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REUSE OF WOOD IN STRUCTURAL PRODUCTS – A GAIN?

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ABSTRACT: There is increasing interest in the reuse and recycling of wood in construction, but still many important unsolved questions about how it should be done safely and economically. Some important research projects, carried out in recent years, have addressed some of these questions, and the first conclusions have appeared. One major challenge of this research is the variability of the resource, and the difficulty of obtaining representative sampling. It is even more important than it is for new timber to be able to meaningfully compare results across projects and draw insights from combined analysis. This paper summarises results about performance of reuse and recycling of wood in different novel Engineered Recovered Wood Products (ERWP): Glue and Cross Laminated Recovered Timber (GLRT&CLRT), focusing on advantages and limitations in order to promote cascading processes in the timber industry.

KEYWORDS: recovered timber, reclaimed timber, recycling, cascading, circular bioeconomy

1 – INTRODUCTION

Timber construction is growing and innovating, with new methods of building and new engineered wood products and treatments. There are, however, limits to sustainable use in timber sector, and circularity models are still missing in some manufacturing processes. Aspects such as design for disassembly, recoverability rates, reusability of elements and recyclability of products are key points that must not be overlooked. This concern is not new; recycling wood waste and timber, for instance, has been recognized in the modern perspective for more than 30 years (e.g. [1], [2]), and recovered timber properties have been studied scientifically for a century or more (e.g. [3]) with practice back to ancient times. But reuse of recovered construction timber is now receiving greater research effort thanks to growing political attention and commercial opportunities. This is being done within a regulatory and normative framework that has an increasing focus on construction product certification and safety.

A significant number of research projects dealing with reusing and recycling timber from demolition have been carried out recently, including European projects as CaReWood (05/2014 - 04/2017), InFutUReWood (03/2019 - 02/2022), RECOWERS (01/2022 - 12/2023), CIRCuIT (01/2019 - 12/2023) and StructuralReuse (04/2021 - 03/2025), and running projects are active in closely related topics, like Grade2New (2024 - 2026), sirkTRE (01/2022 - 12/2025), TiReX (04/2024 - 04/2027), WOODCIRCLES (06/2023 - 05/2027), TU&M (01/2023 - 12/2025), EcoReFibre (05/2022 - 04/2026), and Wood2Wood (01/2024 - 12/2027).

In any case, to move from linear to circular models in the construction sector presents a complex scenario that requires a holistic approach: designing end-of-life alternatives for buildings, improving efficient use of raw materials, wood waste reduction, cascading design, reuse of structural components, recycling products, developing proper standardization framework, and more. Just regarding this paper's topic, reuse of wood in structural products, some key points should be considered as outlined below.

1.1 DESIGN FOR X

Several design methodologies have been developed with the aim of optimizing resource use and minimizing waste generation. These approaches fall within the concept of Design for X (DfX), as they are aligned with the principles of the Circular Economy [4].

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While their primary focus is on the final stage of the building life cycle (facilitating the reintegration of components and elements into new production cycles without compromising their performance or compatibility with future configurations [5]) they also address other phases of the life cycle, as illustrated in Figure 1. The application of these methods helps reduce the demand for virgin materials and lower the impact associated with raw material extraction and processing [6].

One of the most established methodologies within DfX is Design for Disassembly (DfD), which defines a set of criteria to enable the disassembly of construction systems. These guidelines include the use of reversible connections and the selection of materials without treatments that would limit their reusability [7]. Additionally, DfD is closely linked to Design for Adaptability (DfA), which incorporates principles such as expandability, convertibility, and versatility [8], allowing buildings to be modified during their operational phase to extend their functionality. Unlike other approaches within DfX, Design for Disassembly and Adaptability (DfD/A) is supported by regulatory frameworks such as ISO 20887:2020, providing it with formal regulatory backing.

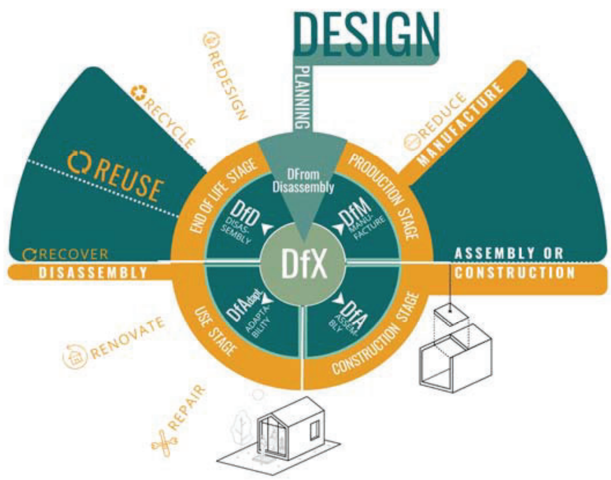

Figure 1: DfX methodologies diagram impacting the different stages of an industrialized building's lifecycle [4].

