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Master's Programme in Building Technology

Technical requirements for assessment and certification of existing timber structures for reuse in construction

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Henri Ranttila

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Author Henri Ranttila

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Thesis supervisor Prof. Gerhard Fink

Thesis advisor MSc Hannes Tähtinen

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Abstract

Demolished buildings are seen as a source of timber for reuse and cascading purposes. Reuse of this resource would both increase the available timber material for construction of timber buildings while simultaneously decrease the volume of incinerated timber.

This master's thesis investigates the certification requirements and assessment methods necessary for reuse of structural timber members. A literature review is amended by interviews with stakeholders in regulatory agencies and with experts in assessment of timber structures. Reuse is defined to distinguish reuse from remanufacturing or cascading. Verification on the construction site is investigated in detail as it is currently the only available certification method for reused construction products in Finland. Requirements for health and safety of reused structural timber are set equal to those set for new structural timber products. The effects of these requirements are investigated both the point of view of harmful substances and of mechanical capacity. Volumes-, building types-, and ages of demolished timber structures are determined to recognize the structure- and member types which are available for reuse purposes. Based on the certification requirements, structural members consisting of composite materials are currently not assessable. Presence of documentation is concluded as an important factor for assessment of structural timber members. Undocumented structures would require a thorough assessment of all physical properties relevant to meeting the essential technical requirements. Based on findings from both the literature and interviews, evaluation criteria are constructed to identify the reuse potential of different member types from a technical point of view. Results from the evaluation indicate that dimensional timbers could be visually graded for reuse through a modification of current visual grading rules. Glue laminated timber (GLT), log constructions and trusses present the greatest reuse potential of evaluated timber members.

Keywords Timber, reuse, assessment, certification, circular economy

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Tiivistelmä

Purettavien puurunkoisten rakennusten osille nähdään potentiaalista uudelleenkäyttöä uusissa rakennuksissa, sekä potentiaalista kierrätystä sahatavaraksi tai jatkojalostusta insinööripuutuotteiksi. Purettavien rakennusten hyödyntäminen samalla sekä lisäisi käytettävissä olevien puuresurssien määrää että vähentäisi polttoon menevän purkupuun massaa.

Tässä diplomityössä tutkitaan puurakenteiden uudelleenkäytön vaatimuksia sekä teknisten ominaisuuksien arviointimenetelmiä uudelleenkäytön teknisestä perspektiivistä. Työn kirjallisuuskatsausta täydentävät haastattelut niin viranomaisten kuin rakenteita ja puutuotteita arvioivien asiantuntijoiden kanssa. Uudelleenkäyttö määritellään nykyisten säännösten mukaisesti, jotta säilyy selvyys siitä, missä menee uudelleenkäytön ja kierrätyksen raja. Vain uudelleenkäytettävät tuotteet voidaan hyväksyttää rakennuspaikkakohtaista varmentamista hyödyntäen. Uudelleenvalmistetut tuotteet tulee hyväksyttää Rakennustuoteasetuksen mukaisesti. Työssä tutkitaan rakennuspaikkakohtaisen varmentamisen asettamia vaatimuksia uudelleenkäytettäville puurakenteille. Uudelleenkäytettävät ja uudet puurakenteet nähdään olevan tasavertaisessa asemassa määräysten vaativuuden näkökulmasta. Vaatimuksia tutkitaan sekä vaarallisten aineiden, mikrobikasvuston, että mekaanisen lujuuden ja jäykkyyden näkökulmista. Purettavien puurakennusten ikä-, rakennustyyppi-, ja purkuvolyymijakauma selvitetään, jotta tutkimuksessa keskitytään lähitulevaisuudessa purettavista rakennuksista saatavilla oleviin rakenteisiin. Rakennuspaikkakohtaisessa varmentamisessa tulee osoittaa olennaisten teknisten vaatimusten toteutuminen koko uudelleenkäytettävälle rakenteelle. Vaatimusten osoittaminen yhdistelmärakenteille, joissa esiintyy puun, liiman ja metallisten liittimien lisäksi muita materiaaleja, on erittäin vaikeaa eikä tällaisille rakenteille nähdä uudelleenkäyttöä ainakaan samassa käyttötarkoituksessa. Dokumentaation saatavuuden nähdään helpottavan arviointia merkittävästi. Lopuksi purettavista rakennuksista saatavien rakenteiden uudelleenkäytön potentiaalia arvioitiin teknisestä näkökulmasta. Sahatavaran uudelleenkäytön mahdollistaisi visuaalisten lajitteluohjeiden päivitys purettavalle sahatavaralle. Liimapuu, hirsirakenteet ja ristikot ovat lupaavimmat rakenneosat uudelleenkäyttöön, kunhan liitoksille saadaan kehitettyä arviointimenetelmä.

Avainsanat Puurakenne, uudelleenkäyttö, arviointi, hyväksyntä, kiertotalous

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Preface and acknowledgements

Upon completion of this master's thesis my six-year journey as a student in Aalto University will come to an end. These years of university studies taught me not only about the science behind practical engineering but also about the complexity of our everyday society. I'm grateful for all my friends and family for support and companionship during my whole study path.

Special thanks to Sweco for sponsoring this master's thesis, and for the subject and advise from Hannes. Supervision from Gerhard provided me with deeper insight into the science of timber structures. I want to thank every interviewee for their valuable insight. Without the interviews many of the conclusions could not have been drawn.

Henri Ranttila

Rome, 25.05.2024.

Symbols and abbreviations

Symbols

$E_{0,k}$	Characteristic modulus of elasticity parallel to grain
$E_{0,mean}$	Mean modulus of elasticity parallel to grain
$E_{90,mean}$	Mean modulus of elasticity perpendicular to grain
$f_{c,0,mean}$	Mean compressive strength parallel to grain
$f_{c,0,k}$	Characteristic compressive strength parallel to grain
$f_{c,90,k}$	Characteristic compressive strength perpendicular to grain
$f_{m,k}$	Characteristic bending strength
$f_{t,0,k}$	Characteristic tensile strength parallel to grain
$f_{t,90,k}$	Characteristic tensile strength perpendicular to grain
$f_{v,k}$	Characteristic shear strength
$f_{v,mean}$	Mean shear strength
$f_{v,r,k}$	Characteristic rolling shear strength
$f_{v,r,mean}$	Mean rolling shear strength
G_{mean}	Mean shear modulus
q_k	Characteristic distributed live load
Q_k	Characteristic point live load

Abbreviations

CLT	Cross laminated timber
CPR	Construction product regulation
DfD	Design for deconstruction
DOL	Duration of load
DoP	Declaration of performance
EAD	European assessment document
ETA	European technical assessment
GLT	Glue laminated timber
hEN	Harmonized European norm
LVL	Laminated veneer lumber
MOE	Modulus of elasticity
MOR	Modulus of rupture
MUF	Melamine urea formaldehyde
NDT	Non-destructive testing
OSB	Oriented strand board
PUR	Polyurethane
PZT	Lead zirconate titanate

reCPR	Revision of the construction product regulation
RF	Resorcinol-formaldehyde
SG	Specific gravity
SLS	Serviceability limit state
TAB	Technical assessment body
ULS	Ultimate limit state

1 Introduction

1.1 Background

Increasing the share of timber as a construction material remains a key objective for the Finnish government (Ministry of the Environment Finland, 2016). Additionally, the European commission aims for 70% of construction and demolition waste to be recycled (Waste Framework Directive 2008/98/EC). These objectives are amended with the goal of a carbon neutral Finland by 2035 (Ilmastolaki 423/2022). However, the nature restoration legislation proposed by the European Commission (Proposal for a regulation of the European Parliament and of the Council on nature restoration, 2022) creates uncertainties to the available volume of timber harvested from forests. Thus, an increase in the use of timber requires other solutions such as structures with greater resource efficiency or reutilization of timber from existing building stock. Reutilization of structural timber would also lead to lower levels of demolition waste as most timber from demolition activities is burned for energy in Finland (Cristescu et al., 2021).

At present, the quantity of reutilized structural timber remains low. Reasons for this include uncertainties in strength and safety of reused timber, low economic efficiency, and lack of actors in the reutilization production chain (Niu et al., 2021). Incentives for reutilization have remained low due to the relatively low cost of timber as Finnish sawmill industry produces sawn products and plywood above the rate of domestic consumption. Around 80% of the production was exported in 2022 (Metsäteollisuus Ry, 2023).

The new land use and building act set to enact on 1.1.2025 (Rakentamislaki 751/2023) outlines procedures for an increased reutilization of structural parts. These include a requirement for a pre-demolition audit. Information of the structures to be demolished would yield valuable data for both current demolition waste separation and for increased knowledge about the type, quantity, and condition of the structures. This information could be used to further steer research into the direction where significant gains in material reutilization are achievable.

1.2 Research objectives

Assessment and certification of timber structures for reuse presents technical and regulatory challenges. Standardized assessment and certification methods are needed to ensure the reused timber and timber assemblies meet the safety and serviceability criteria set by agencies regulating the construction industry (Harte et al. 2020; Niu et al. 2021). Assessment of reutilized timber, especially in the case of reuse where the timber member is not remanufactured, requires new approaches as there are limited possibilities to use the same assessment methods as in the current production practices of new timber products.

Assessment and certification methods for reuse of old structural timber in structural parts of new buildings are studied and evaluated in this master's thesis, with a focus on available assessment methods and current and future certification requirements. In this master's thesis, reuse refers to an old load-bearing structural timber being reused in with only a minor transformation, e.g. resizing. Reutilization refers to all reuse and recycling possibilities, including cascading. An example of reuse would be the use of a glulam beam from the roof of an old sports hall as a roof beam in a new industrial building.

This master's thesis aims to clarify the reuse potential of different timber member types. An evaluation of the reusability of different structural members through application of information from literature, along with results from interviews, creates preliminary guidelines to recognize which structural member types are most likely to be reused from a technical point of view.

1.3 Research approach

This master's thesis begins with a literature review into the relevant research, regulations, statistics, and reports related to reutilization of existing timber structures. Research into reutilization of timber has been ongoing for the past twenty years with more interest and articles being released in the past five years. The relevant requirements for assessment and certification are investigated through interviews as some of the essential information is not available through a literature review only. In addition to the literature study, actors including regulatory agencies are interviewed to find the barriers for certification of reused timber and plans to remove the potentially unnecessary barriers.

At first, in Section 2, the literature review presents the distinction between reuse and cascading of structural timber products. Furter on in this study only reuse, as defined in the proposed revision of the Construction Product Regulation (reCPR) (European Commission, 2022), is investigated. Section 3 focuses on the relevant national and EU laws and regulations related to timber construction products. Buildings are designed with modern Eurocodes and reused timber must either conform to the requirements set in the Eurocodes or the structure must be proven reusable by other, currently unknown means.

In Section 4 the literature review presents available timber material, both in quantity and quality, to determine which structural systems are found in the soon to be demolished structures. Based on previous research, for example by Huuhka et al. (2018), certain structural timber parts are more suitable for reuse than others. Massive timber in the form of log homes, glue laminated timber (GLT) structures, and floor beams constructed of laminated veneer lumber (LVL) are highly suitable for reuse. On the contrary, light framed built-in-place stud walls and light-frame elements may contain hazardous materials and -coatings, the presence of which prohibits reuse. Section 5 of this thesis presents the available assessment methods for evaluating physical properties of to-be reused timber structures. Assessment alleviates the uncertainties related to presence of harmful substances, deterioration, and mechanical strength of the old timber structures. Relevancy of results from the various assessment methods are critically evaluated.

After completion of the literature review a series of interviews were conducted with relevant stakeholders in the reuse process of timber structures. The methodology and results of the interviews are found in Section 6. Findings from both the literature review and interviews are utilized in Section 7, where reuse potential of various structural timber member types are evaluated. The potential focuses on technical potential only.

2 Reuse and cascading of structural timber

Literature presents two primary methods for reutilization of structural timber; reuse and cascading (Rose et al., 2018; Cristescu et al., 2020; Harte et al., 2020; Planke et al., 2023). Proposed revision of the Construction Product Regulation (reCPR) further divides reuse into two categories. According to reCPR, reuse as-is includes use of the structural member in the same application as previously with no transformative actions, while remanufacturing contains transformative actions beyond cleaning, repair, and regular maintenance. Further on in this master's thesis, reuse refers to reuse in structural applications with only minor transformation e.g. resizing, while cascading refers to transformation beyond resizing.

Cascading of structural timber involves disassembly of the structure into its elements. These disassembled timber elements are then reprocessed into new products, including manufacture of structural products such as CLT (Rose et al., 2018; Llana et al., 2022). Cascading enables a larger variety of applications for reclaimed timber in comparison to reuse. Currently, most buildings are demolished, and in Finland the resulting timber waste is predominantly burned for energy (Cristescu et al., 2021). Based on findings from literature, a proposal for the framework in reuse and cascading is seen in figure 1.

To increase suitability of material for reuse and cascading, Harte et al. (2020) propose that demolition of buildings should move towards building deconstruction. Demolition aims for rapid toppling of the structure. This is often done with excavators, especially when buildings with a small footprint are demolished. Materials are separated for recycling and some furnishings such as windows are often removed prior to demolition. Building deconstruction would yield material of larger dimensions. Harte et al. (2020) add that deconstruction increases value of the separated materials while increasing labour costs compared to demolition.

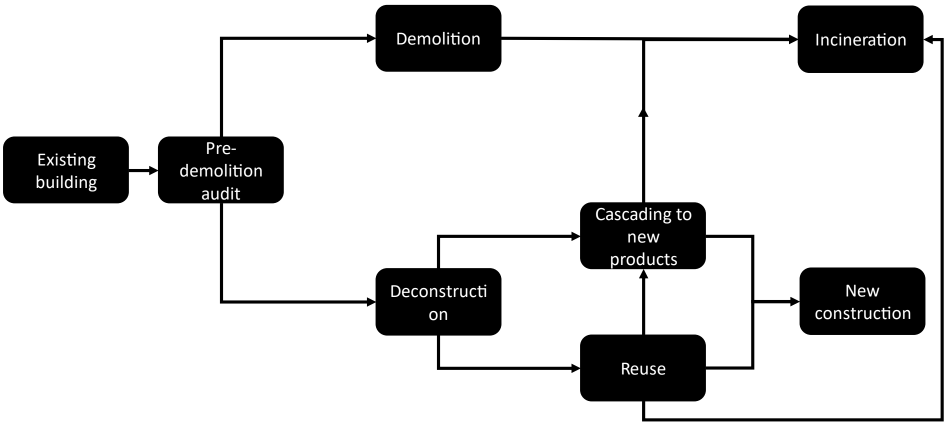

Figure 1. A proposal for reuse and cascading process of structural timber

2.1 Reuse of structural timber

Waste Framework Directive of the European Parliament (Waste Framework Directive 2008/98/EC) defines reuse as “any operation by which products or components that are not waste are used again for the same purpose for which they were conceived”, while preparing for reuse means “checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing”. In context of structural components, it remains unclear at which point an existing structure would become waste in a reuse-oriented deconstruction approach. Further on in this master’s thesis reuse refers to structural timber being reused as structural members with only minimal processing.

Hradil et al. (2014) explain that reuse creates valuable secondary products where the original timber does not downgrade into a lower grade product. Five categories for the size of a reused part are proposed: buildings, structures, structural members, basic structural elements, and building blocks. Reuse value increases when the categorial size increases, while reuse applicability increases in smaller sizes.

Historically, reuse of timber houses, as presented by Puurunen et al. (2000), resulted from the fact that all timber products were handmade and structural components had value due to their embedded labour. Houses constructed of logs were either moved or separated into two parts due to practical reasons including inheritance of the house by multiple children. A low quantity of nailed connections simplified the deconstruction and reconstruction of log houses. Carpentry items including windows and doors were removed prior to deconstruction of the log frame itself. The frame was reconstructed at the new site with possible additions. Reuse of materials from an existing house decreased labour needs and construction time. Puurunen et al. (2000) add that current interests for moving buildings stem from their historical significance. Historical buildings may be in the way of redevelopment and a practical way of conservation is to move the structure to a new location. Houses are sometimes moved in one piece with only the foundation remaining at the original construction site.

