more times a wall panel is reused (the more UCs), the larger the reduction of fossil GWP over the entire life cycle compared to the corresponding BAU scenario.

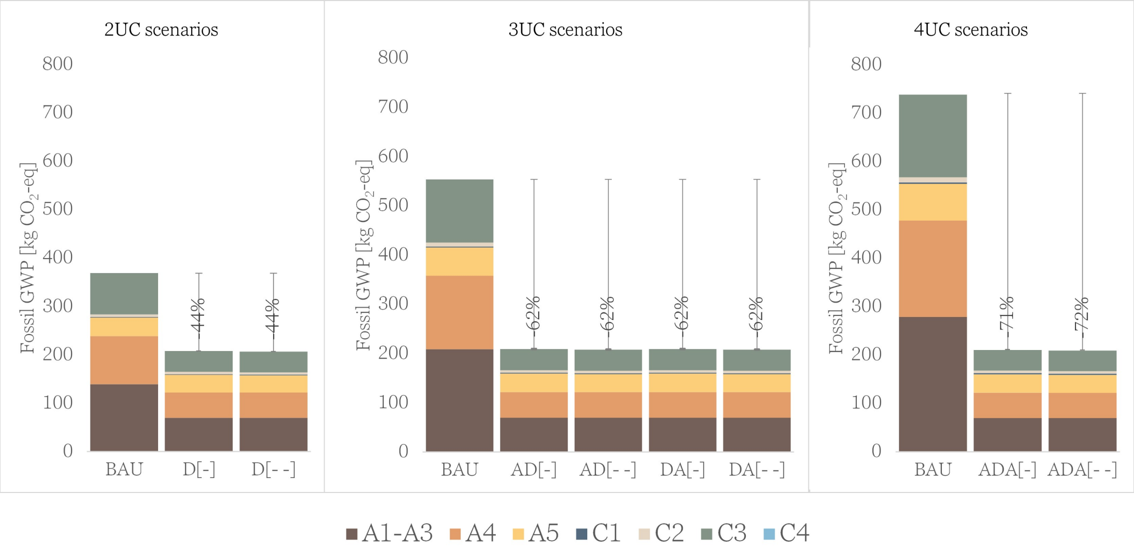


Figure 4.6: Total life cycle fossil GWP per scenario. Left: GWP for scenarios enabling two UCs. Middle: GWP for scenarios enabling three UCs. Right: GWP for scenarios enabling four UCs. Percentages indicate impact reductions compared to the corresponding BAU scenario.

The impact reduction grows with an increasing number of UCs since the absolute value of the environmental impact remains at approximately 206–210 CO_2-eq regardless of the number of UCs. Even though individual scenarios differ somewhat in terms of, e.g., transportation and waste management impacts in each UC, these impacts will be evenly distributed over the total life cycle depending on when there is reuse by adaption or disassembly. For instance, if a panel is reused by disassembly and modified between UCs there will be additional impacts generated by transporting the panel to a new building and transporting the cut-off to an incineration facility. The size of the additional impact is determined by the transport distance and weight of the freight. Since the scenarios are modelled based on the same data with the same distance and emissions factors (i.e., the same vehicle), differences between UCs will thus depend on whether reuse occurs by adaption or disassembly. As mentioned in Section 4.2.1, the largest impact shares are distributed to the first and final UCs due to production and EoL processes while the intermediate UCs display low contributions toward the total life cycle impact. The absolute life cycle impact is thus not affected to any significant degree by how many intermediate UCs there are in a scenario, while the percentage reduction compared to BAU will increase significantly for every iteration of reuse. This suggests that the important impact reduction potential lies in increasing the number of enabled UCs.