However, the effective implementation of DfX requires acknowledging the inherent complexity of buildings, which are composed of various elements with different life cycles, necessitating careful consideration of how these principles are applied [9]. In contrast, while some approaches focus on designing buildings with future disassembly in mind, Design from Disassembly (DfromD) works with already dismantled components, facilitating their efficient reintegration into new constructions. This method does not originate from materials specifically designed for circularity, but instead develops strategies to readapt existing materials, optimizing their structural compatibility, dimensional standardization, and assembly, with the goal of maximizing their reuse within a new construction cycle [10].

1.2 MATERIAL BANKS

Although buildings produce a third of greenhouse gas emissions, it has been suggested that they might be one of the most cost-effective climate change mitigation solutions. Among building materials, wood not only produces fewer production emissions according to life-cycle assessment, but can also store biogenic carbon.

Very large volumes of wood have being put into buildings and structures, and the quantity used is often seen as a virtue (as sequestered carbon). As an example, the eight-story residential building "Limnologen" (Växjö, Sweden) consists of seven Cross Laminated Timber (CLT) stories with some timber frame internal walls, on a concrete foundation and ground floor [11]. An apartment of 125 m^2 in that building used approximately 28 m^3 of timber [12], at the lower end of the range (0.2 - 0.3 m^3/m^2) for similar apartments in multi-storey CLT buildings. Existing and new structures constitute a significant material bank, but also high demand on virgin timber use that might alternatively be met, at least in part, by reused timber.

The recoverability potential of timber from demolished/dismantled buildings is a very promising source for recovered products [13, 14]. For example, research studies conducted in Japan [15, 16] have shown that pieces of wood from heavy-framed houses with a large cross-section, without damage and with few adhering materials, have very high potential for reuse/recycling.

1.3 BUILDING WASTE

Construction and Demolition Waste (CDW) constitutes a large fraction of all the solid waste generated: nearly 30 - 40% of total solid wastes generated globally [17]. CDW consists of numerous materials, including concrete, bricks, gypsum, wood, asphalt roofing, glass, metals, plastics, cardboard, solvents and excavated soil,

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many of which can be recycled or reused. This considerable amount of CDW creates adverse environmental impacts, so the reduction, reuse and recycling of CDW should be a global priority.

It is estimated than 60% of discarded materials is either put in a landfill or incinerated. While 40% is recycled or reused, this is usually for low value uses. Some 95% of the value of material and energy is typically lost at the end of the first use. Material recycling and waste-based energy recovery captures only 5% of the original raw material value [18].

Although timber is commonly used worldwide, its importance for the circular economy has received relatively little attention until recently. Current practices are mostly limited to lower-value and materially degraded uses, such as mulch, firewood and wood-based panel products. However, there are enormous possibilities for wood waste to be reused or recycled as value-added products [19] prior to these more final uses. There is a lack of effective technologies and procedures to characterise waste wood in terms of type and properties, for detecting and removing contaminants and harmful chemicals, and to ensure waste wood quality, material properties, and suitability for various applications (especially in terms of level of degradation and load-bearing capacity). There is also a need for further development of material use alternatives. This involves identifying and developing more conservative or less mechanically demanding material applications, so that lower-quality waste wood can be used with less risk to human health and the environment and material requirements can be met without requiring waste wood of such high quality [20], or with reduced effort and expense to confirm that high quality.

The potential of cascading wood use remains largely unexploited in the EU, Figure 2. Of the 48.3 Mt of waste wood generated in the EU-27 in 2020, 40.2 Mt underwent treatment, meaning less than half (46%) was recovered through (mostly low-level) recycling operations with a large share (54%) ending up in incinerators for energy recovery [21]. Waste wood in the EU-27 mainly comes from three sources: the construction and demolition sector, the commercial and industrial sector, and the waste collection sector (municipal waste). These sectors generated 8.59 Mt, 18.72 Mt, and 10.37 Mt of waste wood, respectively.