Previous examples of reuse, including those presented in the work of Puurunen et al. (2000), were limited to buildings remaining in their previous application or they were downgraded for example from a house to an agricultural building. Furthermore, Puurunen et al. (2000) explain that regulations related to design and construction were local and less detailed than the national and European regulations of today. Zoning laws emerged because of devastating fires in densely built timber city centres. The 1931 zoning law was later repealed by the building law of 1958 (Rakennuslaki

370/1958), which stated that “A building must be constructed in a way that it meets reasonable criteria for strength, health, fire safety, and beauty”. There were no formal building codes for structural design. To compliment this, the rebuilding office of the Union of Finnish Architects began publishing RT (RakennusTieto) cards which contained standards for structural types and -details (Rakennustieto Oy, n.d.). The present land use and building law in Finland (Maankäyttö- ja rakennuslaki 132/1999) and its decree (Ympäristöministeriön asetus kantavista rakenteista 477/2014) set Eurocodes as the design standard for load-bearing structures. Modern building laws and regulations thus apply to reuse of structural parts. Standards and legislation are seen as the most important barriers to reuse according to personnel in various positions of the construction industry surveyed by Hradil et al. (2014). Figure 2 illustrates an example of a process within reuse of timber structures. The process reflects the deductions from literature made by the author of this master’s thesis.

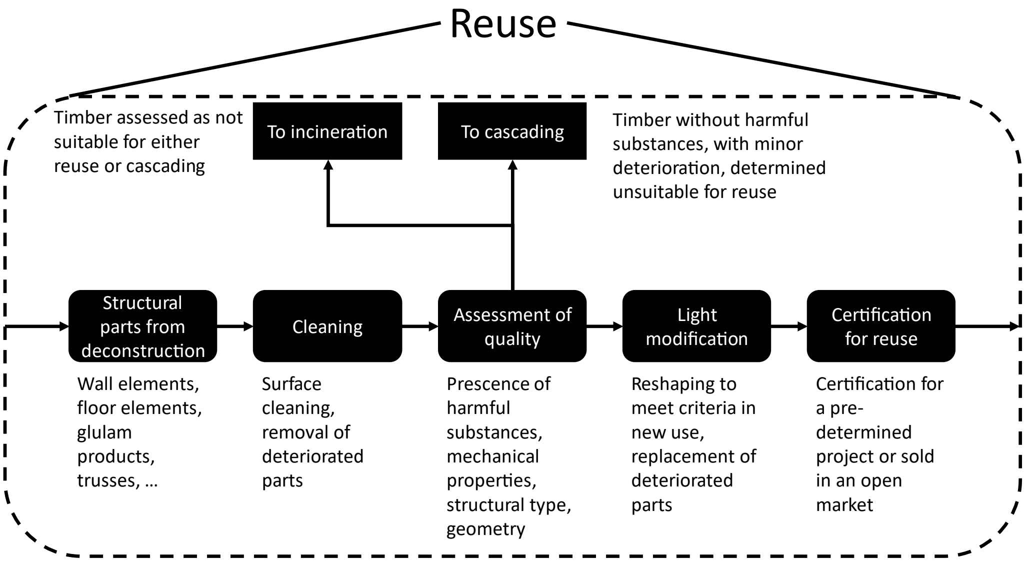

Figure 2. A proposal for the process of reusing structures based on the author’s deductions from various literature

Structural parts may be reused “as is” or through modification of geometry and form. Planke et al. (2023) investigated how structural timber in old Norwegian barns could be reused in construction of a new museum building. The old barns were 3D scanned and the resulting data of the geometry of the barns was used in the design of the museum. Reuse of structures from old barns “as is” proved to be challenging as the demands of a barn differ from those of a museum building. As a result, the timbers from the barns were modified to meet the structural design of the museum. A visual assessment of the properties of the old timbers was performed by certified craftspeople when the barns were dismantled. Visual assessment according to INSTA 142:2009 Nordic visual strength grading rules (SFS, 2010a) provided strength classified timber as specified in EN 338 "Structural timber – Strength classes" (SFS, 2016a). This allowed for Eurocode 5 (SFS, 2004a) based design of the load bearing timbers in the museum. Planke et al. (2023) conclude that challenges in reuse of existing structural timber included the non-standard dimensions of the reclaimed timber. Architectural design of the museum was based on dimensions of the reclaimed timber.

Case studies for reuse of buildings often include the structures being designed for deconstruction. Such structures are included in the review article from Cristescu et al. (2021). Principles in design for deconstruction (DfD) include designing for ease of repair and deconstruction without breaking the structures. Demountable structures, screwed connections, and modular dimensions aid in deconstruction and reuse of the components. One of the case study structures in the article from Cristescu et al. (2021), a temporary market hall constructed in 2016 with glulam columns and LVL beams, was later deconstructed and moved to a new location. The process was followed by Sandin et al. (2023) from deconstruction stage of the market hall in Stockholm to reconstruction as a sports hall in Mölnlycke, Sweden. Advantages of design for disassembly included ease of dismantling and adaptability in reuse. Disadvantages found include the amount of planning needed in deconstruction and protection of structural elements from weather during disassembly.

2.2 Cascading of structural timber

Risse (2019, p.108) defines cascading of timber products as "the sequential use of one unit of a resource in multiple material applications with its use for energy generation as final step". A proposed process for cascading is seen in figure 3. The process is created based on deductions of the author of this master's thesis. Fraanje (1997) explains that cascading prolongs the duration of a mass of timber staying in use. Cascading lowers the quality of timber only in small steps. This quality preservation arises from the use of secondary timber in high-value applications. One cascading chain proposed by Fraanje includes the cascading of pine beams into floorboards, of floorboards into window frames, of window frames into flank boards, and of flank boards into particle boards before incineration. The longevity of materials exceeds three hundred years in this cascade chain. The quality of old timbers is one factor promoting their cascading. Preserved old timbers are often of greater quality than timbers sourced from modern managed forests (Fraanje, 1997).

Cascading timber from demolition waste may find uses in production of CLT (Rose et al., 2018; Stenstad et al., 2021), GLT (Irle et al., 2018; Risse et al., 2019), and OSB (Schild et al., 2019). In comparison with reuse, cascading provides wider possibilities for reutilization of structural timber as the application and form of the timber change from the original use. A case study of GLT production from recovered timber boards (Irle et al., 2018) indicates that around 30% of the demolition waste timber received by a GLT factory could end up in a finished GLT product. They estimate that even with such a low yield the process could become viable with the high value of produced laminations. Due to current regulations, the presence of multiple species of timber in a GLT product manufactured via cascading prohibited the use of these products in structural applications.

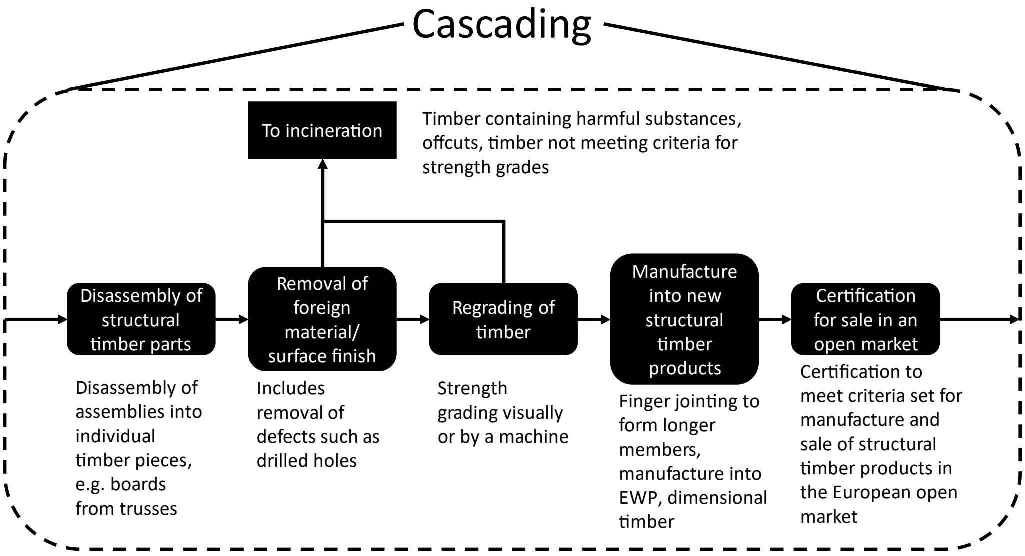

Figure 3. A proposal for the process of cascading process of structural timber. Framework created based on author's deductions from various literature

Current cascading efforts focus on transforming structural timber into wood chips for production of wood-based particleboards (Szichta et al., 2022), while most timber demolition waste is incinerated (Cristescu et al., 2021). Technical challenges prevent a wider application of cascading, especially for higher value products. Llana et al (2022) prepared CLT panels from reclaimed European oak. CLT samples consisted of three layers and samples were made combining both primary and reclaimed oak. After both visual and dynamical strength grading, the CLT panels containing reclaimed timber in the outer layer showed significantly lower MOR values under a four-point bending test while there were only minor differences in MOE compared to the MOE of CLT made from primary timber. Duration of

Load (DOL) effect was concluded as one of the reasons for this. Finger joints failed in the CLT panels made of reclaimed oak and more research is needed to verify strength of glued joints in secondary timber products. Rose et al. (2018) found similar results. The reclaimed timber, in this case softwood, resulted in lower MOR values. New grading methods are needed as reclaimed timber does not follow the same MOE – MOR -relationship that is used to mechanically grade primary timber.

Cascading provides a transformation-based approach while reuse retains the value of a timber product. As seen from the previous case studies, cascading creates reliable structures when reclaimed timber and primary timber are combined. Cascading allows for use of current timber grading practices, with additional requirements for grading set by the engineering properties of reclaimed boards.

3 Regulations

In Finland, national laws and decrees determine the requirements for construction while permitting and monitoring are managed by municipal building control authorities. European Union wide regulations and directives have affected the regulatory framework in construction since 1995, when Finland joined the EU. Regulations such as the construction product regulation (Regulation (EU) No 305/2011) rule the marketing of construction products in the European Union free trade area. However, despite the construction product regulation, responsibility of mechanical resistance, fire safety, stability, and other requirements applicable to buildings are retained at the national level. Regulations among construction products and in this thesis the regulations related to timber structures and -products are investigated for information of the regulatory requirements for reuse of structural timber.

3.1 Laws, decrees, and municipal building control

Legal foundation for construction of buildings is set by the Land Use and Building Act of 1999 (Maankäyttö- ja rakennuslaki 132/1999). This law includes zoning-, building permitting-, design-, and construction qualification requirements. In 2025 a new Construction Law will enact and repeal the building part of the former Land Use and Building act of 1999 (Rakentamislaki 751/2023). The new Construction Law increases the role of climate change mitigation and digitalization in construction. Despite the changes in environmental- and digitalization parts of the legislation, many sections of the new Construction Law follow the principles of the old Land Use and Building Act. Section 4 of the new Construction Law outlines the essential technical requirements for construction of buildings. These include strength and stability requirements of the structure for the duration of its design service life. The law states that “mechanical rules and commonly accepted design principles or reliable test results should be used” in design of load bearing structures. Furthermore, construction products should reliably meet the design criteria for strength and stability. In addition to strength and stability of structures, Section 4 in the new Construction Law determines basis for fire safety, health risks to occupants, noise levels in buildings, and energy efficiency, all of which are relevant parameters in reuse of structural timber products.

More detailed requirements for both design of buildings and characteristics of construction products are set in their corresponding decrees. Many of the decrees related to the Land use and Building act of 1999 have been repealed and replaced since 2000. Eurocodes and its national annexes repealed the National Building Code of Finland for load bearing structures in September 2014 (Ympäristöministeriön asetus kantavista rakenteista 477/2014). Fire safety and structural reliability under fire are regulated in decree 848/2017 (Ympäristöministeriön asetus rakennusten paloturvallisuudesta 848/2017) and energy efficiency and building envelope tightness requirements are laid out in decree 1010/2017 (Ympäristöministeriön asetus uuden rakennuksen energiatehokkuudesta 1010/2017).

The new Construction Law (Rakentamislaki 751/2023) states that municipal building control authorities are responsible for accepting building permits, for accepting designs, for supervision of construction, and for general guidance of construction related activities in municipalities. The responsibility of municipal building control is limited to guidance and overseeing and in the end the party engaging in a building project is responsible for ensuring that the design and construction meets the related laws, decrees, and regulations. While the municipal building control agencies ensure the laws and decrees are met, there are sections in the decrees which allow for deviation of the regulations. Section 57 of the new Construction Law states that for a special reason, a building control authority may allow for minor deviations of the regulations in the building permit, on the condition that the essential technical requirements are met.

3.2 Design codes

Structures meet the essential technical requirements for strength, stability, and serviceability when they are designed with Eurocodes and their national annexes (Ympäristöministeriön asetus kantavista rakenteista 477/2014). Eurocodes relevant to design of timber structures include:

- Eurocode: Basis of structural design (SFS, 2002a)
- Eurocode 1: Actions on structures, Part 1-1: General actions, Densities, self-weight, imposed loads for buildings (SFS, 2002b)
- Eurocode 1: Actions on structures, Part 1-2: General actions, Actions on structures exposed to fire (SFS, 2003)
- Eurocode 1: Actions on structures, Part 1-3: General actions, Snow loads (SFS, 2004b)
- Eurocode 1: Actions on structures, Part 1-4: General actions, Wind actions (SFS, 2005)
- Eurocode 5: Design of timber structures, Part 1-1: General, Common rules and rules for buildings (SFS, 2004a)
- Eurocode 5: Design of timber structures, Part 1-2: General, Structural fire design (SFS, 2004c)

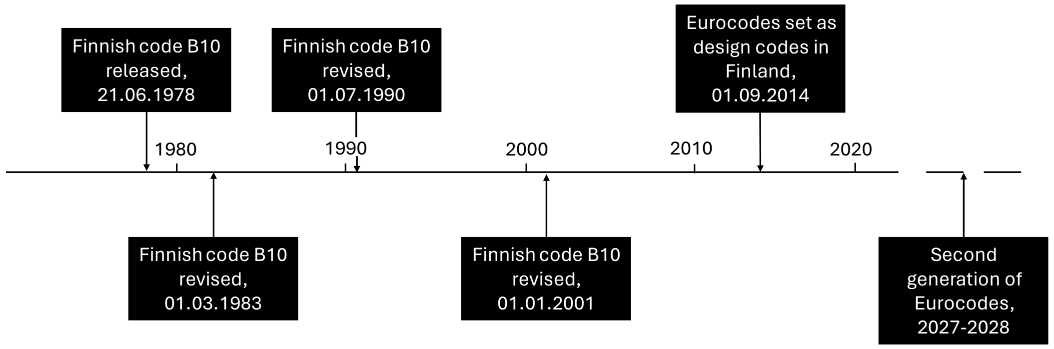

Figure 4. Timeline of timber design codes in Finland

Eurocodes superseded former Finnish codes for structural design in 2014. A timeline of timber specific design codes is found in figure 4. As structures are designed using Eurocodes, the role of former Finnish codes has diminished. However, in the case of reuse of existing structural timber products, old standards and building codes are relevant as most of the available timber for reuse has been designed and constructed with codes preceding the Eurocodes.

The Finnish codes were first published by Ministry of the Interior in 1976 (Ministry of the Interior Finland, 1976). Part B1 in the Finnish codes includes minimum loadings for buildings. Characteristic values are given for live loads on floors both from people and items or equipment, live loads on railings and walls from people, snow loads on roof, and wind loads. In part B2 general rules for load bearing structures are laid out and chapter four of this part is timber specific. General rules are given for qualifications in strength grading of structural timbers. External moisture levels should be accounted for in design, yet no specific rules are given. Finnish code B10, published by Ministry of the Environment Finland, contains rules for design of timber structures (Ministry of the Environment Finland, 2001). The original code B10 was released in 1978 and later revised in 1983, 1990 and 2001. The code specifies structural materials, basis of design, dimensioning of some structural members (beams, columns, mechanical and glued connections, and members containing wooden panels), protection against rot, and construction of timber structures. Load bearing design in part B10 may be calculated with either limit state design or allowable stress design. Finnish code B10 includes fire design of timber structures.