4.2.3 Impact of increasing the number of UCs

Section 4.2.2 highlights that the most influential factor in determining the fossil GWP reductions attained by reusing a CLT wall panel is the number of enabled UCs. Due to assumptions of the expected service life of a CLT structure (see Section

4.1.1), it followed from the scenario development process that a panel was assumed to be reused a maximum of 3 times if opting for a category VHH joint solution, enabling 4 UCs à 25 years. The assumption that a building reaches the end of its life after only 50 years positions the assessment results on the more careful side; in reality, it is more probable that a structure is refurbished after 50 years rather than demolished. In addition, UC lengths way below 25 years might be of relevance for buildings intended for particularly flexible purposes. Consequently, it becomes of interest to analyse the potential maximum impact reduction for a wall panel where an "infinite" number of UCs is enabled.

In this further analysis, impacts due to transport (modules A4 and C2) as well as modification requirements are excluded for the intermediary UCs. This implies two things: 1) that the wall panel is assumed to be reused within the same building over and over, which is relevant either if the expected service life of the structure is extended beyond the recommended 50 years or if the reuse frequency of the panel is shorter than what is modelled in the reuse scenarios, and 2) that all connecting sides of a panel (W2W, W2F, W2R) employ [+] categorised joint solutions to avoid modification. To extend the number of possible UCs using previous assumptions regarding the choice of W2F and W2R joints (VHH[-]) would not have been realistic. Either, the panel dimensions would seize to meet the standard ceiling height requirements after only a few rounds of modification, or, if assuming that no modification is applied between UCs, visible damage such as old screw holes would accumulate along the panel edges for every iteration of removal and reuse. The impact of increasing the number of UCs for a panel where these special conditions apply is shown in Figure 4.7.

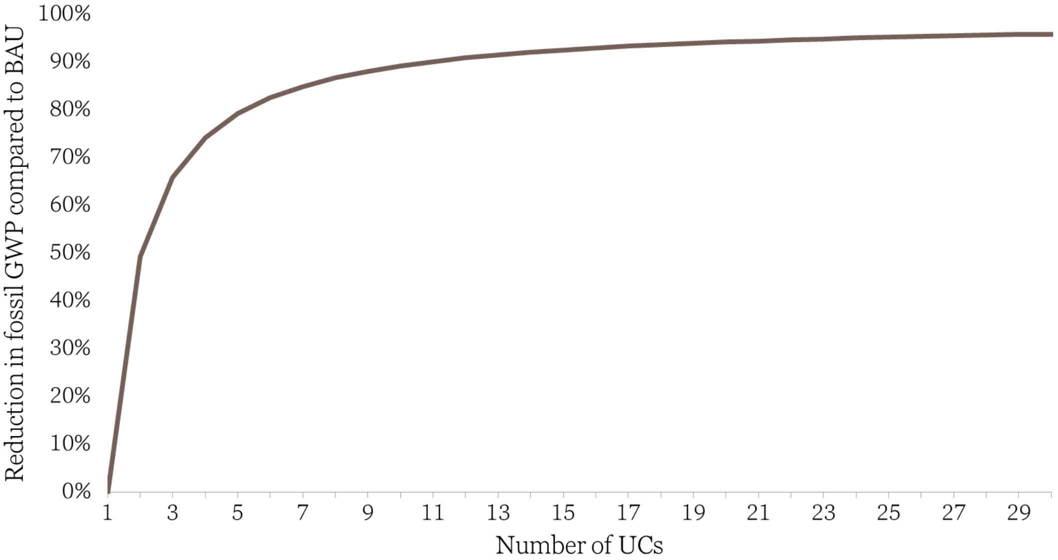


Figure 4.7: Fossil GWP reduction compared to BAU for a CLT wall panel with an infinite number of possible UCs.

As Figure 4.7 illustrates, increasing the number of possible UCs for a CLT wall panel results in an exponential reduction of fossil GWP compared to the corresponding BAU scenarios where new panels are produced at the same frequency as the intended reuse. The slope of the curve starts to decline significantly at around five UCs, implying that reuse over multiple UCs is able to displace environmental impacts associated with linea pathways at a fairly early stage of a reused panel's life cycle.