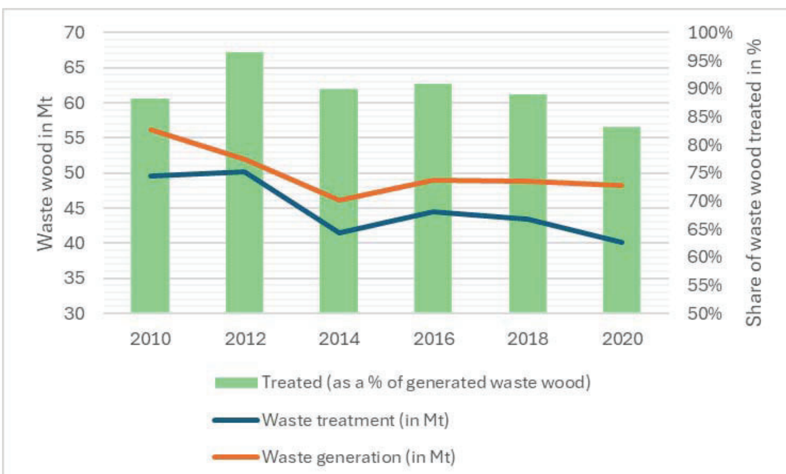

Figure 2: Waste wood generation and treatment in the EU from 2010 to 2020 based on Eurostat data [20].

The situation varies across Europe. In Sweden, more than 20% of CDW is wood, while in southern European countries such as Spain and Portugal, mineral building materials are more common [22].

The recycling of waste wood is often complicated due to the presence of additives (glue, varnish, and paint), pollutants (heavy metals and other harmful substances), and contaminating materials (e.g., glass, plastic, and metal) [23].

1.4 STANDARDIZATION FRAMEWORK

Despite the social, economic and environmental aspects highlighting the importance of reducing, through recycling, construction and demolition impacts, the current standardization framework does not facilitate the use of recovered wood in structural products, even though its technical feasibility has been confirmed by research.

Regarding current European product standards, EN 14080 [24], the norm for requirements of glued laminated timber and glued solid timber, EN 16351 [25] for CLT, and EN 15497 [26] for structural finger jointed timber, reclaimed wood is not mentioned or directly forbidden for manufacturing. Specific lists of species, and restrictions on mixing species present additional hurdles for use of recovered wood; especially in regions with diverse timber in the built environment.

The requirement of strength grading to EN 14081-1 [27] for all these is anyway an effective block since this requires known species, growth area and knowledge of how to account for prior grading, which is a practical impossibility in many cases. Formal strength grading procedures (visual, machine grading or mixed) equivalent to EN 14081-1 are not yet in place due to its complexity and lack of research data. As well as needing a different statistical basis (due to much greater variability than virgin wood from an identified source) there are open research questions about aspects such as duration of load effects, potential degradation of secondary properties, and ways to deal with treated wood.

This means that while there are bespoke approaches for specific projects (e.g. design assisted by testing), and nascent regional or national standards, as Norwegian Standard NS 3691-3 [28], there is presently no route for CE marking via harmonized standards as envisaged by the new European Construction Products Regulation [29]. It is not necessarily the case that harmonized standards are the most commercially viable way forward in practice, but nevertheless the development of local and regional approaches should be coordinated so that future harmonization remains an option.

So, within the aforementioned holistic approach that should be considered to target the circular economy for the timber construction sector and its different paths to achieve it, the main objective of this research work is to demonstrate that recycling demolition waste in Engineered Recovered Wood Products (ERWP) manufactured using recovered timber are suitable for structural applications.

2 – ENGINEERED RECOVERED WOOD PRODUCTS

2.1 FIRST EXPERIENCES USING SOFTWOODS

Potential structural end-uses of recovered timber in solid form, apart from direct reuse, mainly focus on recycling in ERWP, such as Glue and Cross Laminated Recovered Timber (GLRT&CLRT) [30].

First research experiences, as CaReWood project, studied the possibilities of recycling recovered timber in laminated products used as a solid wood replacement for furniture, window frames, mouldings and fittings. However, it concluded that recovered timber cannot be used for load-bearing construction because wood waste may come from different species, which it would be difficult to identify. The InFutUReWood project worked on DfD and recyclability of recovered timber in ERWP and attempted to propose solutions for the species (and source identification and prior grading) problem.

