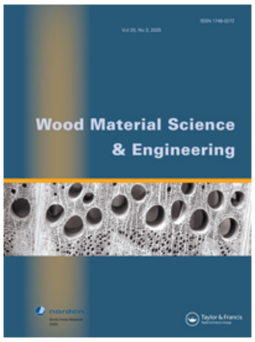

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Circulating structural timber and engineered wood products – challenges and potentials towards reliable evaluation of mechanical properties

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ABSTRACT
Circulating structural timber and engineered wood products require reliable assessment of key mechanical properties. However, existing standards for strength grading sawn timber are not designed for the reuse and recycling of timber and are unsuitable for this in a number of ways. Furthermore, existing procedures for the re-assessment of structural components are mainly focused on the identification of in-use damage and assumptions about the original mechanical properties, and not on the quantitative re-evaluation of the current mechanical properties. In this paper, existing strength grading procedures in Europe are discussed according to their potential for the assessment of reused timber, with observations on shortcomings of the underlying basis when not applied to new, not previously graded timber. Since the situation for reused and recycled laminated components (glued laminated timber and cross-laminated timber) might be simpler, and perhaps more commercially relevant, a framework will be presented to estimate the mechanical properties of these structural components based on the load history and non-destructive assessment methods. The basis could be expanded by future work to allow the re-grading of sawn timber.

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Reuse; salvaged timber; circular economy; properties

1. Introduction

As one of the main consumers of raw materials and energy, and main producer of waste, mostly in the form of major mineral waste, the global construction sector is key in transforming our society towards a circular economy (Sobek 2022). So, instead of directly downcycling valuable materials and products, or sending them to energy recovery or landfill, there is an urgent need to keep products as long as possible in meaningful use and to see materials from demolition and deconstruction as a valuable resource for new products to fulfil similar or new purposes. Furthermore, regulations are increasingly promoting the inclusion of reused construction materials. As an example, Commission delegated regulation (EU) 2023/2486 sets an upper limit on the proportion of construction materials that may be sourced from primary raw materials in relation to the sustainable finance framework. For timber and other biobased construction products, this limit is 80%. The renewability of responsibly sourced timber can bring sustainability advantages over non-biotic construction materials, but it is nevertheless important for environmental reasons to also consider material circularity. There are also potential commercial advantages in terms of material cost, subsidies, and green marketing messages. Due to its versatility and easy processing, there are already manifold reuse, recycling and recovery options for wood. However, aside from chip, particle and fibre wood-based panels, the normative and legal framework for supporting safe use as structural construction products is currently underdeveloped.

Recycling of timber for non-structural applications, e.g. flooring, cladding and furniture, is rather common and, because of its commonly darker colour, appealing and economically attractive (cf. Chini *et al*. 2001, Janowiak *et al*. 2007). For structural timber, the situation is clearly different. The potential for circulating structural timber has been investigated in several studies, e.g. by Fridley *et al*. (1996a, 1996b, 1998), Rammer (1999), Falk (1999), Falk and Green (1999), Falk *et al*. (1995, 1999, 2000, 2008, 2013), Chini and Acquaye (2001), Green *et al*. (2001), Crews (2007), Nakajima and Murakami (2008), Crews and MacKenzie (2008), Yokoyama *et al*. (2009, 2010), Nakajima and Nakagawa (2010), Sousa *et al*. (2015), Llana *et al*. (2022, 2023a, 2023b) and Dong *et al*. (2024). However, there are still several major barriers in maintaining the load-bearing function of timber products in a further service life beyond extending the life of the original building. The main barriers include missing standards and regulations for re-grading, re-classifying and re-certifying salvaged timber for load-bearing structural purposes (cf. Falk *et al*. 1995, 2008, 2013, Rammer 1999, Chini *et al*. 2001, Crews 2007). Current grading standards, which are formulated for new timber, are limited in this way due to a number of reasons, such as: missing criteria for damages coming from erection, use and deconstruction; if not carrying any stamps on the product, missing knowledge about the timber species, its origin (growth region) and strength class; and lack of information

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about surface treatment or penetration with potentially harmful substances that might also have affected mechanical properties (cf. Hafner *et al*. 2013, Sandberg *et al*. 2022, prNS 3691 2024). The same applies to current product and design standards which are also explicitly formulated only for new timber. So, there are also a lot of legal and insurance issues which currently act as barriers to circulating structural timber and timber construction products.

Aside from the effort of overcoming barriers related to structural timber, in general, the higher the degree of processing, embodied energy and added value, the higher the environmental and economic motivation for reusing instead of downcycling the components. However, although reusing structural timber construction products is, in this respect, best done directly, i.e. in their full original dimensions, it might be that viable reuse options require some degree of re-processing. This is because, for the next service life, parameters such as dimensions, mechanical properties (i.e. strength class), and appearance need to match the demands of modern markets; an observation which was also confirmed for circulating timber in non-structural products, cf. Chini *et al*. (2001). For structural timber, circularity potential depends also on the cross-sectional dimension. Falk *et al*. (2013) state that structural timber with large cross sections seems to be better suited for reuse, or to be resawn to boards as a base material for the production of timber construction products. This is, in principle, also confirmed by Llana *et al*. (2023b) and Dong *et al*. (2024) who see larger cross sections better for reuse, and smaller and medium cross sections for up-cycling, i.e. as raw material for higher value timber construction products such as glulam (GLT) and cross-laminated timber (CLT). Currently, the large size members on wood reuse markets tend to be from old structures, with perhaps species, wood quality and dimensions that are less readily available now than in the past. In the case of GLT and CLT, the commercial motivation becomes more about the technical performance than the rarity. The availability of glued laminated timber construction products will increase for reuse and recycling in the future, as the volume of mass timber products, such as glulam and CLT, increased rapidly within the last two decades. Furthermore, the possibilities to reuse timber products as raw material, or at a component level, will also change due to the increasing use of modular timber construction and the societal and political demand towards considering reusing and recycling already at the first use planning phase. It is expected that such demands force new developments in reversible fastener and joint solutions which would make deconstruction processes much faster, reduce damage, and raise the economic potential. However, before reusing material, components or whole modules the main target must be to extend the design life with proper quality materials, construction, maintenance, adaptability and reparability, as studied for example by Berkmann (2024). These aspects also need to be supported by appropriately adapted standards.

Nevertheless, for the coming years reclaimed timber will be coming from already existing buildings. The paper in hand focuses primarily on possibilities to circulate structural timber, and here in particular on modifications necessary to the existing set of strength grading standards to also accommodate salvaged timber obtained from building deconstruction, demolition or renovation. Furthermore, options for circulating timber construction products are analysed and discussed in a broader context. An extensive literature review forms the basis of the results in this secondary research study. Much of the literature consists of peer-reviewed articles. These articles are complemented with standards and theses relevant to reusing structural timber and engineered wood products. In addition, unpublished, technical discussions, insights from previous research projects, and engagement with industry inform this study. The formulated research questions (RQ) include:

RQ1: How to delineate reuse, recycling, and recovery operations within the general framework of circulation of structural timber and engineered wood products?

RQ2: What are the key differences in properties of salvaged structural timber in comparison to properties of new structural timber products?

RQ3: Which factors to consider in the assessment of properties of both salvaged structural timbers and reused glued laminated timber construction products?

2. General aspects regarding reusing structural timber

2.1. R-strategies

For the support of this ongoing transformation process, and for its clarification and evaluation, different levels and sub-levels of circularity have been defined, which operate under the name "10 R-strategies of circular economy" (0R to 9R), which are organised in three levels (Potting *et al*. 2017). Those sub-levels addressed, at least partly, in the following are "3R reuse", "4R repair", "5R refurbish", "6R remanufacture", "7R repurpose" and "8R recycle". Whereas 3R to 6R aim for "extending the service life of products or at least of some of its parts" (level two), 7R and 8R aim for "meaningful use and circularity of the products" (level 3). Examples of the addressed R-strategies with regard to timber constructions, and thus on products like structural timber and timber construction products, are given in Table 1. In conclusion, there are, in principle, a lot of options to circulate timber products for load-bearing purposes before "9R recovering" (also part of level three). Although these possibilities are clear and straightforward on paper, they are not yet fully established.