Eurocodes and former Finnish codes differ in both the characteristic loadings, allowable deformations, and material design properties. Therefore, relative differences in design capacities depend on type of loading, member type, and serviceability limits in the specific application. A simplified comparison of a GLT roof beam in a structure in Helsinki area designed with Finnish codes is compared against Eurocodes, with detailed calculations presented in Appendix A. The span is equal to 12 meters. A beam is first designed for ULS and SLS in Finnish codes and the resulting GLT beam cross-section is then evaluated in Eurocode-based design for differences in both ULS and SLS. This simplified calculation does not account for fire design or any other design consideration and is intended to only give an indication of the magnitude of changes in design capacities.

As seen from the calculations in Appendix A, allowable loading of the GLT beam differs in SLS deflection design, while there are practically no differences in ULS design. In Eurocode-based design, stricter SLS deflection criteria, increased characteristic snow loading, and creep induced design deflection all decrease the allowable loading. In this example case the allowable distance between adjacent roof beams would decrease by 50%.

Snow presents a major loading for any roof structure in Finland. Characteristic snow loads are based on meteorological data of the 98th percentile snow water equivalent load. In the Finnish code B1 from 1976, imposed load due to snow varies from 1.4 kN/m² on the western coast of Finland to 1.8 kN/m² in eastern Finland. The national annex for Eurocode 1 specifies greater characteristic snow loads. Western coast snow loads are 2.0 kN/m² while in northern Lapland and northeastern Finland the snow loads are a maximum of 3.5 kN/m². Differences in characteristic snow loads in selected cities are shown in table 1.

Table 1. Characteristic snow loads in selected Finnish cities, a comparison between Eurocode 1 (EN 1991-1-4, national annex) and Finnish code B1.

Snow load (char.) / City	Eurocode q_k (kN/m²)	Finnish code B1 q_k (kN/m²)
Helsinki	2.5	1.8
Turku	2.5	1.4
Tampere	2.5	1.7
Kuopio	2.5	1.8
Vaasa	2.0	1.4
Oulu	2.4	1.6
Rovaniemi	3.0	1.8

3.3 Certification of structural timber products

Structural timber products are a permanent part of buildings and are thus regulated by the EU Regulation No 305/2011. This regulation is commonly known as the Construction Product Regulation (CPR). The open market in

European Union requires harmonized legislation for construction products. CPR regulates construction products mainly through CE-marking. The CE-marking is compulsory for all construction products for which a harmonized European standard (hEN) has been published. Harmonized standards exist for most timber products, and some are listed in table 2. According to Regulation (EU) No 305/2011, these standards were created to ensure that construction products meet the essential technical requirements listed in part 4.1 of this thesis. The manufacturer of a CE marked construction product draws a Declaration of Performance (DOP) for the product and assumes responsibility for its conformity (Regulation (EU) No 305/2011). The harmonized standards were created with focus on products manufactured industrially in factories. The standards and their quality specifications do not recognize reused products and thus CE-marking of reused timber products via hEN standards remains impossible.

Another voluntary avenue in Regulation (EU) No 305/2011 for CE-marking of construction products is possible through European Technical Assessment (ETA) if a European Assessment Document (EAD) exists for the construction product. Technical Assessment Bodies (TAB) issue EAD's. The manufacturer of a construction product requests for an ETA process where the TAB assesses the quality of the construction product manufacturing and evaluates the process of internal quality management. If approved, the manufacturer may label the construction product with a CE-marking and create a DoP for the product (Regulation (EU) No 305/2011). Certain standards and EAD's are listed in table 2. In Finland, Eurofins Expert Services Oy is the only TAB. As with the harmonized European standards, the ETA's are available only for factory produced timber products. CPR does not currently recognize reused structural timber products.

A proposal for revision of the CPR (reCPR) (European Commission, 2022) alleviates the Union wide regulatory scheme for reused and remanufactured construction products. Proposed article 10(2-3) enables nationally legislated exemptions for reused and remanufactured products from the Construction Product Regulation on the condition that the reused products do not circulate outside the member state. National exemptions remain to be legislated as the proposed revision of the CPR awaits agreement from the European Parliament. These national exemptions are investigated more in the interview part of this thesis.

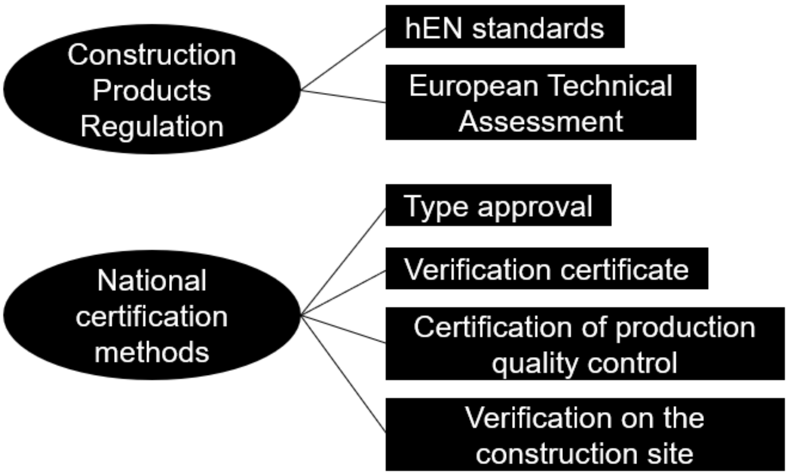

Figure 5. Avenues of construction product certification through Construction Products Regulation (EU) or national certification methods.

In addition to the current CPR there are national procedures for certification of construction products. Law for certification of some construction products (Laki eräiden rakennustuotteiden tuotehyväksynnästä 954/2012) specifies four avenues for certification. These are type approval, verification certificate, certification of production quality control, and verification on construction site. Type approvals are given by Ministry on the Environment Finland. They are given separately for each construction product. As of February 2023, no type approvals exist for timber products. Verification certificates are issued for products which are not suitable for type approval. Internal quality control of manufacturing is a key criterion for attaining verification certificate and reused products that are not manufactured are not suitable for a verification certificate. The same issue arises with using production quality control for certification of reused construction products. The final national certification method, verification on construction site, remains the only avenue for reuse of structural timber products. Building control authorities require verification on construction site if there are no certifications ensuring that the construction product meets the essential technical requirements. The party engaging in a building project has responsibility for obtaining a verification on construction site. Building control authorities only approve or disapprove certificates presented by the party engaging in a building project and do not assess the products themselves. An overview of the six different verification methods is seen in figure 5.

Verification on the construction site implies by its name that it would be an alleviated certification process. This is not the case. A better translation of the verification process could be "verification of a construction product based on the essential technical requirements in the intended application". Details of verification on the construction site are investigated through interviews in Section 6.

Table 2. Harmonized European standards (hEN) and European assessment documents (EAD) for selected structural timber products and metal type connectors.

Timber product/connector	European standard: EN European Assessment Document: EAD
Wood-based panels for use in construction	EN 13986 (SFS, 2015)
Glued laminated timber and glued solid timber	EN 14080 (SFS, 2013)
Strength graded structural timber with rectangular cross section	EN 14081 (SFS, 2019)
Prefabricated structural members assembled with punched metal plate fasteners	EN 14250 (SFS, 2010b)
Structural laminated veneer lumber	EN 14374 (SFS, 2005b)
Connectors	EN 14545 (SFS, 2008)
Dowel-type fasteners	EN 14592 (SFS, 2022)
Solid wood panelling and cladding	EN 14915 (SFS, 2020)
Structural finger jointed solid timber	EN 15497 (SFS, 2014)
Cross Laminated Timber	EAD 130005-00-0304 (EOTA, 2015)
Screws and threaded rods for use in timber constructions	EAD 130118-01-0603 (EOTA, 2019a)
Three-dimensional nailing plates	EAD 130186-00-0603 (EOTA, 2018)
Timber building kits	EAD 340308-00-0203 (EOTA, 2019b)

4 Material stock in buildings

This section focuses on presenting the potentially reusable structural timber. Both quantity and form of structures are introduced. Data is gathered from quantified embedded timber in section 4.1 as well as from demolition statistics presented in section 4.2. The information on different building types gathered from literature later assists in evaluation of reusability of structural timber with relation to assessment and certification criteria.

4.1 Quantity of timber in buildings

The quantity of embodied timber in buildings may be estimated with the combination of floor area, age structure and building type specific intensity of timber per floor area. In a literature study by Nasiri et al. (2021) they estimated the total mass of timber in existing Finnish residential building stock. Finland has a long tradition of constructing buildings, especially residential buildings, from timber. Nasiri et al. (2021) combined the age structure and floor area of Finnish residential houses with timber intensity from Swedish data as there was no data available of the timber intensity in Finnish buildings. They conclude that the total mass of embodied timber in attached and detached houses equals 17.5 million tons. Around 25% of the embodied timber could be applicable for reuse according to Höglmeier et al. (2017), based on a study of the embodied timber in Bavarian houses. Thus, the total reusable mass of timber in Finnish residential buildings equals around 4.5 million tons. For context, in 2022 the Finnish sawmill industry produced 11.2 million cubic meters (around 4.5 million tons) of sawn timber products (Metsäteollisuus Ry, 2023).

Use of timber in buildings is not limited to attached and detached houses and the total mass of reusable timber increases when other building types such as agricultural buildings, sports halls and commercial buildings are included. However, no studies included the timber intensity in these building types. This data would be useful to further determine the full reuse potential of timber structures.

4.2 Demolished timber structures

Embodied timber represents the maximum potential for reuse. Available demolition statistics present information of the age and building type of demolished structures. This aids in identifying the currently available timber and timber members from demolition as varying structural systems have been used in the past one hundred years. Potential for reuse depends on the structural system, with light framed walls being less suitable for reuse than massive timber (Huuhka et al., 2018).

Demolition rates for all building types and -materials were studied in a statistical analysis by Huuhka & Lahdensivu (2016). Data includes Finnish statistics of demolished buildings between 2000 and 2012. 48% of demolished buildings and 33% of demolished floor area had a timber load-bearing structure. Timber buildings had a comparatively low mean floor area of 123 m^2. Of the timber structures, building types with the greatest demolished floor area include detached houses (1.3 million m^2), commercial and office buildings (310 000 m^2), public buildings (285 000 m^2), industrial buildings (270 000 m^2), warehouses (249 000 m^2), utility buildings (127 000 m^2), agricultural buildings (121 000 m^2), and row houses (102 000m^2). Demolished area in other building types represent a total of 288 000 m^2. A large share of detached houses results in the low mean floor area of demolished timber buildings. Figure 6 represents this data graphically.

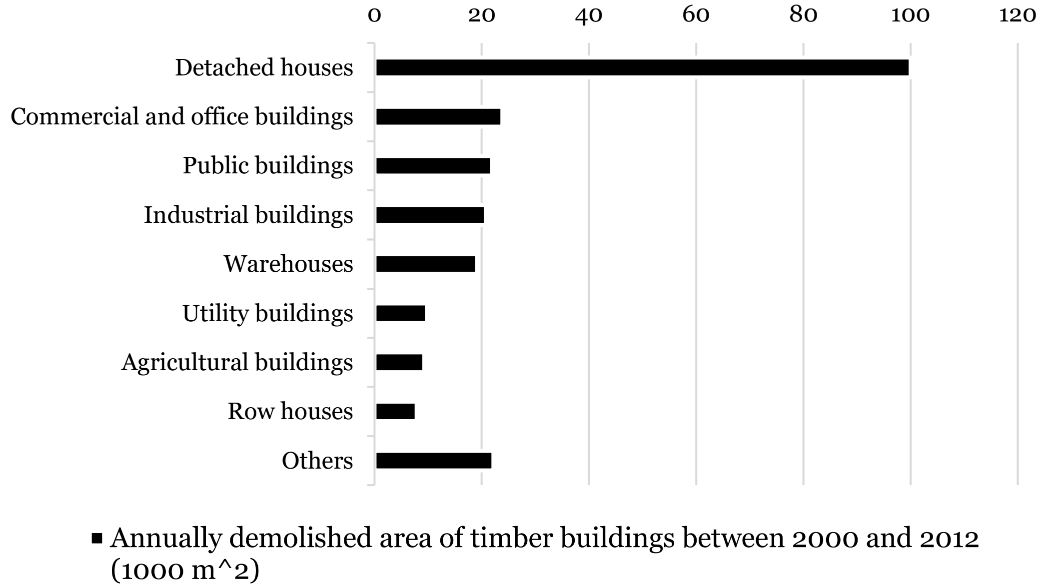

Figure 6. Floor area of annually demolished timber buildings between 2000 and 2012. Data from Huuhka & Lahdensivu (2016).

The data presented by Huuhka & Lahdensivu (2016) details the building year of different building types demolished between 2000-2012. This data does not separate the buildings by their load-bearing material. However, another table in the study states that timber is the primary load-bearing frame material in the following building types: detached houses, row houses, dormitories, utility buildings and agricultural buildings. This leads to the deduction that in these building types the building age at demolition -data represents primarily timber buildings.

Huuhka & Lahdensivu (2016) state that detached houses are demolished at a comparatively old age with a 64-year mean age at the time of demolition. Agricultural buildings and dormitories are demolished at mean ages of 35 and 36 years, respectively (Huuhka & Lahdensivu 2016). Mean age at demolition poorly describes the age distribution of demolished buildings. For example, within the category "detached houses" demolition rates above 100 000 m^2 per decade apply to houses built in several decades from 1920's to 1960's. Figure 7 provides a graphical, more detailed representation of the construction date of timber buildings demolished between 2000 and 2012. Detached houses and public buildings are chosen due to their relatively large floor area of demolished timber buildings as well as the fact that 87% of detached houses and 34% of public buildings with a known structural material are specified as timber buildings.

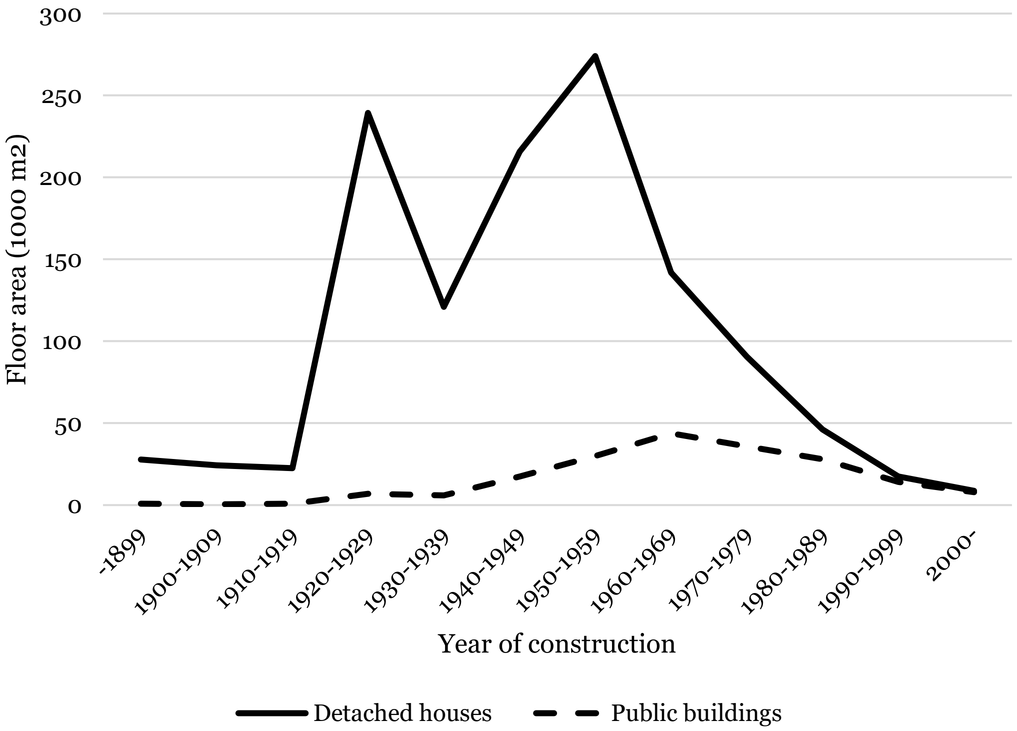

Figure 7. Construction date distribution of timber buildings demolished between 2000 and 2012. Data from Huuhka & Lahdensivu (2016).

