



Designing for reuse in timber buildings: The environmental benefits of aligning the time of nature and time of use

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ABSTRACT

Timber is emerging as a key bio-based material for decarbonizing the construction sector and supporting circular economy goals. This study explores how Design for Deconstruction and Reuse can extend the timber value chain by enabling the reuse of structural components with the same function after disassembly. Current regulations often prioritize energy recovery, thereby limiting the circular potential of timber. We address this gap by modelling ex-ante cascading reuse scenarios for a timber building and assessing the generated environmental benefits through Life Cycle Assessment. Results show that maintaining the structural function of timber across multiple lifecycles significantly reduces environmental impacts compared to downcycling or incineration. This approach provides a systems perspective on timber use, aligning with the need for sustainable, bio-based solutions in the construction industry. To fully leverage timber's potential for carbon sequestration and resource conservation, standards must evolve to support reuse strategies that preserve material value across the built environment.

1. Introduction

Urban contexts will play a pivotal role in fighting climate change as the world's population continues to increase, and it is impractical to reduce the construction of new houses and buildings. The construction industry is recognized as a significant driver of socio-economic growth in all countries (UNEP, 2021), but it is also the primary consumer of energy and natural resources. The construction sector consumes approximately 50 % of all raw materials extracted, and globally, more than 42 billion tons of material are used per year (UNEP, 2021). It also generates one-third of all waste worldwide (UNEP, 2021) and accounts for 37 % of global energy-related CO₂ emissions (UNEP, 2023). About 10 % of these emissions are due to construction materials (UNEP, 2023). The building sector contributes 21 % of total global greenhouse gas (GHG) emissions (12 Gt CO₂eq), 18 % of which are attributed to the concrete and steel used in construction and refurbishment stages (Cabeza et al., 2022). Given the construction industry's nature as a driver of economic growth and its significant impacts, its role in accomplishing the UN Sustainable Development Goals (UN, 2015) and reducing environmental impacts (Maier, 2021) through the principles of

circularity and sustainability (Roithner et al., 2022; UNEP, 2023) could be substantial. The choice of building materials is crucial for reducing the embodied emissions of buildings (Hu, 2023; Pomponi and Moncaster, 2016; Pomponi et al., 2020).

Timber products have recently gained attention as a potential solution for transforming the building sector from a carbon emitter to a net carbon sink (Churkina et al., 2020; Le et al., 2024). A new category of wood building materials that utilizes low-grade, smaller-diameter trees and manufacturing waste as the primary raw materials has gradually emerged (Duan et al., 2022). These products, known as mass timber construction products, are exceptionally durable and versatile within their use phase (Duan et al., 2022). The use of wood in the construction sector can replace more carbon-intensive non-renewable materials, contributing to climate change mitigation and resource conservation (Amiri et al., 2020; Hildebrandt et al., 2017; Sikkema et al., 2023). There has been recent interest in the environmental impact of mass timber construction products, particularly cross-laminated timber (CLT) and glulam, due to their lower contribution to global warming compared to concrete and steel (Duan et al., 2022; Rasmussen et al., 2021). Most articles on this topic compare Life Cycle Assessments (LCAs) of buildings

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constructed with reinforced concrete and CLT. Global Warming Potential (GWP) and Life Cycle Primary Energy (LCPE) are the most commonly evaluated categories. Duan et al. (2022) reviewed 62 papers and found that mass timber buildings generally have lower GWP and LCPE than reinforced concrete or steel buildings.

Several studies have demonstrated that increasing the use of wood-based building materials is an effective method for storing carbon above ground (Arehart et al., 2021; Churkina et al., 2020). Wood is a renewable resource produced by forests that absorb carbon dioxide (CO₂) as they grow. By using wood to produce durable goods, such as buildings, carbon can be stocked for a long time, generating a large mitigation benefit (Churkina et al., 2020). Thus, buildings can be a sort of “second forest”, and while they continue to store carbon, further wood can be provided sustainably by forest regeneration (Churkina et al., 2020; Garcia et al., 2020). For the sake of simplicity, we hereby refer to the carbon transfer between the atmosphere and the wooden biomass as CO₂, regardless of the carbon oxidation status, instead of referring to CO₂ for the absorption and to carbon for the storage (or stock) in wood.

The Circular Economy is one of the main building blocks of the EU Green Deal (EC, 2019), Europe’s agenda for sustainable growth. The EU’s new Circular Economy Action Plan (EC, 2020) paves the way for a cleaner and more competitive Europe. Among its aims, it focuses on the sectors that exploit the most resources and where the potential for circularity is high (including construction and buildings), aiming to make circularity work for people, regions, and cities.

In this context, the high recovery and recycling potential, as well as the possibility of multiple reuses of wood, allow for a reduction in waste generation and extend the lifetime of wood as a material. Compared with concrete, wood generally has a much higher potential for flexible building assets and reversible construction due to the lightweight of the material and the dry connections (Klinge et al., 2019; Munaro et al., 2022). Timber construction material lends itself to cascading (multiple reuse), defined by Vis et al. (2016) as “*the efficient [use of] residues and recycled materials [.....] to extend total biomass availability in a given system*”. Technically, cascading occurs when wood is processed into a product and then used at least once more, either as a material or for energy recovery (Vis et al., 2016). Depending on the number of final uses and times of reuse, cascading is categorized as single-stage (the wood product is used once more for energy purposes) or multi-stage (it is used at least once more as a material before disposal or energy recovery) (Vis et al., 2016).

Post-consumer waste wood is often chipped to produce particleboard (PB) (Besserer et al., 2021; Vis, 2016), used in packaging and furniture (Husgafvel et al., 2018), or burned to recover energy (Ramage et al., 2017). Using wood in a cascading manner can lead to lower energy consumption and CO₂ emissions (Thonemann and Schumann, 2018). By implementing LCA of various cascading options, Risse et al. (2017) demonstrated that utilizing wood in a cascading manner can greatly lower resource consumption and enhance the efficiency of wood. Brunet-Navarro et al. (2021) showed that the long-term reuse and recycling of timber can promote CO₂ storage and reduce CO₂ emissions by replacing non-wood materials. However, none of these previous assessments of the environmental benefits of cascading wood consider the possibility of reusing recovered timber for the same function (namely as construction material) at the end-of-life stage and quantifying the benefits.

Currently, the wood value chain is managed through linear business-as-usual (BaU) practices, in which energy recovery is considered the best option for waste wood (Niu et al., 2021). However, better end-of-life strategies and waste valorization are envisaged for their environmental benefits (Arias et al., 2025). The lack of European standards and regulations for wood recovery makes the reuse of wood difficult. However, a few individual countries already have rules in place that support the implementation of some level of cascading. Another barrier is the current low demand for recovered material (Cristescu et al., 2020; Le et al., 2024).

The standards that currently guide LCA of buildings (EN 15804:2012+A2:2019 and the specific EN 16485:2014 for wood materials) have some shortcomings for wooden buildings: EN 15804:2012+A2 does not allow selection of “cradle to gate” system boundaries for products containing biogenic carbon and the inclusion of biogenic carbon storage. This implies overlooking its potential in mitigating climate change. EN 16485 (2014) considers four possible End-of-Life (EoL) scenarios for construction wood after a single use lasting as long as defined by the reference service life (RSL): landfill (i.e., release of CO₂ stored in wood); energy recovery (i.e., burn); recycle (cut and burn); reuse (chip and burn). This would imply that burning wood is a carbon-neutral activity, regardless of where and especially when the CO₂ is absorbed or released. However, all options mandate burning the wood as the only possible final step, incurring the release of all the CO₂ absorbed and stocked in wood during tree growth, even if a recycling process is selected. Therefore, the four scenarios considered for the end-of-life might not be entirely carbon neutral.

This paper aims to stimulate better management of the wood value chain by promoting the reuse of mass timber construction products, maintaining their original function before downgrading, and diverging from current regulations. LCA is applied to the illustrative case of a timber building designed ex-ante to enable multi-stage cascading. This highlights the potential environmental benefits that a longer wood value chain can generate through the multiple reuse of mass timber construction products for the same function.