The original purpose of the timber component (whether if it was used as a joist, column, within a framework, etc.), might not be known for products on the market offered for the next service life, especially for the smaller standard dimension common components. Having reliable information about this seems like it could only be an exception rather than a rule. Consequently, it is hard to tackle the optimal level of circularity. This information is easier to obtain when reusing timber components in the same rebuilding project, which can also be advantageous to reduce the impact of renovation and redevelopment, i.e. the environmental rating of the construction project. Furthermore, using components differently to their previous purpose(s) offers the chance to utilise their full potential, i.e. without the need to consider the strength-reducing duration of load effects from the previous but different use case (see Section 2.2 below).

Table 1. Examples of addressed R-strategies for structural timber and timber construction products.

R-strategy group	R-strategy	Examples
Reuse (level two)	3R reuse	Reusing products again for the same purpose directly without significant modification beyond cleaning (e.g. beams as beams and columns as columns).
	4R repair	Reusing products again for the same purpose after repairing (e.g. of damaged zones or of cracks and bondlines in glulam beams), without changing the product performance or classification.
	5R refurbish	Reusing products again for the same purpose after enhancing their properties to the current state-of-the-art (e.g. by reinforcing against brittle failure modes or by raising the bearing capacity at supports).
	6R remanufacture	Reusing engineered wood products again for the same purpose after re-dimensioning components within allowed boundaries without losing the classification and certification if it would be new.
Recycling (level three)	7R repurpose	A new use of the product for a different purpose, with different requirements. This could be structural or non-structural.
	8R recycle	Processing salvaged structural timber and timber construction products to raw materials to produce new timber construction products. - Up-cycling: e.g. by producing products of higher market value such as glulam or CLT from salvaged structural timber (cf. Rose *et al*. 2018, Llana *et al*. 2022, 2023b, Dong *et al*. 2024). - Re-cycling: by maintaining the original value of the product, e.g. by processing structural timber after trimming local zones, planing of cross sections and reclassification to structural timber (cf. Falk *et al*. 1995, Fridley *et al*. 1996a, 1996b, 1998; Falk 1999, Falk *et al*. 1999, 2000, 2008, Chini and Acquaye 2001, Crews 2007, Crews *et al*. 2008, Crews and MacKenzie 2008, Nakajima and Murakami 2008, Nakajima and Nakagawa 2010) or finger jointed construction timber. - Down-cycling: by processing timber to strands, flakes or particles to produce wood-based boards such as OSB and particle boards, wood fibre insulation, or some other product.
	9R recovering	Utilising the embodied thermal energy of timber and release of stored CO_2 back into the natural cycle.

Since a universal delineation of the R-strategy categories for the next service life might not be possible, and for ease-of-use in discussing the following points, R-strategies are grouped according to their sub-level with "reuse" as surrogate for "level two" and "recycling" for "level three". It should also be noted that these terms are also differently defined in the new European Construction Products Regulation (CPR) (Regulation (EU) No. 2024/3110), with "reuse" referring to the situation where the essential characteristics of a product have not changed and "remanufacture" referring to the situation where they have. In the case of structural timber, essential characteristics are changed when the timber is regraded, even if nothing else is changed. "Recycling" refers to the situation where the structural timber returns, conceptually, to the state of being a material from which a new product is made. In the case of "reuse", under the CPR, it is necessary to have transferred information about the deconstruction to the point when the new Declaration of Performance and Conformity is made. Within that framework, most future scenarios for timber reuse are likely to be in the normative and regulatory frame of remanufacture or recycling, but it is nevertheless still useful to use the 10R terminology to describe the practical actions.

2.2. Time-related effects on timber: aging and long-term loading effects

Time-related effects on timber include aging of timber depending on exposure to abiotic actions, and long-term loading effects, such as duration of load (DoL) effects, fatigue and creep. These are still under scientific debate and very controversially discussed in the literature. Long-term loading effects, as a result of the rheological and viscoelastic nature of timber, can be further divided into the group of potential irreversible decrease in strength properties with (i) increasing time under pseudo-constant load (duration of load (DoL) effect; static fatigue) and (ii) increasing number of varying load cycles (fatigue), as well as in the group of, at least to some extent, reversible increasing deformations, known as creep. For summaries on aging effects in timber, i.e. on changes in physical properties such as colour, chemical composition and microstructure of timber over time, see Popescu *et al* (2009), Kránitz (2014), Sonderegger *et al*. (2015), Kránitz *et al*. (2016), Cavalli *et al*. (2016), Xin *et al*. (2022) and Zhang *et al*. (2024). In those studies, changes in colour, chemical composition (e.g. changing shares of crystalline and amorphous celluloses, polyoses and lignin) and damage visible as cracks within and between cells on a microscopic level are reported. However, in contrast to studies on DoL and fatigue, which clearly show a decrease in strength with increasing time under constant load and number of load cycles, respectively (reviews are provided for example by Karacabeyli and Soltis 1991, Madsen 1992, Rosowsky and Fridely 1995, Barrett 1996 and Köhler 2007), results from tests on salvaged timber in comparison with control samples from supposedly equally rated new timber are not that clear, and very difficult to research because growth conditions also changed over time meaning timber was not necessarily equivalent to begin with. Overall, the herein referenced studies on aged and long-term loaded timber (extent and accumulated duration of loading usually unknown) report on unchanged or decreasing strength properties and mostly unaffected elastic properties and density (see, for example, the review by Cavalli *et al*. (2016)).

The main reasons for contrary results in the literature are the large uncertainties related to the representativeness of the control samples, the variability of timber in general, and the difficulty in testing enough old wood to properly distinguish actual changes from random chance. Furthermore, whereas changes in colour and chemical composition are directly a function of the time the timber was exposed to sunlight, weathering and other effects, changes in mechanical properties are primarily (but not only) related to the load history, i.e. the accumulation of load/stress levels and corresponding times under load/stress.

One pragmatic approach, which acknowledges the findings from aging, long-term loading effects and state-of-the-art in timber design is provided in FWPA Standard G01 (2024), the Australian standard for visual grading of recycled hardwood timber. This approach, which is based on comprehensive research activities as reported in Crews (2007), Crews *et al*. (2008) and Crews and MacKenzie (2008) and considers also the outcomes of Falk *et al*. (2008) and others, takes advantage of the fact that DoL effects are particularly relevant for short- and medium-term stresses, whereas long-term stresses show a DoL effect that is largely independent of the duration of exposure.

In conclusion, differences in the effects of aging and long-term loading on strength and elastic properties influence the allocation of grading classes to strength classes (since relationships between strength and strength indicate properties might be shifted downwards). They also influence the possible and meaningful applications of salvaged timber products, which might become more directed to design situations that are rather governed by serviceability than by ultimate limit states. The load history is usually unknown, at least on component level. Consequently, any possible loss in properties from environmental exposure and loading in the previous service life caused by DoL and/or fatigue and/or aging effects on timber are also unknown and the remaining physical/mechanical properties need to be estimated on a conservative basis.

2.3. Deconstruction process

When discussing options for circulating timber products with the aim of retaining their load-bearing purpose, it needs to be stated that current buildings in general are not designed for careful deconstruction and disassembling of the components. Aiming to maintain the value of timber products during careful deconstruction might incur significant additional costs and delays and might be restricted by safe working rules. On the other hand, using current standard demolition processes can cause severe damage to the components, greatly lowering residual quality and value. This damage can come from the act of removal of the element, and from subsequent handling and storage on the site. Even with careful disassembly, damage can also have occurred prior to demolition while the building was unoccupied and uncared for. This situation might change in the future by aiming for deconstruction to be considered in the design phase of new buildings, but for the current building stock, and for most of the demolition in the foreseeable future, other strategies are needed. These other strategies include manual deconstruction of the current building stock.

2.4. Harmful chemicals and biological damage

Harmful chemicals, which may be present in salvaged timbers, should not be cascaded to the next material application (see also Hafner *et al*. 2013, prNS 3691 2024). The CPR (Regulation (EU) No. 2024/3110) states that hazardous materials contained within a construction product should not adversely affect the health of building occupants. For salvaged timber, harmful chemicals include past preservatives (perhaps containing chrome, copper, arsenic or persistent organic pollutants) and past finishes (which may contain lead) (Huuhka *et al*. 2018). In some types of buildings, contamination can also occur from activities that take place inside. As well as the health implications, chemicals can potentially also affect the mechanical properties of the wood, and the way that strength grading indicators correlate with mechanical properties (Ridley-Ellis *et al*. 2016).