4.3 Structural systems in demolished buildings

The structural systems found in timber buildings vary depending on the building type and year of construction. Huuhka et al. (2018) outlined the historically used structural systems in their research paper. These include log construction, light-frame construction, trusses, and massive timber structures. Table 3 presents information about the different structural systems and -parts in different building types and -building eras.

4.3.1 Log construction

Huuhka et al. (2018) state that earliest records of log construction in Finland date back to the 11th century. Log construction remained the primary form of timber construction until the 1940-1960 period when material shortages led to development of light-frame timber construction. Log construction consists of horizontal timbers stacked on top of another. Both round logs and logs with hewn sides are used. Logs are scribed to fit tightly together, and the ends of logs at corners are notched to interlock with the adjacent wall. Logs are tied together with pins made of either timber or steel. Vertical holes are drilled to the logs to accommodate the pins. Round logs are not clad on the exterior while hewn logs are often clad with timber boards. Floor and roof structures were made of logs until the 19th century when sawn timber replaced logs in these structural parts. Log construction regained popularity in late 20th century when laminated logs entered the market along with machine cut surfaces and corners.

Log houses from prior to 1940's are still present. Around 25 million square meters of timber houses constructed prior to 1940 remain in 2017 according to statistics from Nasiri et al. (2021). Annual demolition rates for timber structures constructed prior to 1940 exceed one hundred thousand square meters indicating a modest potential of log houses for reuse from a quantity point of view.

4.3.2 Light-frame timber buildings

Light-frame timber buildings originated in the early 1830's in Chicago, USA (Sprague, 1981). At the time, as expressed by Sprague (1981), a system called balloon framing was used. In balloon framing the wall studs extend from the foundation to the roof structure. According to Huuhka et al. (2018), light-frame emerged as the primary load-bearing structure in detached houses during the post World War 2 reconstruction period in Finland. The post-war houses were built using a balloon-frame. Huuhka et al. (2018) explain that light-frame structures consist of timber with dimensions smaller than in log construction. This led to material savings. Framing materials were sometimes pre-cut, and construction of houses took less time than in log construction.

Cristescu et al. (2021) describe that vertical loads are carried by studs with dimensions of 48-100 x 100-198 mm^2. They are spaced 50-70 cm apart and are tied together with top and bottom plates. External surface of the studs is lined with either diagonal timber boards or in newer construction with wooden or gypsum panels. This provides stability to the structure. Diagonal boards do not provide wind protection and a tar paper protects the structure from wind and moisture. Exterior cladding consists of timber boards in either vertical or horizontal direction. Planer chips and other wood-based materials insulate the cavities between studs in post-war houses while mineral wool insulation fills the cavities in houses built after the 1960's (Huuhka et al., 2018).

Rafters support the roof structure and floors are commonly supported by dimensional timbers, as expressed in Huuhka et al. (2018). Trusses have replaced rafters as the load bearing structure in timber roof structures. The post-war timber houses were predominantly built in-place. Production of houses from prefabricated elements has seen a rise in popularity since the 1980's. Huuhka et al. (2018) estimate that 40% of timber buildings are currently made of prefabricated elements. They add that elements are of higher quality and more suitable for reuse than built in-place structures. Both planar and volumetric light-frame elements are used to build detached houses and up to eight storey apartment buildings (Puuinfo Oy, 2020a).

Data presented by Nasiri et al. (2021) shows that in 2017 the total floor area of attached and detached houses concentrates to construction dates between 1940 and 1990. Future demolition of timber houses would thus consist mainly of built-in place light-frame structures.

4.3.3 Portal frames and trusses

Far and Far (2019) introduce the form and applications of portal frames. Portal frames are structures where the load bearing horizontal and vertical structures are connected by a moment resistant joint. This results in an open floorplan with a high ceiling. Typical spans range from 15 to 20 meters. Portal frames are erected in a short period of time due to the possibility of prefabrication. Portal frames were first used in the 1960's. Timber portal frames are found in industrial-, warehouse-, agricultural-, and sports buildings.

Historical load-bearing forms of portal frames are explained by Huuhka et al. (2018). Timber boards in a portal frame were at first connected by nailing. In the 1950's glues were introduced resulting in hybrid timber connections of nails and glue. Glue lamination evolved in the 1960's after which timber in portal frames has been primarily glue laminated. A bolted moment resistant connection is often found between the vertical and horizontal members of modern portal frames. This leads to ease of disassembly later when the building is deconstructed.

Basics of trusses and their use are found in the article from Huuhka et al. (2018). Trusses are a material efficient structure type for spans and roofs. Trusses consist of top- and bottom chords connected by web diagonals and -verticals. The members are made of sawn or planed timber, and in newer truss structures also from glue laminated timber. Truss structures are highly optimized to meet the use specific criteria of loading, span, inclination of top- and bottom chord, and designated points of support. Connections between the chords and web are either metal nail plates or in the case of older trusses a nailed connection with timber boards transferring the load from one member to another.

Huuhka et al. (2018) present that use of prefabricated trusses started in late 1970's and remains the primary structural system for roofs in detached houses. In addition, timber trusses are found in modern timber apartment buildings, agricultural buildings, and commercial buildings.

4.3.4 Massive timber structural frames

Massive timber framed buildings are presented in the work of Huuhka et al. (2018). Massive timber structures consist of cross laminated timber (CLT), glue laminated timber (GLT), and laminated veneer lumber (LVL). GLT consists of multiple sawn or planed timber lamellae glued together with a longitudinal grain orientation in every lamella. Thickness of lamellae varies and according to modern standard SFS-EN 14080 (SFS, 2013) individual lamellas are 6 to 45 mm in thickness. Both beams, columns, and frames are made with GLT. Post and beam structural frames are a common use for glue laminated timber. GLT containing building types include commercial- and industrial buildings. Cristescu et al. (2021) further explain the benefits of massive timber structures. Post and beam structures are open due to the skeletal frame. This allows for an adaptable floorplan where partition walls are movable.

Structure and applications of LVL products are introduced by Puuinfo Oy (2020b). LVL consists of thin veneers glued together. Usual veneer thickness is 3 mm, and the veneers may be glued either with parallel or perpendicular grain orientation. Beams, floor joists, columns, frames, trusses, and carpentry products are made with LVL. However, use of LVL increased only in the 1990's (Ilgin & Karjalainen, 2022) and thus buildings soon demolished are not likely to contain LVL products.

CLT, as explained by Puuinfo Oy (2023), consists of timber boards laminated in a crosswise direction. This produces massive panels which are used in wall- and floor structures. CLT elements are machined in factory within an accuracy of +/- 1 mm. CLT structures include multi-storey apartment buildings. Self-weight of CLT in relation to its compressive strength is lower than in competing materials, namely reinforced concrete. CLT provides stability in addition to resistance against vertical loading. According to Cristescu et al. (2021), CLT emerged in the early 2000's in Finland and thus the availability of CLT for reuse purposes remains low for many decades.

Table 3. Structure types and structural parts found in buildings of different building types and -eras. *Note.* Adapted from “Puurakenteiden uudelleenkäyttömahdollisuudet.” by Huuhka, S., Köliö, A., Annila, P., & Poti, A. (2018). *(Muuttuva rakennettu ympäristö; Nro 4), (Rakennetekniikka. Tutkimusraportti.; Nro 165),* p.22. Tampere: Tampere University of Technology. OpenAccess.

Building type	Structural system	Structural parts/-elements
Residential houses -1940	- Log construction - (Light-frame)	- Logs - Sawn timber - Roof rafters
Residential houses 1940-	- Light-frame - (Log construction)	- Logs - Planed and laminated logs - Dimensional timber - Roof rafters - Trusses - Prefabricated elements
Apartment buildings 1940-1950	- Light-frame	- Sawn timber - Roof rafters
Apartment buildings 1990-	- Light-frame - Post and beam structure - CLT	- Dimensional timber - Volumetric elements - LVL - CLT - Trusses
Early commercial buildings -1960	- Light-frame - Portal frame, - (Log construction)	- Sawn timber - (Logs) - GLT
Commercial buildings 1960-	- Post and beam structure - Portal frames - (Light-frame)	- GLT beams and columns - GLT portal frames - Trusses - Sawn timber
Industrial- and warehouse buildings	- Post and beam - Portal frame	- GLT beams and columns - GLT portal frames - Trusses - Sawn timber
Agricultural buildings	- Portal frame - Post and beam - (Light frame)	- GLT portal frames - Trusses - Sawn timber
Sports buildings	- Portal frame - Post and beam	- GLT beams and columns - GLT portal frames

5 Assessment of existing structural timber

This section examines the available assessment methods for existing timber structures intended to be reused. Assessment of the different physical properties yields information on whether the structure meets essential technical requirements in reuse. These essential technical requirements were investigated in Section 3 of this thesis. Assessment is essential to ensure the reused timber material does not contain harmful substances (Zhu et al., 2022). In addition, the properties of timber may have changed due to long term duration of load (DOL) effects (Svensson, 2009) or due to moisture related deterioration (Mindess, 2007). Currently, production of new structural timber products and their assessment relies on standardized production methods or on third-party monitoring of the production process. As explained in Section 3 of this thesis, there are no standardized procedures for certification of existing timber structures for reuse. Thus, assessment should meet the criteria for a verification on construction site -certification. These criteria depend on the individual municipal building control authorities. Specifics of the criteria are investigated through interviews with relevant authorities in section 6 of this thesis.

In Finland there are ongoing development projects to form assessment criteria for GLT and later also for reused dimensional timbers. City of Helsinki circular economy cluster administrates the first development. Rakennustietosäätiö (directly translated to Construction information foundation) leads the second development project called UURAKET.

5.1 Three-dimensional measurement of structures

Geometry and dimensions of a building or its structural parts may be evaluated through documentation or on-site measurements. The original documentation, when available, contains the relevant architectural and structural dimensions of the building. However, availability of documentation decreases when the age of the building increases. Structural drawings detail the dimensions of individual structural members and may even contain the material properties of the timber itself. With available documentation the need for on-site measurements decreases drastically. On-site dimensional measurements should in this case focus on confirming that the dimensions of structural members match with their documentation.

A detailed on-site measurement procedure is required whenever documentation does not match with the true dimensions of the members or in the case of missing documentation. Methods for measurement of building structures are presented by Norin (2023). Measurements are either linear or angular, and these measurements complement each other. Traditional measurement techniques include linear measurement with measurement tapes and angular measurement with theodolites. This labour-intensive process is expensive and modern measurement tools such as laser scanners have replaced manual measurements in documentation of existing structures.

Norin (2023) presents state of the art three-dimensional measurement techniques for documentation of existing structures. Three-dimensional laser scanners create a digital point cloud which represents the building. Surface laser scanners are divided into three primary categories depending on their mode of operation. The first one is pulse scanner. Pulse scanners measure the time of flight to a surface and back to the scanner. The two other scanner categories introduced in the paper by Norin (2023) are phase scanners and triangulation scanners. Phase scanners operate on the principle of measuring phase shift of the emitted and received signals. Triangulation scanners utilize a laser emitter and a camera that records the location of the laser point. With a known distance between the laser emitter and the camera, the location of the laser point in the camera image indicates the distance to a surface. Laser scanning provides a highly automated and accurate representation of the building. These three-dimensional measurements are valuable in the pre-demolition stage while manual measuring may be more practical for the dimensions of individual structural members post-deconstruction.

Laser 3D scanning was used in the case study by Planke et al. (2023), where an old barn was 3D scanned using a modern Leica BLK 360 laser scanner. This scanner operates on the principle of pulse scanning. Results from this case study indicate a highly accurate 3D scan with an average error of just 3 mm. A Building Information Model (BIM) was created from the 3D scan data. This scan in conjunction with manual measurements provided the dimensions of the existing timber members. Mechanically damaged parts of timbers were easily identified from the 3D BIM.

5.2 Hazardous substances and microbial growth

5.2.1 Hazardous substances

Hazardous substances within timber structures may be in the form of coatings, treatment agents, and in connected parts containing hazardous substances. Presence of substances listed in the REACH and POP regulations of the EU probits the reuse of the structural timber member (Zhu et al., 2022). Removing hazardous substances from circulation ensures that they do not concentrate in the reuse chain (Huuhka et al., 2018). This section focuses only on hazardous substances and their detection, while rot and microbial growth are discussed later in section 5.2.2.

Detection of possible hazardous substances is essential to ensure that the reused timber does not pose danger to the health of building occupants. According to Huuhka et al. (2018), hazardous substances such as asbestos, PCB, PAH-compounds, and lead are not commonly found in the timber parts, apart from old lead-based paints. These substances are commonly removed when the timber is separated from the attached parts which may contain the hazardous substance.

Huuhka et al. (2018) introduce timber treatments and surface coatings which are today classified as hazardous substances, and which may be found in old timber buildings. Harmful pressure treatments include Chrome-Copper-Arsenic (CCA) and Chrome-Copper (CC), and they were used from 1950's to 2000. These are known carcinogens. Timber treated with creosote was extensively used in railway sleepers and telephone poles. Creosote may sometimes be found in structural timber. Use of creosote in buildings was banned in 2003. Creosote is a carcinogenic compound and released when treated timber is cut or released during demolition. Chlorophenols are timber preservatives which were used until 1980's. The health effects of chlorophenols are still unknown. In old timber buildings there is a noticeable odour due to release of chlorophenols.

Current assessment methods related to hazardous substances in structures were designed to ensure safe demolition and safe treatment of demolition waste. The Finnish audit for hazardous substances RT 103501 (Rakennustieto Oy, 2022) does not examine the existing structures for potential reuse. Structural members are not evaluated with indoor environmental emissions in mind. A wider audit for hazardous substances, as proposed in research paper from Zhu et al. (2022), should be conducted for the structural members which are intended for reuse. This would include research into the original materials, treatments, added hazardous substances, and possible hazardous substances which may have contaminated the structure in use.

Zhu et al. (2022) further explain that responsibility and certification issues arise due to a lack of common guidance for assessment of hazardous substances in structural members. As presented above, the presence of chemicals listed in REACH and POP regulations prohibits reuse. In the case of future issues, such as indoor air pollution due to presence of hazardous substances which were not detected or removed in the assessment stage, responsibility for the indoor air problem would fall on the stakeholder who certified the structural member for reuse, and ultimately to the party engaging in a building project. Common guidance would alleviate this issue as assessment bodies could rely on official guidance and not solely on their own expertise.

5.2.2 Microbial growth

Deterioration in the form of rot or mould growth are presented in the work by Mindess (2007). Biological deterioration occurs when moisture, warmth, and oxygen are present for a micro-organism to grow. Rot fungi depolymerize cellulose molecules in timber and thus decrease the strength properties of timber. Mould fungi feed on carbohydrates from sapwood. This creates a visible coloured growth on the surface of a timber member. However, the presence of mould fungi does not affect the mechanical properties of timber. Mould growth may decrease the quality of indoor air.

Rot and mould growth require elevated moisture levels, as explained by Mindess (2007). Timber should remain below fibre saturation point to prevent their growth. Normally, buildings are designed to prevent moisture accumulation on structural timber parts. However, design and construction errors enable moisture condensation and accumulation on timber parts. This has led to premature rotting of structural timber (Mindess, 2007).

Effects of deterioration on strength of timber are expressed in the 2014 McGraw-Hill Yearbook of Science and Technology (McGRAW-HILL, 2014). At first deterioration due to rot decreases the impact strength of timber. Subsequent deterioration decreases bending strength and soon all strength properties are greatly reduced. A deterioration level resulting in a less than 10% loss in mass of timber may not be visually detectable. At this stage the timber has already lost over 20% of its MOE and close to 40% of its compressive strength.