2. Materials and methods

2.1. Case study

Our approach is based on a theoretical structural frame for a five-storey commercial timber building, utilizing prefabricated elements, a non-structural façade, and a post-and-beam system, all of which adhere to the Design for Deconstruction and Reuse principles to ensure high versatility and adaptability (Kibert, 2003). Adopting the post-and-beam system and reducing the number of structural elements provides the desired versatility. The Design for Deconstruction and Reuse system enables the individual components of the building to be readily separable and reused elsewhere, thus meeting the rapid change needs of urban contexts (Kibert, 2003). The building has an area of 7290 m² and a total height of 20 m (see Figure S1 in the Supplementary Materials). The assessment only includes the main and structural building components, i.e., reinforced concrete foundations and stairs, glulam beams and columns, CLT slab, roof and core walls, laminated veneer lumber (LVL) façade, insulation, and steel façade cladding. Thus, this study does not refer to a completed commercial wooden building, as only the main structural components are accounted for and considered in the cascading evaluation.¹ Additionally, we assumed a very conservative building composition, with approximately 55 % concrete (weight basis), to comply with Danish standards regarding acoustic performance (BR10, 2010). In other countries, standards may be more flexible, enabling a reduction in the proportion of concrete and an increase in the amount of wood. In this case, our results would be even more favourable for wood reuse. It is worth noting that this case study is presented as a theoretical application scenario grounded in state-of-the-art construction techniques, with a particular emphasis on dry-assembled elements and mechanical connection strategies that facilitate disassembly, reuse, and enhanced end-of-life management (Vaugh Thistleton Architects, 2024). The proposed solutions have been partially explored through a small-scale demonstrator, which remains in operation and provides

¹ It should be noted that the amount of engineered timber considered in the current evaluation is less than what could constitute a finished building.

preliminary insights into their feasibility²

All wooden components are postulated to come from sustainable forest management practices (Churkina et al., 2020; Hafner and Schäfer, 2018). Since we focus on the primary wood elements, minor and furnishing elements (such as internal partitions made of gypsum plasterboard, fixtures, tiles, doors, and windows), as well as equipment and plumbing, are excluded from the assessment. The RSL of the building is set at 50 years, as in most LCA studies (Marsh, 2017), and as imposed by ISO 15686-1 (2011) and BS EN (1990) (Eurocode 0).³

2.2. System modelling

By definition, the system considered by standards is confined to the life cycle of a single building. This excludes any possible destiny other than the 4 “EoL” in EN 15804:2012+A2:2019 and, thus, truncates the system boundary of the underlying wood value chain. Consequently, a change in terms of what the system is considered is necessary to allow for any other destiny, including reuse for the same function. In our study, this shift involves expanding the system boundaries forward in time to fully utilize the properties of timber elements that were safeguarded after their initial use. Therefore, rather than considering the life cycle of a single building, we consider the service provided by two identical buildings with the same life cycle, existing side by side in time. The EoL is subsequent to this time and follows the options proposed by standards, resulting in system boundaries coinciding with twice the use time of the timber elements, reaching 100 years (50+50).

2.3. Cascading modelling

Two different cascading scenarios were considered for the building elements (Fig. 1):

- REUSE WITH THE SAME FUNCTION (RUSF) SCENARIO (Fig. 1i): after 50 years, the building is disassembled: the timber elements (i.e., framework, slab, core, façade) are reused, the degree of reusability depending on the element’s function (see *Material for reuse (%)*, Table 1). Timber elements are reused at a different site for the same purpose (i.e., constructing a new building). The timber elements suitable for reuse are reassembled in a new building with the same structure, characteristics, and RSL. Scraps from disassembly are used to produce PB or are incinerated and replaced with virgin material during new construction. At the end of the second building’s life cycle, the post-consumer waste wood from its dismantling is assumed to be cascaded and recycled into PB, as it cannot be reused for another timber building due to technical reasons, specifically the loss of the required mechanical properties of the wood. When the PB reaches the end of its life, it is incinerated.
- BUSINESS AS USUAL (BaU) SCENARIO (Figure 1ii): After 50 years (end of RSL), the building is demolished and disposed of; the wood elements (i.e., CLT, glulam, and LVL) are incinerated.

In the RUSF scenario, the recovery of timber elements from the first building, which is reused in the second building, can be influenced by factors such as wood quality and the deconstruction phase. The amount of wood suitable for reuse will depend on the quality of the material at RSL. To be reused, the elements and their mechanical properties must be unaltered. Since all the wood used in the building is protected and not exposed to external or internal weathering, it falls in use class 1 (EN

335:2013), and its durability is guaranteed. Thus, in a best-case scenario, 100 % of the wood used in the first building can be reused in the second. However, taking a conservative approach that considers deconstruction operations and ease of disassembly (components like the façade might be more challenging to disassemble), a lower recovery rate is assigned to these elements than to more easily dismantled beams and columns (see *Material for reuse (%)*, Table 1). Empirical studies indicate that reuse rates can range from 50 % to nearly 100 % when appropriate disassembly and recovery methods are employed, depending on the building type and design strategy (Ahn et al., 2022; Bertin et al., 2020; Di Ruocco et al., 2023). Although degradation mechanisms such as fastener corrosion, moisture damage, and design limitations may reduce reuse potential in practice, currently timber system designs are increasingly conceived for durability and planned disassembly, as in the case considered in the present study (Waugh Thistleton Architects, 2024). This perspective is consistent with De Wolf et al. (2020), who demonstrated that design-for-disassembly approaches and related technological solutions significantly enhance the likelihood of reuse, supporting the assumption that service lives can extend up to 90–100 years.

Thus, we defined three options for RUSF of the first timber building structural frame: “best” Scenario 1, “intermediate” Scenario 2, and “worst” Scenario 3 (Table 1). Scrap from the first building unsuitable for reuse is treated as post-consumer waste wood that may be incinerated or recycled to PB, leading to at least two additional hypotheses (hereafter referred to as configurations). Scrap from the first building can be incinerated (Configuration A) or recycled to produce PB and then incinerated (Configuration B) in varying percentages. Thus, we have six possible RUSF cases for the timber building (Table 1).

Fig. 1 shows the two cascading scenarios. In the BaU scenario (1i), red arrows indicate material flows of virgin wood from the first to the second building, recycling 2nd building to PB, and incineration of PB at EoL. The brown arrow indicates the percentage of wood scrap from dismantling the 1st building that was recycled to PB (post-consumer wood). In the RUSF scenario (1ii), the red arrows indicate the material flows of timber from the first and second buildings to incineration at EoL.

2.4. Life cycle assessment

A Life Cycle Assessment (LCA) was conducted in accordance with the ISO 14040:2006 and ISO 14044:2020 standards, as well as the EN 15804:2012+A2:2019 requirements. To compare scenarios, BaU and RUSF must fulfil the same function and be based on a common functional unit. The functional unit used to ensure scenario comparability was the commercial service provided by a building (its structural framework) over a 100-year period. This is the simplest choice to ensure direct comparability. In any case, as long as the building surface area (7290 m²) and material quantities are maintained, other options could be suitable for the second building’s design, obtained by a different assembly of the engineered timber components. This choice also assumes that the second building is placed in the same climatic and normative context as the first building, which could approximately mean a country-wise applicability or, at least, a sub-national region-wise applicability. In fact, we assumed reuse in an area nearby; therefore, the transport phase linked to the reuse can be neglected. Instead, other functions, such as the domestic use of the material recovered from the first building, are harder to envision due to the close relationship between the design of the components and the building’s function (Yang et al., 2024). Moreover, using the commercial service provided by a building over a 100-year period as the functional unit makes it possible to avoid allocation problems between life cycles, since, regardless of the allocation choices applied, the total sum of impacts and benefits remains the same over 100 years of commercial service. For the allocation between reusable elements and particleboard (PB), we followed EN 15804:2019 by applying the 0–100 approach. This choice aligns

² See <https://www.build-in-wood.eu/post/new-timber-test-building-to-help-the-construction-sector-build-in-wood>

³ In some Environmental Product Declarations (EPDs), companies may declare that wood has RSLs of >100 years in service classes 1 and 2 (e.g., the EPD of Stora Enso company for its CLT (EPD reference number S-P-02033)); however, ISO 15686-1 and BS EN 1990 (Eurocode 0) impose 50-year RSLs.