Timbers containing problematic biological damage, whether in the form of decay due to microbes or due to wood destroying insects, should be rejected. The presence of problematic biological damage not only increases the risk of health implications to building occupants, but also compromises wood properties. Assigning strength properties to timbers with decay may prove unreliable as the residual, undecayed cross section may not be reliably assessed, see for example Nocetti *et al*. (2024). Active decay and infestation must also be detected and dealt with.

2.5. Economic and environmental perspective

The need to reuse structural timber might be forced by circumstances, such as remote location or rebuilding after a large-scale disaster such as an earthquake or hurricane. However, in general, the reuse of timber is in direct competition with the option of using new timber, or some other construction material. Considerations prior to grading salvaged timber include economic feasibility and the achievable environmental benefits. In order to determine the best course of action early on, and avoid wasted effort, these should preferably be assessed prior to deconstruction and prior to the decision to grade a set of structural timbers. The degradation arising from the deconstruction process should also be considered. The considerations are often interrelated, for example, environmental benefits are connected to economics through the marginal abatement cost (cf. Gillingham and Stock 2018). The presence of harmful substances, decay and damage leads to rejection of some of the salvaged timbers and consequently increases the cost of accepted timbers.

Economic feasibility depends on the relation between the productivity of salvaging timber and on the value of salvaged timber. Labour hours (lh) for salvaging structural timber from deconstructed houses in Japan were investigated by Nakajima and Murakami (2008). They report a deconstruction productivity of 2.5 lh/m^2 of deconstructed building. The labour requirement for salvaging and de-nailing one cubic meter of structural timber was 15.7 lh, as reported in Nakajima and Murakami (2008). Similar deconstruction productivity rates of 3.1–4.8 lh/m^2 are reported by Dantata *et al*. (2005) for the United States. At the deconstruction productivity of Nakajima and Murakami (2008), and at a mean construction labour cost of 28.5€/lh in the EU (Eurostat 2023), the labour costs alone are 450€/m^3 of salvaged small-dimension timber in various qualities and dimensions, before accounting for costs to make the salvaged timber suitable for use again. This is to be contrasted against the wholesale price of new, ready to use, timber, of approx. 400–600€/m^3 (Finanzen.net 2025).

Economic feasibility would increase for timbers of large cross-section found in e.g. historical timber framed structures and in mass timber products. These have additional value also due to a lower quantity of fasteners per volume of salvaged timber and a more efficient deconstruction process. Dong *et al*. (2024) report much better circularity for salvaged joists than for studs. In addition to their larger cross sections, joists usually feature fewer fasteners which led to 93% yield in length compared to 61% for the studs. Llana *et al*. (2022, 2023b) investigated the upcycling potential of oak structural timber for the production of glulam and CLT. They found a very low yield of only 13%, due to high losses in harmonizing the cross sections, much lower than typically reported in literature from which around 30% is mentioned. A large number of metal fasteners, about 1400 pcs/m^3 of scantlings produced from salvaged timber, was found in salvaged rafters examined by Böhm *et al*. (2025). Not only does the removal of fasteners incur expense, but also the possibility that something might remain posing a significant risk to machinery, such as planers and finger jointers.

Environmental benefits arising from the use of salvaged timber include substitution of e.g. concrete, steel, plastics or virgin timber in construction. The deconstruction study of Nakajima and Murakami (2008) concludes that salvaging and reusing timber decreased carbon dioxide emissions by approximately 1.5 tons for the case study of a deconstructed 100 m^2 Japanese light-frame house. Out of the 10 m^3 of salvaged timber, 35% was reused and the rest was downcycled into particleboard. This 1.5-ton carbon dioxide emission reduction required 240 h of extra labour compared to normal demolition. Thus, the labour requirement for a reduction of one ton of CO_2 emissions required 160 labour hours, or approximately 3000€ per ton of reductions in CO_2 emissions using the mean EU construction labour cost and value of the reused timbers. This should be contrasted against the social cost of carbon, which was around 50€ per ton of CO_2 in 2017 (Gillingham and Stock 2018). In the EU Emissions Trading System (EU ETS), the price of a ton of CO2 has fluctuated between 50 and 100€ during the years 2022–2024 (Trading Economics 2025) and is projected to rise to 200€ by 2035 (BloombergNEF 2024). EU ETS already covers much of the carbon-intensive construction material sectors such as cement production and steelmaking (European Commission n.d.). The static abatement cost could somewhat decrease through learning-by-doing, resulting in the long-term dynamic abatement cost being lower than the static one (Gillingham and Stock 2018). It should also be understood that the environmental considerations go beyond carbon, with potential benefits in terms of biodiversity and land use that are harder to evaluate.

In view of these small yields and in a broader perspective, it needs to be decided whether the effort and additional energy necessary for processing the salvaged structural timber for reuse or recycling is beneficial for the environment, society and the economy compared to directly downcycling and energy recovery. Downcycling and energy recovery are value chains for salvaged wood that are now well established.

3. Strength grading salvaged timbers

3.1. General

The current grading standards, such as the product standard for structural sawn timber EN 14081-1 (2019) and visual grading rules that comply with it, such as DIN 4074-1 (2012), were formulated for not previously graded new timber. So, before salvaged structural timber can be circulated for load-bearing purposes, re-grading, re-classification and re-certification are seen as of utmost importance to fulfil legal requirements and to serve the demands of customers for safe, reliable and officially regulated products. Several aspects clearly differ between new and salvaged timber, including:

- Mixing of timber species and growth areas
- The presence of potentially harmful chemicals that might also affect grading
- Biological damage
- Mechanical damage of timber during previous use and (de)construction activities
- Geometrical irregularities such as wane, varying cross-sectional dimensions and holes
- Need for reprocessing of cross-section dimensions and surfaces
- Possible reduction in strength properties due to duration of load effects (DoL)
- Inhomogeneity and statistical distribution of the salvaged timber population due to possible prior grading and sorting mechanisms, resource mixing, etc.
- Shorter lengths of salvaged timbers

An important aspect is related to the source of salvaged timber where different levels of knowledge are possible. The best-informed level would be to salvage the timber directly from a building and to have, at least to some extent, information about its original application (i.e. if it served as beam, column, etc.), environmental exposure (e.g. humidity, UV radiation) and load level (stress in service). However, contrary to this rather ideal situation there is the rather uninformed level in which salvaged timber comes via a reclaim merchant collecting timber from many sources. This makes it difficult to categorise the previous function, quality, and exposure.

Species and corresponding growth area of a piece of salvaged timber are usually unknown, unless apparent from stamps and records. Species and growth area are needed for the application of current strength grading rules (Ridley-Ellis *et al*. 2016), and species is needed to be known for the application of the European product standards for structural finger jointed timber (EN 15497 (2014)), glulam (EN 14080 (2013)) and CLT (EN 16351 (2021)). There could be a mix of species even within a single building (Arriaga *et al*. 2007, Falk *et al*. 2008, Nocetti *et al*. 2024). The mix of species and growth areas depends in a large part on the geographical location from which timbers are salvaged from. There exists less mixing of species and growth areas in countries that have historically been net exporters of timber products. For example, in Norway, the timbers in buildings may be assumed to contain only Norway spruce and Scots pine of Nordic and Baltic origin. In a country with a long history of importing timber, such as the UK, the species and growth areas of structural timber are very diverse (Bather 2022). Exact species identification through inspection is restricted by aging, weathering, coatings, dirt, etc, and ultimately by what is possible to differentiate by wood microstructure (cf. Crews 2007, Falk *et al*.

2008, Sandberg *et al*. 2022). For species identification, there are a variety of methods available and some of these methods, e.g. computer vision, are already effective in identifying various species, at least on the genus level (Silva *et al*. 2022). However, for strength grading it is sometimes important to know species even at the subspecies level (e.g. for *Pinus nigra*) and genus may not be sufficient. An insight into the meaning of species in the European commercial timber context is given in Ridley-Ellis *et al*. (2023). While there are some methods for determining likely timber origin used in policing the illegal timber market, such as mass spectrometry, these are impractical for use in strength grading.

