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Assessment of Load-Bearing Timber Elements for the Design for Disassembly

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Abstract: This literature review examined the functionality of the connection or connections and disassembly as a general strategy. The prerequisites that arose for disassembly were, among other things, damage tolerance, reduction of emissions compared to raw materials, costs, and guaranteeing safety. The set of criteria for disassembly was defined from the structural engineers' perspective through the literature review. The criteria focus on joints, which are key to the success of disassembly. Five different criteria were used to evaluate joints in this study. The criteria were ease of access to components, ease of disassembly, independence, simplicity, and standardization. The evaluation was executed for different widely used connections in timber constructions. The criteria were evaluated subjectively from one to four. As a conclusion, the load-bearing timber elements have a promising future in design for disassembly. Design for disassembly aims to promote reuse and other features to increase the life cycle of structural elements. It has the potential to reduce the usage of raw materials and significantly decrease the emissions of construction.

Keywords: design for disassembly; load-bearing timber elements; timber connections

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1. Introduction

Environmental issues such as the climate crisis, depletion of natural resources, and biodiversity loss are addressed, for example, through carbon emissions accounting. In Finland, the emissions from the construction sector account for 30% of the country's total emissions, with building materials contributing to about 15% of these emissions [1]. There are also challenges related to the management of construction waste. For the years 2018–2020, 95% of the wood waste was utilized for energy generation [2]. The utilization of wood waste should be made more efficient according to the principles of the waste hierarchy. The waste hierarchy according to Article 4 of the Waste Directive is presented in Figure 1 [3].

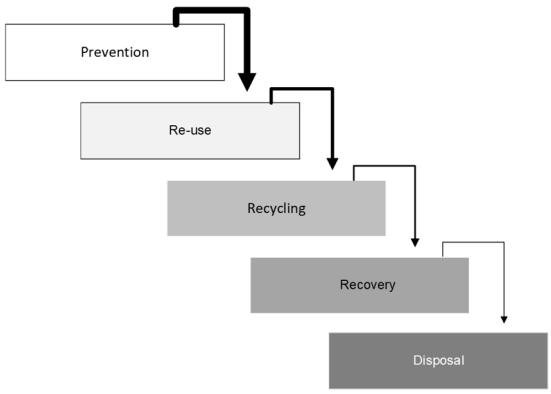


Figure 1. The waste hierarchy, according to [3].

The waste hierarchy distinguishes between reuse and recycling. In reuse, materials are utilized for the same or different purposes without ever becoming waste. In recycling, materials serve as raw materials for producing new products, resulting in a decrease in their level of refinement [3].

The reusability and recycling of building materials have been studied, for example, at the Tampere University of Technology. In 2018, the university conducted a preliminary study on the possibilities of reusing timber structures. This preliminary study provides a comprehensive overview of various timber structures. It includes observations on the disassembly of different joints and the impact of joint technology based on wood. The study indicates that suitable structures for disassembly include glued laminated timber structures, veneered timber structures, and solid wood panel structures [4].

The conclusions of the study also state that the joint location affects the strength and modifiability of wood. The structural properties of wood are best preserved at the joint if the joint can be reused as it is, or if the structure is shortened at the joint area and a similar joint is recreated [4].

As the use of wood as a construction material may increase due to the aforementioned measures, there are limited recycling opportunities for dismantled timber structures within the principles of the circular economy. Therefore, the possibilities for utilizing wood should be expanded through increased reusability. This study focuses on the disassembly of timber structures through the examination of joint characteristics, providing a few examples of connection assessment. The main objectives are to determine how the disassembly of connections can be assessed. The research questions guiding the study are what factors should be considered in defining disassembly, which joint characteristics are significant for disassembly, and how the assessment can be conducted in practice.

Log structures, such as laminated log structures, are excluded as they are not commonly used as load-bearing elements in industrial wood construction. This study focuses on the disassembly of timber structures and their joint components, excluding other building materials.

The purpose of the study is to describe the needs related to timber construction in terms of the design for disassembly. Additionally, the study provides general guidelines for the realization of the design for disassembly. The study addresses the current construction culture, so it does not examine the possibilities for utilizing existing building stock. Only the structural properties that disassembly can affect, such as the load-bearing characteristics of the structure, are discussed. The study also does not delve into post-demolition activities, such as potential uses. However, the study does highlight what aspects should be considered in the design phase to enable future disassembly and subsequent reuse.

2. Materials and Methods

The research contains a literature review to present relevant laws and scientific research results related to the design for disassembly. Based on these, the main focus of the study is on defining a method for assessing the disassembly of typical load-bearing glued laminated (GL) structures and cross-laminated timber (CLT) structures. The proposed evaluation method is applied in detail to two representative examples, and additional examples have been presented for a larger set of structures based on [5].

In Europe, there is currently no implementation of Eurocode or any other equivalent unified regulation for the design of disassembly. The International Organization for Standardization (ISO) published the first version of a standard addressing sustainability in buildings and civil engineering works in 2020 [6]. This standard provides principles, requirements, and guidelines for the design of disassembly and adaptability. It also offers guidance on documentation and implementation. The principles for disassembly according to [6] are presented in Table 1.

Table 1. Disassembly principles according to ISO 20887 [6].