5

Discussion

The study has assessed the reuse potential and environmental impact of reusing CLT on a component level and not a building level. Even though one building element accounts for a very small share of the total environmental impact of a structure, it can be argued that the reuse potential of individual elements is what determines the circularity of the building as a whole. Consequently, assessing reuse on a component level can be claimed to be of high interest. The following Sections discuss the results, limitations, methodologies, and potential improvements of the study. Section 5.1 addresses the reuse potential analysis, followed by Section 5.2 which deals with the environmental impact assessment. Finally, suggestions for future research are presented in Section 5.3.

5.1 Discussion of the reuse potential analysis

The analysis of reuse potential aimed to evaluate how the choice of joint solution affects the reuse potential of a load-bearing CLT inner wall, hence, to answer the first research question. By analysing existing research of how joints affect the reuse potential, it was found that previous studies have ranked joints according to reuse potential in a framework, however these lack a direct correlation to CLT specific joints. Therefore, a framework of the reuse potential for common CLT joints on the Swedish market was constructed. In addition, the analysis identifies two joint-specific factors affecting the reuse potential: the direction of removal enabled by the joint, and the damage caused by the joint on the wall panel upon removal. The resulting framework categorised the CLT joints according to Groups that was based on these two joint-specific factors.

5.1.1 Key results of the analysis

The resulting framework shows that the most common W2W joints available on the Swedish market are more compatible with reuse than W2F and W2R joints, since the majority of the W2W joints are categorised as Group VHH. In addition, the W2W joints have a greater spread over the Groups than the others, which may indicate different possibilities of application than for the W2R and W2F joints. For instance, hooking brackets are not compatible with adaption but are a good alternative for disassembly with high reuse potential since they enable vertical removal and no damage to the element. This implies that different joints can be used for different demands and still contribute to a high reuse potential.

However, the results show that there are no W2F joints available on the Swedish market that are compatible with reuse through adaption, i.e., they do not enable horizontal removal. Since the removal of a wall panel is dependent on all joints around all edges, the reuse potential of the wall is dependent on that all joints enables the same direction of removal. To clarify, if one joint only enables vertical removal, it does not matter if the other joints enable removal in all possible direction, the removal of the wall panel will still be restricted by the one joint that limits the reuse potential. Therefore, with today's joint technology, adaption is not practically feasible due to the restrictions on reuse caused by the joints. Additionally, several of the analysed joints are favourable from a reuse perspective since they do not cause damage to the CLT wall panel. However, the majority of these joints only enable vertical removal of the wall panel and are thus not compatible with adaption. The ones that do enable adaption instead have a negative impact on the reuse potential due to e.g. screw holes. These result implies that there are currently no joints on the Swedish market that are fully compatible with reuse, where *both* adaption and disassembly are enabled.

5.1.2 Impact of analysis delimitations and assumptions

The analysis is mainly based on three previous studies where the reuse potential was examined, of which two were conducted by the same author. The limited number of included studies in the analysis is simply due to the scarcity of literature in the field. By reviewing the existing literature, it was found that these tend to be centred around either the adaptability of non-timber-specific joints or timber-specific joints from a technical perspective. Since these studies include frameworks where they have ranked joints according to reuse potential, the decision of creating a new framework of CLT joint's impacts on the reuse potential of a wall panel can be considered well-motivated. However, the scarcity of literature also implies that the results may be shaped by Durmisevic's studies. Even though the authors of this study were aware of this issue when creating the framework, it may still affect the depth of the analysis and the results.

The analysis of the joint solution's impact on the reuse potential of a CLT wall is limited to the joints included in the CLT Handbook by Swedish Wood. This delimitation was made with the aim of analysing the currently available and common joints in the Swedish market. However, there may be other joints that are not included in the handbook that might have broadened the analysis and the resulting framework. For instance, there might be joints that have not yet entered a large scale market in Sweden that are more compatible with reuse. The results might have differed if the analysis had included more joints.