Salvaged structural timber might be treated or penetrated by (potentially) harmful chemicals that prevent any further circulation. For other impurities, e.g. contamination by substances others than timber, such as (non-removeable) fasteners and fittings, concrete residues and coatings, circulation can be restricted by processing problems and interfere with strength grading methods (cf. Hafner *et al*. 2013, prNS 3691 2024). The current European standard for strength grading (EN 14081-1 (2019)) is restricted to treatments for biological durability only, meaning they cannot be used on timber with other kinds of treatment (e.g. fire protection) or chemical or thermal modification. Leiter *et al*. (2022) investigated the ability of frequency domain fluorescence lifetime imaging microscopy (FD-FLIM) to detect treated timber. The results in Leiter *et al*. (2022) indicate that separation of treated and non-treated timber could be possible with FD-FLIM.

Biological damage (due to insects, bacteria, fungi, etc.), modifications from first construction becoming damage for reuse (holes for fasteners, notches, slots, etc.), and damage arising from use and deconstruction might limit or even prevent circularity; any local reductions in cross sections due to fastener holes, notches or slots need to be evaluated in respect to their dimensions, combined effect, and position within the cross section (cf. Falk *et al*. 1999, Chini *et al*. 2001, Fridley *et al*. 2001, Falk *et al*. 2003, Crews 2007, Falk *et al*. 2008, FWPA Standard G01 2024, prNS 3691 2024, Pasca *et al*. 2025). Splitting of timber, such as cracks, checks and fissures from drying, processing and moisture content changes in use, as well as geometric deformations, such as twist, bow, spring and cup, might prevent or at least limit any further use significantly (cf. Falk 1999, Rammer 1999, Green *et al*. 2001, Falk *et al*. 2008, Llana *et al*. 2023a, 2023b), and are also limited by rules in EN 14081-1 (2019) written for new timber. Warp does not necessarily decrease the strength of a piece of timber (Arriaga *et al*. 2023) beyond its impact on the elastic instability of members. Timbers containing wane also do not show a statistical difference in strength when compared against timbers of similar nominal size without wane (Arriaga *et al*. 2007). Practical reasons related to constructability may reject timber that contains wane and warp, but wane may be regarded as an appealing character feature of reclaimed timber that adds, rather than detracts, from its commercial value.

One aspect also relevant for new timber, but particularly important for salvaged timber, is that it usually has to be reprocessed for circulation by operations such as planing of the surfaces. Significant changes in cross-section usually lead to loss of prior grading validity and strength class; cf. EN 14081-1 (2019). The reason for this is that a number of strength-influencing characteristics, most visibly the size and extent of knots and knot clusters, have an effect relative to the cross-sectional dimensions. Changes in cross section after grading result in changing the relative size of these flaws and thus necessitates re-grading. This is one further complexity for reuse when relying on the original grading since it might not be known how much the cross-section was previously reduced after strength grading. In the case of planed timber, it was likely already reduced close to the limit. However, since tests have shown that density and stiffness do not change significantly with resizing it is possible to make a pre-grading assessment of these prior to a new planing or resizing operation to avoid processing timber likely to fail the formal strength grading step on the resized timber (cf. Dong *et al*. 2024).

The usually unknown history of exposure (climate, weather, substances, etc.) and loads result in aging of timber and long-term loading effects with not yet fully known impact on properties (cf. Sonderegger *et al*. 2015, Kránitz *et al*. 2016, Brandner and Ottenhaus 2022, Zhang *et al*. 2024). Studies on aging and long-term loading effects indicate in general unchanged or decreasing strengths but constant elastic properties which (as outlined already in Section 2.2) mean a consequential shift in prediction models for strength based on visual characteristics and non-destructive testing (NDT) of stiffness (cf. Brandner and Ottenhaus 2022). The available predictive models are also based on data from relatively modern resources, and may also not apply to old timber, with different growth conditions. In addition, aging and degradation might lead to salvaged timber having a different level of secondary properties, requiring different equations for these, and perhaps also different adjustment equations for things like moisture content. Calibration of secondary properties for salvaged timber would require extensive destructive testing programs, although these could focus on the properties of the largest concern and the resources thought to be most likely affected. As well as properties listed in EN 384 (2022), such as tension perpendicular to grain and shear strength, there are also concerns about things like increased brittleness.

Possible prior strength grading and other sorting processes might have preferentially removed the better timber, meaning grading thresholds for ungraded timber, do not produce the same characteristic values. This is the reason why EN 14081-1 (2019) specifies that previously graded structural timber may not be graded to the same or different strength classes unless the change in timber population has been accounted for. Salvaged timbers are often previously graded by some formal or informal grading method and contain a mix of grades (Bergsagel *et al*. 2022). Previous grading may be apparent if there are markings on individual boards. However, strength-graded timber that was unmarked, or had the marks removed could have been used and detecting the grade would be problematic through visual methods, in the absence of background records. For machine-graded timber, there should normally be grade stamps, but these (and other paperwork) do not give information about the machine type, grade combinations or settings used. If higher grades were taken out at the time of grading, this could have significantly altered the shape of the statistical distribution (especially for

Table 2. Incompatibilities of current, EN 14081-1 framed grading rules when applied to salvaged structural timbers.

Criterion	Deviations found within salvaged timbers	How could the criterion be estimated?	How to account for the criterion in salvaged timbers?
Rectangular cross-section within set tolerance class [EN 14081-1], [EN 336]	- Various cross-sections [Osuna-Sequera *et al.* 2024] - Cross-sectional dimensions outside of EN 336 (2013) tolerances [Dong *et al.* 2024]	- Cross-section and its variability are measurable	- Wider dimensional tolerances, account for irregularities during grading, and acceptability for reuse - Reprocessing to certain tolerance classes
Limits for wane, distortion, fissures and other damage [EN 14081-1]	- Rules written for new timber often cause high rejection rate for salvaged timber	- Features are measurable	- Different criteria for salvaged timber, depending on intended use
Known species [EN 14081-1], [EN 14081-2 2022]	- Varying mix of species [Cavalli *et al.* 2016, Falk *et al.* 2008]	- Species potentially identifiable with stamps, records, or visual methods [Silva *et al.* 2022]/ NIRS [Ma *et al.* 2019]	- Species identification on a board/population level - Species independent grading
Known growth area [EN 14081-1], [EN 14081-2 2022]	- Varying mix of growth areas	- Growth area might be estimated from e.g. import data	- Conservative assumption of growth area
May not contain treated timber [EN 14081-1] (while preservative treatment is allowed, this is usually applied after strength grading)	- Treated timber may be present [Leiter *et al.* 2022]	- Surface treatments visually recognizable - Preservative treated timber identifiable with FD-FLIM [Leiter *et al.* 2022]	- Separate treated timber during grading/sorting - Grading approaches that take treatments into account or are unaffected by them
No re-grading without accounting for it [EN 14081-1]	- Salvaged timber likely graded prior to first use, but difficult to account for [Dong *et al.* 2024]	- In the absence of evidence otherwise, salvaged timber may be assumed to be previously graded and the potential effect of this taken into account conservatively	- New grading approach that is not dependent on known statistics about a population of timbers
Length / width ratio [EN 408], [EN 384]	- Short lengths observed, often below 2 m [Dong *et al.* 2024]	- Measurable	- Use of grading indicators and testing standards which are suitable for short pieces
Visual grading rules [EN 14081-1]	- Salvaged timber rejected by current rules [Llana *et al.* 2023a]	- Visually detectable damage	- Formation of new visual grading rules and visual override rules
Release of harmful substances [EN 14081-1]	- Harmful substances embedded/ connected after sorting and grading [Schild and Cool 2021]	- Detection of treated timber visually & with e.g. FD-FLIM [Leiter *et al.* 2022]	- Detection of treated timber visually & with e.g. FD-FLIM
Biological durability [EN 14081-1]	- Durability depends on species and growth area [Scheffer and Morrell 1998]	- Requires species identification and knowledge of growth area	- According to identified species or estimated conservatively
Variability of incoming material [EN 14081-1]	- Salvaged timber an inhomogeneous material source in species, age, cross-section, length, and quality	- Knowledge of previous use - Stamps and records - Visual characteristics - Species identification	- A new grading scheme that accounts for the variability
Secondary properties [EN 384]	- It is not known if the equations for secondary properties, used for new timber, are all conservative for salvaged timber	- Secondary properties of concern can be evaluated by direct testing	- Creation of a set of secondary properties equations specifically for salvaged timber
Duration of load effects / aging	- Not accounted for in grading standards	- Estimation of loading in previous use	- Decrease of short-term characteristic strengths and adaptation of modification factors

density and stiffness) in a way that would lead to overestimation of the characteristic value if not accounted for.