Biological deterioration affects both strength and indoor air quality. The new Construction law (Rakentamislaki 751/2023) states that construction products should not emit harmful substances to the indoor air during their service life. Thus, timber containing biological deterioration should be detected not to reintroduce the harmful biological growth to buildings. Mould growth is less of a problem in applications where there is no contact between the timber and indoor air.

An article from Dietsch & Köhler (2010) introduces various methods for assessment of existing building structures. These include practical methods for detection of deterioration. Detection of biological deterioration may be either non-destructive through visual assessment and hammer tapping, low-destructive through drill resistance evaluation, or semi-destructive through core sampling. Visual assessment yields only preliminary information of the state of deterioration. As mentioned, the deterioration may be unnoticeable even as the mechanical properties have already decreased. Hammer tapping is a highly inspector-dependent process where a timber member is hit with a hammer and the subsequent sound is analysed by the inspector. Hammer tapping gives a rough estimation about the depth of deterioration. Only significant deterioration may be detected as this assessment method is highly subjective. In the case of reuse, significant deterioration detected via hammer tapping would result in the timber member not being reused.

Resistance drilling, also presented in the article from Dietsch & Köhler (2010), measures the density variation in timber. A small diameter needle is used as the drill bit which classifies this method as low-destructive. Density variation due to deterioration is highly detectable in drilling resistance as semi-deteriorated timber creates a lowered resistance in comparison with sound timber. Complete deterioration provides no resistance.

Core sampling is the final deterioration assessment tool introduced by Dietsch & Köhler (2010). Core samples with a diameter of 5 mm are drilled from the timber sample where surface deterioration is visible. The holes left by core sampling classify this as a semi-destructive assessment method. The results from both core sampling and resistance drilling are local. Global estimation of the extent of decay would require multiple samples.

Strength loss due to deterioration would likely result in the timber member not being reused. With common guidelines missing, the extent of allowable surface microbial growth in reused timber members remains unevaluated. These will be discussed more in Section 6 of this master’s thesis.

5.3 Long-term strength and elasticity

5.3.1 Strength and elasticity of pure timber

Existing timber structures and the individual timbers in them have mechanical properties which consist of original timber properties, and subsequent reductions in properties due to deterioration, DOL effects, and mechanical damage. This subsection investigates these factors and methods to assess the strength of timbers in existing building stock. Nordic visual timber strength grading criteria is designed for primary timber (SFS, 2010a) and current visual grading methods are not directly applicable for reused timber. While there are international standards for visual grading of reused timber, e.g. Australian interim standard “Recycled Timber – Visually Stress Graded Recycled Timber for Structural Purposes” (Crews et al., 2008), no European standards are found for grading reused timber.

Timber found in demolished buildings may either originally, at the time of construction, be informally graded or graded to strength classes according to Finnish code B10 (Ministry of the Interior Finland, 1978). As in Eurocodes, the characteristic strength values specified in B10 correspond to the fifth percentile strength of the strength distribution within timbers in a strength class. The original strength class may be found from structural documentation. To verify that the timbers are indeed of the strength class as specified in documentation, stamping or other form of identification should be checked from the timber itself. Often the documentation of old buildings has been either lost (Dietsch & Köhler, 2010) or information about the strength of structural timber members has not been specified. In this case the timber members must be completely reassessed such that they are assigned a EN 338 (SFS, 2016a) compliant strength class.

Regardless of the availability of original strength class, the deterioration level and related loss in mechanical properties should be evaluated. This was explained in detail in Section 5.2.2 of this master's thesis. In reuse the level of deterioration would be limited to surface deterioration only. The Australian visual grading standard for recycled timber (Crews et al., 2008) specifies that depth of primary rot should not exceed 3 mm. An allowable level of deterioration must be established for reused European softwoods.

In addition to biological deterioration there may be mechanical damage accumulated during use and deconstruction phases. Studies have evaluated the effect of nail holes and damage (Nakajima & Murakami, 2007; Falk et al., 2008), and bolt holes (Falk et al., 2003), on mechanical properties of structural timber boards. Nakajima and Murakami found that an increase in number of nails decreases the MOR of reclaimed timbers. A threshold value of 30 nails/meter on the opposing edges of a board decreases MOR significantly.

Research by Falk et al. (2008) provides an extensive experimental study on the mechanical properties of Douglas-fir structural boards sourced from deconstructed buildings. A total of 980 boards consisting of 2x6, 2x8, and 2x10 inch material were visually graded into US Select Structural and Number 2 grades. Falk et al. (2008) state that visual grading according to standard WCLIB 2000 does not recognize nail holes or damage and cracks arising from deconstruction and the grader used his own expertise to evaluate the effect of these defects on grade. After visual grading the boards were edgewise bent to failure in a four-point bending test. Conclusions found by Falk et al. (2008) include that face nail holes show no clear effect on the MOR of timber boards. Edge nail holes on the tension side lowered MOR by around 10%. Through cracks decreased MOR by as much as 27%. In the test sample the overall mean MOR was 25% lower than in comparable new Douglas-fir boards. Interestingly, MOE was 10% greater in reclaimed boards than in comparable new Douglas-fir boards.

The effect of drilled holes was evaluated by Falk et al. (2003). They conclude that the effect of a hole is equivalent to a knot with twice the diameter of the hole. The location of holes was concluded relevant. Holes at the edge of a timber lower its strength significantly more than holes spaced just one hole diameter away from the edge.

The data on mechanical properties of deconstructed timbers remains fragmented. Studies include varying species with varying dimensions. The age, previous loading, and climatic conditions of timbers vary. Further, examined sample sizes are often small. The most comprehensive study found was the experimental investigation from Falk et al. (2008). Relevant studies into mechanical properties of reclaimed softwoods are aggregated in table 4.

Table 4. An aggregation of relevant studies related to mechanical properties of reclaimed softwood timbers.

Author & Release date	Species	Cross-section	Number of samples	Age of timber (years)	Properties assessed	Grading
Arbelaez et al., 2019	Douglas-fir	43x91 mm^2	265	>100	Dynamic MOE	Dynamic: Metriguard 340
Arriaga et al., 2007	Scots & Corsican pine	90-190 x 160-220 mm^2	84	50-170	MOE MOR SG	Visual: UNE 56544
Esteban et al., 2010	Scots pine	100x120, 100x150 mm^2	28	110	MOR, $f_{v,mean}$	Visual: UNE 56544
Falk et al., 2000	Douglas-fir	8x8 in.^{2}	60	55	MOE, $f_{c,0,mean}$	Visual: WCLIB standard No.17
Falk et al., 2008	Douglas-fir	2x6-10 in.^{2}	980	70	MOE MOR SG	Visual: WCLIB standard No. 17
Kranitz, 2014	Norway spruce	?	44	90-320	MOE, MOR	-
Llana et al., 2023	Norway spruce	95x145 mm^2	19	71	MOE MOR SG	Visual: B52001-1 & DIN4070-1, Ultrasound: Pundit 200 Vibration: STIG
Stenstad, 2021	Mixed softwoods from Norway	48x98 mm^2	226	?	Mean MOE, $f_{v,r,mean}$	Visual: Insta 142, Ultrasound: Brookshuis MTG, Four-point bending: EN 408

Note: ? = unknown from study, - = not evaluated in study

Long term high magnitude loading causes permanent creep and a decrease in strength of timber. This phenomenon is commonly known as the duration of load (DOL) effect. DOL depends on the load history of a structure, as explained by Köhler & Svensson (2011). Load history is often not known and thus the level of loading and subsequent level of DOL effects are unknown. In the Australian standard for visual grading of recycled timber (Crews et al., 2008) this issue was solved by assuming that the DOL effects have progressed for between 5 months to 50 years. This leads to a conservative decrease in the assumed resistance of reused timber members. Crews et al. (2008) state that for hardwoods the magnitude of decrease in strength properties varies. The standard implies that for recycled timber, in comparison with primary timber classified to the same grade, the strength reduction was up to 45%. Eurocode 5 (SFS, 2004a) considers DOL effects through a load-duration- and service-class dependent modification factor. For solid timber and GLT in service classes 1 and 2 (moisture induced deterioration not likely) and with permanent loading, the modification factor is 0.60, reducing allowable long-term stresses in a member. This limits accumulation of damage due to DOL effects.

Crews et al. (2008) propose that as the DOL effects are nonlinear and already considered in the Australian visual grading standard through a reduction of characteristic short-term strength for reused timber, DOL effects on secondary timber should only account for a further 2% and 10% reductions for short-term- and long-term capacities, respectively. More research is needed to evaluate whether this approach would be suitable for Nordic softwoods.

Studies (Falk et al., 2008; Cavalli et al., 2016) conclude that the effects of aging or DOL show no clear effect on the MOE of timber members. Falk et al. found a 10% increase in MOE of reclaimed boards in comparison with new boards of the same species. They conclude that density of recovered timbers may have affected these results. Cavalli et al. (2016) aggregated results from various studies to review whether there is consensus on the effects of ageing on timber. Some of the studies reviewed suggested an increase in stiffness and some found a decrease. Stability of stiffness properties was also accounted for in the Australian standard (Crews et al., 2008).

As mentioned, there are currently no European standards for visual grading of reused timber. There is ongoing research related to standardised classification of timber within the RECOWERS project (European Commission, 2021). The results of this research project have not been released. The project description states that a European standard will be created based on the findings of the research project. Novel assessment procedures such as infrared thermography are proposed. The state of standardised assessment for strength grading of reused timber will be investigated through expert interviews in part 6 of this thesis.

If the original strength grade is available, a new strength grade may be assigned through a strength grade decrease of one or two grades, as proposed by Crews & McKenzie (2008) and Hradil et al. (2014). The downgrade should equal two grades for heavily loaded members, members that have been in contact with exterior climate, and for members with an unknown loading. Else the member should be downgraded by one grade. Table 1 in EN 338 (SFS, 2016a) suggests that a downgrade of two C-classes lowers characteristic bending strength by 16-22%, tensile strength parallel to grain by around 28%, and compressive strength parallel to grain by 10-13%.

As strength grades in both the former Finnish code B10 (Ministry of the Interior Finland, 1978) and EN 338 (SFS, 2016a) are based on the 5th percentile strength values, the classes are comparable. This comparison is found in table 5, where the classes found in the code B10 are compared against those found in EN 338. A similar comparison could be done for classes of glue laminated timber. However, the code B10 does not state whether the glulam strength grades are for homogenous or combined glulam products. Investigations in table 5 of this master's thesis reveal issues in reflecting the former Finnish sawn timber grades to those found in EN 338. Stiffness properties in relation to strength properties are lower in code B10 strength classes in comparison with the C-classes. Additionally, the shear strength $f_{v,k}$ in code B10 classes does not fulfil any of the shear strengths in C-classes. Thus, direct transfer of former strength class into the current C-classes would be problematic.

It would be useful to compare the former T-class grading rules with the visual grading rules of INSTA 142. If the rules are similar, a transfer of T-class grades into current C-class grades could be made. The T-class grading rules are found in a book from Risto Lipitsäinen titled "Sahatavaran lujuuslajitteluopas". Unfortunately, the book was not obtainable for this master's thesis. Another issue is that there are only four timber strength classes in code B10. This means that a downgrade of two classes would not be possible for the two lowest grades as there is no grade to downgrade to.

Hradil et al. (2014) state that there should always be a visual assessment to evaluate the level of damage in the member. It would thus be more advisable to assign a completely new C-class for reclaimed timber according to visual grading rules specifically designed for grading reclaimed timbers. In some specific applications, such as recently graded C-class timber from short term constructions, the grade reduction method could be utilized.

Characteristic strength of timber is calculated according to EN 14358 (SFS, 2016b). The characteristic values are determined for a clearly defined reference population. This could be the sawn timber from a certain region, for example. For reused timber the reference populations are not clearly defined. The material stock in Finnish buildings likely contains Scots pine and Norway spruce originally sourced from Finland. However, the construction, use, and demolition phases of a building have created diverging material properties for structural timbers. Thus, reclaimed timbers do not form a clearly defined reference population. Even well documented structures may have structural members which are not realized according to documentation. This was the case in the collapsed Siemens Super Arena in Denmark, where investigations related to the design and manufacture of the failed glulam roof truss revealed that laminations had knots larger than allowed for the grade specified in the design documentation (Hansson & Larsen, 2005).

Table 5. Strength and stiffness values of graded timber T-classes in old Finnish code B10 and an evaluation whether numerical values in a T-class meet those of a current EN 338 specified C-class. T-classes from Ministry of the Interior Finland (1978).

Timber T-Class (Finnish code B10) Strength property (N/mm²)	T18 Fulfils no C-class completely.	T24 Fulfils no C-class completely. Fulfils C16 in strength, except for $f_{v,k}$.	T30 Fulfils C14, except for $f_{v,k}$. Fulfils C22 in strength, except for $f_{v,k}$.	T40 Fulfils C16, except for $f_{v,k}$. Fulfils C27 in strength, except for $f_{v,k}$.
$f_{m,k}$	13	18	22	29
$f_{t,0,k}$	6	12	14	19
$f_{t,90,k}$	0.4	0.4	0.4	0.4
$t_{c,0,k}$	12	17	21	28
$f_{c,90,k}$	5	5	5	5
$f_{v,k}$	2	2	2	2
$f_{v,r,k}$	1	1	1	1
Stiffness property (kN/mm²)	T18	T24	T30	T40
$E_{0,k}$	3.3	4.5	5.5	7
$E_{0,mean}$	5	5.5	7	8.5
$E_{90,mean}$	0.16	0.18	0.23	0.28
G_{mean}	0.34	0.36	0.46	0.56

5.3.2 Glue joints and metal type connections

This section investigates the glued connections and metal type fasteners found within structural timber members. The long-term durability of connections and the available assessment methods for identification of the details of connections are evaluated. In reuse the structural member does not undergo transformation. As a result, e.g. glulam members and trusses would be used as is, without modification of the glued- and metal type connections within them. The original manufacturing methods and subsequent changes in the physical properties of both the glue lines and connections thus need assessment to evaluate the remaining capacity of a timber member.

Various types of glue or adhesive have been used. Franke et al. (2015) state that adhesives include at least casein, melamine-urea-formaldehyde (MUF), resorcinol-formaldehyde (RF), and polyurethane (PUR). Dietsch & Tannert (2015) divide adhesives into two primary categories: formaldehyde based- and isocyanate adhesives. Manufacturing documentation, when available, reveals the type of adhesive used. The type of adhesive may be confirmed through a laboratory analysis. Certain adhesives are not applicable to service class 3 conditions.

Glue laminated structures may have weakened during the first service period. According to Dietsch & Tannert (2015), cracking in glue line and cracking next to glue line account for over 40% of the damage found in existing glue laminated structures. Cracking and delamination of the glue joint decrease the capacity of a glue laminated member. The magnitude of capacity reduction depends on the size and location of cracks and on the relative proportion of delamination. Serrano (2006) investigated eighteen failures of Swedish large-span timber structures. In six cases, delamination or poor adhesion was concluded as the primary source leading to structural failure, highlighting the importance of glue line integrity.

In the case of reuse, the integrity of glue lines needs confirmation. In EN 14080 (SFS, 2013) the conformity of glued joints is evaluated through initial type testing and subsequent factory production control. Annexes C and D of EN 14080 provide methods for delamination test- and shear test of glue lines, respectively. Specific limit values are given for percentage of allowed delamination and on the shear strength and percentage wood failure of glue line samples.

Core samples are a form of semi-destructive assessment method for testing shear strength of glue lines, as expressed in annex D of EN 14080. However, the results of this highly local form of assessment are questionable. Tannert et al. (2012) performed an experimental investigation into the relevance of core samples in the evaluation of bending- and shear capacities of reclaimed glulam members. They conclude that a core sample yields only local information about the shear strength of a glue line. No correlation ($R^2=0.06$) was found between the shear strength of glue lines in core samples and the ultimate bending strength of the beam from which the core samples were taken from. Additionally, the shear strength of the beam adjacent to the core samples could not be estimated from the core samples. Similar results are found by Franke et al. (2013). Franke et al. conclude that core samples are not applicable in the delamination test due to unequal stress situation in comparison to the standard, larger delamination sample. Both the delamination test and shear strength test are needed as delamination test evaluates the moisture induced transverse tensile delamination while the shear test evaluates the local shear capacity.