Only two factors that have an impact on the reuse potential of a CLT wall panel are included in the developed framework: the direction of removal and damage caused by the joint upon removal. However, there are other aspects that can be assumed to have an important impact on the reuse potential as well that were not assessed in this study. For instance, whether a wall panel can be reused or not is highly dependent on potential damage or changes in the load-bearing capacity of the wall caused during its life cycle. The framework includes only if the joint damages the wall panel at the location of the joint, but not if the joint causes stresses on the panel that affect its strength and load-bearing capacity. Such factors are very important for future users of the wall since it defines for what purpose the wall can be reused. Moreover, since the analysis departed from an element perspective there will also be additional building-level factors affecting the reuse potential that have not been included. For instance, when a load-bearing inner wall is removed from a building there will likely be issues of accessibility related to either adjacent elements or installations in the building. Excluding such factors from a the study have shaped the results of the analysis since the element's actual reuse potential is intertwined with the building context. Therefore, including a building perspective when assessing reuse potential in future studies may be an important subject for further research.

There are other challenges of implementing reuse within the construction sector that have not been included in this study and are associated with the joint solution. For instance, the currently available joints on the market are often customised for easy assembly since the effectiveness of constructing a building is a cost issue, and since they are developed from a linear economy. For reuse to be implemented at a large scale, it is important to consider joints that both have high reuse potential and also enable easy assembly and disassembly. Furthermore, other practical issues of implementing reuse are, e.g., the unknown future demands and technical development. For instance, if the elements of a building that are designed for disassembly are planned to be reused in 50 years, joint-and material techniques will most likely have developed. Nevertheless, there are still many challenges related to the practical issues of reuse. The results may have differed if the study had included more factors that affect the practical feasibility of reuse.

5.2 Discussion of the environmental impact assessment

The environmental assessment aimed to evaluate the fossil GWP impact of reusing a CLT wall panel, hence, to answer the second research question. Based on the framework developed in the analysis, the different joint Groups were translated into several scenarios for reuse. In addition, a BAU scenario was constructed to be able to compare the impacts of reusing a CLT wall panel with a traditional linear use where the wall panel is treated as waste after its first use cycle. The assessment of the fossil GWP impact of all scenarios was made with LCA, which was based on data from an EPD for CLT. The LCA resulted in two main comparisons: one of the impact allocation across use cycles and one of the total life cycle impact.

5.2.1 Key results of the assessment

The results of the environmental assessment indicate that reusing a CLT wall panel can contribute to significant impact reductions compared to the corresponding linear pathway of a panel (BAU). The potential life cycle impact reductions are approximately 44% for for scenarios enabling 2 UCs, 62% for scenarios enabling 3 UCs, and 72% for scenarios enabling 4 UCs. From the perspective that single building elements make up larger structures (and thus, buildings), the results are in line with previous studies demonstrating the potential benefits of reuse on the element, structure, and building levels (Andersen et al., 2020; Cruz Rios et al., 2019; Eckelman et al., 2018; Minunno et al., 2020).

The number of enabled UCs is found to exert the most notable influence on the total potential impact reduction, corresponding to findings by Cruz Rios et al. (2019) and Eckelman et al. (2018). The potential impact reduction increases exponentially for every enabled UC, until virtually no additional contribution is made to the total life cycle impact when reusing a panel into one additional UC. In other words, it could be argued that a panel should be reused as any times as possible to maximise the utility gained per unit of impact and provide the maximum benefit compared to BAU. However, these results can be assumed to depend strongly on the allocation method used in the EPD and should thus be evaluated in more detail by comparing allocation approaches. Furthermore, the study excludes factors that can be assumed to also affect the reuse potential, and thus environmental impact, of a wall panel (accessibility, load-bearing capacity etc.). In order to fully evaluate the effect on the number of enabled UCs, a more comprehensive reuse potential analysis should be made where several factors are simultaneously assessed.