The current test standards (including EN 408 (2012)) are difficult to apply to a resource that has typically shorter lengths than new timber. Additionally, some machine grading techniques, and handling mechanisms, do not work for short lengths. The length of preprocessed gradable salvaged timbers is often below a length to width ratio of 20:1 (Bergsagel *et al.* 2022, Böhm *et al.* 2025, Nasiri *et al.* 2025). This also limits the use of straightforward acoustic dynamic modulus of elasticity measurements (Bergsagel *et al.* 2022).

Table 2 contains most of the incompatibilities if salvaged timbers were to be graded according to EN 14081-1 (2019). The fourth column in Table 2 expresses possible pathways to overcome the incompatibilities in a grading system developed specifically for salvaged timber. These are discussed further in Section 3.3. Even though Table 2 highlights the incompatibilities of salvaged timber, several of the aspects might be also true for new timber. Examples are (i) a potentially large variability of the incoming material resulting from e.g. variations between growth regions and growing conditions (Ranta-Maunus and Turk 2010) and (ii) clarifications for re-grading of new timber following, for example, reprocessing. Furthermore, also for new timber a more detailed clarification of wood species and how to deal with mixtures, could be added to the codes. Grading rules in EN 14081-1 (2019) are derived separately for each timber population which consists of a single species or species group and a specific growth area. The grading rules are applicable to populations of sawn timber that are representative of the original population the grading rules were derived for. Thus, changes in the population of timbers, including mixing of species, mixing of growth areas, the influence of previous grading, and various types of damage mechanisms outlined earlier in this section prohibit the general use of EN 14081-1 (2019) framed grading rules on salvaged timber (the assignment to a strength class), even if sorting criteria are still compatible.

3.2. Existing standards for grading salvaged timber

The lack of well-established standards for circulating salvaged timber within 3R and 8R (see Table 1) has been recognised. Meanwhile, some projects started to establish nascent standards for grading and allocation of design values for properties. One example is Forest and Wood Products Australia Standard G01 (2024), for which the underpinning research started already much earlier with the projects of Crews (2007), Crews *et al*. (2008), Crews and MacKenzie (2008), along with parallel works at that time in the US by Falk *et al*. (2008) and others. This standard G01 (2024), in its current formulation, sets minimum requirements for visual structural grading of salvaged hardwood timber in two visual grading classes. It also provides some guidance for softwood. In addition to the visual classes, the species of the timber must be identified to assign the timber into a correct strength class. The standard covers circulation of structural timber in its original cross-sectional dimensions as well as structural timber resawn from components with larger cross section. By doing so, additional grading parameters, such as diameter, number and position of holes from fasteners as well as notches, end splits, checks, rot, want, wane, bow, spring and twist, and cup are included. Within the informative appendix, a design guideline is presented. It is concluded that elastic properties remain whereas effects of long-term loading need to be considered for strength. As the load history, especially on the component level, is usually unknown, a pragmatic and conservative proposal is to assign strength properties two strength classes (in their system) lower than for new timber but to compensate for this for the next design/service life by much higher modification factors in the range of 0.90–1.00 instead of 0.57–1.00 as currently applied for new structural timber. Furthermore, Standard G01 (2024) provides zones for the safe positioning of dowel-type fasteners and notches as well as rules for the design of connections.

The draft Norwegian Standard prNS 3691 (2024) presents a somewhat different approach compared to Standard G01 (2024). Separated into three parts, it provides rules for the re-evaluation of salvaged Nordic and Baltic grown spruce (*Picea abies*) and pine (*Pinus sylvestris*) timber of rectangular cross section to be applied again for load-bearing purposes. Part 1 of this standard is on the terminology and general rules, part 2 on impurities (and contamination by substances others than timber, e.g. fittings, fasteners, concrete residues, paint, impregnation) and part 3 on visual strength grading. Differentiation is made in (i) known/unknown source, (ii) specific/mixed previous product, (iii) clean / treated timber, (iv) with/without holes, and (v) with/without fasteners. The assessment rules apply to structural timber at least 50 mm wide and 36 mm thick, without face- and edge-gluing but which might be finger-jointed end-to-end. The parameter groups are classified into "natural defects" (parameters also applied to new timber) and "deteriorations from previous use" (holes, cracks, notches, biological degradation, etc.), with the latter subdivided into "small" and "large" defects according to specified limits in the standard. The newly introduced assigned strength classes for recycled timber, "R-classes", are directly related to "C-classes" as established for new timber in EN 338 (2016) whereby the elastic properties remain and the strength properties are similar for "small defects" and one class lower for salvaged timber with "large defects", i.e. declassification according to allowed losses in cross section/resistance. In contrast to FWPA Standard G01 (2024), any deterioration from aging and in particular from DoL effects is neglected. After re-classification recycled timber with "small defects" is regarded to have the same mechanical properties as new timber, whereas recycled timber with "large defects" has one class lower strength properties**.** This is not due to aging and DoL but due to the reduced capacities of its net cross-sections. Given that approach, recycled timber according to prNS 3691 (2024) might be similarly used in the design as new structural timber.

While Norway has a very homogeneous use of species and growth area, and a long-standing history of strength grading practice with few changes, this is not the case for much of the rest of Europe. Therefore, the Norwegian approach is not directly applicable to the more varied situation across Europe, but the general framework of the approach is a step forward in developing the criteria to consider. Both standards have in common that they are in principle based on grading standards for new structural timber which have been extended by characteristics typical for salvaged timber.

3.3. Considerations for deriving a grading system for salvaged timbers

Grading of salvaged timber is here defined as strength grading of previously used, salvaged, structural timber, or timber for which the original grade may not be valid anymore for some other reason. This section considers only solid timber with no adhesive joints. The recommendations outlined herein cover factors that need to be considered but are not fully complete due to this still being an active area of research. In particular, no numerical values are given for the reduction in strength of a piece of timber due to e.g. duration of load effect or mechanical damage, as they are case-specific and under-researched.

At its heart, strength grading needs to balance the cost of the process with the raised value of the graded timber. Grading of salvaged timbers should begin by rejecting the pieces that are not suitable for reuse, would likely not pass grading, or would require a too high processing cost. Rejecting these pieces early saves the cost of processing them and might also preserve a higher co-product value than could be obtained if rejecting them later in the process. It is highlighted that timber rejected at this stage and downcycled could still be a valuable resource for several engineered wood products such as particle boards or recovered as valuable green energy. Rejection criteria should reflect the basic acceptance criteria presented in Table 1 in EN 14081-1 (2019), with additional limits specific to defects found in salvaged timber, and more leeway for criteria that are not important for the intended use of the salvaged timber. For example, holes and hole groups of certain sizes could be allowed with the subsequent reduction in declared mechanical properties. The effect of holes on bending strength was recently investigated by Pasca *et al.* (2025), among others. Large holes and notches are more generally problematic than just reducing strength as they affect the fire performance of timber members. In fire design, residual cross-sections are evaluated from the full cross-section. The exact size and position of large holes and notches should be known to account for them in design. Thus, large irregularities in cross-section should lead to rejection of the timber. The accepted tolerances in warp and cross-sectional dimensions should be decided according to practical limitations, e.g. constructability. Differentiation between wane and wane-like manmade corner damage should be made as mechanically damaged corners may lower the strength of a timber member since, unlike wane, they cut the grain.

Deriving a grading system for salvaged timbers is problematic, as salvaged timbers contain many irregularities that are not present or are present to an acceptable level in new timbers sawn from logs of known species and origin. These irregularities were broadly introduced in Section 3.1. As with strength grading of new timber, the approach needs to be based on the non-destructive assessment of properties and features that are indicative of the grade-determining properties, but rather than aiming to predict the characteristic values of all the timber that would pass thresholds, it should estimate properties on a piece-by-piece basis to better account for the greater variability and unknown effects on the statistical distributions from prior grading and sorting. Effective grading requires a transition from the present strength indicating properties and thresholds for graded populations towards strength indicating models for individual pieces building up design values for a set. Probabilistic models can assess the strength of individual pieces of timber and be combined to estimate the design properties for a set of pieces. An assessment model for the bending strength of in-situ timber joists was conceived by Bather (2022). Various models with different predictors were employed and the model with dynamic modulus of elasticity and knot clusters as predictors proved to be most accurate in predicting characteristic bending strength. Salvaged timbers are not in-situ and so more predictors could be included to model the strength of salvaged timbers.