Principles
Ease of access to components and services
Independence
Avoidance of unnecessary treatments and finishes
Supporting reuse (circular economy) business models
Simplicity
Standardization
Safety of disassembly

Ease of access to components and services ensures that disassembly can be carried out without damaging surrounding parts. Independence ensures the performance of ad-jacent components is preserved, and the functionality of connection systems for disassembly and reuse is considered. Simplicity aims to enable the easy identification and handling of disassembled parts. In addition to the principles presented in Table 1 of the standard, four measures are listed that can promote these principles. Firstly, preference should be given to materials or components that can be easily, safely, and cost-effectively replaced or removed and transported. Secondly, enabling disassembly, such as designing lifting or temporary support systems for the dismantling phase, is suggested. Thirdly, the planning of component handling from installation to disassembly and subsequent transportation and reinstallation is emphasized. Lastly, storing spare parts facilitates the replacement of damaged components with new ones in the event of failure [6].

Design for disassembly (DfD) is a term that describes the design aimed at facilitating the utilization of building components, materials, or systems in modifications and after final demolition. Design encompasses the development of installations, components, materials, construction techniques, and information and management systems in a way that facilitates reuse. The goal of reuse is to maximize economic value and minimize environmental impacts by maintaining the circularity described in Section 1. The design for disassembly aims to enable the flexibility, modifiability, and reusability of the entire building. The publication sought influences from different cultures to establish principles for disassembly [7]. The research lists ten principles for disassembly, which are presented in Table 2.

Table 2. Disassembly principles according to Guy and Ciarimbol [7].

Principles	Definition
Document materials and methods for deconstruction	Deconstruction plan and other essential designs such as structural drawing
Selection of materials	Taking into account the future impacts in terms of both quality and reuse
Design connections that are accessible	Visually, physically, and ergonomically accessible connections that can be dismantled without expensive tools, while following safe work procedures
Minimize or eliminate chemical connections	The detachment of components should be easy, and the use of materials causing health and environmental hazards, such as glue, should be avoided
Use bolted, screwed, and nailed connections	Standardized solutions reduce the number of tools required and speed up the work
Separate mechanical, electrical, and plumbing systems	Clear separation of different components from each other

Table 2. *Cont.*

Principles	Definition
Design to the worker and labor of separation	Reduce the complexity of the demolition process
Simplicity of structure and form	Simplicity and standardized dimensions enable easy dismantling
Interchangeability	A modular, independent, and standardized solution increases the possibilities for reuse
Safe deconstruction	Safe work practices and tools, as well as effective material separation, promote workplace safety and reduce risks

One research on design for disassembly with structural timber connections compares approved connections in Europe and their characteristics. The study examines properties related to both DfD and reusability. Three scoring methods, ranging from simplified to more comprehensive, are used to compare the connection properties. Next, a weighted scoring is assigned to the achieved properties, where highly important properties are assigned a weight of 3, important properties a weight of 2, and necessary properties a weight of 1. The research addresses connections between columns and beams, such as panel connections. Within these structures are carpentry connections, fasteners, mechanical connectors, and itemized bolted and screwed connections. Structural connections include various types of carpentry and finger joints [8]. Mechanical connections encompass column shoes, angle plate connections, and manufacturer-developed connections, such as UV-T hook connections [9]. The purpose of this study was to score the properties of these connections. The respective properties and their explanations are presented in Table 3.

Table 3. Common disassembly principles according to Pozzi [8].

The Evaluation Criteria	Definition
Number of elements	Assess designed components for the connection, which affect the price, labor time, and complexity of the joint; simplicity is preferred
Complexity of elements	Assess the complexity of the structural system; simpler solutions provide wider possibilities for reuse
Prefabrication degree	Assess the degree to which the connection system is prefabricated in the factory environment, which affects the number of installation stages, labor time, and costs; it is recommended to maximize the level of prefabrication for connection systems
Ease of assembly	Assess the procedures needed to assemble the components, considering accessibility to connection, requirements for specialized expertise, specificity of tools, and necessary protective equipment; ease of use is preferred
Degree of freedom	Assess the degree of freedom: which direction the connection system is free to move and needs to be locked on site, therefore minimizing the degree of freedom is desired, even though connections systems with a higher degree may be simpler

Table 3. *Cont.*

The Evaluation Criteria	Definition
Structural strength	Assess the strength of the connection; maximizing the structural strength is preferred
Finishing	Assess the final visibility of the connection system, considering accessibility and fire safety; hidden connection system is preferred
Ease of disassembly	Assess the procedures needed to disassemble the components same as ease of assembly; ease of use is preferred
End-of-waste cycle	Assess the amount of waste generated during the dismantling and reassembling process; a minimal amount of waste is preferred
Reusability	Assess the number of times a component can hypothetically be reused, considering factors such as the potential for redesign and quality assurance barriers; maximizing reusability is preferred
Costs	Assess the cost associated with production and/or purchase of connecting and connected elements; prefer low costs

The assessment was conducted using the scale factors. The study found that the overall result did not significantly change when using different weighting criteria. However, a more detailed method allowed for a more nuanced identification of differences between the joints. The study noted that the presented research method posed challenges as the evaluation was partly subjective. While some aspects could be objectively assessed, such as structural strength and the number of elements, other evaluations, such as re-usability, were considered highly subjective in the study. The results presented the best connection system for each of the elements based on the scoring. The key attributes considered were the assessment criteria 4 and 8 from Table 3, which emphasized easy installation and dismantling. The study found that plug-in connection systems were best suited for reusability. These connection systems have the advantage of not requiring the structure to be fragmented into individual parts. The study acknowledges that the weighting of evaluations can influence the outcome, but it is not universally applicable [8].