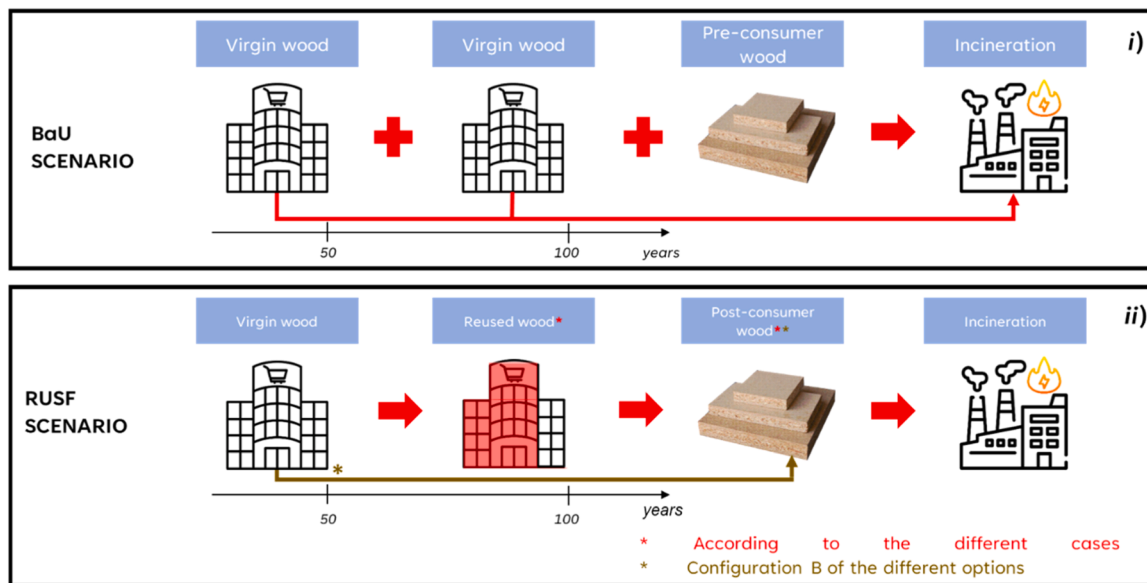


Fig. 1. Representation of the system under assessment i) BaU scenario (in 100 years, two buildings of virgin timber are built); ii) RUSF scenario (red arrows show the flow of timber up to 100 years with reuse of timber and scrap, i.e., post-consumer wood). Note that the RUSF cases are modelled to generate the same amount of particleboard as the respective BaU, meaning that wood scrap from other origins, such as sawmills (pre-consumer wood), is needed.

Table 1

RUSF cases for the first building (virgin wood label in Fig. 1i) based on different reuse rates and treatment of scrap (quantity of PB produced by each scenario in Table 3).

Element and component		Glulam framework, CLT slab			CLT core			LVL façade		
Case		Material for reuse (%)*	Scraps (%)		Material for reuse (%)*	Scraps (%)		Material for reuse (%)*	Scraps (%)	
SCENARIO	Configuration		Incineration	PB production		Incineration	PB production		Incineration	PB production
1	A	98	2	–	90	10	–	70	30	–
	B	98	1	1	90	5	5	70	15	15
2	A	75	25	–	70	30	–	50	50	–
	B	75	12.5	12.5	70	15	15	50	25	25
3	A	50	50	–	50	50	–	30	70	–
	B	50	25	25	50	25	25	30	35	35

Configuration A: 100 % of scrap (i.e., wood unsuitable for reuse) is incinerated (i.e., 2 %, 10 %, and 30 % in Scenario 1 for Glulam framework, and CLT slabs, CLT core, and LVL façade, respectively; 25 %, 30 % and 50 % in Scenario 2 and 50 % and 30 % in Scenario 3).

Configuration B: 50 % of scrap (i.e., wood unsuitable for reuse) is incinerated, and 50 % is cascaded to PB.

* expert judgment.

perfectly with the system and cascading modelling described above and diverges from the common practice induced by standards (e.g., treating a building as a system product and establishing a temporal boundary of 50 years).

Table 2 lists the variables used for comparison of the two scenarios.

Given the different reuse rates and scrap treatment (Table 1), the volume of PB produced by each RUSF case varies (Table 3).

This led to further considerations for properly comparing the results of the two systems. Given the system expansion represented by the PB production add-on, there are three possible ways to implement the comparison:

- 1) Assuming that all cases (1A, 1B, 2A, 2B, 3A, 3B) and BaU scenario produce the same overall volume of PB as 3A from the two buildings (1080 m³, Table 3), which represents the minimum volume of post-consumer wood for PB production. Any excess scrap generated in the other case is incinerated.
- 2) Comparing each RUSF case with an equivalent BaU scenario that produces the same amount of PB. Each RUSF case produces a different amount of wood scrap, which is used in the production of

PB. The corresponding BaU scenario is set to produce the same amounts of PB from pre-consumer wood.

- 3) Assuming that all cases (1A, 1B, 2A, 2B, 3A, 3B) and BaU scenario produce the same overall volume of PB as 1B (2254 m³, Table 3), which represents the maximum volume of PB production.

Nevertheless, the comparison based on the maximum volume of PB was not carried out because the results would have been misleading and out of the scope of the present work. Case 1B produces the greatest volume of PB (2254 m³, Table 3), but setting this volume as the output to compare cases with the corresponding BaU scenario would have meant that the missing volume of wood for PB production of all the cases would come from pre-consumption wood. Such a comparison would not have been useful for evaluating how cascading can affect the impacts of timber buildings at the end of their life, but would have been influenced by the addition of a certain amount of PB from pre-consumption wood in all cases. The optimization is kept strictly related to the functional unit, i.e., the building service, rather than to the production of PB from pre-consumer scrap. For reference, we also modeled the calculation to match the potential PB production for each case.

Regarding the system boundaries, the analysis employs a cradle-to-

Table 2
Variables used for comparison of cascading scenarios (BaU and RUSF).

Variables	BaU SCENARIO	RUSF SCENARIO
Number of buildings in virgin wood	2	1 + a percentage of virgin wood (variable according to scenario) to replace wood scrap from deconstruction
Number of stories	5	5
Reference Service Life of each building	50 years (total timespan 100 years)	50 years (total timespan 100 years)
Origin of wood	Virgin wood for both structural frame of buildings	<ul style="list-style-type: none"> • 1st building (structural frame): virgin wood • 2nd building (structural frame): wood recovered from 1st and a percentage of virgin wood (variable according to scenario) to replace deconstruction scrap
PB production (wood origin)	Pre-consumer waste wood from sawmills	Post-consumer wood residues from dismantling both buildings
Building End of Life and treatment of wooden elements	Demolition and incineration	<ul style="list-style-type: none"> • 1st building (structural frame): dismantling and reuse of wood in 2nd building. • 2nd building (structural frame): wood recycled to particle board

Table 3
Volume of particle board (PB) produced by RUSF cases (total and for 1st and 2nd building).

RUSF case	PB from scrap of 1st building (m ³)	PB from dismantling of 2nd building (m ³)	PB total volume (m ³)
1A	0	2199	2199
1B	55	2199	2254
2A	0	1657	1657
2B	345	1657	2002
3A	0	1080	1080
3B	615	1080	1695

A technical loss of 5 % due to transport and production processes was included in the PB calculation (Höglmeier et al., 2015).

grave approach, starting with the extraction of raw materials and concluding at the end-of-life stage of the considered products. Regarding the lifecycle of the two buildings (structural frame), modules A and C (from cradle to grave, as defined in EN 15804:2019) were included in the assessment. Since the assessment focuses on the timber elements and their potential for reuse, the operational phase (Module B) was excluded. Nor was the replacement of material for maintenance included, as it was assumed to be unnecessary for an RSL of 50 years.

Credits generated by recycling or energy recovery (module D) were assumed to be zero (prudential approach). In line with EN 15804:2019, the 0–100 approach was followed to allocate the impacts to the building; therefore, the scrap for the PB production is burden-free. The impacts of energy recovery were assigned to the product system that generates the waste.

All input flows related to materials, energy demand, chemicals, and auxiliary materials involved in the lifecycle phases analysed are included in the boundaries. Regarding geographical scope, the study is limited to European countries.

