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ENVIRONMENTAL BENEFITS OF POST-USE MATERIALS RECOVERY: A CIRCULAR ECONOMY CASE STUDY OF A CROSS-LAMINATED TIMBER MULTI-STOREY BUILDING IN A LIFE CYCLE PERSPECTIVE

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ABSTRACT: Careful selection of construction materials and the efficient management of post-use materials are vital for resource-efficient buildings with lower environmental impacts. This study explores the implications of circular economy practices, entailing efficient post-use materials recovery for reduced environmental impacts of cross-laminated timber (CLT) multi-storey construction. The global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) of a CLT building are explored in a life cycle perspective, including include all building materials-related activities in the product, construction, end-of-life stages, with a focus on circularity strategies – cascading, reuse, and recycling of post-use building materials. The results show that the building's end-of-life stage represent a significant share of the total life cycle GWP impacts. However, the stage represents a relatively smaller share of the AP and EP impacts. The implementation of circularity significantly reduces the life cycle climate impacts of the building. The end-of-life stage, which represents about 20% of the total material-related GWP impact, can be effectively mitigated through these circularity strategies. Cascading proves to be a better option compared to reuse and recycling, offering a GWP benefit of 70 $kgCO_{2eq}/m^2$. Comparatively, the GWP benefit from cascading is 64% and 72% higher than that of the reuse and recycling options, respectively. This study highlights the importance of life cycle perspective and circularity strategies at the end-of-life stage of CLT buildings to reduce environmental impacts.

KEYWORDS: Cross-laminated timber reuse, circular economy, post-use materials, construction waste, life cycle environmental benefits.

1 – INTRODUCTION

In the European Union (EU), about half of all the extracted raw materials and energy consumption, and 36% of the total waste stream are linked to the construction sector [1, 2]. In Sweden, construction works generate about 10 million tons of waste every year, [3]. Currently, a significant share of the construction waste in the EU, including in Sweden, ends up in landfills and low-value applications as backfills [1, 3, 4].

According to the International Resource Panel [5] and Ellen MacArthur Foundation [6], achieving the 1.5°C target set by the Paris Agreement requires integrating circular economy strategies with ongoing initiatives in energy efficiency and decarbonisation of the built environment. Circular economy principles focus on maintaining materials in use for as long as possible through reuse, recycling, and cascading, thereby reducing reliance on virgin resources and minimizing environmental impacts. This transition is particularly relevant for construction materials, whose production accounts for 11% of global CO_2 emissions [7]. The EU [8] and Swedish government [9] identified the building and construction sector as a priority area for circularity and the transition to a circular economy. The EU circular economy action plan aims to promote circularity along the entire life cycle of products, including buildings [10].

1.1 SIGNIFICANCE OF MATERIAL-RELATED IMPACTS

Recent studies show that energy and environmental impacts associated with the materials comprising a building can be a significant part of the total life cycle impacts. For example, Malmqvist et al. [11] found that the production stage of a Swedish building accounts for about 56% of the life cycle global warming potential (GWP) impact, compared to the operational energy use which accounts for 39% of the GWP impact. Petrovic et

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al. [12] also found material-related impacts from building production and maintenance stages to account for 67% of the life cycle GWP of a Swedish building.

Initiatives to reduce environmental impact assessment of building materials have been recently introduced in EU, including Sweden [13, 14]. The EU Directive on energy performance of buildings (recast) emphasised measures to reduce the whole life-cycle greenhouse gas (GHG) emissions of buildings including material production, construction, operation, renovation and end of life stages, [14, 15]. In Sweden, the climate declaration of buildings regulation [16] requires assessment of the carbon footprint of new buildings. Similarly, France's building environmental regulation includes requirements for embodied carbon emissions of buildings [17].

In efforts to promote low-carbon building materials, cross-laminated timber (CLT) is gaining increasing interest for use in mid-rise, multi-storey building construction [18]. While the literature [19] on life cycle assessment (LCA) of buildings underscores the climate benefits of CLT buildings in lieu to other building structural material, most of the documented studies concern the production stage [20]. Moreover, Andersen et al. [21] observed that much of the literature on the environmental impact of CLT in construction has concentrated on the climate change impact, while overlooking other environmental impact categories. This could result in unintended burden shifting if the other environmental impacts of CLT buildings are not explored and addressed in efforts to mitigate the environmental impacts of these buildings [21, 22].