For mainstream commercial softwoods modulus of elasticity derived indirectly via dynamic measurements or direct mechanical bending should be used as one predictor for the strength of timber as the modulus of elasticity and bending strength show moderate to high correlation regardless of growth area, especially for individual species such as Norway spruce (Ranta-Maunus and Denzler 2009). The measurement of dynamic modulus of elasticity is complicated by the fact that salvaged timber is typically shorter than new timber but is still possible. In the Gradewood project (Ranta-Maunus *et al.* 2011) Scots pine and Norway spruce timbers from various European nations were measured with nondestructive methods and destructively tested in both bending and tension. The coefficient of determination between either bending- or tensile strength and static modulus of elasticity was 0.53–0.66 depending on the species and type of destructive loading. Although variation in timber quality may be found between growth areas the underlying relationship between nondestructively measured properties and strength holds regardless of growth area, albeit with a lower correlation than within individual growth areas. The creation of strength-predicting models requires large datasets or destructive testing programs. A more conservative approach to strength estimation would simplify the modeling process and the overall grading process. A conservative approach means that not all predictors need to be assessed. For example, omitting species identification with subsequent reduction in declared strength properties would simplify the grading process. Grading salvaged timbers to a predefined application eases the process as less critical properties can be assessed to a conservative level.

Grading salvaged timbers should involve separate indicators for all three grade-determining properties (strength, stiffness and density), unless some are not important for the intended use, or are not close to being grade determining. Density and stiffness are relatively easy to measure non-destructively. To estimate the strength of a piece of timber a basket of nondestructively measurable predictors can be used. Both global (e.g. information about species, dynamic modulus of elasticity, whole board density) and local (e.g. arrangement of knots, slope of grain, mechanical damage, decay) predictors can be measured as neither can fully estimate the strength of a salvaged timber without the other (Nocetti *et al.* 2024). Moreover, either thresholds for indicators need to adjust dynamically to the quality of the resource being graded, or grading needs to be very conservative to account for variability and the possibility of prior grading or sorting having modified the statistical distributions. In other words, the prior population characteristics are unknown before grading. Fluctuation in resource quality is a known problem also for grading new timber and Ranta-Maunus and Turk (2010) presented an approach to dynamic settings that adapt to fluctuation in the recorded indicating properties during grading. The 2018 revision of EN 14081-2 introduced the approach of adaptive settings for machine strength grading, but this still relies on the stability of the correlations and population that does not exist in general for reclaimed timber.

There are four approaches to resolve the issue of species and growth area mixing. The first one is to develop a grading system that is largely independent of species and growth area of the timbers with some large-scale separation e.g. between softwoods and hardwoods. Such a system was developed for virgin hardwood timbers by van de Kuilen *et al.* (2007). In the second approach, the likely species and growth areas may be assumed based on stamps, records or historical data about the trade of timber and timber construction products. This approach is more applicable in geographical areas in which a limited number of different species and growth areas are encountered in the salvaged timber population. The other two approaches focus on species identification. Various species identification methods, including machine vision (Silva *et al.* 2022) and near-infrared spectroscopy (Ma *et al.* 2019, Leiter *et al.* 2022) are rapidly developing in both precision and ease of use. In the third approach, the species of a portion of the batch of salvaged timber are identified. This information could be utilized to adjust the model for strength according to the species mix identified. In the fourth possible approach, the species of each piece of timber could be identified separately.

The benefit of this approach would be a more accurate grading outcome and the possibility to cope with a wider range of species. However, differentiating species on the level of individual boards becomes less reliable when the number of possible species increases. The fundamental limits of wood identification also restrict this approach where there are morphologically similar species present but with different mechanical properties.

The strength prediction derived from nondestructively measured predictors requires further reduction to account for the possible effects of mechanical damage and DoL. A reduction due to mechanical damage could be included in the assessment of the visual characteristics of a timber board. For DoL statistical reductions in characteristic short-term strength are needed. The reduction could be approached pragmatically as in FWPA Standard G01 (2024). As the reuse of structural timbers becomes more mainstream more data will be available to adjust the strength reduction in salvaged timbers due to DoL effects. Initially, a conservative approach would be suitable. In addition, it is not known whether the current equations for secondary properties lead to conservative values for secondary properties in salvaged timbers.

The scale of grading reclaimed wood, and the need for close visual inspection for damages, fasteners, etc., suggest that visual grading methods would be most appropriate, but with the addition of machine assessment of stiffness and density to cope with greater resource variability. As already mentioned, the machine assessment could assist in the assessment of timber strength. However, the boundary between the frame of visual grading and the frame of machine grading is not clear in EN 14081-1 (2019) and might be considered to depend on circumstances. Falk *et al*. (2013) see four possible ways for visual grading of salvaged timber, which correspond to three potential approaches in European grading procedures: (1) create a new system of strength classes for recovered wood, most likely with lower strength; (2) use the existing grading system but knock down to lower class(es); (3) use existing strength classes and apply a different partial safety factor and/or different modification factors in the structural design.

4. Glued laminated timber construction products

4.1. Overview

There is a large interest in reusing glued laminated timber construction products (GLTCPs), essentially due to their high material volume even within individual buildings. As already mentioned above, circulation of larger cross sections motivates “3R reuse”, “4R repair”, “5R refurbish”, “6R remanufacture” and “7R repurpose” rather than “8R recycle”. This is even more true for already highly processed GLTCPs such as glulam, CLT and LVL. The number of co-products (usually with a short service life), such as sawdust, chips and off-cuts, and process energy motivate a long service life far beyond the typical design life of 50 years. Table 3 presents an overview of potential applications for the reuse and recycling of glulam.

Compared to reusing structural sawn timber the size and consistency of products like CLT and glulam remove much of the complexity, as regards resource identification, previous grading and the possibility of stronger pieces having been removed. Nevertheless, to ensure that salvaged GLTCPs can be used widely again for structural, load-bearing purposes a sufficient evaluation procedure is still essential. Within such procedures, for example, it must be ensured that timber with environmental degradation, or at least the degraded parts of the components, are excluded. Furthermore, the mechanical properties need to be quantified and classified accordingly so that reliable values can be used in structural design verification. In principle, every kind of available information, such as load history, various non-destructive and semi-destructive inspection methods, could be considered for such an evaluation. Therefore, the development and establishment of widely applicable standardized procedures are crucial.

4.2. Reusing sawn timber-based GLTCPs

As already mentioned above, the best option for sawn timber-based GLTCPs would be “3R reuse”, by completely maintaining the full dimensions of the GLTCPs and their initial purpose, as it is best to also include the connections if possible. However, this might be hard to achieve in practice. If the new application is governed by the ultimate limit state (ULS) design and not serviceability limit state (SLS) design and a decrease in strength to account for the effects of aging and long-term loading (the DoL effect) is applied the product may underperform in design strength capacity. Again, knowledge of the past load history and perhaps an engineering judgement and simple classification in loading categories {mild; medium; heavy} would support and extend any further use options, but it also requires knowledge of the previous construction, the situation of installation and the building use. Refreshing surfaces by planing or sanding is possible, at least to some extent so as not to lose any strength class classification of the base material boards and thus of the GLTCP itself.

Product information might be missing, such as the original strength class, applied product standards or production rules, knowledge about the type(s) of adhesive used for finger jointing, side and face bonding, as well as knowledge of the layup (e.g. homogeneous or combined). In the case of combined layup, especially if the timber lamellas were machine strength graded, a useful visual judgement of laminations’ quality is challenging, if not impossible.

One major legal issue is related to the bonding: current adhesives approved for structural, load-bearing purposes are certified for a design life of 50 years only. In this regard, all related testing regimes and quality assurance measures in the frame of initial-type testing, external and internal production control are somehow aligned to this design life. Block shear tests, with/without exposure of specimens to certain climate cycles, as well as delamination tests (see EN 14080 (2013), EN 16351 (2021)) and other shear test setups (see EN 13354 (2008)) and related limit values/acceptance criteria are simply based on the experience that products so far accepted and placed on the market fulfil their functions for the approved time period, without exactly knowing how far those limits could be relaxed to still deliver products ready for the market. With a look at older timber structures which already exceeded the design life, it seems adhesives used in the past

Table 3. Examples of applications for reuse and recycling of glulam (Note: only structural timber and GLTCPs).