For the Life Cycle Inventory (LCI), foreground data concerning the composition of the building, i.e., the list of building components and their quantities, are presented in Table S1 of the Supplementary Material, which also details the different cases for virgin wood used. The design and calculation of the buildings meet the most restrictive standards for acoustic performance and fire safety (in compliance with BR10, 2010). As such, the relative quantities of some materials (particularly concrete) may be higher than the European average. The demountability of the system may therefore be higher than that of existing solutions, resulting in a consequent reduction in the amount of topping concrete layer above the CLT slabs.

Background data were sourced from Ecoinvent 3.6 (Wernet et al., 2016), which provides representative European averages and is widely recognized as a reliable database for life cycle assessments. Since the study focuses on the European context, this choice ensures consistency and comparability with other research in the region. Nevertheless, since the study focuses on reuse in the same location and the case study is hypothetical, we opted to use average data. Nevertheless, it should be acknowledged that regional variations (e.g., differences in energy mixes or timber sourcing practices) may influence the absolute impact values, but it is not the core of the current study, and as such, we suppose that the results and the validity of the proposed approach will not be altered. SimaPro v. 9.0 software was used to perform the Life Cycle Impact Assessment (LCIA).

The extraction of raw materials used in the building was modeled using Ecoinvent 3.6 (Wernet et al., 2016). The manufacture of timber elements (glulam, CLT, and LVL) was inventoried using confidential primary data from an engineered timber company and from the literature (Rüter et al., 2012). For all other materials, the production process upstream was based on data from Ecoinvent 3.6 (Wernet et al., 2016) and Environmental Product Declarations (EPDs). For transport of materials from the factory to the building site and from the building site to the waste treatment plant, we assumed a distance of 100 km (Höglmeier et al., 2015). We assumed 16–32 metric ton trucks (gross weight) and an emission class of Euro V. The energy demand associated with the construction phase (A5) was calculated, starting with the diesel and electricity consumption declared in the EPDs. For disassembly (RUSF scenario), energy consumption was assumed equal to that of assembly. Fuel consumption for demolition (BaU scenario) was estimated using the model developed by Ivanica et al. (2022). Waste treatment was modelled according to European waste treatment statistics for steel and concrete (Eurostat, 2018) and statistics declared in EPDs for the other materials.

The method EF 3.0 (Fazio et al., 2018), which is aligned with EN 15804:2019, was used to perform LCIA. The impact indicators selected were: Climate Change (CC), Depletion Potential of the stratospheric Ozone layer (ODP), Acidification Potential (AP), Eutrophication Potential freshwater (EP-freshwater), formation potential of tropospheric ozone (POCP), Abiotic Depletion Potential for non-fossil resources (ADP-mineral & metals), and Abiotic Depletion Potential for fossil resources (ADP-fossil).

Regarding the biogenic carbon cycle, timber products were assumed to be carbon neutral, according to the standards. Thus, no biogenic CO₂ uptake during forest growth nor emissions associated with biogenic CO₂ release at end-of-life were computed.

Since we adopted a conservative precautionary approach, credits for avoided impacts (e.g., from burning wood with energy recovery) were not assessed, which is why we refer to “incineration” of wood instead of “energy recovery”.

2.5. Validity of the study

The study is grounded in a theoretical case application, complemented by a small-scale demonstrator. The proposed dry-assembly and mechanical connection strategies constitute the fundamental condition for enabling the reuse-with-same-function approach. Regardless, modelling choices such as the share of reusable materials (Table 1), even if in line with other studies (see, for example, Ahn et al., 2022; Bertin et al., 2020; Di Ruocco et al., 2023), will require validation through empirical evidence, which will, however, be possible in the future. The range of shares considered addresses this uncertainty to compensate for the lack of empirical evidence.

For the background data, this work relies on the Ecoinvent 3.0 database, which is Europe-centred. This might limit the global representativeness of the results in absolute and potentially relative terms, for instance, due to possible variability in timber quality and disassembly efficiency. Further work should investigate the validity of the proposed

building system solution in other contexts and link the related foreground system with background data retrieved from different databases, such as USLCI⁴ for the United States context. The intra-European validity might also be subject to uncertainty, mainly due to the existence of country-specific regulations that might be more or less restrictive. However, the Danish context is among the most restrictive in Europe; thus, the validity of the study can be expected at least in the European context.

Moreover, the study focused on a specific design that follows the Design for Deconstruction and Reuse principle (Waugh Thistleton Architects, 2024). However, other relevant solutions, as well as combinations of them, should be considered to investigate their potential to further increase the environmental benefits. For instance, modular building systems, hybrid materials, or recycled components could be combined with the solution studied in this paper to further gain insight into the potential of buildings to mitigate environmental impacts.

3. Results

The Life Cycle Assessment (ISO 14040:2006 and ISO 14044:2020) used a cradle-to-grave approach. Specifically, the RUSF scenario considers the reuse of timber components that fulfill the same function in a second building with the same characteristics and size as the first building. After this stage, the wood is cascaded and used to produce PB. For the RUSF scenario, six cases were developed based on different assumptions regarding the share of wood destined for reuse and waste treatment operations for the remaining wood scraps, i.e., recycling into PB or incineration.

3.1. Environmental impact assessment of the RUSF scenario

The Life Cycle Impact Assessment (LCIA) was conducted by considering the aforementioned assumptions regarding the amount of PB included in the comparison. As such, the product system (BaU and RUSF scenarios, Fig. 1 and Table 2) has been assessed considering that all cases produce the same volume of PB, equal to the minimum volume produced by the RUSF scenario (i.e., case 3A). The potential environmental impact assessment and comparison results are reported in the centre column of Table 4. In a second comparison, the product system of Fig. 1 was assessed considering that each RUSF case matches its potential PB production (Table 3) and is compared to its equivalent BaU. Results are reported on the right side of Table 4. The table shows all the impact category indicators and the percentage variation in RUSF cases 1B and 3A compared to the corresponding BaU for the two PB production hypotheses (Tables S2 and S3 show the assessment and comparison for RUSF cases 1A, 2A, 2B, and 3B). Cases 1B and 3A recycle the most considerable quantity of material (2254 m³ of PB) and produce the most energy (producing 1080 m³ of PB only), respectively. The other cases represent intermediate states.

The results indicate a reduction in emissions for all indicators in cases, irrespective of the amount and destination of wood scrap assumed. These reductions show similar values for both calculation approaches (i.e., minimum PB production volume or potential PB production). In the least-impact case identified by the analysis (case 1B), GWP is reduced by ~13 %, ODP by ~19 %, POCP by 25 % maximum, AP by up to 16 %, EP by ~24 %, ADP fossil by up to 17 %, and ADP minerals and metals by 1 %. The results of the latter two environmental impact indicators should be interpreted with caution, as recommended by EN 15804:2012+A2:2019, because uncertainties in these results are high, or limited experience exists for the indicator. We therefore focus on interpreting the other categories.

Table 4

Results of cases 1B and 3A and variation (%) between them and the corresponding BaU scenario. The centre column shows figures derived from the assumption that PB production equals the RUSF case 3A (1080 m³) for all cases. The right columns compare 1B and 3A with the corresponding BaU, where the PB output matches the actual production potential. Note that in this instance, the results for case 3A would be unchanged and are therefore not shown.

Cases	PB minimum production volume			PB potential production volume	
	BaU _{3A}	1B	3A	BaU _{1B}	1B
PB hypothesized (m ³)	1080	1080	1080	2254	2254
Climate change (GWP)					
t CO ₂ eq	3518.4	3066.6	3248.0	3801.3	3293.6
Variation from BaU (%)	–	–12.84 %	–7.69 %	–	–13.36 %
Ozone depletion (ODP)					
kg CFC11 eq	0.41	0.3	0.4	0.5	0.4
Variation from BaU (%)	–	–19.36 %	–11.48 %	–	–19.21 %
Photochemical ozone formation (POCP)					
t NMVOC eq	16.3	12.7	13.9	18.8	14.1
Variation from BaU (%)	–	–22.08 %	–14.45 %	–	–24.73 %
Acidification (AP)					
kmol H ⁺ eq	17.5	14.8	15.9	19.7	16.6
Variation from BaU (%)	–	–15.37 %	–9.12 %	–	–15.65 %
Eutrophication, freshwater (EP)					
kg P eq	154.2	117.3	133.8	166	125.8
Variation from BaU (%)	–	–23.89 %	–13.20 %	–	–24.22 %
Resource use, fossils (ADP fossils)					
GJ	52,899.3	44,040.4	47,807.9	58,442.9	48,887.0
Variation from BaU (%)	–	–16.75 %	–9.62 %	–	–16.35 %
Resource use, minerals and metals (ADP minerals)					
kg Sb eq	40.9	40.5	40.7	41.2	40.7
Variation from BaU (%)	–	–1.00 %	–0.58 %	–	–1.10 %

* To avoid repetition, the second part of the results for 3A and corresponding BaU are not shown, being the same as in the central column. Even when considering a different perspective of comparison, 3A remains the highest-impact case.