A study on the structural performance of hybrid timber wall systems for emergency housing facilities has been conducted in Italy [10]. The study performed experimental investigations on the durability of the hybrid timber wall structure and its connections. The purpose of this innovative structure is to enable rapid construction and intact dismantling of the components. The aim is to connect the structures to each other and to the foundations in a way that allows for later disassembly and reuse. The structure itself is designed to be simple and reasonably sized, facilitating the movement of wall elements from one location to another without specialized equipment. Pre-installed connections, called X-Mini, have been developed for the elements using the X-RAD connection developed for cross-laminated timber (CLT) structures. X-Mini is secured to the structure using screws and connected to the desired location with two bolts. For disassembling, only the bolts need to be removed. The connection components are installed at each corner of the structure, enabling wall-to-wall and wall-to-corner connections [10].

Based on the experimental tests and calculation methods, limit values were determined for the elements and connections. Further research needs identified included improving the toughness of the connections and enabling the use of the proposed model for two-story buildings [10]. Table 4 presents the characteristics by which the study assessed the disassembly of the structural system.

Table 4. Disassembly principles according to Casagrande et al. [10].

Features for Disassembly
Assembly's speed and simplicity
Disassembly's speed and simplicity
Prefabrication
Weight
Stiffness of connection system

The study [11] has been conducted in Australia on the dismantlability of light timber frame (LTF) connections. LTF is a standardized lightweight timber frame construction system used in Australia. The research findings indicated that in the disassembly of connections, it is advantageous to use steel or aluminum connections instead of timber connections. The connection components are pre-attached to the elements, for example, with screws, and disassembly does not require detaching the connection from the element. The presented connections in the study have been developed in Europe, but only a few referenced studies have addressed disassembly. The strength of the connections was tested according to ETA and Australian standards by attaching them to graded pine. The weaknesses and areas for improvement related to connection attachment were also highlighted. The observations revealed, among other things, the most preferable screw installation angle. The hypothesis of the preferable installation angle for the connection is based on theoretical deduction, so the study notes that further experimental testing is still necessary. The problematic areas identified in the study included connection alignment. Natural deformations occur in wood due to moisture, making it more challenging to reconnect the connectors, which in turn complicates the detachment and reinstallation of the disassembled structure. The practical structures are longer than the test elements, so deformations can be greater in practical implementations, which may pose even more significant challenges in reconnection [11]. Table 5 presents the estimated characteristics of the disassembly of the connections considered in the study.

Table 5. Disassembly principles according to Yan et al. [11].

Features of Connection System
Standardization
Prefabricate
Stiffness of connection system
Visibility of connection system
Strength and ductility of connection
Feasibility

Another study was conducted with the aim of identifying models of early- and late-stage strategies in the building lifecycle to increase the amount of reusable timber. The research was based on case studies and interviews. According to [12], early-stage strategies include reconnection of connections, structural independence, and the degree of prefabrication. Late-stage strategies were classified as timber reclamation and adaptability. These areas were explored through the case studies. Most of the case studies were in Europe, where efforts were made to reuse building components or enable future reuse. Different strategies and connections were employed in the various case studies to facilitate disassembling. Some projects were designed for disassembly, while others utilized structures for reuse. In certain cases, both early-stage and late-stage strategies were employed, where structures were designed for disassembly and reusable components were incorporated into the construction process. The study identified challenges such as increased construction

costs, compliance with standards, the quality of reusable timber, and longer construction times. One benefit observed in the case studies was the minimal amount of timber waste generated. The study concluded that early- and late-stage strategies are closely interconnected, and the success of these strategies depends on an iterative process led by designers. The study also highlighted the difficulty of measuring the effectiveness of these strategies [12].

3. Proposed Evaluation Method

From the literature review presented in Section 2, it can be observed that the reviewed studies address similar perspectives and criteria for promoting the circular economy. This chapter examines these perspectives and delves into the presented criteria in more detail.

3.1. Comparison of the Presented Criteria

In the literature review presented in Section 2, one publication is standard, while the rest are research studies. The standard is international and does not have a direct equivalent in Europe. The research studies vary from general overviews to case studies focusing on specific aspects. There are also differences in the research methodologies employed. Some studies were more concerned with strategy development, while others examined the actual disassembly of the connected structures. In the study [8], a wider range of connection types was investigated, whereas others focused on the functionality of a few connections in specific scenarios. Both [8] and [11] discussed similar types of connections in their studies.

Among the criteria presented in the study, one publication [7] listed criteria in a different manner compared to the others. The importance of human safety was highlighted in their criteria, and ease of disassembly was mentioned in several criteria justifications. Other studies did not prioritize occupational safety to the same extent in their criteria. While there were similarities in the subject, the approach differed from the others.

The other criteria presented in Section 2 did not differ significantly from each other. In the study [8], structural strength was identified as an important characteristic, although the strength properties of the disassembled elements were not experimentally presented. In the study, the preservation of strength was achieved without causing any damage to the connection. The need for component separation was also addressed. It is necessary to consider how small components of the structural systems should be disassembled. This should be considered during the design phase to ensure a sensible dismantling process. For example, in the study [13] it was proposed, that prefabricated elements should be preserved as they are during the disassembling phase. Pre-fabrication refers to the level of prefabrication of the elements, such as pre-attached connection structures. A higher level of prefabrication facilitates disassembly by reducing the amount of work required during the disassembly phase.