Future application	Without major modifications to cross-section	Significant modification of cross-section	Modified to small GLT, glued solid timber	Repurposed to structural timber or new GLTCPs
Same type of loading as in previous use	Glulam roof beam reused as glulam roof beam.	Glulam roof beam used as glulam roof beam with decreased cross-section	–	–
Different type of loading from previous use	Glulam roof beam used as board stack ceiling	Glulam roof beam used as a column	–	–
Undetermined future loading	Glulam members of known / unknown previous use but undetermined future use	Glulam members of known / unknown previous use with decreased cross-section but undetermined future use	Glulam laminated products sawn from glulam such as resawn glulam	Structural timber sawn from glulam

still have reserve capacities and appear capable of much longer service life. Rammer and Moura (2013) evaluated the structural quality of the second-oldest glued laminated structure in USA. The building was proof-loaded shortly after its construction and deformations were measured. Later, during deconstruction, the arches were loaded again for research purposes. Rammer and Moura (2013) conclude that the glued laminated arches show an insignificant decrease in stiffness nearly eighty years after the construction of the arches. The strength of the arches was compromised by inadequate spacing of fasteners in the original design.

Anyway, experience in practice has also led to the exclusion of some adhesive types, such as urea formaldehyde (UF), which is no longer permitted for use in load-bearing timber construction products due to its susceptibility to hydrolysis. GLTCPs containing such adhesive are, consequently, excluded from any circulation option below 8R. As the adhesives of today might be seen as much more developed it could be easily argued that their performance might be even better allowing also for much longer design service lives. On the other side, current production lines are much more optimised with respect to the preparation of the timber components (surface quality, conditioning, etc.), the amount of adhesive and the overall bonding process including application, open and closed times as well as bonding pressure. Such optimisation has usually the target to produce sufficiently reliable and economically favourable products, sufficiently in respect to currently set requirements but without unnecessary over-capacity.

Assessment requires methods to evaluate the bondline quality of aged timber construction products as well as the effect of long-term loading. On one hand, testing and quality assurance regimes mirroring accelerated artificial aging linked to realistic use scenarios/expositions of products in real constructions are needed. On the other hand, for already existing constructions, i.e. the current stock of timber structures, methods and criteria for determining the residual load-bearing capacity of bonded joints are necessary. One exemplary work exactly addressing this last aspect is the guideline of Dietsch *et al*. (2021).

4.3. Assessment of sawn timber-based GLTCPs

To ensure that salvaged structural timber (products and components) will be used widely again for structural, load bearing purposes a sufficient evaluation procedure is essential. The reuse of the main structural components from a larger timber construction that will be demolished may be associated with sufficient value so that a detailed investigation becomes efficient by economy of scale, also from an economic perspective. The aim of this subsection is to present a framework that is formulated on a mathematical basis, capable to handle in principle all possible types of information and an essential part in future regulations handling the reuse of salvaged timber.

The information for estimating mechanical properties of timber elements can be of very different nature; for example, it can originate from various building phases (e.g. the planned conditions) and different hierarchical levels of data collection, (e.g. (partly) known load history; results of various non-destructive and semi-destructive inspection methods; see e.g. Dietsch and Köhler 2010 for an overview of different inspection methods). Depending on the investigation, however, different types of information are collected. They can be grouped as direct and indirect information, and as equality-type and inequality-type information. Table 4 shows a compilation of information from non-destructive inspections and evaluations, classified according to the type of information for the estimation of the strength properties.

A framework to consider different types of information is Bayesian updating. For the procedure prior information that can be quantified needs to be available. Such prior information can be e.g. the already mentioned planned conditions (if available) or an expert opinion; obviously the prior information is associated with uncertainties (see e.g. Rackwitz (1983) for more information). Depending on the type of information different updating procedures are available, see e.g. Rackwitz (1983), Faber *et al*. (2000), Faber (2012), Fink and Köhler (2014, 2015). In Fink and Köhler (2014), a framework for the estimation of the strength properties of existing timber structures using Bayesian updating is presented. Although the selected investigation methods might be different, the general principles are also valid for the estimation of mechanical properties of timber elements for the purpose of reuse. Furthermore, the approach can be also extended for the evaluation of timber connections or even entire structural systems. This could also be potentially used for the evaluation of existing buildings, for example for the sake of adoptions or renovations.

As already mentioned for reusing entire glulam beams, several aspects besides the estimation of the mechanical properties, need to be considered. Examples are the original declaration of performance and the material storage. An alternative approach could be the further processing into smaller components (e.g. glued solid timber elements with standardized dimensions) or components with common cross-sections that are acting as a base material for glued products such as glulam and CLT for which thin resawn products of such glulam members might be used as single layers (discussed in the following sections). Regarding the quantitative assessment, the same NDT methods as presented in Table 4 are suitable, however, especially regarding the destructive tests a significantly larger sample might be possible. Furthermore, existing strength grading methods (both visual and machine grading) can be applied, and the results can be used to enhance the estimation. Additionally, the combination of flexural minor and major axis measurements with longitudinal resonance, or application of x-ray methods, might reveal information about whether the layup of glulam is homogeneous or combined. This information could be used, for example, to guide the lengthwise cutting of salvaged glulam beams into lamellae for the production of new glulam products.

4.4. Recycling GLTCPs

Apart from upcycling salvaged timber to glulam and CLT there are also some recycling options for these products themselves. With a focus first on glulam, such members could be resawn to lamellas by following exactly the face bondlines so to generate again sawn timber which could be directly used for structural purposes or serve again as base material for GLTCPs. Losses in cross section, in particular in a thickness direction, need to be considered which, on a rather regular basis, exceed the allowed changes in cross section without losing the strength class of the lamellas before they were glued to glulam. So, re-grading and re-classification needs to be done. This is also motivated by the circumstance that glulam often features combined rather than homogeneous layup, i.e. are composed of lamellas of different strength classes, and missing information on the layup. In Europe, the layup of combined glulam is typically symmetric, i.e. with outer lamellas of higher strength class and inner lamellas of lower strength class. With a look on at least the last three decades, before 2013 and the release of the new version of EN 14080 (2013) combined glulam featured only two different lamella strength classes with at least 1 / 6 of the glulam height of higher strength lamellas in the outer zones, see EN 1194 (1999). Meanwhile, symmetric layups with of up to three different lamella strength classes are possible. With this new release also the number of different glulam strength classes increased to better utilise the potential of the raw material. However, diversity in product types and product classes additionally increases the complexity in circulation; a circumstance which should be considered in the development of future regulations and product standards.

Resawing of glulam beams can be done also in another direction, orthogonal to the wide face of the lamellas. Thereby so-called strip-lamellas can be produced which consist of a number of cross-sectional parts of the former glulam composing lamellas. The advantages of this way of recycling are the freedom in the thickness and width of such lamellas, and if again used for glulam beams as a potential alternative for block-glued glulam. However, there are also some obstacles that need further consideration, such as the already mentioned and more common combined layup of glulam, which results in a rather heterogeneous mechanical potential of such strip lamellas and limits the flexibility in cutting them to different widths, as well as the influence of juvenile and mature timber zones within the lamellas. Concerning the latter, glulam lamellas are usually produced from the main sawn products by saw-cutting the central prism of a log to boards. In doing so, strip lamellas cut from the middle part of glulam beams usually have a higher share of juvenile core timber than those from the outer part which results in different physical/mechanical potentials, as demonstrated for example in Obernosterer *et al.* (2023).

In contrast to glulam, resawing of CLT to gain board lamellas as base material is not really an option. However, there are other strategies that might be of interest for salvaged CLT which are currently already possible for residual parts of new CLT. One strategy is to process small CLT components of similar layup to larger components via large finger jointing, as for example presented in ETA-06/0009 (2022). Another strategy is presented in ETA-14/0349 (2022). Here, so-called REX-lamellas, based on de Monte (2017), are produced by cross-cutting lamellas from residual CLT components in new production. These lamellas are recycled as cross layers of new CLT-alike panels. Both strategies offer possibilities for recycling

Table 4. Examples of different types of information for the estimation of the strength properties of glulam beams based on non-destructive inspections and evaluations.

Direct & equality type information
- Destructive testing is the only possible way to get direct and equality type information for strength. For the quantification of an individual structural component this is not possible (as the component is damaged after testing). However, for the estimation of the strength properties of a set of glulam beams (assuming they belong e.g. to the same strength class, fabricated by the same producer, etc.) destructive tests performed on selected samples could be used to estimate the strength properties of the entire sample.