4. Discussion

4.1. Comparison with other studies

Due to differences in the systems under assessment, it is not possible to compare these results with the scientific literature on cascading principles and timber buildings (Cordier et al., 2022; Duan et al., 2022; Szichta et al., 2022; Thonemann and Schumann, 2018). In previous studies, the reuse of timber with the same function has only been hypothesized, and related discussions are speculative rather than supported by quantitative estimations of environmental benefits, or reuse is not considered at all, or is considered only as a biofuel (Piccardo and Hughes, 2022; Thonemann and Schumann, 2018). Instead, we considered the fundamental importance of the ex-ante design of buildings, which enables the reuse of a large amount of the structural components for the construction of another building at the end of its life, providing quantitative estimates of the environmental benefits and filling the existing knowledge gap. By postulating the reuse of timber for the

⁴ <https://www.nrel.gov/analysis/lci>

construction of another building as the second stage, we highlighted the maximum valorization of quality in opposition to downgrading, consisting in a better value chain management, while other papers consider recycling in terms of other wood-based products (thus resulting in a downgrading of the timber). This is achieved by expanding the system under assessment in line with the extended lifetime of engineered timber elements, and in accordance with the desirable elongation of the timber value chain. Ignoring the possibility of a timber building becoming a second timber building fails to fully appreciate the benefits of engineered timber over traditional construction materials. Our assessments, considering multiple reuses through cascading, can be regarded as a first step towards evaluating the environmental virtues of timber buildings.

The evaluation of circularity in terms of material reuse for the same function was not directly addressed in this study, as this aspect has already been thoroughly investigated in existing literature (Feng et al. 2022, Lisco and Aulin, 2024) and is further supported by ISO 20887 (2020), which states that introducing design-for-disassembly principles can reduce or prevent waste and increase resource efficiency. Nevertheless, the assessment of circularity as a broader concept remains contested, with no universally accepted methodology currently available (Khadim et al., 2023). In recent years, several frameworks and indicators tailored to the building and construction sector have been introduced (Akanbi et al., 2019; Khadim et al., 2022, 2023) due to the particular characteristics of the construction industry; among the others, longer service life, multiple stakeholders, customization, and context-dependency (Akanbi et al., 2019). However, none has been standardized (Khadim et al., 2023). The diversity of approaches makes the selection of a specific indicator inherently subjective (Lisco and Aulin, 2024).

On this basis, the present study does not re-examine material reuse as a circular practice. Instead, it focuses on its environmental implications—for example, its potential to mitigate climate change impacts—acknowledging that circular practices, while valuable, do not inherently lead to more sustainable buildings or ensure a reduction in environmental burdens (Buyle et al. 2019).

While not directly addressing engineered timber, several studies have explored modular systems, hybrid solutions, and recycled components, providing useful benchmarks for comparison. Minunno et al. (2020) quantified the savings from reusing the components of a modular building made of steel and concrete compared to recycling, highlighting a 27 % lower GWP of the building designed for recycling compared to the same building designed for reuse, and a 78 % reduction of the recycled one versus the same building made of virgin materials. The study was limited to a 50-year lifespan and did not focus on the second life cycle of the reusable components, but simply postulated their re-use. Antwi-Afari et al. (2022) conducted an LCA study on a steel-based building with a concrete foundation designed with modular components and a lifespan of 100 years. In this case, only the recyclability of the materials was assessed across various scenarios and different allocation approaches, regardless of EN standards, whilst no reuse options were considered. Yang et al. (2024) investigated the reuse of a free-standing modular unit made of a structural steel frame and a precast concrete slab, following the design for disassembly principle with a lifetime of 50 years, comparing different allocation approaches highlighting how such a modeling choice affects the results across subsequent life cycles, but did not quantify the impact of savings compared to linear scenarios. Joensuu et al. (2022) compared three design options for the same building: 1) concrete-based, 2) timber-based, and 3) concrete-based with non-structural timber components, the latter following the design for disassembly principles. The study considered both a 30-year and a 50-year lifespan of the building and subsequent uses. The study found that the second option would save approximately 13 % of the GHG emissions compared to the first (business as usual) option, while the second option would achieve a 16 % reduction. While not considering reuse, Zahabi et al. (2025) compared a hybrid timber-steel building with full timber, full steel, and full concrete

equivalent alternatives, identifying the full timber option as the least impactful in terms of GWP (−16 % compared to concrete, the worst case). Al-Najjar and Dodoo (2021) studied a modular CLT multi-storey building, focusing on the sensitivity of the results on the modeling choices. However, no reuse after the first life cycle is considered, but only recycling. Lukić et al. (2020) investigated the production of three low-energy modular buildings made with reinforced concrete, masonry, and CLT, highlighting the GHG emission savings provided by the CLT compared to the other two materials. Still, no reuse or comparison with non-modular equivalent buildings was performed. Passarelli (2019) compared a modular CLT-based system allowing reuse against a non-modular CLT system without reuse over two life cycles of 30 years, showing that only a sustainable management of the forest can enable savings. However, the studied building is limited to a studio module, rather than a multi-storey building. This highlights the distinct advantage of timber-based modular systems in extending material lifespans, while also pointing to the need for robust modeling of reuse scenarios beyond single life cycles.

4.2. Benefits of cascading in the assessment of timber buildings

We modelled and assessed RUSF cases with the main aim of highlighting the fundamental property of timber buildings for a circular economy in urban contexts: the possibility of re-using timber at least three times (twice for building and then for PB) before EoL energy recovery. The more wood reused and the more scrap recycled to PB before incineration, the greater the benefits. Case 1B (green in Table 4) exhibits the best environmental performance across all indicators and achieves the most significant emission reduction. It maximizes the amount of wood suitable for reuse and recycling. By contrast, case 3A (red in Table 4), in which post-consumer wood waste recovered for material reuse or recycling is the lowest, shows the worst environmental profile of the RUSF cases and the lowest emission reduction with respect to BaU for all indicators (see Tables S4 and S5 for LCIA results and comparison of case 1A, 2A, 2B, and 3B). Our results show that a RUSF case for timber constructions based on circularity would reduce environmental impacts under all hypotheses. This can be considered a test of robustness. The results obtained considering the whole system show that significant emission savings can be achieved with respect to business-as-usual (i.e., reuse with the same function vs incineration/energy recovery). While we focused on a commercial building, the same approach can be applied to other building types, such as residential ones, to obtain similar benefits. This is due to the focus on the building system (i.e., post and beam with reusable elements) rather than the specific shape (and related function) of the building itself. This should support policymakers in planning the urban development of future sustainable cities.