Based on the findings related to local semi-destructive testing, there is a need for global assessment of glue line integrity. A dissertation written by Sanabria Martín (2012) develops a non-destructive assessment method for evaluation of glue line delamination with utilization of air-coupled ultrasound propagation. Theory section of the dissertation presents visual means for detection and measurement of delamination with the use of feeler gauges. Visual method of glue line assessment only detects edge open cracks. However, this preliminary form of assessment reveals valuable information in the case where visual delamination is found. According to Sanabria Martín, thermography and optical methods are only applicable to thin, veneer type sections. X-ray based assessment lacks sensitivity to debonding while tomography-based methods are slow in assessment.

Ultrasound methods present the greatest potential for ND assessment of delamination (Sanabria Martín, 2012). Sanabria Martín concludes that air-coupled ultrasound propagation may be utilized in glulam up to 500 mm in width. Slanted lateral transmission, where the transducer and receiver are on opposite sides of adjacent lamellae, enables detection of bonding defects in glue laminated structures of any length and height. The type of adhesive does not affect the results of this assessment method. Delamination with a >150 µm gap are detected. The applicability of ultrasound testing was confirmed by Neuenschwander et al. (2013). Delaminations in a 90-year-old glulam roof beam were successfully detected by ultrasound assessment.

Yahmi et al. (2023) developed process charts for evaluating reusability of glulam structures. Delamination and cracking are both evaluated as “cracks”. Visual investigations of crack location are combined with measurements of crack length, width, and depth. Later in the paper Yahmi et al. (2023) perform a case study on approximately 40-year-old glulam portal frames from a deconstructed textile factory. Only minor (crack depth <1/6 of member width, maximum opening of 2.5 cm, crack length <2 m and <20% of member length) cracks were found within the member. Shear tests on 150 x 20 x 10 mm^3 samples revealed that the shear strength of examined glulam member did not fulfil the requirement for glue line shear strength as specified in table 10 of EN 14080 (SFS, 2013). Percentage of wood failure was lower than threshold values in the standard. Yahmi et al. (2023) state that this should be considered as priori information when assigning design capacity for a reused GLT member. Water infiltration had caused discoloration on the glulam member under investigation. Shear tests revealed that this infiltration reduced the shear capacity of the glue line adjacent to the water infiltration, even as the glue was determined to be MUF, a type I glue suitable for all service classes.

Eurocode 5 (SFS, 2004a) based design of connections with metal type fasteners should be investigated before delving into the assessment of existing metal to timber connections. In Eurocode 5, the capacity of a metal fastener to timber joint depends on the following parameters: fastener type, dimensions and characteristic tensile strength of the fastener, characteristic timber density, embedment depth, direction of loading, and orientation and spacing between fasteners. Additional requirements are set for distance of fasteners from the edge of a timber member. A Eurocode 5 based determination of connection capacity would not be possible unless a prior evaluation is given for the mentioned parameters. Such a level of assessment raises questions about its feasibility. A local, sample type assessment of connections would likely be insufficient as the existing timber structures containing metal type connections were often hand built on site, resulting in variation in quantity and spacing of fasteners. Design documentation of the connection may not be available. Even in the case of available documentation the structure may have been realized with deviation from the design documentation.

With these limitations in mind, it should be investigated whether it would be more practical to evaluate the capacity of existing connections through other means. Joints and connections in existing structures are conventionally assessed visually, as in the inspection of the Nikola Tesla Museum by Stepinac et al. (2017). These visual investigations are conducted to assess the level of damage and potential irregularities in timber connections. In the case study Stepinac et al. (2017) found that in many cases the joints had an improper installation of fasteners, leading to cracking and decreased capacity. Visual investigations yield both qualitative results and quantitative results of connections. For example, the number of nails/bolts could be quantified.

Novel assessment methods for evaluating the integrity of connections include piezoceramic transducers and active sensing (Han et al., 2019), and coaxial correlation method (Kurtenoks et al., 2023). Han et al. (2019) performed an experimental investigation on recognizing relative integrity of metal type connections by use of lead zirconate titanate (PZT) transducers. The evaluated connector types include screws, bolts, nail plates, and decussation connectors. Connection integrity was decreased by loosening bolts and screws, by prying open nail plates, and by removing screws from the decussation connector. The results from Han et al. (2019) indicate that active sensing describes well the relative integrity of screwed- and bolted connections. For nail plate- and decussation connections the relationship between received packet energy and integrity of connections was not as strong.

Kurtenoks et al. (2023) investigated the coaxial correlation method experimentally by evaluating moment integrity between two plywood sheets. The sheets were connected by bolted and screwed angle brackets. Coaxial correlation method utilises vibration-based measurements of joint stiffness. A dimensionless parameter, volume root mean square value, related clearly to the observed joint stiffness. Kurtenoks et al. (2023) conclude that this method could be applied to monitoring of joints.

There are two issues in applying these joint assessment methods for evaluation of joint capacity. First, these measurements provide qualitative data in relative form. A relative assessment aids in finding discrepancies between similar joints. However, no absolute values of the joint capacity could be made, and a prior estimate of capacity requires other evaluation methods. The second issue relates to the fact that these joint assessment methods are in their infancy. A development into practical tools is necessary before they could be applied in the field by practicing assessment experts.

Long-term durability of metal type fasteners does not pose a major issue for reuse of structural timber members. Nguyen et al. (2011) created an overview of the potential causes of fastener corrosion. These include saline environment, high humidity, treatments in timber, and industrial pollutants. Saline environments are found next to seas. In Finland, this does not pose an issue as the Baltic Sea has a low salinity in comparison with ocean salinity. Corrosion due to high humidity may be found in reused members. However, a significant level of corrosion indicates that moisture has likely induced decay to timber as well, decreasing potential for reuse. Treated timbers and timber members exposed to industrial pollutants are unlikely to be reused, based on findings from section 5.2.1 of this master's thesis.

5.4 Use of previous loading as a proof load

In addition to the already presented visual and non-/semi-destructive methods, capacity of structural members could be assessed through a principle of proof loading. This form of assessment would assist in evaluation of capacity for undocumented structural members, or members which contain many metal fasteners, e.g trusses. Principles for proof loading timber structures are outlined in the work of Köhler (2014). In proof loading the member is loaded to a predetermined stress level. A survival of this loading means that the strength of the member is greater than the load. This decreases uncertainty of the capacity of a timber member. Köhler (2014) proposes the proof loading for existing timber structures. Similarly, the proof-loading concept could be extended to reused members. One "proof load" could be the load history of the structure. Proof loading includes a quantitatively known loading. For example, bending a beam in a four-point bending test would yield quantitative, inequality type results of the load-bearing capacity. However, the cost of extensive laboratory proof loading may disincentivise its use.

In literature the applied loading predominantly consists of a stepwise added, quantified loading. Arangjelovski et al. (2015) investigated in-situ proof loading of a cracked GLT roof beam. The testing included a measurement of strains during addition of a proof loading. The resulting deformations were compared against numerical FEM structural analysis of the beam. The measured strains and subsequent stresses were utilized to calculate a reliability index for the GLT beam in its design loading case. Dietsch & Köhler (2010) state that proof loading necessitates the measurement of strains. EN 380 (SFS, 1994) specifies the process and details of a standardized proof loading procedure.

An assessment of structural capacity with the use of previous loading as a proof load creates multiple limitations to the value of the analysis. The actual, endured loading of a structural member depends not only on the overall dead-, live-, and environmental loading, but also on the distribution of loading between members and within the structural system. Quantification of the actual live- and environmental loads may be problematic. Data of endured maximum floor loads are not specified in any documentation. The environmental loads could be quantified through meteorological data. However, uncertainties remain especially on the level of endured snow loads. In Finland, the snow loads of wide-span structures are often lightened by removal of snow from the roof prior to the maximum expected snow loading. In gable roof systems the snow may have fallen off the roof, especially if the roof has a metal surface and a steep slope. Proof load analysis through environmental data necessitates that the loading in the reused structure is similar as in the original structure.

A proof loading principle would assist in removing doubts of the structure (Dietsch & Köhler, 2010). Proof loading by itself only ensures that the structure meets the capacity for a certain type of loading. For members with insufficient documentation and complex geometries and joints, e.g. old trusses, proof loading may be the only way to ensure its capacity. This type of structural design remains out of the scope of Eurocodes. Thus, building control authorities are likely doubtful of it and further research is required to ensure the applicability of proof loading in the assessment of structural timber member for reuse.

6 Interviews

As apparent from the literature review, there are gaps in literature and regulations related to requirements for both certification and assessment. Consequently, a decision was made to include interviews in this thesis for better understanding of the verification on building site -certificate and of the assessment requirements under which different timber structures are subjected to. This section presents the interview methods and -results.

6.1 Methodology

Interviewees were chosen based on the findings from the literature review. Descriptions of interviewees are found in table 6. It became apparent that regulatory bodies had to be interviewed for a deeper understanding of the certification requirements set for reused construction products. Organizations working within the field of assessment were also interviewed as the state of assessment methods and potential actors for assessment could not be found from existing literature and official guides. In the initial stage, a total of four interviews were agreed upon. Two of the original interviewees were from the private sector and the other two from the public sector. During the first round of interviews more relevant personnel were identified and further two interviews were held with both a private and public organization.

Table 6. Descriptions of the interviewees

Interviewee no.	Public/private organization	Background	Experience (years)	Interview length (min.)
1	Public	MSc, structural engineering	12	75
2	Private	MSc, structural engineering	25	60
3	Private	Structural engineering	40+	110
4	Public	MSc, architecture	30+	57
5	Private	PhD, indoor environment engineering	10+	69
6	Public	BSc, forestry engineering	30	74

The interviews were conducted as semi-structured interviews. A series of mostly open-ended questions was constructed. The questions include general questions about the interviewee and the role of the organization they represent, current certification requirements, current assessment methods, the role of different actors within the realm of reuse of structural construction products, and about research needed to further advance reuse of structural timber products. A total of 17 common questions were discussed with the interviewees. These common questions are found in Appendix B. Additionally, 4-6 separate, more specific questions were discussed with the interviewees. These questions were constructed individually for all the interviewees based on prior knowledge about the expertise of the organization. The separate questions are not published to preserve the anonymity of the organizations.

The interviews were held remotely over Microsoft Teams and were recorded for post processing of answers. Duration of interviews varied from 57 to 110 minutes. The questions were sent to all the interviewees beforehand for them to prepare answers. In some cases, literature found in the literature review part of this thesis was sent to the interviewees together with the questions. After each interview the answers were written and categorized for later presentation of the conclusions of the interviews. Categorization into themes was based on an educational book into coding of qualitative data (Auerbach & Silverstein, 2003).

6.2 Results

The results of the interviews are presented topic by topic. The subsections aggregate related themes together. These themes and subsections are closely related to the themes found in the literature review. The work of Auerbach & Silverstein (2003) focused more on coding qualitative data from social sciences. The interviews in this master’s thesis are expert interviews to qualified personnel within the built environment sector, resulting in little room for interpretation of interview data in comparison with interview data in social sciences. Thus, the coding and post processing of interview transcripts in this master’s thesis focused on finding statements related to the same or similar topic.

6.2.1 Certification

Reuse vs remanufacturing

Results of the interviews indicate that an important factor is whether the reuse of a product is seen as reuse, the certification which falls under verification on the construction site, or as remanufacturing, in which certification is possible only through the CPR and CE-marking. According to interviewees, the distinction between these two remains vague. Shortening a glulam beam, for example, retains the product within reuse while resurfacing was already considered as remanufacturing. Product specific limitations for reuse are under development.

Verification on the construction site

Based on conclusions from all six interviews, verification on the construction site is the only way to certify structural timber products for reuse. Most interviewees see verification on the construction site remaining as the primary avenue for reuse due to its high suitability for reuse purposes. Some stated that in the future, an ETA could be a certification method for reused structural timber products.

Interviewees have found that the parties engaging in building projects often do not have sufficient knowledge about the process of verification on the construction site. First, the process is seen as a possibility to certify construction products with a lighter form of assessment than in the other certification methods. This is not the case as all the relevant essential technical requirements need assessment in all the certification methods, including in verification on the construction site. Second, the verification should always be an expert statement about the suitability of the construction product for its intended use. The expert should be proficient in the field related to the essential technical requirements of the construction product. Interviewees advise that the proposed expert in assessment for reuse is confirmed proficient by municipal building control authorities. Additionally, during these early stages of reuse the certificates drawn up should be verified through building control authorities. And third, interviewees state that the parties engaging in a building project are responsible for obtaining a verification on the construction site -certificate. Building control authorities only conduct proportional control into the certification of building products at a construction project.

Conflicting regulations

Interviewees see the current regulations in conflict as the new Construction Law (Rakentamislaki 751/2023) requires low carbon solutions in new construction, such as reused and remanufactured products, while there are no explicit certification requirements for reused and remanufactured products. Additionally, there are cases where deconstructed construction products intended for reuse were seen as construction waste by the authorities. Current regulations do not recognize the difference between construction waste and potentially reusable products. Authorities require that the product from deconstruction should have a future application known at the time of deconstruction to avoid waste status. This was deemed impractical. Future changes to regulations may be made after authorities have evaluated the results from ongoing reuse development projects. Interviewees confirmed that no new decrees related to reuse of structural products are to be enacted in the short-term.

Certification of mechanical properties

In the interviews a system of conservative capacities was discussed. At least during the early stages of reuse, a prior estimate on capacities of reused structural members could be achieved by downgrading the characteristic capacities found in original documentation. A conservative estimate is seen as the most promising way to certify that the reused structural member has at least similar capacity as in a new structural member of similar characteristic values. A structural engineer should evaluate potential risk factors related to the capacities of a reused structural member and report them to the entity who performs the assessment. In the absence of documentation, all the mechanical properties of a member need assessment from the ground up.

Certification for the health of structures

Interviewees see timber as a relatively easy material to certify that the reused product meets the requirements for health concerns. Materials and possible chemicals used in the production of sawn timber and glue laminated timber are well known. Three major harmful substances in the form of pressure treatments, surface coatings, and microbial damage, may be found in existing timber structures. Microbial damage is not allowed in reuse if the member is used in structures where the member may affect indoor air quality. A three-tiered certification system related to harmful substances was proposed by interviewees: if no harmful substances are present, the product may be used in all applications; if only microbial growth is present, the product may be used in applications where indoor air quality is not of concern; and if pressure treatments or harmful coatings are found the product is not reused at all.

During the interviews it was found that limit values for different harmful substances are under development. The report from Zhu et al. (2022) was developed together with toxicologists and toxicologists are working on development of limit values for harmful substances. There has been discussion whether M1 emissions classes could be applied to reused construction products.

Eased requirements for reused timber products

The interviewees were asked whether they see a possibility for reused products to be certified with less strict requirements than new timber products. Every participant stated that both new and reused products should have equivalent technical requirements. All the technical requirements set for new products should be fulfilled by reused products. This applies especially to health and indoor air factors. One interviewee commented that introducing a risk of indoor air pollution via reused products creates issues of responsibility. Thus, assessment for harmful substances is seen as extremely important. A conservative design for structural capacity of reused members was seen as a possibility to reach at least similar probability of failure as in new structural timber products. Conservative capacities were proposed to decrease the risks in reuse of structural members.

6.2.2 Assessment

Overview

The absence of instructive documents or standards creates doubts to the assessment of timber structures for reuse. This was stated by both authorities, and organizations working in practical assessment. Both the accepted assessment methods and needed sample sizes remain unknown. The interviewed assessment agencies stated that some form of guidance is needed, both to ensure that the building control authorities accept the results of assessment and that a quote about the cost of assessment could be made.

The scope of assessment, already projected to be more extensive than assessment of new products for factory production, increases as level of documentation decreases. If documentation is available, the interviewees suggested that it would be sufficient to perform assessment to confirm that the structure meets the documented properties. With no documentation, all properties would be under doubt and a thorough assessment procedure would be needed.