Negligible differences in total life cycle impact are observed for scenarios enabling the same number of UCs. This suggests that the level of modification requirement governed by the choice of joint solution and the timing of adaption versus disassembly throughout the life cycle of a wall panel play insignificant roles in determining the total environmental impact. However, edge modification and type of reuse do affect the distribution of impacts when analysing individual UCs. Among the 3 UC scenarios it is observed that early reuse by adaption in the life cycle allocates less impacts to the intermediate UC and more impacts to the last UC, while early reuse by disassembly produces the opposite outcome. Consequently, the incentive for reuse within a building (adaption) might be larger between the first and second UC and the incentive for reuse between buildings (disassembly) might be larger between the second and third UC for these scenarios. However, the intermediate UCs display the lowest impacts due to the absence of production and incineration processes, thus indicating that the largest incentive for reuse generally appears when the subsequent cycle is an intermediate UC.

As a final remark to the key results, it is important to keep in mind the qualitative differences between reuse enabled by adaption and reuse enabled by disassembly although not exactly present in the results of the study. Opting for Group VH and VHH joint solutions which enable reuse within a the life cycle of a building will be of higher value in a building intended for flexible purposes. On the other hand, a Group V joint solution enabling reuse only at the end of a buildings service life might be fully adequate if the purpose of the building can be assumed to remain quite fixed. The value of a high reuse potential should thus be understood in the specific context of a building.

5.2.2 Impact of assessment delimitations and assumptions

The data used for the impact calculations were collected from an EPD of new CLT produced by Swedish manufacturer Stora Enso (2020). In the development of the reuse scenarios it was assumed that each scenario departed from the production and use of a new CLT wall panel, thus, the option of retrieving and reusing CLT elements from the existing building stock is not represented in the analysis. However, as CLT structures are still quite new to the construction sector it can be hypothesized that the supply of available pre-used CLT elements is low and that it is more relevant to assess the future benefits of reusing CLT that is recently manufactured or will be manufactured in the near future.

Furthermore, a height of 2.70 meters and a length of 4 meters were assumed for new CLT wall panels in the scenarios. If modifications were assumed to be required between UCs, the height was reduced to 2.50 meters and the length to 3.8 meters . Although based on national technical property requirements (Boverket, 2019a) and product data (Stora Enso, 2020), these assumptions do not imply that the potential impact reductions presented in the results are dependent on specific panel dimensions. The dimensions can easily be adapted to fit other measurement requirements by changing the input values for the RFs derived by Equations 4.1, 4.2, and 4.3. The results of the assessment are also dependent to some extent on the assumption that a W2F joint solution that is more flexible than the options included in Swedish Wood's Handbook can be adopted within CLT construction practice. However, this appears feasible as the study has shown that there available options which follow the same connection principle but where considerations are made to the dependence in assembly and disassembly.

The LCA in this study is only based on data from one manufacturer, since there is insufficient availability of EPD data with the same scope as in this study. Using data from only one source may have had an impact on the reliability of the results as well as the relevance of the results for other stakeholders and manufacturers. However, if that is the case, other stakeholders may still find the study interesting with respect to the method and assessment of the impact of reuse. Furthermore, using EPD data entails several uncertainties since it is impossible to know exactly what is excluded and included in the original LCA. These uncertainties may affect the results of the impact assessment of reuse. If a full-scale LCA had been conducted, all data would have been controlled and modified for each scenario, and greater variations of the fossil GWP impact for the scenarios might have been achieved.

5.2.3 Policy suggestions

In the environmental assessment, the total impact of a CLT wall panel is calculated based on the impact contributions of each individual UC regardless of whether they are assumed to occur within a building (adaption) or between buildings (disassembly). While this makes sense when assessing a single construction element, in reality, it might not correspond to how the impacts of a panel would be declared for during its life cycle as part of structural systems. Since it is only mandatory to provide climate declarations for new buildings and not for refurbishments or adaptions of existing buildings, the environmental benefits attained by opting for a pre-used element will likely only be demonstrated if it is moved to and used in a new building. In order to create incentives for reuse both by adaption and disassembly, it can thus be argued that construction works taking place within a building's life cycle should be declared for in the same manner as when constructing a new building.