4.3. Sensitivity analysis

Further circular use of wood scrap can be hypothesized: 1) energy recovery from incinerating post-consumer wood scrap (from dismantling buildings) could fuel PB production, replacing electricity from the grid and natural gas; 2) varying PB quantities (Table 3) influence the energy obtained from incineration, with different sensitivity outcomes. Based on the RUSF scenario, energy recovery in a cogeneration plant (Ecoinvent 3.6) with 15 % electrical and 45 % thermal efficiency partially/fully replaces grid electricity and gas heat (see Sensitivity analysis on further circularity measures, Supplementary Materials, for assumptions, computations, and results). This additional hypothesis highlights further environmental impact reductions for RUSF cases with higher wood recovery (Case 1A under both hypotheses, as shown in Tables S6 and S7 in the Supplementary Materials). The results highlight that environmental trade-offs emerge when comparing cases with higher PB production (Case 1B) to those with lower PB production (Case 3A). As shown in Table 4, if scraps are burned, the benefits do not compensate for the emissions due to the additional scrap collection and

processing. As such, the downcycling of timber into PB does not offset the benefits of RUSF. Consequently, while PB production can marginally contribute to energy substitution, the overall climate benefit can be better achieved through direct reuse of timber with the same function. Therefore, in the case of energy valorization of wood scraps the results suggest that the environmental investment (i.e., emissions resulting from scrap collection and processing to produce PB) exceeds the reduction in environmental impact. Thus, it can be argued that when timber cannot be reused for construction, it is wiser to recycle it to higher-quality and longer-lasting products such as furniture and flooring. This would increase the useful life of wood towards 100 years (so that the temporal horizon of GWP100 is matched) or enable one or two forests to mature (assuming an average regrowth period of ~75 years - Stewart et al., 2009). This suggests that improved wood value chain management can be achieved by prioritizing the secondary reuse of post-consumer wood as a key factor in stimulating higher levels of sustainability within the construction sector and related sectors, thereby establishing a longer and more circular value chain. It should be finally emphasized that the theoretical PB outcomes are primarily a function of disassembly efficiency: the more effective the selective dismantling and recovery of intact elements, the smaller the scraps available for downcycling into PB. In this respect, the PB values presented here serve as an indirect indicator of dismantling performance rather than as fixed material flows. This interpretation is consistent with design-for-disassembly approaches, which highlight that connection techniques and documentation practices strongly determine recovery rates (De Wolf et al., 2020). Furthermore, since the case study applies Danish construction standards—among the most restrictive in Europe and with the highest concrete percentage over the total mass—the scenario is already precautionary, thereby reinforcing the robustness of the findings. In less stringent regulatory contexts, it is reasonable to hypothesize better environmental performances; nevertheless, further investigation is necessary.

4.4. Standards

International building and construction sector standards are the basis for planning future development of cities that are committed to reducing the impact of climate change (to comply with the International Agreements on Climate Change, for instance, see the Paris Agreement, Global Covenant of Mayors). Yet they were formulated for traditional buildings and materials; they cannot be correctly applied to engineered timber buildings. Two main limitations emerge from our study, where general international building standards were applied strictly:

- ISO 15686-1 (2011), ISO 15686-8 (2008), and BSN (1990) EUROCODE-0 set the RSL of a building at 50 years, though timber buildings may last more than 100 years, and even with an RSL of 50 years, disassembled materials can be reassembled into a “new” building, doubling the RSL to 100 years or more;
- Applying cascading according to the current EN15804:2012+A2:2019 standard, only avoidance of extraction of virgin wood for new CLT and glulam is accounted for, ignoring the carbon stock maintained in the recycled wood, until it is finally burned. Nor is forest renewal accounted for during the life of the first timber building. There is no regrowth or renewability in the case of concrete.

If these principles were observed by the standards, our results would be very different. A step in this direction is the recent Italian Decree n. 90 of 8 May 2023,⁵ envisaging the reuse of engineered timber as a replacement for virgin timber, rather than a waste material. This highlights the current and future regional variability of regulations and linked practices.

Our work suggests that the reuse with the same function for timber elements should be included among the possible EoL scenarios allowed by EN 16485 (2014), allowing the expansion of the assessed system, and the consequent change in terms of system boundaries and functional unit in LCA, before applying any other existing EoL scenarios currently allowed.

5. Conclusions

The implementation of circular economy practices in the construction sector is crucial for reducing its massive resource exploitation and emissions, and wood can help achieve this objective, spurring the sustainability of cities' planning and development. Timber is more abundant, renewable, and has higher reuse and recycling potential than fossil-based materials (e.g., concrete and steel). When even just a small part of the engineered timber is reused, benefits are obtained.

Our study shows that reusing recovered timber for the same function should be considered the preferred option in conceiving a timber building and its life cycle, so that it is designed to generate climate benefits. We show that to capture such benefits, it is necessary to shift from an analytical perspective focused solely on the building to a systems approach with the entire value chain, including reuse and recycling phases, resulting in better value chain management, thus implementing a sort of “*systems industrial ecology*”. Such a shift should capture benefits not only in environmental but also in socio-economic terms by involving different stakeholders (Bastianoni et al., 2023). Our work represents a first step toward a more comprehensive appraisal of the environmental benefits of timber buildings, focusing on multiple circular reuse within cascading systems that begin with a “*first reuse*” serving the same function as the “*first use*”. This is meant to help fill the knowledge gap and address regulations limitations, revising circular economy practices and guidelines within LCA standards (Malabi Eberhardt et al., 2021).

Timber buildings must be designed for easy deconstruction and reuse, with high timber recovery rates. This would foster a new economic sector, currently prevented by the lack of raw materials (reusable engineered timber) and corresponding regulations for new use. The regulations, currently designed for fossil-based buildings, should align with revised standards, allowing for the full capture of the benefits of using, and especially re-using, engineered timber as a building material with the same function as the original.

According to Stewart et al. (2009), a 75-year reference service life would ensure that a new forest can grow during the building's life, replacing the wood used and creating a twin forest. By definition, LCA focuses on the “*technosphere*”, beginning with human intervention and evaluating its environmental impacts. It does not account for the resource itself, its availability, or renewability, nor for the role of the ecosystem in providing it; rather, it focuses on the various impacts a production process is expected to have locally and globally. These limitations hinder fully capturing the benefit of using timber for building, neglecting its renewability and its reusability (Sporchia et al., 2025).

The reuse of engineered timber elements with the same function is one of the aims of the Circular Economy Action Plan, which seeks to

⁵ Ministero dell'ambiente e della Sicurezza Energetica, DECRETO 8 maggio 2023, n. 90 Regolamento recante inserimento del legno lamellare in forma di cippato nell'allegato X, parte II, sezione 4, paragrafo 1, alla parte quinta del decreto legislativo 3 aprile 2006, n. 152. (23G00098) (GU Serie Generale n.165 del 17-07-2023) available at: <https://www.gazzettaufficiale.it/eli/id/2023/07/17/23G00098/sg>

increase circularity in the construction sector, as well as two of the three urgent paths towards decarbonizing the construction sector outlined by UNEP (2023). As such, only by embedding reuse with the same function into design practices and regulatory frameworks can timber buildings make a meaningful contribution to a circular, low-carbon, and resource-efficient built environment.

CRedit authorship contribution statement

Nicoletta Patrizi: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Fabio Sporchia:** Writing – review & editing, Validation, Formal analysis. **Anna Ruini:** Writing – review & editing, Visualization, Validation, Formal analysis. **Elena Neri:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Morena Bruno:** Writing – review & editing, Validation. **Giulia Zarroli:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Simone Bastianoni:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Nadia Marchettini:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