Recognizing potentially reusable structural parts at an early stage of assessment, prior to deconstruction/demolition, is highly desired. Two major reasons were brought up in the interviews. First, the information contained within the structural part decreases after deconstruction. In its original position the environmental conditions, adjacent harmful substances, and other potential risk factors are more easily recognized. Second, deconstruction was seen as a more labour intensive and costly process in comparison with demolition. Early recognition of possible barriers for reuse would minimize the risk that a structural member is first deconstructed and later assessed as not suitable for reuse.

Composite structural members containing materials other than timber and glue are seen as radically more difficult to assess. Metal type connections were unfortunately not discussed about in the interviews, and thus no conclusions on their assessment may be drawn. Members containing multiple materials including light-frame walls and prefabricated elements are difficult to assess as not only the properties of the timber but also of every other material would have to be assessed to meet the criteria of their newly manufactured counterparts. Conclusions of the interviews suggest that at first assessment and reuse likely focuses on reusing members containing only timber, glue, and perhaps even metal type fasteners.

Assessment of mechanical properties

The mechanical properties indicated in documentation were seen valuable for timber assemblies and glued members. The documented prior characteristic strengths would be confirmed through non-destructive tests as destructive testing of large-scale members was deemed impractical for reuse purposes. The fact that the structure has endured loads for its entire service life was seen as usable information for evaluation of capacity. For individual sawn timbers, the prior strength grade was regarded as insignificant, as visual assessment for a new grade could be done simultaneously with assessment of the level of biological and mechanical damage.

A thorough assessment of the mechanical properties in the absence of documentation was questioned. The testing sample size would likely require a considerable portion of the whole population, e.g. roof trusses of a house, to assign the relevant characteristic mechanical properties for the population. The heterogenic nature of members from existing buildings, resulting from differences in design, manufacturing, use, and deconstruction, results in the populations being at maximum the population within an individual building. The interviewees compared this against the populations in factory production, where assessment of the population through initial type testing and subsequent factory production control suffices.

Assessment for health of structures

Unfortunately, no experts into either field investigation of hazardous substances or -indoor air quality were interviewed. There was only limited experience within the interviewees on the practical condition assessment of buildings. One key finding was that the personnel qualified to perform condition assessment are highly likely to be qualified for assessment of structural products for reuse, at least from the point of view of harmful substances. This is supported by the fact that there will not be any new decrees related to the proficiency requirements of personnel conducting assessment on harmful substances in reused construction products. Up to date guides and skilled investigators result in Finland being among the top countries in detection of harmful substances.

According to interviewees, current development into assessment of harmful substances in reused construction products is limited to members originating from indoor spaces and being reused to indoor spaces. This is because outdoor exposure leads to a variety of biological risks, further complicating assessment. Reuse within the indoor environment already results in complex assessment, as the date of manufacture, original location within a building, prior environmental stresses, later renovations, and future use affect the assessment process.

Potential surface microbial growth was not seen as a barrier to reuse if the surface growth could be mechanically removed. Mechanical removal would decrease the cross section, necessitating an evaluation of the effects of reduced cross section on the mechanical properties of the member. The fact that surface microbial growth is easily removed was seen as relative benefit for timber, as embedded harmful substances in other materials could not be removed. Microbial growth which requires more than surface removal would likely result in the member not being reused.

Contrary to assessment of mechanical properties, documentation is seen as playing only a minor role in assessment of harmful substances. An assessment of harmful substances is already mandatory for buildings intended for demolition. Documentation might give a hint about the use of a harmful substance in a specific location.

6.2.3 Roles in reuse

Party engaging in a building project

The parties engaging in a building project are not seen proficient in all fields of a construction project. This often appears as the engaging parties not understanding the construction product documentation and their role to initiate the process of verification on the building site. Interviewees stated that as a final responsible entity in a building project, the responsibility of reused structural products ultimately falls to the party engaging in a building project. Thus, parties engaging in a building project have been reluctant to use reused construction products as common certification requirements and procedures have been missing. Requirements for reuse should be discussed with municipal building control authorities.

Designers

It was noted that designing structures with reused structural members creates considerable changes both to the role- and practical work of structural engineers and architects. First, a structural engineer would be needed to evaluate the reuse potential of members from an engineering point of view. The engineer would inform the expert in assessment of the potential risks and of properties which necessitate a more comprehensive assessment. Second, the geometry and remaining capacity of the reused member would limit structural design, for example in the form of allowable spans. As a result of this, architects should be notified of these limitations. Interviewees suggested that design would likely move to a more iterative direction.

Another issue concluded from the interviews was that when designing with reused structural products, deconstruction and construction would be separated by at least two years. Due to inherent practical reasons, reused structural members, especially any member with severely limited adaptability for different applications, require consideration already at the design stage of the building the reused member would be part of. Reused sawn timber was seen as likely to be marketed parallel to newly sawn timber, bypassing this design limitation.

Organizations- and personnel qualified for assessment
At present, the interviewees do not recognize economic operators who have experience on assessment of timber structures for reuse. No single operator has expertise on how to evaluate both the mechanical properties and the presence of harmful substances in an existing structure. During these early stages of reuse, it is likely that multiple operators would collaboratively assess the reused members. Altogether, more operators are needed especially for assessment of mechanical properties. Official guidance for reuse was seen as a necessity among the operators who currently assess new structural timber products.

6.2.4 Development of visual grading rules

An interviewee stated that visual grading rules for recycled sawn timber are currently in early-stage development in Finland. INSTA 142 Nordic visual strength grading rules (SFS, 2010a) are used as a basis for this development. In the early-stage investigations timber falsework from infrastructure projects is visually assessed for damage and a small sample will be tested destructively for bending strength. No new grading rules are released from this early-stage development. The development focuses on small dimension timbers.

Mechanical damage and cracking are expected as the major additions to the INSTA 142 rules. Additional reporting about the prior environmental conditions and loading of timbers are proposed. Prior strength grade, whether the former Finnish T-class or current C-class, would not be considered in the visual grading. INSTA 142 grading was stated to produce timber that more confidently meets criteria for the assigned grade in comparison with machine graded timbers. Downgrading of machine graded timbers in later visual grading is not seen as a drawback.

7 Evaluation of reuse potential by member type

7.1 Criteria for various reuse scenarios

The process of assessment and certification depends both on the properties of the reused member and on the requirements of the new application. Phase 1 pre-demolition audit procedure for the same application is shown in figure 8. In phase 2 post-deconstruction assessment the remaining doubts of the structural members are removed. Verification on construction site -certificate creates issues for determining the extent of phase 2 assessment. Based on findings from interviews, the verification documentation may be created only after knowing the future application of a structural member. It is likely that three rounds of assessment are needed. First, a pre-demolition audit to recognize the potentially reusable members. Second, a phase 2 post-deconstruction assessment to evaluate each member individually with visual and non/semi-destructive testing. The phase 2 assessment eliminates storage of non-reusable members and assigns potential applications for the reusable members. Finally, a third phase would be needed to draw up the verification on construction site -certificate. In phase 3 the requirements of the new application are compared against the properties assigned for a member in phase 2.

In this master's thesis, reuse potential is developed based on phase 1 requirements. Assessment potential of timber, glue joints, and metal connections are also considered. Findings from literature review and interviews indicate that there are four principal end of life scenarios for deconstructed timber members:

- The member may be reused in the same application. In this scenario the reused members are required to meet the requirements set for equivalent newly produced members. (A)
- The member could be downgraded to an application with lower requirements. (B)
- The member could be deconstructed further into individual timbers or into non-composite members. These are then either reused as dimensional lumber or remanufactured to new products through cascading. (C)
- As a final option, if phase 1 investigations indicate no potential for reuse or cascading, the member is disposed as waste. (D)

Value of reuse increases as member size and adaptability to various applications increase. For this reason, the descending order for potential is A, reuse in same application; B, reuse in an application of lower requirements; C, deconstruction of member into individual timbers; D, disposal as waste. The criterion for each scenario varies, and within a scenario the criteria depend on the type of structural member.

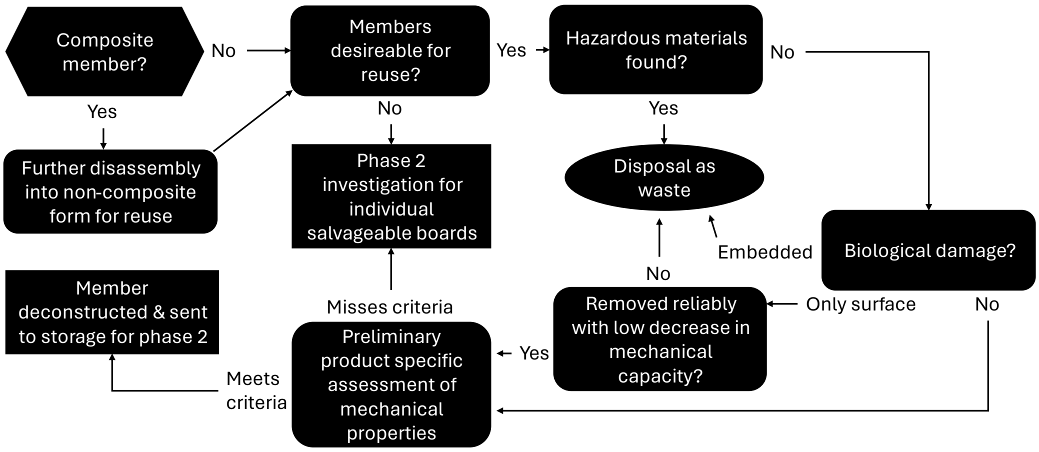

Figure 8. Pre-demolition audit phase 1 investigations to recognize potentially reusable timber members

As noted, the phase 2 investigations heavily depend on member type, age, prior use, and intended future use. For these reasons, no process charts are conceived. General properties of members found in buildings and requirements for reuse are presented below in tables 7 and 8.

Table 7. Properties of existing timber members.

Properties of deconstructed timbers depend on:
Member type
Original design: - Use of design codes - Designed loading - Dimensions - Details of joinery
Manufacturing / construction process: - Base timber material - Manufacturing production control - Adhesive properties - Realized structure vs. documented structure - Coatings
Prescence of hazardous substances
Moisture related degradation: - Environmental conditions - Structural details - Moisture leaks
Renovations
Magnitude of loading
Damage during deconstruction

Table 8. Technical requirements for member in reuse.

Requirements for member in reuse:
Design loading and resistance (ULS)
Allowable deformations (SLS)
Design geometry
Service class
Restrictions on hazardous substances
Restrictions on microbial growth - No microbial growth if in contact with indoor air - Removal of surface growth and subsequent reduction in capacity
Long-term durability
Fire safety

7.2 Potential for reuse and cascading

7.2.1 Log construction

Table 9. Evaluation of log constructions for reuse potential

Criteria	Evaluation
Availability of documentation	Structural documentation unlikely for hand hewn/-scribed log houses. Factory produced log houses more likely to have documentation.
Prescence of hazardous substances	Pressure treatments unlikely; harmful coatings may be present.
Microbial growth	Microbial growth likely in bottom course of logs, course under openings, and on exterior surface.
Engineering and architectural potential	Notched corners limit reuse to same geometry/floorplan as in deconstructed building.
Assessment of timber properties	All surfaces accessible for assessment.
Assessment of glue joints	Glue joints in laminated logs assessable.
Assessment of connections	No metal type connections embedded in reused members.

Reuse of log constructions would be possible in both type A and B. The floor joists and roof rafters from log construction may find a use in type C reuse or cascading. However, only limited volumes of these sawn timbers are available from individual buildings. Milling of deconstructed logs from log homes, while possible, would classify as remanufacturing and thus out of the scope of this thesis.

7.2.2 Light-frame construction

Table 10: Evaluation of light-frame constructions for reuse potential

Criteria	Evaluation
Availability of documentation	Documentation unlikely for old built-in-place structures. Documentation possibly available for buildings with factory produced elements/members.
Variety of materials	Walls include structural timbers, metal fasteners, insulation, air barrier, interior sheeting… Trusses consist of timber and metal connections.
Prescence of hazardous substances	Pressure treatments in bottom plates, or hazardous chemicals in non-timber materials possible. Trusses unlikely to contain hazardous substances.
Microbial growth	Microbial growth likely in exterior walls. Possible growth in rafters/ top chord in trusses due to leaks in roof.
Engineering and architectural potential	Geometry of walls limited to original geometry. Trusses limited to original span.
Assessment of timber properties	Timber embedded in walls not assessable. Trusses visually assessable after deconstruction.
Assessment of connections	Embedded connections in walls. Trusses contain nailed or nail plate connections, the assessment of which remains uncertain.

Walls of light frame structures are unlikely to see type A or B reuse. Trusses from light-framed buildings could find either a type A or B reuse. Deconstructed walls and trusses, in addition to floor joists and roof rafters, could be salvaged from light-frame structures. Reusable timber boards with a length of >3 m are unlikely found in sufficient quantities. The option of cascading light-frame structures requires further investigation.

7.2.3 Wide-span trusses

Table 11: Evaluation of wide-span trusses for reuse potential

Criteria	Evaluation
Availability of documentation	Documentation a prerequisite for reuse. Availability of documentation not known.
Prescence of hazardous substances	Unlikely
Microbial growth	Possible growth in top chord in trusses due to leaks in roof. Low redundancy for mechanical removal of surface growth.
Engineering and architectural potential	Reused trusses have geometry and span predetermined.
Assessment of timber properties	Condition of timber visually assessable after deconstruction.
Assessment of connections	Trusses contain nailed or nail plate connections, the assessment of which remains currently uncertain.

Trusses show technical potential for type A and -B reuse. Trusses provide a high potential for cascading into timber boards, as hazardous substances & microbial growth are unlikely encountered. Metal type connections within trusses are limited to nodes, easing disassembly into individual boards.

7.2.4 Glue laminated members

Table 12: Evaluation of glue laminated members for reuse potential

Criteria	Evaluation
Availability of documentation	GLT class may be available from the member
Prescence of hazardous substances	Pressure treatments unlikely in service class 1 and 2 members, harmful coatings may be present.
Microbial growth	Microbial growth possible if GLT in contact with exterior envelope & moisture sources.
Engineering and architectural potential	Reuse allows for cutting of GLT members to suit requirements in new use. Beams often contain openings for building services.
Assessment of timber properties	Only 2-3 surfaces of laminations assessable visually. Laminations should conform to documented grade.
Assessment of glue joints	Glue joints between lamellae locally assessable. New non/semi-destructive glue line assessment methods needed.
Assessment of connections	Assessment methods for conformity of glued-in rods and adhesion not available.

Glue laminated members pose the greatest potential for type A reuse, with a possibility for type B reuse. Sawing glulam into smaller sections, while possible, remains out of scope for this master's thesis.

7.2.5 Temporary structures

Temporary structures in the form of concrete falsework, temporary work platforms, and other temporarily constructed support structures, are a source of timber boards for either reuse or cascading. The potential to salvage timber from these structures came up in the interviews of this master's thesis. A relatively small quantity of fasteners, short service life, and timber with a cross section corresponding to current milling and grading standards all contribute to the suitability of temporary structures for reuse purposes. Further, the timber is likely untreated and microbial growth is limited due to its short service life. In the future, these temporary structures could be designed and constructed with salvaging deconstruction in mind.

Conclusions

The two main goals of this master's thesis were to clarify the certification requirements and investigate potential assessment methods to evaluate whether a reused structural timber product meets the certification requirements. Available timber material was investigated before certification and assessment methods were narrowed down according to the available timber material. The member types with most technical potential for reuse were identified.

First, the concept of reuse was defined. In reuse the structural timber may not undergo transformation beyond cleaning, repair, and minor resizing to fit the new application. Clear boundaries for transformation beyond reuse could not be concluded in this master's thesis. Results from interviews suggest that member specific definitions between reuse and remanufacturing are under discussion. This distinction remains important as remanufactured members are certified through hENs or through ETA.