5.3 Future research

Since this study is limited to assessing the reuse potential of a CLT wall panel, it lacks sufficient depth to be able to apply the framework on other CLT elements (e.g. slabs and beams). Furthermore, since the study only includes CLT it is hard to say whether the framework can be applied on other structural systems (e.g. post-and-beam structures). Therefore, the framework needs to be developed and analysed based on the application on other structural components and systems. Hence, suggestions for future research is to assess if the developed framework in this study can be used for general application.

Other factors that have been excluded in this study, but is still important the reuse potential of a CLT wall panel, is e.g. durability and accessibility. By including more perspectives of reuse potential, it would be possible to investigate which factor is the most critical when it comes to deciding the reuse potential of CLT. In addition, it would also enable a further analysis of to what degree the reuse potential and environmental impact is determined by the choice of joint solution.

Furthermore, this study has had a very detailed focus on joints, but other construction-specific or societal aspects are equally important for reuse to be incentivised and feasible on a large scale. Ensuring that future demands can be satisfied with today's construction technology and the development of techniques to manage construction "waste" as resources are two examples of important future research subjects.

6

Conclusion

The aim of this study was to assess the impact of inter-element joint solutions on the reuse potential and environmental impact of load-bearing CLT wall panels. Two main research questions and corresponding methodologies guided the study towards fulfilling its aim: a reuse potential analysis encompassing a review of previous studies which rank joint techniques according to reuse characteristics, and an environmental assessment employing a simplified LCA method.

One of the main findings from the analysis is that the direction of removal enabled by a joint solution as well as the potential damage it can inflict are two important factors in determining the reuse potential of construction elements. Consequently, a framework is developed where joint solutions for CLT wall panels are categorised according to these characteristics. Through the categorisation it is found that there is currently no combination of common joint solutions within Swedish CLT construction that enable reusing a panel both within the life cycle of a building (adaption) a between buildings (disassembly), and that this is primarily due to a lack of W2F joint solutions enabling horizontal removal. Even if opting for a W2F joint solution similar to the connection techniques common today, the reuse potential of a CLT wall panel is still inhibited by potential damage caused by the joint. An important conclusion of the study is thus that to promote more flexible reuse within CLT construction it is necessary to develop joint solution that enable several types of reuse and that have as little impact as possible on the quality of elements.

A set of reuse scenarios is developed based on possible life cycle pathways of a CLT wall panel employing different inter-element joint solutions. It is found that the choice of joint solution can be tied to the enabled number of UCs during the life cycle of a CLT wall panel through what kind of reuse is enabled by the joint. In turn, the LCA results indicate that the number of enabled UCs strongly influences how much the environmental impact of a wall panel can be reduced compared to a conventional, non-circular pathway. Reuse within the life cycle of a building (adaption) can be assumed to enable more UCs during a panel's life cycle and thus result in a lower total environmental impact, however, the value of adaptable solutions depends on the building context. Furthermore, the results highlight that the intermediate UCs demonstrate much lower environmental impacts than the first and last UCs. If current regulations around building climate declarations are updated so as to account for refurbishments and adaptions, they might provide more incentives for reuse by allowing for the accounting of these benefits

For future studies, it is recommended that the reuse potential framework is applied to other types of CLT elements, and potentially also other structural timber systems, to further assess joint solutions' impact on reuse potential. In order to provide a more holistic view on the reuse potential of CLT elements it is also suggested to use the joint-based framework in a cross-analysis of other factors affecting reuse potential, such as accessibility and durability. Including more factors would enable a more thorough assessment of the environmental impacts of reuse. It is the hope of the authors that the study can provide inspiration for and contribute to a wider implementation of reuse within CLT construction. By focusing the study on a particular construction detail such as joints, the study has the potential to support various stakeholders engaged in circular design practices.