Direct & inequality type information
- Load history: the bending strength of the beam in the past was at least as high as the bending stresses caused by loadings at that time; because of DoL effects in timber and possible additional damage in conjunction with high loading meanwhile the actual bending strength might be lower. At the same time, the information of survival together with the DoL can also be used to exclude low realizations of the basic population (Köhler 2014).
- Proof loading: the bending strength of the beam is at least equal to the bending stresses from proof loading. As before also here possible damage arising from the proof loading needs to be considered.

Indirect & equality type information
- Stress waves or ultrasonic runtime: e.g. estimation of the strength properties based on the dynamic modulus of elasticity using correlation models.
- Deformation measurement: e.g. estimation of the strength properties based on the static modulus of elasticity back calculated from deformation measurements from well-defined static systems and loads by means of correlation models.

Indirect & inequality type information
- Status inspections (e.g. visual inspection, environmental conditions, moisture content, cracks, resistance drilling, endoscopy); please note: such inspections can be very useful for the identification of environmental degradation, however, for the purpose of a quantitative assessment beyond rejection they are of minor importance and thus not further considered here.

CLT residues again in (larger) CLT panels in conjunction with some limitations/reductions in some mechanical properties which, if planned effectively, might not limit their application (see also Vessby *et al*. 2023).

Overall, glulam-alike products with strip lamellas or CLT-alike products with REX-lamellas in the cross layers provide interesting recycling options for the first cycle but both have in common that the next recycling options become more and more limited which is caused by the increasing complexity of the resulting new timber construction products. This is something that also needs to be considered in the evaluation of current and potential future recycling options.

4.5. GLTCPs from salvaged timber

With a focus on board-based GLTCPs, and an awareness that in the future more and more salvaged timber needs to be circulated, a lot of studies have been conducted that focus on upcycling salvaged timber by processing it to boards and bonding them to higher-value timber construction products, cf. Rose *et al*. (2018), Llana *et al*. (2022, 2023b), Dong *et al*. (2024). Rose *et al*. (2018), for example, analysed the production of CLT from mixed softwood salvaged timber and compared their performance in compression in-plane and out-of-plane and in bending out-of-plane against control samples from new timber (three replicates for each configuration and timber source). Although the cross-sections and applied grading procedure were the same it is not clear how equivalence in timber quality of salvaged and control series was secured. The specimens were rather small and thus of limited representativeness. Comparison of elastic and strength properties from compression tests indicate no time-related effects whereas the bending strength of CLT from recycled timber was on average 60% lower and the modulus of elasticity in bending on average 100% higher, a surprising circumstance considering the positive relationship between elastic and strength properties which in this case rather suggests even a greater strength reduction than already observed. They conclude that large defects and concentrated small defects have a great impact whereas single small defects appear negligible. Llana *et al*. (2022) and Llana *et al*. (2023b) analysed the recycling potential of salvaged oak timber for the production of five-lamella glulam (six specimens in each series) and three-layer CLT (three specimens in each series). They investigated specimens composed of either only salvaged or new timber as well as mixed layups. The quality of the timber used for glulam and CLT was obviously not matched (densities are clearly different); the same applies to new and salvaged timber. This and the low sample size impede the comparability of results and any sound quantitative conclusions. Anyway, differences between the modulus of elasticity in bending and the density of new and salvaged timber are in line with expectations but the bending strength of glulam and CLT made of salvaged timber is only half of that of new timber. For CLT it is concluded that the material in cross layers does not influence the bending properties. Overall, the yield of salvaged timber in the final products glulam and CLT was really low and only 13%; in reference to literature values around 30% are mentioned and a similar value (33%) is also stated in Janowiak *et al*. (2007). Dong *et al*. (2024) demonstrated in principle the applicability of salvaged softwood timber to produce CLT by testing 15 three-layer CLT specimens in bending. They outline the advantageous application of CLT from salvaged timber as floor elements as they are usually governed by SLS instead of ULS design criteria. Furthermore, they also demonstrated the applicability of load-bearing models developed for CLT in bending out-of-plane for new timber and also for salvaged timber.

All these studies are motivated by the need to cope with the greater variability and uncertainty of salvaged timber due to aging, diversity in past exposures and loadings, and overall variety in timber species, origin and product quality. By face and edge bonding of such timber components to large-dimensional, quasi-rigid composite-acting timber construction products such as glulam and CLT higher variabilities are even advantageous as higher homogenisation effects, i.e. reduction in variability, by the common action of these components is usually serial, sub-parallel acting systems are achievable (cf. Daniels 1945, Colling 1990, Brandner 2012, Fink 2014, Rose *et al*. 2018, Dong *et al*. 2024). In addition, CLT has an overall special status if used as a plate. SLS criteria usually govern the design of CLT plates. In cases where ULS might become relevant, the common layups and applications of plates as floor and roof elements result mainly in one-dimensional acting components for which the contribution of the cross layers is negligible overall; apart from their function as spacers for increasing the Steiner share. Even for CLT as a wall element, i.e. as a diaphragm, the contribution of cross layers against tension and compression in-plane is negligible. So apart from shear in- and out-of-plane (rolling shear) in most cases the material in cross layers could be easily replaced by components with less strength but similar elastic properties and density to provide balanced sharing of loads between layers and maintain the anchorage capacity of dowel-type fasteners. These previous works (Rose *et al*. 2018, Llana *et al*. 2022, 2023b, Dong *et al*. 2024) also have in common their preliminary character, which allowed to demonstrate in principle the executability of producing glulam and CLT from board material gained from salvaged timber components, with a summary of a lot of lessons learned from the overall production process. So, the future focus might be more directed to analyses of the differences in production, on economic issues (whether better to downcycle to OSB, particle boards or to "9R recover") and differences in physical/mechanical properties. One economically disadvantageous factor is the increased frequency of finger joints. Damage to machinery presents a major risk in finger jointing salvaged timber due to embedded fasteners and impurities, as expressed by Bergsagel *et al*. (2022). The available preliminary studies are unfortunately not sufficient to give full answers to these questions as the samples are far too small to derive any clear quantitative and more general conclusions.

5. Conclusions

In this study the differences in properties of salvaged timbers and salvaged glued-laminated timber construction products was studied in comparison to similar products that have seen no previous use. Clear differences are found.

Salvaged structural timbers contain more variation in properties than timbers sawn from a clearly defined species or species group and growth area. In addition to the mixing of species and growth areas, the population characteristics of salvaged timbers depend on previous grading, in-use damage, and previous load conditions. An overview was given on the factors to consider when deriving a grading system for salvaged timbers. Grading criteria should reflect the requirements of the intended future use of the salvaged timbers. A more conservative approach may simplify grading, especially when strength is assessed to a conservative, lower level.

There is a great motivation to reuse, rather than recycle, GLTCPs due to the embedded processing required to originally produce them. GLTCPs are ideally reused with only surface cleaning and assessment of properties. In contrast to salvaged timbers, GLTCPs are more consistent in their form and material properties further motivating reuse. In the assessment of GLTCPs, multiple levels of information may be used depending on the availability of background information such as original declaration of performance. Potential barriers to reuse include the extension of service life of adhesives. Adhesives are certified only for a certain service life, often fifty years, while some adhesives such as urea formaldehyde should not be reused. Practical geometrical reasons and questions related to the quality of adhesives may motivate recycling and re-sawing of GLTCPs. Due to loss of material during sawing process, the sawn lamellae should be re-graded even when prior information tells the original grade of lamellae. GLT poses more potential for the production of lamellae than CLT as resawing CLT produces lamellae in which the base material runs both in longitudinal and transverse directions. One recycling option for CLT could be large finger jointing into larger panels. GLTCPs could also be produced from salvaged timber. Such processing has multiple benefits, including overcoming issues related to the short length of salvaged timber and homogenisation of material properties. Challenges include an increased need for finger jointing and an overall greater risk of contaminants such as embedded fasteners to cause damage to timber processing machinery.

By addressing all these challenges in circulating salvaged timber it should be noted that this renewable material has enormous potential for a second and further design lives in load-bearing structural applications, either directly applied as structural timbers or as part of a timber construction product, with regard to the still remaining physical/mechanical properties; a potential that is waiting to be exploited and made accessible through appropriately adapted re-grading, re-classification and re-certification regulations and legal framework conditions.

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Contribution

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