The potential of recycling recovered timber in CLRT was experimentally tested for the first time in Europe in 2018 using mixed recovered softwoods and new Scots pine [31]. Rose *et al.* tested 3 cross laminated timber specimens (820x105x51 mm^3) of 3-layers, in bending, and 9 small specimens in compression from recovered and new timber. For these results the cross laminated timber from recovered timber had higher stiffness and lower strength than cross laminated timber from new sawn timber. It should be noticed than 70% of specimens failed in finger joints. It was concluded that CLRT is a viable alternative for some structural applications, but advanced classification and processing strategies are required to maximize its performance.

Irle *et al.* [32], in 2019, looked at advanced strategies for recycling solid wood and post-consumer Medium-density Fibreboards (MDF) boards. Two main approaches were presented: the extraction of Nano-Crystalline Cellulose (NCC) from waste MDF (focusing on extracting very high-value chemical products), and the manufacture of laminated beams from recovered wood. The conversion of MDF into NCC offered high added value and could overcome current recycling limitations, while laminated beams can represent a viable alternative for building structures. The research highlighted the need to improve industrial processes to increase the efficiency and quality of recycled products.

Carrasco *et al.* [33] explored the possibility of manufacturing railway sleepers by reusing discarded wooden sleepers, promoting a circular economy in the railway industry. Nondestructive tests were performed to assess the structural integrity of the recovered sleepers prior to reprocessing into glulam. The study found that about four to five recycled sleepers can produce a new one with acceptable structural characteristics. Although the rate was not high, a methodology of manufacturing glulam beams from recovered sleepers was developed. This research emphasized the role of recycling in reducing virgin wood consumption and minimizing the environmental impact of the rail industry.

In 2020, Arbelaez *et al.* [34] tested 18 cross laminated timber panels of 3-layer (2,300x300x94 mm^3) in four-point bending from recovered and new Douglas-fir, and from MDF. Authors found poorer properties of CLT with MDF in the cross layer. Moreover, cross laminated timber panels made of recovered and new timber was found to have similar stiffness. However, delamination tests were challenging, suggesting the need to improve manufacturing processes to ensure better adhesion in industrial environments.

Stenstad *et al.* [35] tested 28 cross laminated timber panels of 3-layer (2,400x150x100 mm^3) manufactured using recovered Norway spruce only in the cross layer. Results indicated that recovered wood can meet structural standards if it used in inner layers of the cross laminated timber, which would allow the use of virgin wood to be reduced without compromising structural safety. However, the study identified challenges in the quality of adhesive bonds and the variability of recycled material properties.

Dong *et al.* [36], in 2024, presented a study on the reuse of recovered timber from demolitions to manufacture cross laminated timber. 15 cross laminated timber panels of 3-layer (2,550x320x102 mm^3) manufactured

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using mixed species untreated softwood recovered timber were used in that research. Nondestructive techniques were used to determine the dynamic modulus of elasticity and full-scale bending tests were performed to validate the structural strength of the CLRT. It was concluded that nondestructive testing can accurately predict the strength of recovered timber. In addition, the CLRT panels met structural standards and showed potential for sustainable construction applications, albeit with reductions in bending strength due to defects and material degradation.

To summarize, the aforementioned studies tested different configurations of ERWP with recovered softwood timber, and agreed that recovered wood can be used in the manufacture structural elements, although with variations in mechanical strength and adhesion, emphasizing the need for bending and delamination testing to ensure structural safety.

2.2 GLRT AND CLRT MADE OF RECOVERED EUROPEAN OAK

In 2022, Llana *et al.* [37], took 40 pieces of recovered European oak (*Quercus robur* L.) with an average cross-section of 146x164 mm^2, and an average length of 2,488 mm and sawed them into boards for GLRT and CLRT manufacturing. The pieces were recovered from the demolition of a 200-year-old house in the Basque Country, Spain. Figure 3 shows recovered European oak pieces from demolition in supplier's storage area.

Broken or damaged ends were cut off and nails were removed from the recovered pieces, before sawing them into 25x105 mm^2 boards with an average length of 2,400 mm. A total of 169 boards from the 40 recovered pieces were obtained in the sawing process.

In addition, 72 new European oak timber boards with average dimensions of 27x114 mm^2 and a length of 2,336 mm were acquired in a new timber supplier.