In [10], explicit conditions, research, or analysis regarding the disassembly and preservation of intact connection systems were not presented. Disassembly seems to assume that the bolts in the connections are easily accessible and that the structure does not get damaged during various stages of work. The proposed model is designed for earthquake-prone areas, so its direct application may be challenging due to different strength design requirements. However, the ideology of the connection system may provide benefits in the design of disassembled connections.

In a study [11], the preservation of strength was primarily ensured through mechanical connectors that do not require removal for successful disassembling, in contrast to a connection where, for example, screws would need to be removed. The research methods used are not directly applicable in general, as the strength of Australian timber differs from, for example, Finnish timber. However, the connections have ETA approval, which could enable their use in Finnish construction.

3.2. Criteria Selected for the Evaluation Method

The general criteria for disassembly are defined in ISO 20887 standard [6]. The purpose of the standard is to be widely applicable to the subject, which is not required by the criteria presented in other studies. Although the standard has not yet been adopted in Finland, it is presented in Section 2. It can be assumed that in the future, at least an equivalent to the content of ISO 20887 will be introduced in Finland, as this standard has already been discussed in the context of building lifecycle characteristics.

In this study, the connections are evaluated by comparing them to the assessment criteria presented in [6] in Section 2. Table 6 provides a comparison between the criteria in [6] and the criteria presented above. Only the criteria related to the early-stage strategy from the criteria used by [12] are considered in this study.

Table 6. Comparison of ISO 20887 criteria with other studies.

Criteria	ISO 20887 [6]	Guy and Ciarimbol [7]	Pozzi [8]	Casagrande et al. [10]	Yan et al. [11]	Piccardio and Huges [12]
Ease of access to components	x	x	x	-	-	-
- speed	-	-	-	x	-	-
- visibility of connection	x	x	-	-	x	-
Independence	x	*	*	-	-	x
- degree of freedom	-	-	x	-	-	-
- stiffness of connection	x	-	-	x	x	-
- strength and ductility of connection	x	-	-	x	x	-
Avoidance of unnecessary treatment	x	-	*	-	-	-
- finishes	x	-	x	-	-	-
- minimize or eliminate chemical connections	x	x	-	-	-	*
Supporting reuse circular economy business models	x	-	*	-	*	-
- reusability	x	-	x	-	x	-
- material selection	x	x	-	-	-	-
Simplicity	x	x	*	x	-	-
- joint assembly	x	*	-	-	-	x
- number of elements	x	*	x	-	-	-
- element complexity	x	-	x	-	-	-
Standardization	x	*	-	-	x	x
- prefabrication	x	-	x	x	x	x
- use bolted and screwed connections	-	x	*	*	*	*
- interchangeability	*	x	-	-	-	-
Safety of disassembly	x	x	-	-	-	-
- documentation	x	x	-	-	-	-

Table 6 presents the criteria based on [6] as main headings. The criteria from the comparative studies are listed under the main headings according to the relevant topics they are considered to belong to. An "x" is used to indicate if a particular source mentions the criterion in its justifications. A "-" is used to indicate if the criterion is not mentioned in the publication. Ambiguous points are marked with an "*", indicating that the study references the topic.

The criteria set reveals contradictions. For example, Ref. [8] refers to the visibility of the connection according to Table 3 and states that hidden connections work well in terms of fire design. On the other hand, Ref. [6] suggests that visible connections facilitate disassembling. In this study, finishing refers to on-site actions, such as fire protection. Based on the referenced studies in Section 2, it can be concluded that the desired outcome depends on which characteristic is considered most important. In the assessment, it must be considered that it is not feasible for every structural component to fulfill every criterion, as seen in the conflicting benefits between fire protection and connection visibility.

The most common criteria are ease of access to components, visibility of connection, stiffness, strength, ductility of connection, reusability, simplicity, and standardization as

shown in Table 6. At least three studies adopted these criteria. So, these criteria are considered relevant. When evaluating the ease of access to components, the visibility of connection is also taken into consideration. Factors such as stiffness and strength and ductility of connection can be associated with the assessment of independence. The reusability is a prerequisite for the implementation of the entire process and the other criteria facilitate the implementation of this.

Despite its scope, Ref. [6] does not reference all the criteria described in Section 2. These criteria are presented in Table 7.

Table 7. Criteria outside ISO 20887, where "-" means that the criterion is not mentioned, "*" means that the criterion mentioned, but not used and "x" mean that the criterion is mentioned.

Criteria	ISO 20887 [6]	Guy and Ciarimbol [7]	Pozzi [8]	Casagrande et al. [10]	Yan et al. [11]	Piccardio and Huges [12]
Stiffness of structure	-	-	x	x	-	-
Ease of assembly	-	-	x	x	x	-
Ease of disassembly	-	*	x	-	-	-
Weight	-	-	-	x	-	-
Separate mechanical, electrical, and plumbing systems	-	x	-	-	-	*
Design to the worker and labor of separation	-	x	-	-	-	-
Costs	-	-	x	-	-	x
End-of-waste cycle	-	-	x	-	-	-

Even though this study focuses solely on dismantling, structural strength is still significant. Strength is one of the fundamental aspects of structural design, and it can be stated that a structural element without strength has no value, as in, for example, decayed wood. Therefore, it is important to acknowledge that reliable strength is a prerequisite for dismantling, and design solutions should aim for the good durability of structures. However, its durability depends on other aspects of the design, such as waterproofing.