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A

Overview of reuse scenarios

Table A.1: Overview of all reuse scenarios including scenario name, enabling joint Groups and scenario pathway steps.

Scenario	Enabled by joint Group	Scenario layout
D[-]	V[-] VHH[-]	• Use 1 (50 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **upper/lower** edges that goes to incineration • Use 2 (50 yrs) in Building 2 • EoL incineration
D[- -]	VH[- -] VHH[- -]	• Use 1 (50 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **all all** edges that goes to incineration • Use 2 (50 yrs) in Building 2 • EoL incineration
AD[-]	VHH[-]	• Use 1 (25 yrs) in Building 1 • Assume that user is OK with screw holes • Use 2 (25 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **upper/lower** edges that goes to recycling • Use 3 (50 yrs) in Building 2 • EoL incineration
AD[- -]	VH[- -] VHH[- -]	• Use 1 (25 yrs) in Building 1 • Assume that user is OK with screw holes • Use 2 (25 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **all** edges that goes to recycling • Use 3 (50 yrs) in Building 2 • EoL incineration
DA[-]	VHH[-]	• Use 1 (50 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **upper/lower** edges that goes to recycling • Use 2 (25 yrs) in Building 2 • Assume that user is OK with screw holes • Use 3 (25 yrs) in Building 2 • EoL incineration

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Table A.1 – continued from previous page

Scenario	**Enabled by joint Group**	**Scenario layout**
DA[- -]	VHH[- -]	• Use 1 (50 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **all** edges that goes to recycling • Use 2 (25 yrs) in Building 2 • Assume that user is OK with screw holes • Use 3 (25 yrs) in Building 2 • EoL incineration
ADA[-]	VH[- -]	• Use 1 (25 yrs) in Building 1 • Assume that user is OK with screw holes • Use 2 (25 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **upper/lower** edges that goes to recycling • Use 3 (25 yrs) in Building 2 • Use 4 (25 yrs) in Building 2 • EoL incineration
ADA[- -]	VHH[- -]	• Use 1 (25 yrs) in Building 1 • Assume that user is OK with screw holes • Use 2 (25 yrs) in Building 1 • Modification before reuse – cut off 10 cm along **all** edges that goes to recycling • Use 3 (25 yrs) in Building 2 • Use 4 (25 yrs) in Building 2 • EoL incineration

B

Assumptions for the environmental impact assessment

Table B.1: Overview of the system boundaries and the assumptions from the EPD as well as the additional assumptions made for the LCA.

Life cycle stage	**Module**	**Process**	**Assumptions from EPD**	**Assumptions for LCA**
Product	A1	Raw material	Includes extraction and processing of raw materials (e.g., forestry operations, glue production)	
	A2	Transport	Includes transport (trucks+train) of raw materials (spruce and pine logs) to mill	
	A3	Manufacturing		
Construction	A4	Transport	Includes transport of finished CLT product to construction site (average European customer)	When adaption: A4=0; when disassembly: A4=C2
	A5	Construction		When adaption: A5=C1; when disassembly: A5=A5

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Table B.1 – continued from previous page

Life cycle stage	**Module**	**Process**	**Assumptions from EPD**	**Additional assumptions**
Use	B1	Use	No environmental impacts are expected in the use phase, i.e., no harmful substances are released to air, water, or ground (B=0)	
	B2	Maintenance		
	B3	Repair		
	B4	Replacement		
	B5	Refurbishment		
	B6	Energy use		
	B7	Water use		
EoL	C1	Deconstruction		
	C2	Transport	50 km distance assumed to the sorting facility	
	C3R	Preparation for reuse		
	C3I	Preparation for incineration		Incineration is assumed as waste management for all scenarios
	C4R	Product for reuse		
	C4I	Chips to incineration	75 % efficiency	Incineration is assumed as waste management for all scenarios
Loads and benefits	DR	Reuse of product, substituting virgin material		Excluded from the LCA
	DI	Substitution of natural gas in heat production		

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