References

- Ahn, N., Dodoo, A., Riggio, M., Muszynski, L., Schimleck, L., Puettmann, M., 2022. Circular economy in mass timber construction: state-of-the-art, gaps and pressing research needs. *J. Build. Eng.* 53, 104562.
- Akanbi, L.A., Oyedele, L.O., Omotoso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Delgado, J.M.D., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *J. Clean. Prod.* 223, 386–396. <https://doi.org/10.1016/j.jclepro.2019.03.172>.
- Amiri, A., Ottelin, J., Sorvari, J., Junnila, S., 2020. Cities as carbon sinks—Classification of wooden buildings. *Environ. Res. Lett.* 15, 094076.
- Antwi-Afari, P., Ng, S.T., Chen, J., Zheng, X.M., 2022. Determining the impacts and recovery potentials of a modular designed residential building using the novel LCA-C2C-PBSCI method. *J. Clean. Prod.* 378, 134575. <https://doi.org/10.1016/j.jclepro.2022.134575>.
- Arehart, J.H., Hart, J., Pomponi, F., D’Amico, B., 2021. Carbon sequestration and storage in the built environment. *Sustain. Prod. Consum.* 27, 1047–1063.
- Arias, A., Feijoo, G., Moreira, M.T., Tukker, A., Cucurachi, S., 2025. Advancing waste valorization and end-of-life strategies in the bioeconomy through multi-criteria approaches and the safe and sustainable by design framework. *Renew. Sust. Energ. Rev.* 207, 114907. <https://doi.org/10.1016/j.rser.2024.114907>.
- Bastianoni, S., Goffetti, G., Neri, E., Patrizi, N., Ruini, A., Sporchia, F., Pulselli, F.M., 2023. LCA based circularity indices of systems at different scales: a holistic approach. *Sci. Total. Environ.* 897, 165245. <https://doi.org/10.1016/j.scitotenv.2023.165245>.
- Bertin, I., Mesnil, R., Jaeger, J.M., Feraille, A., Le Roy, R., 2020. A BIM-based framework and databank for reusing load-bearing structural elements. *Sustainability.* 12 (8), 3147.
- Besserer, A., Troilo, S., Girods, P., Rogaume, Y., Brosse, N., 2021. Cascading recycling of wood waste: a review. *Polymers (Basel)* 13 (11), 1752. <https://doi.org/10.3390/polym13111752>, 2021.
- Brunet-Navarro, P., Jochheim, H., Cardellini, G., Richter, K., Muys, B., 2021. Climate mitigation by energy and material substitution of wood products has an expiry date. *J. Clean. Prod.* 303, 127026. <https://doi.org/10.1016/j.jclepro.2021.127026>.
- Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *J. Clean. Prod.* 218, 141–156. <https://doi.org/10.1016/j.jclepro.2019.01.306>.
- Saheb Cabeza, L.F., Bai, Q., Bertoldi, P., Kihila, J.M., Lucena, A.F.P., Mata, É., Mirasgedis, S., Novikova, A., 2022. Buildings. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK and New York, NY, USA. <https://doi.org/10.1017/9781009157926.011>.
- Churkina, G., Organschi, A., Reyer, C.P., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E., Schellnhuber, H.J., 2020. Buildings as a global carbon sink. *Nat. Sustain.* 3 (4), 269–276. <https://doi.org/10.1038/s41893-019-0462-4>.
- Cordier, S., Blanchet, P., Robichaud, F., Amor, B., 2022. Dynamic LCA of the increased use of wood in buildings and its consequences: integration of CO2 sequestration and material substitutions. *Build. Environ.* 226, 109695. <https://doi.org/10.1016/j.buildenv.2022.109695>.
- Cristescu, C., Honfi, D., Sandberg, K., Sandin, Y., Shotton, E., Walsh, S., Cramer, M., Ridley-Ellis, D., Risse, M., Ivanica, R., Chuláin, C.U., Harte, A., de Arana-Fernández, M., Llana, D.F., Íñiguez-González, G., García Barbero, M., Nasiri, B., Hughes, M., & Krofl, Ž., 2020. Design for deconstruction and reuse of timber structures-state of the art review. 92 pp. ISBN: 978-91-89167-67-4 (electronic).
- Danish Ministry of Economic and Business Affairs and Danish Enterprise and Construction Authority (2010). The Building Regulations 2010 (BR10). ISBN: 978-87-92518-60-6.
- De Wolf, C., Hoxha, E., Fivet, C., 2020. Comparison of Environmental Assessment Methods When Reusing Building Components: A Case Study, 61. *Sust. Cities Soc.*, 102322.
- Di Ruocco, G., Melella, R., Sabatano, L., 2023. Timber buildings deconstruction as a design solution toward near zero CO2e emissions. *Buildings* 13 (1), 157.
- Duan, Z., Huang, Q., Zhang, Q., 2022. Life cycle assessment of mass timber construction: a review. *Build. Environ.*, 109320.
- EN 15804:2012+A2:2019 ‘Sustainability of construction works - environmental product declarations - core rules for the product category of construction products, 2019.
- EN 16485, 2014. Round and Sawn Timber—Environmental Product Declarations—Product Category Rules For Wood and Wood-Based Products for Use in Construction. European Committee for Standardization.
- EN 335:2013 - Durability of wood and wood-based products - use classes: definitions, application to solid wood and wood-based products, 2013.
- European Commission, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM 640, 2019final. <https://eur-lex.europa.eu/legal-content/EN/>.
- European Commission, 2020. A new Circular economy Action Plan for a cleaner and more competitive Europe. COM (2020), 98 final.
- Eurostat, 2018. Eurostat circular economic indicators-recovery rate of construction and demolition waste. <https://data.europa.eu/data/datasets/uczdo4z1o5qcllbdtkbkh?lo cale=en>.
- Fazio, S., Biganzoli, F., De Laurentiis, V., Zampori, L., Sala, S., Diaconu, E., 2018. Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods. EUR 29600 EN, Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/090552>. ISBN 978-92-79-98585-0, JRC114822.
- Feng, H., Chen, Q., De Soto, B.G., Arashpour, M., 2022. Using BIM and LCA to evaluate material circularity: contributions to building design improvements. In: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, 39. IAARC Publications, pp. 9–16.
- García, R., Alvarenga, R.A.F., Huysveld, S., Dewulf, J., Allacker, K., 2020. Accounting for biogenic carbon and end-of-life allocation in life cycle assessment of multi-output wood cascade systems. *J. Clean. Prod.* 275. <https://doi.org/10.1016/j.jclepro.2020.122795>.
- Hafner, A., Schäfer, S., 2018. Environmental aspects of material efficiency versus carbon storage in timber buildings. *Eur. J. Wood Wood Prod.* 76 (3), 1045–1059. <https://doi.org/10.1007/s00107-017-1273-9>.
- Hildebrandt, J., Hagemann, N., Thrän, D., 2017. The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustain. Cities Soc.* 34, 405–418. <https://doi.org/10.1016/j.scs.2017.06.013>.
- Höglmeier, K., Steubing, B., Weber-Blaschke, G., Richter, K., 2015. LCA-based optimization of wood utilization under special consideration of a cascading use of wood. *J. Environ. Manage.* 152, 158–170. <https://doi.org/10.1016/j.jenvman.2015.01.018>.
- Hu, M., 2023. A look at residential building stock in the United States-mapping life cycle embodied carbon emissions and other environmental impact sustain. *Cities Soc.* 89, 104333. <https://doi.org/10.1016/j.scs.2022.104333>.