In Table 7, the most common criterion is the ease of assembly. On the other hand, if assembling is easy, disassembling could also be. The weight mentioned in Table 7 could be included, for instance, as a criterion for ease of disassembling. The advantages of lightness are primarily achieved through material choices, so the impact of connection design on weight differences is not considered significant in this study. Therefore, this characteristic has not been selected as one of the evaluated criteria.

Two studies classify costs as a criterion, while [6] evaluates costs as an action. The structure must be technically disassembled before considering the costs associated with disassembling, as disassembly itself can bring cost reductions. Technical disassembly cost reductions may arise, for example, from the cost of design when documentation of disassembly is improved, the cost of disassembling when disassembly is easier, and transportation costs when components can be made more transportable.

The criterion of ease of disassembling could be combined with the criterion of easy access to structural elements, as indicated by the subheadings in Table 7: speed and visibility of the connection. When examining these two characteristics, various connection features may be relevant, such as a bolted connection protected by a structure. A bolted connection itself is easy to disassemble, but the protective structure may hinder access to the connection components. In this study, the criteria are kept separate for evaluation purposes.

Table 8 presents the evaluation criteria used in this study. The criteria are based on the most common criteria in Tables 6 and 7. Through other studies, the criteria have been modified and refined to align with the objectives of this study.

Table 8. Criteria selected for the evaluation method.

Criteria	Definition	Explanation	Application in this Study
Ease of access to components	Clarity of structural layers, separability of components with different lifespans	Repairability without damaging surrounding parts, visible connections, consideration of workspace, simple steps for performing the action	Assessment of access to the connection, number of work stages, and workspace
Ease of disassembly	Evaluation of actions during dismantling	Considers the level of expertise required, specificity of tools, and necessary protective equipment	Assessment of the detachability of the connection: work methods, quantity and type of tools, and space required for their implementation
Independence	Removal of a specific part without affecting other structures	Separation of materials, suitability of connection types for detachment/modification	Assessment of the impact of surrounding structures on disassembling and the separability of connection components
Simplicity	Clear and straightforward design	Minimal use of different materials and elements, avoidance of decorativeness	Assessment of the number of different connection components, their recognizability, and identification within the structures
Standardization	Specific requirements for products/components/processes	Clear procedures for work stages, transportation, storage, and reuse, uniform properties, enhance future possibilities	Assessment of the functionality of the same connection component for reconnection, considering ease of finding the matching connection pair and performing the reconnection

Criteria 1 and 2 in Table 8 have an important distinction. The first criterion evaluates access to the connection components. The second criterion, on the other hand, considers how the connection itself functions during disassembly. In this study, the term "standardization" does not require its own standard, and adherence to good construction practices is sufficient.

Three criteria presented in [6] have been omitted from Table 8 in this study: avoidance of unnecessary treatments, supporting reuse circular economy business model, and safe disassembling. The criterion of minimal modification needs is relevant, but it may be more suitable for evaluating surface materials or facade structures rather than as a criterion for load-bearing structural components since it refers to constructional insignificant treatments or practices that are generally not applied to load-bearing structures.

To support the implementation of a circular economy model, various actions are sought to advance a model similar to the 6R framework. Designing for disassembly can be considered one of the actions, so within the scope of this study, the evaluation of other actions is not addressed. Safe disassembly includes the documentation of information required by the disassembly plan, including the presentation of structural drawings, as specified in [6].

3.3. Scoring of Criteria

In this study, the connections are evaluated for disassembly based on the criteria defined in Table 8. The fulfillment of each criterion is assessed on a numerical scale from one to four as defined in Table 9. The purpose of the scoring method is to provide a comprehensible representation of the assessment, rather than establish a ranking.

Table 9. Evaluation scale.

1	2	3	4
Criterion is not or almost certainly not met.	There is an opportunity for meeting the criterion, but it is still unlikely.	Criterion is likely to be met.	Criterion is certainly or almost certainly met.

4. Results

This study aims to apply the developed method to assess typical connections used in GL and CLT constructions. Connection components include all the elements that have structural significance. Surrounding structures encompass all other assumed or depicted parts. This study presents two examples of connection assessments as well as additional assessment results for a larger set of connections [5].

The assessment assumes that the building will be disassembled entirely in a logical sequence. This means that non-load-bearing structures are removed before the load-bearing structures, and the disassembling process follows a logical order, avoiding, for example, premature removal of stiffening structures in the early stages of demolition.

The assessment method defined in Tables 8 and 9 is first applied to a glued laminated timber beam-to-column connection depicted in Figure 2.

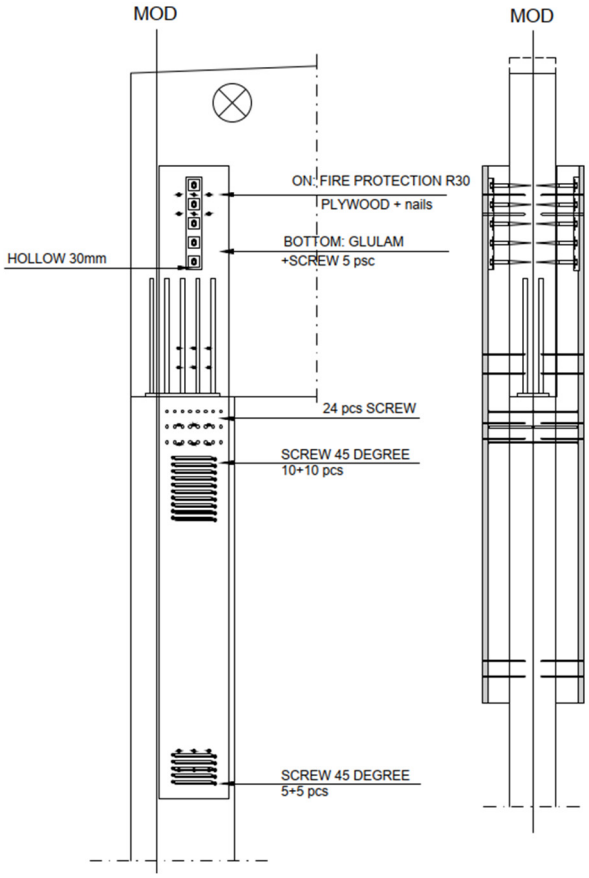


Figure 2. Connection of GL beam and column [5]; side-view (**left**) and front-view (**right**).