Reused structural timber products are certified through a verification on construction site -certificate. This remains the only form of certification for the foreseeable future. Verification on construction site is always an expert investigation to ensure that a construction product meets the criteria of essential technical requirements for the specific application.

Certification criteria determine the required level of assessment. There are at least two development projects which aim to create guidance on the assessment methods and required sample sizes. At first the development focuses on assessment guidance for GLT, and later on visual grading of reused dimensional timbers. Composite members which contain materials apart from timber, glue, and metal fasteners would require an extremely extensive level of assessment and they are not currently seen as reusable.

A review of the assessment methods presented in literature and standards indicates that current methods are adequate for assessment of dimensional timbers, while they do not adequately assess the capacity of glue joints and metal connections for reuse purposes. A reused member should fulfil a similar level of reliability as new timber members. New assessment methods are needed for estimating the capacity of members in existing structures as reliably as in factory production. Alternatively, conservative design capacities are proposed to reach a confident level of structural reliability.

Harmful substances are detectable with current on-site investigation methods. Banned hazardous substances prohibit reuse. A removal of surface microbial growth allows reuse in all applications, whereas unremovable growth limits reuse to applications with no requirements for indoor air quality.

A technical reuse potential was evaluated for the identified structural members and -systems. GLT and log constructions present the greatest potential, along with regraded dimensional timber. Trusses are limited in potential by their restricted geometry and lack of practical assessment methods. Further research efforts should focus on the assessment methods of the GLT and trusses. Additionally, case studies of practical assessment are needed to investigate whether the intended assessment methods are economically applicable. Overall, the total cost difference and difference in emissions between new and reused structural products should be calculated and compared against green premiums in other forms of climate change mitigation.

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Appendix A

Design capacity for a GLT roof beam in both Finnish codes B1 and B10 from 1978 and in Eurocode 5.

Basic assumptions:

- In ULS only bending- and shear strengths considered
- In SLS allowable deflection considered
- Lateral bucking prevented
- Capacity under fire not considered
- Service class 1 conditions in both cases
- Effects of DOL not considered

Symbols:
A = Cross-sectional area of beam
B = Width of beam
D_t = Distance between trusses
E = Mean modulus of elasticity
$f_{b,k}$ = Characteristic bending strength
$f_{b,d}$ = Design bending strength
$f_{v,k}$ = Characteristic shear strength
$f_{v,d}$ = Design shear strength
g_k = Characteristic line load due to self-weights
q_k = Characteristic line load due to variable loads
g_{sw_beam} = Beam self-weight per length
g_{sw_roof} = Roof self-weight per length
H = Height of beam
I = Second moment of area
k_{def} = Deformation modification factor
k_{mod} = Strength modification factor
L = Span of beam
l_c = Characteristic line load in design based on Finnish codes
l_d = Design line load
M_d = Design bending moment at mid-span
$M_{d,max}$ = Maximum allowable design moment at mid-span
q_{snow} = Variable load from snow per length
V_d = Design shear force next to support
W = Section modulus
W_{req} = Required section modulus to fulfil design criteria
w_{all} = Allowable final deflection in Finnish code B10
w_c = Pre-camber
w_{fin} = Final deflection
$w_{k,g}$ = Instantaneous deflection due to self-weight

$w_{k,q}$ = Instantaneous deflection due to variable load
$w_{net,fin}$ = Net final deflection
$\sigma_{b,d}$ = Design bending stress
γ_m = Material partial safety factor
τ_d = Design shear stress

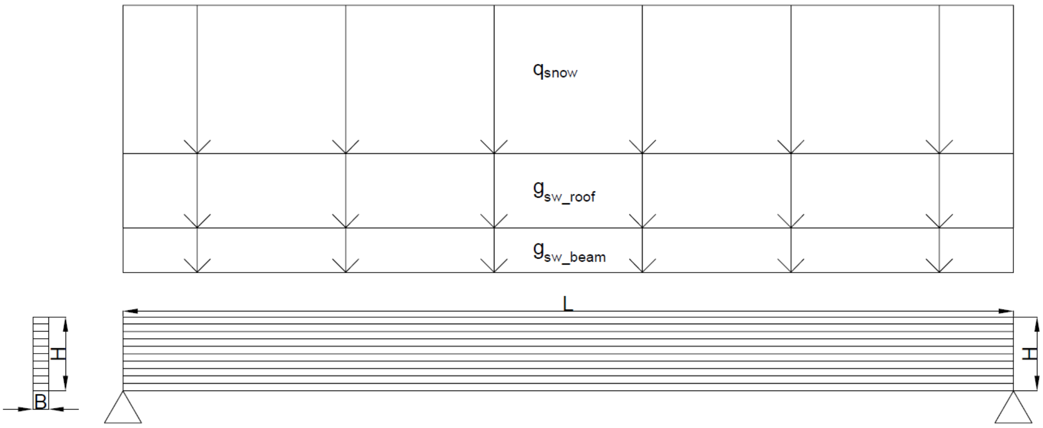

Figure 9. A schematic of the GLT beam and its loading.

Dimensions, loading, and mechanical properties in example based on Finnish codes:

- Span L = 12 m
- Distance between beams 4 m
- Beam width B = 200 mm
- Height of 800 mm assumed for self-weight
- Beam self-weight
  $g_{sw\_beam} = B * H * 390\ kg/m^3 * 9.81\ m/s^2 = 0.61\ kN/m$
- Roof self-weight $g_{sw\_roof} = 0.5\ kN/m^2 * 4\ m = 2\ kN/m$
- Snow load $q_{snow} = 1.8\ kN/m^2 * 4\ m = 7.2\ kN/m$
- Beam in service class 1 & load-duration class B (snow load in load duration class B, self-weights in load-duration class A)
- GLT class L40, $f_{b,k}$ = 29 MPa, $f_{v,k}$ = 2 MPa, E = 8.4 GPa

ULS restricted height of beam according to Finnish codes:

Bending:

$$Requirement: \frac{\sigma_{b,d}}{f_{b,d}} \leq 1 \tag{1}$$

$$f_{b,d} = \frac{f_{b,k}}{\gamma_m} = \frac{29\ MPa}{1.3} = 22.31\ MPa \tag{2}$$

$$\sigma_{b,d} = \frac{M_d}{W} \tag{3}$$

$$M_d = \frac{l_d * L^2}{8} = \frac{(1.2 * g + 1.6 * q) * L^2}{8}$$
$$= \frac{\left(1.2 * (0.61 + 2)\frac{kN}{m} + 1.6 * 7.2\frac{kN}{m}\right) * (12\ m)^2}{8} = 264\ kNm \tag{4}$$

Required section modulus W_{req}:

$$W_{req} = \frac{M_d}{f_{b,d}} = \frac{264\ kNm}{22.31\ MPa} = 0.0118\ m^3 \tag{5}$$

Required beam height H:

$$W_{req} = \frac{B * H^2}{6} \tag{6}$$

$$H = \sqrt{\frac{6 * W_{req}}{B}} = \sqrt{\frac{6 * 0.0118\ m^3}{0.2\ m}} = 0.59\ m\ \approx 0.60\ m \tag{7}$$

Shear capacity:

$$Requirement: \tau_d < f_{v,d} \tag{8}$$

$$V_d = \frac{l_d * L}{2} = \frac{\left(1.2 * (0.61 + 2)\frac{kN}{m} + 1.6 * 7.2\frac{kN}{m}\right) * 12\ m}{2} = 88\ kN \tag{9}$$

$$\tau_d = \frac{3}{2} * \frac{V_d}{A} = \frac{3}{2} * \frac{88\,kN}{0.2\,m * 0.6\,m} = 1.1\,MPa < f_{v,d} = \frac{2\,MPa}{1.3} = 1.54\,MPa \tag{10}$$

SLS criteria for maximum deflection: L/200
Assuming a pre-camber of L/400, the maximum deflection may be multiplied by 1.25, giving an allowable deformation of:

$$w_{all} = 1.25 * \frac{L}{200} = 1.25 * \frac{12\,m}{200} = 75\,mm \tag{11}$$

Required second moment of area:

$$w_{all} = \frac{5 * l_c * L^4}{384 * E * I} \tag{12}$$

$$I = \frac{5 * l_c * L^4}{384 * E * w_{all}} = \frac{5 * (0.61 + 2 + 7.2)\,\frac{kN}{m} * (12\,m)^4}{384 * 8.4\,GPa * 0.075\,m} = 0.0042\,m^4 \tag{13}$$

$$I = \frac{B * H^3}{12}$$
$$H = \sqrt[3]{\frac{12 * I}{B}} = \sqrt[3]{\frac{12 * 0.0042\,m^4}{0.2\,m}} = 0.631\,m \ \approx 0.64\,m \tag{14}$$

SLS midpoint deflection restricts beam height to a minimum of 0.64 m.
The load-case of only self-weights was not considered as snow load poses majority of loading for the beam and the permanent self-weight load case would not limit the beam cross-section.
DOL effects possible as the beam ULS design capacity is close to 100 %. Thus, a reduction in design capacities could be justified.

Next, the capacity of a BxH = 200 mm x 640 mm GLT beam is calculated in Eurocode-based design. Here we assume the same self-weight for the roof structure. With these assumptions we can evaluate either the allowable span or distance between GLT beams in Eurocode-based design. Here the difference in distance between beams is evaluated.

Design information in Eurocode-based design:

- L=12 m
- B=0.2 m
- H=0.64 m
- Distance between beams = D_b
- Beam self-weight
  g_{sw_beam} = B * H * 390 kg/m^3 * 9.81 m/s^2 = 0.49 kN/m
- Roof self-weight g_{sw_roof} = 0.5 kN/m^2 * D_b
- Snow load q_{snow} = 2.5 kN/m^2 * D_b
- Service class 1, medium term load-duration class in snow loading
- Maximum deflection with pre-camber for a straight beam:
  $w_{net,fi}$ = L/300, w_{fin} = L/200
- Pre-camber of w_c = L/400
- γ_m=1.25
- k_{mod}=1.0 (Values in Finnish code B10 represent medium-term loadings in service class 1)
- k_{def}=0.60
- Modulus of elasticity E = 8.4 GPa

Design strengths in Eurocode:

$$f_{b,d} = k_{mod} * \frac{f_{b,k}}{\gamma_m} = 1.0 * \frac{29\ MPa}{1.25} = 23.2\ MPa \tag{15}$$

$$f_{v,d} = k_{mod} * \frac{f_{v,k}}{\gamma_m} = 1.0 * \frac{2\ MPa}{1.25} = 1.6\ MPa \tag{16}$$

Bending capacity:

$$Requirement: \sigma_{b,d} \leq f_{b,d} \tag{17}$$

Ultimate capacity at equality of stress and capacity.

$$f_{b,d} = \frac{M_{d,max}}{W}$$

$$M_{d,max} = f_{b,d} * W = f_{b,d} * \frac{B * H^2}{6} = 23.2\ MPa * \frac{0.2\ m * (0.64m)^2}{6} = 317\ kNm \tag{18}$$

Distance between beams at ultimate bending moment:

$$M_{d,max} = \frac{l_d * L^2}{8} = \frac{\left(1.15 * (g_{sw_{beam}} + g_{sw_{roof}}\right) + 1.5 * q_{snow}) * L^2}{8}$$
$$= \frac{\left(1.15 * (0.49\frac{kN}{m} + 0.5\frac{kN}{m^2} * D_b\right) + 1.5 * 2.5\frac{kN}{m^2} * D_b) * (12m)^2}{8} = 317\ kNm$$
$$From\ which\ D_b = 3.94\ m$$
(19)

Design capacity for bending in Eurocode 5 would limit distance between beams to 3.94 m, which is practically the same as the 4 m in Finnish codes.

Design criteria for shear capacity:

$$\tau_d < f_{v,d}$$
(20)

$$\tau_d = \frac{3}{2} * \frac{V_d}{A}$$
$$= \frac{3}{2} * \frac{0.5 * \left(1.15 * \left(0.49\frac{kN}{m} + 0.5\frac{kN}{m^2} * 3.94m\right) + 1.5 * 2.5\frac{kN}{m^2} * 3.94m\right) * 12m}{0.2m * 0.64m}$$
$$= 1.24\ MPa < f_{v,d} = 1.6\ MPa$$
(21)

SLS deflection at midpoint:
w_c = 30 mm (L/400 pre-camber)
Allowable final deflection w_{fin}= L/200 = 60 mm
Allowable net final deflection $w_{net,fin}$= L/300 = 40 mm
$$w_{net,fin} = w_{fin} - w_c$$
(22)

➔ Allowable final deflection controls design deflection

Characteristic loading:
$$g_k = g_{sw_{beam}} + g_{sw_{roof}} = 0.49\frac{kN}{m} + D_b * 0.5\frac{kN}{m^2}$$
(23)

$$q_k = D_b * 2.5\frac{kN}{m^2}$$
(24)

Second moment of area I:

$$I = \frac{B * H^3}{12} = \frac{0.2m * (0.64m)^3}{12} = 0.0044\ m^4 \tag{25}$$

Deflection due to permanent and variable load (snow):

$$w_{k,g} = \frac{5}{384} * \frac{g_k * L^4}{E * I} = \frac{5}{384} * \frac{(0.49 \frac{kN}{m} + D_b * 0.5 \frac{kN}{m^2}) * (12m)^4}{8.4\ GPa * 0.0044\ m^4} \tag{26}$$

$$w_{k,q} = \frac{5}{384} * \frac{c_k * L^4}{E * I} = \frac{5}{384} * \frac{D_b * 2.5 \frac{kN}{m^2} * (12m)^4}{8.4\ GPa * 0.0044\ m^4} \tag{27}$$

$$\begin{aligned} w_{fin} &= \left(1 + k_{def}\right) * w_{k,g} + \left(1 + 0.2 * k_{def}\right) * w_{k,q} \\ &= (1 + 0.6) * \frac{5}{384} * \frac{\left(0.49 \frac{kN}{m} + D_b * 0.5 \frac{kN}{m^2}\right) * (12m)^4}{8.4\ GPa * 0.0044\ m^4} \\ &+ (1 + 0.2 * 0.6) * \frac{5}{384} * \frac{D_b * 2.5 \frac{kN}{m^2} * (12m)^4}{8.4\ GPa * 0.0044\ m^4} = 0.060\ m \end{aligned} \tag{28}$$

From which D_b = 2.02 m.

This indicates that Eurocode-based design of beam deflections would limit the allowable distance between beams to only 2.02 m /4 m * 100% = 50% of the original distance between beams as calculated with Finnish codes B1 and B10 from 1978. Reasons for this include higher characteristic snow load, lower allowable deflections, and design deflections due to creep in Eurocodes.

Appendix B

Common interview questions

General questions

1. Introduce yourself shortly. What do you focus on in your current employment, your experience, education.
2. What is the role of your organization in the built environment?
3. What is/could be the role of your organization in reuse of timber structures?

Current certification methods for reuse of timber structures

4. On a general level, how do you evaluate the current certification methods and -requirements for reuse of timber structures?
5. How do you see the current state of assessment of timber for reuse? In this context assessment refers to assessment of physical properties.
6. Are reused structures and structures made of primary timber treated with the same criteria related to essential technical requirements?
7. Verification on building site remains the only avenue for reuse of timber structures under current regulations. What specifically needs to be presented of the reused timber product for a verification on building site -certificate?
8. Will verification on building site remain an avenue for certification in reuse of structures in the future?

Documentation and properties of reused timber structures

9. How does the availability of building documentation affect reusability of structural products?
10. How elaborate documentation is required of the reused structural products?

11. How does the presence of harmful substances affect reusability of a timber structure?

12. What is the necessary extent of assessment for adequate reliability of the properties of reused timber?

Role of different actors in assessment and certification

13. Is there an economic operator who has capability to assess a to-be reused timber product and take the responsibility of a “manufacturer”?

14. How does the operation of your organization change more structures are sourced from existing buildings?

15. What could be the role of building designers in reuse, specifically in assessment and certification?

Actions to promote assessment and certification

16. What are the necessary developments within assessment and certification of reused structural timber products?

17. Do you have suggestions on what kind of research should be conducted to promote assessment and certification?