- Husgafvel, R., Linkosalmi, L., Hughes, M., Kanerva, J., Dahl, O., 2018. Forest sector circular economy development in Finland: a regional study on sustainability driven competitive advantage and an assessment of the potential for cascading recovered solid wood. *J. Clean. Prod.* 181, 483–497. <https://doi.org/10.1016/j.jclepro.2017.12.176>.
- International Standard Organization (ISO), 2006. Environmental Management and Life Cycle Assessment principles and framework, goal and scope definition and life cycle Inventory analysis. *Life Cycle Impact Assessment and Life Cycle Interpretation* (Geneva), 14040.
- International Standard Organization (ISO) 14044, 2020. Environmental Management and Life Cycle Assessment, Requirements and Guidelines. Geneva.
- International Standard Organization (ISO) 20887, 2020. Sustainability in Buildings and Civil Engineering works. Design for Disassembly and Adaptability. Principles, requirements and guidance, Geneva.
- International Standard Organization (ISO) 15686-1, 2011. Buildings and Constructed Assets — Service life Planning — Part 1: General principles and Framework. (Geneva).
- International Standard Organization (ISO) 15686-8, 2008. Buildings and constructed assets Service-life planning Part 8: Reference service life and service-life estimation.
- Ivanica, R., Risse, M., Weber-Blaschke, G., Richter, K., 2022. Development of a life cycle inventory database and life cycle impact assessment of the building demolition stage: a case study in Germany. *J. Clean. Prod.* 338.
- Joensuu, T., Leino, R., Heinonen, J., Saari, A., 2022. Developing buildings' Life cycle assessment in Circular economy-comparing methods for assessing carbon footprint of reusable components. *Sustain. Cities. Soc.* 77, 103499. <https://doi.org/10.1016/j.scs.2021.103499>.
- Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. *J. Clean. Prod.* 357, 131859. <https://doi.org/10.1016/j.jclepro.2023.110498>.
- Khadim, N., Agliata, R., Thaheem, M.J., Mollo, L., 2023. Whole building circularity indicator: a circular economy assessment framework for promoting circularity and sustainability in buildings and construction. *Build. Environ.* 241, 110498. <https://doi.org/10.1016/j.buildenv.2023.110498>.
- Kibert, C.J., 2003. Sustainable construction at the start of the 21st century. *Int. E-J. Constr* 1–7, 2003.
- Klinge, A., Roswag-Klinge, E., Radeljic, L., Lehmann, M., 2019. Strategies for circular, prefab buildings from waste wood. *IOP Conf. Series: Earth Environ. Sci.* 225 (1). <https://doi.org/10.1088/1755-1315/225/1/012052>.
- Le, D.L., Salomone, R., Nguyen, Q.T., Versele, A., Piccardo, C., 2024. Status and barriers to circular bio-based building material adoption in developed economies: the case of Flanders. Belgium. *J. Environ. Manage.* 367, 121965. <https://doi.org/10.1016/j.jenvman.2024.121965>.
- Lisco, M., Aulin, R., 2024. Taxonomy supporting design strategies for reuse of building parts in timber-based construction. *Constr. Innov.* 24 (1), 221–241. <https://doi.org/10.1108/CI-11-2022-0293>.
- Lukić, I., Premrov, M., Leskova, Ž.V., Passer, A., 2020. Assessment of the environmental impact of timber and its potential to mitigate embodied GHG emissions. *IOP Conf. Ser.: Earth Environ. Sci.* 588, 022068. <https://doi.org/10.1088/1755-1315/588/2/022068>.
- Maier, D., 2021. Building materials made of wood waste a solution to achieve the sustainable development goals. *Materials*, 14, 7638. <https://doi.org/10.3390/ma14247638>.
- Malabi Eberhardt, L.C., van Stijn, A., Kristensen Stranddorff, L., Birkved, M., Birgisdottir, H., 2021. Environmental design guidelines for circular building components: the case of the circular building structure. *Sustainability*. 13 (10). <https://doi.org/10.3390/su13105621>.
- Marsh, R., 2017. Building lifespan: effect on the environmental impact of building components in a Danish perspective. *Archit. Eng. Des. Manag.* 13 (2), 80–100. <https://doi.org/10.1080/17452007.2016.1205471>.
- Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: a circular economy case study of a modular building. *Resources. Conserv. Recycl.* 160, 104855. <https://doi.org/10.1016/j.resconrec.2020.104855>.
- Munaro, M.R., Tavares, S.F., Bragança, L., 2022. The ecodesign methodologies to achieve buildings' deconstruction: a review and framework. *Sustain. Prod. Consum.* 30, 566–583. <https://doi.org/10.1016/j.spc.2021.12.032>.
- Niu, Y., Rasi, K., Hughes, M., Halme, M., Fink, G., 2021. Prolonging life cycles of construction materials and combating climate change by cascading: the case of reusing timber in Finland. *Resour. Conserv. Recycl.* 170, 105555. <https://doi.org/10.1016/j.resconrec.2021.105555>.
- Passarelli, R.N., 2019. Environmental benefits of reusable modular mass timber construction for residential use in Japan: an LCA approach. *Mocs* 157–164. <https://doi.org/10.29173/mocs89>.
- Piccardo, C., Hughes, M., 2022. Design strategies to increase the reuse of wood materials in buildings: lessons from architectural practice. *J. Clean. Prod.* 368, 133083. <https://doi.org/10.1016/j.jclepro.2022.133083>.
- Pomponi, F., Hart, J., Arehart, J.H., D'Amico, B., 2020. Buildings as a global carbon sink? A reality check on feasibility limits. *One Earth*. 3, 157–161. <https://doi.org/10.1016/j.oneear.2020.07.018>.
- Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment—What does the evidence say? *J. Environ. Manage.* 181, 687–700. <https://doi.org/10.1016/j.jenvman.2016.08.036>.
- Ramage, M.H., Burrige, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O., 2017. The wood from the trees: the use of timber in construction. *Renew. Sustain. Energy Rev.* 68, 333–359. <https://doi.org/10.1016/j.rser.2016.09.107>.
- Rasmussen, F.N., Andersen, C.E., Wittchen, A., Hansen, R.N., Birgisdóttir, H., 2021. Environmental product declarations of structural wood: a review of impacts and potential pitfalls for practice. *Buildings* 11 (8), 362. <https://doi.org/10.3390/buildings11080362>.
- Risse, M., Weber-Blaschke, G., Richter, K., 2017. Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany. *Resour. Conserv. Recycl.* 126, 141–152. <https://doi.org/10.1016/j.resconrec.2017.09.017>.
- Roithner, C., Cencic, O., Honic, M., Rechberger, H., 2022. Recyclability assessment at the building design stage based on statistical entropy: a case study on timber and concrete building. *Resour. Conserv. Recycl.* 184. <https://doi.org/10.1016/j.resconrec.2022.106407>.
- Rüter, S., Diederichs, S., Holzwirtschaft, A.Z., 2012. *Ökobilanz-Basisdaten Für Bauprodukte Aus Holz*. 303 pp. Braunschweig, Germany: Johann Heinrich Von Thünen-Institut (vTI). Bundesforschungsanstalt für Ländliche Räume, Wald und Fischerei.
- Sikkema, R., Styles, D., Jonsson, R., Tobin, B., Byrne, K.A., 2023. A market inventory of construction wood for residential building in Europe—in the light of the Green Deal and new circular economy ambitions. *Sustain. Cities. Soc.* 90, 104370. <https://doi.org/10.1016/j.scs.2022.104370>.
- Sporchia, F., Bruno, M., Neri, E., Pulselli, F.M., Patrizi, N., Bastianoni, S., 2025. Complementing energy evaluation and life cycle assessment for enlightening the environmental benefits of using engineered timber in the building sector. *Sci. Total Environ.* 970, 179030. <https://doi.org/10.1016/j.scitotenv.2025.179030>.
- Stewart, B., Neily, P., Quigley, E., 2009. Selection cutting in red spruce - A comparison of methods Establishment report. *Nova Scotia Natural Resour* 88. Report for 2009-1 No.
- Szichts, P., Risse, M., Weber-Blaschke, G., Richter, K., 2022. Potentials for wood cascading: a model for the prediction of the recovery of timber in Germany. *Resour. Conserv. Recycl.* 178, 106101. <https://doi.org/10.1016/j.resconrec.2021.106101>.
- Thonemann, N., Schumann, M., 2018. Environmental impacts of wood-based products under consideration of cascade utilization: a systematic literature review. *J. Clean. Prod.* 172, 4181–4188. <https://doi.org/10.1016/j.jclepro.2016.12.069>.
- United Nations (UN), 2015. Transforming Our world: the 2030 Agenda for Sustainable Development. General Assembly. Seventieth session. A/RES/70/1.
- United Nations Environment Programme (UNEP), 2021. 2021 Global Status Report for Buildings and Construction: Towards a Zero Emission. Efficient and Resilient Buildings and Construction Sector, Nairobi.
- United Nations Environment Programme (UNEP), 2023. Yale Center for Ecosystems + Architecture. Building Materials and the Climate: Constructing a New Future. <https://wedocs.unep.org/20.500.11822/43293>.
- Vis, M., Mantau, U., Allen, B., 2016. In: Study on the Optimised Cascading Use of Wood – No. 394/PP/ENT/RCH/14/7689. Publications Office of the European Union, Luxembourg.
- Waugh Thistleton Architects, 2024. Build-in-Wood Systems guide. Available at. http://www.build-in-wood.eu/files/ugd/db4a54_2087a3cc1b8b450bae7d3054ec864fee.pdf.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230.
- Yang, Y., Zheng, B., Luk, C., Yuen, K.F., Chan, A., 2024. Towards a sustainable circular economy: understanding the environmental credits and loads of reusing modular building components from a multi-use cycle perspective. *Sustain. Prod. Consum.* 46, 543–558.
- Zahabi, N., Gu, H., Gong, M., Blackadar, J., 2025. A comparative whole-building life cycle assessment of the four framing systems of the Bakers Place building using the Tally LCA tool. *Buildings* 15, 1192. <https://doi.org/10.3390/buildings15071192>.

Further reading

BSN Eurocode - Basis of structural design, 2002. BS EN 1990:2002 + A1:2005. British Standards Institute, Brussels.