Figure 2 consists of joint parts that are screws and nails, threaded rods, and steel panels for supporting pressure. This connection is rather intricate due to its diverse components. For instance, disassembling the wooden panel is rendered impossible due to the adhesive bonding between the column and the panel. However, this limitation becomes irrelevant when the disassembly solely pertains to the work conducted at the construction site. A successful disassembly requires separation at the joint between the beam and the wooden panel, as the threaded rod is affixed with glue in the factory and does not necessitate disassembly. Table 10 presents the disassembly evaluation for the connection.

Table 10. Disassembly evaluation for the GL beam-to-column connection.

Criteria	Points	Justification
Ease of access to components	3	No covering structures
Ease of disassembly	2	Two different types of screws, lots of screws that do not need to be disassembled
Independence	3	Easy to find, members attached to the beam must be removed before the disassembly
Simplicity	2	Large number of screws, from which only some must be opened
Standardization	3	Easy to reuse if bigger screws can be used

The second example is a half-lap joint between two CLT walls [14] as depicted in Figure 3. The connection is composed of several parts, including multiple screws, a waterbar, and an elastic grout. The joint is protected by thermal and steam insulation. Disassembling the joint will be straightforward as long as the screw heads remain undamaged. The evaluation results for the connection are presented in Table 11.

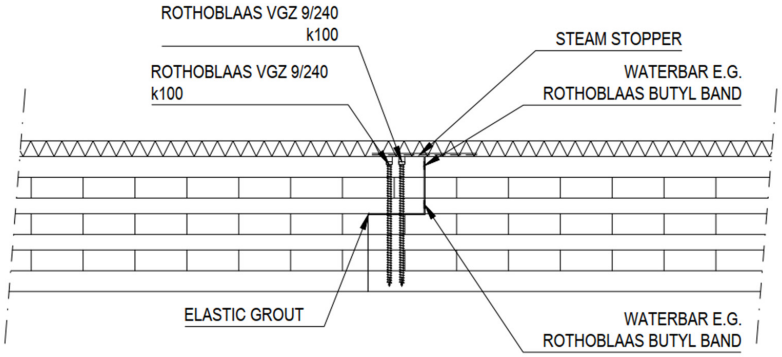


Figure 3. Connection between two CLT walls.

Table 11. Disassembly evaluation for the CLT half-lap connection.

Criteria	Points	Justification
Ease of access to components	3	Thermal insulation is the only obstacle and it is easy to remove
Ease of disassembly	3	Only screws are used in the connection
Independence	3	The wall must be supported when disassembled because originally, they might support each other
Simplicity	2	Large number of screws must be found and opened; elements might get damaged if even one of the screws remains unopened
Standardization	3	Easy to reuse if bigger screws are used

Using the evaluation methodology similar to the examples presented above, the set of various connections depicted in Figure 4 is considered, and the obtained results are given in Table 12. For a detailed reasoning of the evaluation, see [5].

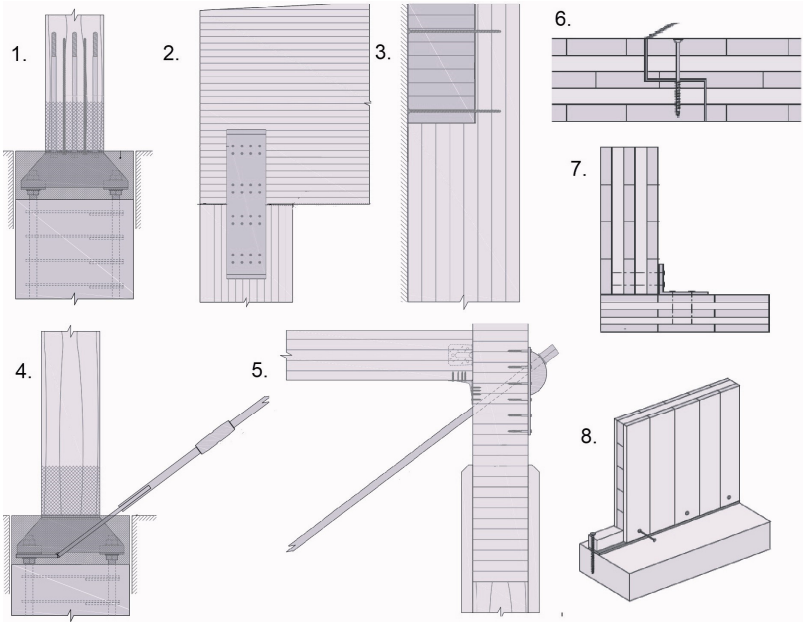


Figure 4. Example picture of connections, according to [14,15].

Table 12. Evaluation summary for connections depicted in Figure 4.