Recovered and new boards were conditioned until they had a Moisture Content (MC) of approximately 15%. All of the boards were then planed to the final dimensions of 20x100 mm^2, and visually and nondestructively graded. For the ERWP production, finger-joints were not used in any lamellae of the specimens/boards. Loctite HB S309 Purbond (Henkel, Düsseldorf, Germany) was used as adhesive between layers.

12 glue laminated timber specimens of 5 lamellae and 100x100x1,900 mm^3 dimensions were manufactured: 6 using recovered timber (GLRT) and 6 using new timber (GLTN).

Figure 3: Recovered European oak pieces in supplier's storage area.

12 cross laminated timber panels of 3-layer and 60x300x1,800 mm^3 dimensions were manufactured: 3 from recovered timber (RRR), 3 from recovered timber in the longitudinal layers and new timber in the cross layer (RNR), 3 from new timber in the longitudinal layers and recovered timber in the cross layer (NRN) and 3 from new timber (NNN).

Mechanical Properties Results

ERWP made from reclaimed European oak exhibited a Modulus of Elasticity (MOE) comparable to that of new timber. In cross laminated panels, average MOE values ranged from 11,180 to 12,106 N/mm², while in glue laminated timber, varied between 11,175 and 11,777 N/mm², with no statistically significant differences between configurations.

However, Modulus of Rupture (MOR) was notably lower in ERWP. Cross laminated panels with reclaimed longitudinal layers (RRR and RNR) had a mean MOR of 44.7 - 46.5 N/mm², compared to 74.0 - 72.8 N/mm² in those made with new wood (NNN) or reclaimed timber in central layer (NRN). In glue laminated timber the difference was similar: 38.1 N/mm² versus 73.5 N/mm², in GLRT and GLTN, respectively.

Influence of Configuration

In cross laminated panels, the use of reclaimed wood in longitudinal layers significantly reduced MOR, whereas its use in the transverse layer did not affect this

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parameter. For example, the RRR (all reclaimed layers) and RNR (reclaimed in longitudinal layers) configurations showed MOR values 38 - 40% lower than configurations with new wood in longitudinal layers (NRN and NNN). In glulam, pieces made entirely from reclaimed wood exhibited 48% lower strength than those made from new wood.

Density and Material Consistency

The density was slightly higher in EWRP: 769 kg/m³ in cross laminated panels and 770 kg/m³ in glulam, compared to 730 kg/m³ and 713 kg/m³ in products with new timber. The coefficients of variation (CoV) for density were low (2.09 - 4.59%), indicating uniformity in physical properties. Although density did not show a direct correlation with MOR, its stability suggests that reclaimed wood maintains sufficient structural integrity, supporting its use in applications where stiffness is a priority.

Structural Viability and Process Efficiency

Despite the reduction in MOR, the minimum recorded values (35.8 N/mm² in CLRT and 31.9 N/mm² in GLRT) exceed the requirements for non-critical structural applications. However, process yield was low (13%) due to waste generation during sawing and the discarding of damaged sections or those with nails. This low utilization highlights the need to optimize grading and processing techniques for reclaimed wood to improve its economic and environmental sustainability.

4 – CONCLUSIONS

The research converges on the technical feasibility of recycling reclaimed softwoods and hardwoods from demolition in engineered timber products, but highlights the need to optimize manufacturing processes, improve adhesive bonding and develop nondestructive models for grading.

Differences in defects' impact reflect the complexity of standardising heterogeneous raw materials as old timber, while the diversity of approaches underlines the multifaceted potential of reclaimed wood in circular economy.

For structural properties, bending tests showed no significant differences between modulus of elasticity obtained in glue laminated timber pieces and cross laminated timber panels from recovered and new timber. Conversely, strength was far higher in new than in recovered timber in both products. In cross laminated timber panels, only the type of timber (recovered or new) used in the longitudinal layers determined the differences in bending strength values. Even though strength values of Engineered Reclaimed Wood Products are lower than those produced with new timber, values are still high enough for structural applications; especially when design is governed by something other than strength.

Finally, despite all experiences this current international research interest highlights the importance of recycling in reducing construction and demolition waste and environmental impact of the construction sector; authors noted that current standards do not facilitate the use of recovered wood in structural products, despite its technical feasibility. Production and economic challenges are significant, but also depend on the demands of standards; so, future studies should integrate technical, economical, and environmental perspectives to appropriately scale presented scenarios.

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