	Connection	Ease of Access to Components	Ease of Disassembly	Independence	Simplicity	Standardization
			Glulam			
1.	Foundation connection	1	1	4	3	3
2.	Beam-and-column connection (see Figure 2)	3	2	3	2	3
3.	Notched beam-to-column connection	3	3	4	4	3
4.	Connection of column base and diagonal stiffener steel rod	1	1	2	3	4
5.	Connection of column top and diagonal stiffener steel rod	3	3	2	3	4
			CLT			
6.	Half-lap connection (see Figure 3)	3	3	3	2	3
7.	Corner connection by angle brackets	3	3	3	2	3
8.	Foundation connection	2	3	3	2	3

Although Table 12 provides scores for disassembly, it is not possible to compare the obtained average scores between GL and CLT structures or even between different connections. Table 12 allows for comparing the fulfillment of individual criteria among

connections or comparing differences between the connection presented in the literature and the project-specific example connection. Generally, the shading in Table 12 is predominantly light, indicating preferable conditions for the disassembling of load-bearing timber structures.

From Table 12, it can be seen also that the two first criteria are least fulfilled in connection to the foundation. In GL structures, simplicity and standardization are in general well-fulfilled characteristics. Based on the assessment result for the standardization criterion, the connection structures have a great potential for component reuse. Similar connections are used in other buildings, and the connections can be modified for successful reuse. The clear weakness in the CLT structures is the simplicity criterion, which can be attributed to the higher number of connection points per structure.

Although the background of the study and the resulting criteria focus on research conducted in timber construction, certain generalizations can be derived from the assessment. Generalizations can be found in the justifications of the assessments, such as the high number of connection points. Other design choices that impair disassembly include molding and a large number of different components per connection. From a disassembling perspective, desirable characteristics include a low number of connection components and clear connection systems.

5. Discussion

The presented study is focused on the general needs for the design for disassembly of timber structures. Based on the literature survey, the collection of factors that influence the design for disassembly is defined, and an evaluation method is proposed. The method is applied to typical GL and CLT applications to analyze their characteristics for potential disassembly and reuse. In the referenced studies discussed in Section 2, the evaluation criteria for design for disassembly do not differ significantly from each other. The non-standard criteria adhere to similar topics as the standard itself, see Tables 6 and 7, respectively. Therefore, it can be concluded that the emerged criteria for disassembly are currently sufficient for assessing the phenomenon within the scope of this study.

5.1. Reliability

The main objective of this study was to assess the disassembly of connections. The assessment was carried out using the criteria presented in Table 8, and the criteria were applied to actual structures as summarized in Table 12. In this study, the practical evaluation of connections was subjective, as the scoring used in the study was very rough. The purpose of the scoring is to assess the necessary attributes for disassembling connections in a simple manner. With this method, objective evaluation may be challenging because the evaluation criteria are indicative and leave room for interpretation by the assessor.

The assessment of disassembly is influenced by the disassembling method, whether only a part or the entire building is being disassembled. The underlying assumption of this study is that the building is fully disassembled. However, the perception of disassembly can vary significantly if there are different methods. Therefore, the initial assessment of disassembly made in the early stages of a project may change because the final method is decided only at the end of the building's life cycle. However, it is hoped that the initial evaluation conducted in the early stages would assist in decision making and practices in the later stages.

The assessment does not reveal the structure's tolerance to damage or its strength properties. These can be considered prerequisites for a structure to be designed for disassembly. Based on the literature, it can be stated that large structures, which typically include load-bearing elements, have a high damage tolerance [13]. Therefore, load-bearing elements should not have any issues with maintaining their strength properties for reuse.

Standardization is one of the selected features for disassembly. Although standardization addresses the possibilities for reuse, it does not aim to determine the reuse destination of a structure in advance. Standardization seeks to establish the conditions for finding

alternative options, which would facilitate the progression of structural design toward the goal of designing a structural system that functions based on the available properties of the structures. The challenge in this lies in the fact that the properties of reusable structures cannot be known in advance, and in the design phase, it may not be possible to allocate which building components will be reused.

The examination of connections is a very narrow part of the entire building. However, in the literature discussing disassembly, there is often a reference to connection structures. Many studies focusing on disassembly also delve into the functionality of connection components. This indicates that the assessment of a building's disassembly should begin with the examination of connection components.

5.2. Effect of Limitations

The literature presented in the study focuses on timber construction, but the generalizations presented in Section 3.2 can be further expanded, for example, to steel beams. When the connection structure is divided into parts, similarities can be found in the connection structures of different building materials, such as the use of molding at the connection. Additionally, the criteria listed in ISO 20887 are intended to be universally applicable. Therefore, for similar characteristics, it can be assumed that they are equally usable for disassembly regardless of the building material.

The developed criteria are based on the literature. From the referenced studies, publications listing criteria for disassembly or examining the characteristics of connections mentioning disassembly were selected. Based on the criteria used in the research publications, a set of criteria applicable to construction culture practices was created. The number of publications used as references is not critical because the criteria identified in these publications are consistent.

In addition to the criteria, other considerations are presented in Section 2. One of these considerations is the cost. However, cost estimation is not relevant if the building cannot be technically disassembled. The costs associated with design for disassembly focus on the costs of building design and the material costs of connecting components, which were not possible to evaluate within the scope of this study. The actual disassembling takes place decades later, making it currently difficult to predict the costs at that time.

The number of examined connections was limited to fit within the scope of the study. From these examples from the literature, different types of connections relevant to disassembly were chosen for assessment. These connection solutions represent commonly used connection types.

Disassembly also aims to promote emission reductions in building materials. This study does not take a stance on which building components produce the most material emissions. The emissions are calculated per unit weight, and the significance of load-bearing structures can be assumed to be substantial. Therefore, it is important to strive for emission reduction in load-bearing structures through material choices or reuse.

The limitation of the study to industrial construction is based on the research conducted by [4], where, for example, stud-frame walls, commonly used in single-family housing, are not considered as easily reusable as, for instance, column-beam systems. Industrial components are usually larger, which enhances their damage tolerance.

Timber construction is also associated with log construction. Disassembling and reusing log structures have been more common than with other timber structures. By focusing on industrially produced element structures, the study concentrates on projects implemented on a larger scale.

The examination in this study only encompasses solutions currently used in structural design. This is intended to highlight how the current approach can affect disassembly. However, design for disassembly should not be confused with a demolition plan, which may be required for the reuse of old building stock. Therefore, problems related to the demolition phase, such as the reuse destinations of reusable parts, are excluded from the study.

In addition to load-bearing capacity, structures generally have other properties, such as fire and acoustic properties. The significance of these properties for disassembly was not addressed in this study.

5.3. Recommendations

The study demonstrated that design for disassembly is not solely about favoring screws and bolts. The selection of joint components is an important aspect of the topic, but Table 8 presents a comprehensive scope. Therefore, the proposed method can be used as support for structural design. If one wanted to score the disassembly characteristics of a building to create a point value indicating its disassembly potential, a more detailed scaling would be required. The scoring cannot be used as is to create an average for assessing the disassembly of a connection, as especially the first two criteria, easy access to components and ease of disassembling, can hinder the actual disassembling phase. An alternative approach, for example, would be to define minimum threshold values for all criteria. Therefore, the outcome of this study serves as a guiding document for structural design.

When assessing disassembly, the assumption was made that the structure would be disassembled as a whole, just as it arrived from the factory. In the design process, it is important to take this into account and clearly define the sufficient level of disassembly. It needs to be defined in which parts the building components are disassembled.

Based on Table 12, there is significant potential for disassembly in timber construction. Utilizing the criteria more extensively would provide better insights into its effectiveness and possible areas for improvement. When utilizing the criteria, the suitability for the specific application needs to be considered. In this study, the avoidance of unnecessary treatment was excluded due to its inapplicability, as the finishing work for load-bearing structures typically only includes technically necessary actions.

As given in Table 9, the rating of each criterion was done on a scale of 1 to 4. It should be noted that the rating value consequences are strongly linked with the evaluated criterion. For example, getting the lowest rating for ease of access might prevent disassembly, but the lowest rating for standardization affects only component reuse. Similarly, the highest rating of four in the presented assessment in this study does not imply that the evaluated characteristic is achieved in the connection in the best possible way. The suitability of connection structures for disassembly can still be improved, and the criteria developed in this study can aid in this improvement.

5.4. Future Research

Studies and methods for designing disassembly should be explored for other building materials. In addition to structural capacity, the functionality of other characteristics of the structure during disassembly requires research.

No practical experiments were conducted in this study. Practical experiments could provide more precise scoring for certain characteristics and verify that the designed connection is indeed possible to disassemble. Also, this will need the comparison of different types of joints implemented for the same purpose.

The study presented inconsistencies in the criteria. More detailed guidance would require investigating these contradictions to ensure more consistent use of suitable criteria in different situations.

Although experimental testing on disassembly was found in the referenced study presented in Section 2, the connection types may not be directly applicable universally due to different guidelines and material properties. However, many studies noted the use of highly prefabricated joints, known as plug-in joints, that can be assembled on-site without additional work. Such connections could also be investigated for general use in timber construction.

If the disassembly of different structural solutions were to be more comparable, the assessment would need to be made more objective. The same criteria and scoring could be used in a study examining how different experts in the field score the connections.

Implementing comprehensive scaling for different connection types could also facilitate more precise scoring of different characteristics.

The evaluation of the criteria did not consider the significance of individual criteria for the goal of intact disassembly. Therefore, the scoring presented in the study should be refined by establishing minimum values for each criterion to determine if the goal of the disassembly design has been achieved. This would reduce ambiguity regarding the success of disassembly, which could be facilitated by assigning weighting factors to determine the significance of the criteria.

The assessment of the connection could be expanded to entire building systems, in which case the importance of independence would increase. In this study, the assumption was that the surrounding structures could be detached without damaging other structures, if there was no other information regarding disassembly.

To establish a functional business model for disassembly, the cost implications in the design and construction phases should be investigated. The following questions could be asked when the cost-related matter is studied: Does design for disassembly lead to significant cost increases in the design phase? Can design for disassembly accelerate the final process, reducing costs in the disassembly phase, and how does the cost of old material compare to new material to make reuse economically viable? Costs must consider the increasing prevalence of timber construction, which may reduce unit costs. The costs of pilot projects may not necessarily indicate the actual scale.

Durability is a prerequisite for disassembly, as a faulty structure cannot be reused, at least not in its entirety. The purpose of disassembly is to reuse structures before the end of their life cycle. It would be important to understand how durability and life cycle design affect when a disassembled part can still be reused and how to ensure the safety and healthiness of the structure after disassembly. A reusable structure requires approval and proof of suitability for its intended use. Standardized methods are needed to establish reuse practices in the construction industry.

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