A comprehensive approach to sustainable construction must consider the entire material cycle, from raw material extraction to end-of-life management [23]. Buildings have finite lifespans, and materials from end-of-life structures can either become waste requiring disposal or valuable resources for reuse. Effective end-of-life material management is essential for minimising life environmental impacts of buildings. For example, Al-Najjar and Malmqvist [24] showed that reusing 94% of concrete elements can reduce embodied carbon by 82% [33], significantly cutting resource use and promoting circular material flows in buildings. Thormark [25] demonstrated that a residential building incorporating a high proportion of recycled and reused materials had significantly lower life cycle energy use compared to one constructed with virgin materials. Almusaed et al. [26] explored the potential benefits of using recycled materials in the construction sector, and noted that recycled materials can lead to 40% reduction GHG emissions and 30% decrease in energy consumption compared to virgin alternatives.

1.2 AIM AND SCOPE

This study explores the environmental impacts of building with CLT volumetric units in a life cycle perspective, focusing on the implications of circular economy practices for post-use materials of the building at the end-of-life stage. The circular economy practices studied are reuse, recycling, downcycling, and cascading, entailing the sequential use of post-use material for different purposes and over time. The study primarily focuses on Global Warming Potential (GWP) but also includes Acidification Potential (AP) and Eutrophication Potential (EP), as these are core environmental indicators according to EN 15804:2012+A2:2019/AC:2021, which guides buildings' LCA. AP reflects contributions to acid rain, which can impact ecosystems; the concrete and steel industries are major contributors. EP relates to nutrient enrichment, which can potentially cause algal blooms. Malin et al. [27] found that GWP accounts for 80–95% of buildings' environmental costs, with AP contributing up to 18% and EP less than 2%.

2 – METHODOLOGY

A CLT building is used as a case study to examine the implications of different post-use building material management practices towards circular economy from a life cycle perspective.

2.1 CASE STUDY BUILDING

The building (Figure 1) is a three-storey residential structure completed in 2022 in Stockholm County, Sweden. It consists of 41 volumetric CLT units, with a total gross floor area of 1,440 m², accommodating 20 flats ranging from one to four rooms. The façade system consists of fibre cement and timber panels. The external wall assembly includes CLT, an internal gypsum board layer, insulation, and exterior cladding. The roof comprises tar paper over tongued-and-grooved timber boards. The foundation consists of prefabricated concrete elements with expanded and extruded polystyrene for thermal protection, placed on crushed stone layers.

Figure 1. Illustration of the studied CLT building in Sweden.

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Total mass of materials comprising the finished building is 1308 tonnes, corresponding to 908.3 kg/m^2. The relative distribution of the mass of the materials is presented in Figure 2. Crushed stone in the foundation constitutes the largest share of the building material mass. This is followed by CLT, which serves as the primary structural material for exterior and interior walls and intermediate floors. Insulation materials account for approximately 16% of the total mass, providing both thermal protection and acoustic benefits. In addition to CLT, other wood products used in construction, including lath, plywood, paraquet represent about 2% of the total mass. Other non-wood materials, such as tar paper, sealant, paint, filler, mortar, reinforcement, glue, polyethylene, fibre cement, ceramic, and asphalt, collectively contribute to 2% of the total material mass.

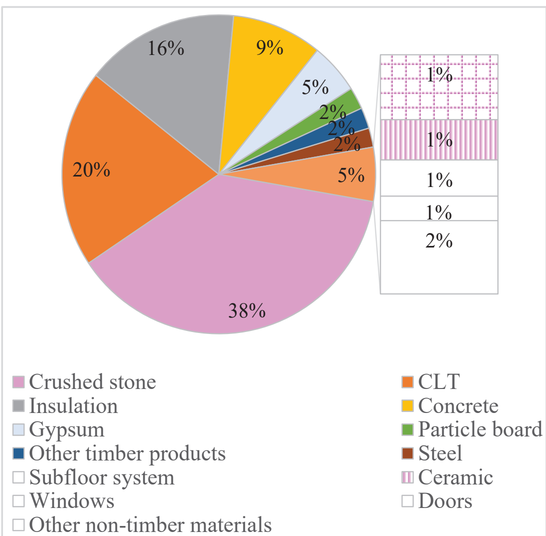

Figure 2. Relative share material mass in the studied building. The total mass of the finished building is 1308 tonnes.

2.2 LIFE CYCLE ANALYSIS

A life cycle analysis (LCA) approach following the normative standard EN 15978 [28] is used to analyse the GWP, EP and AP of materials-related activities and processes associated with the building.

A schematic representation of the system boundary of the analysis, following EN 15978 [28] and EN 15804 [29], is presented in Figure 3. This is defined to include all activities connected to the product (A1-A3), construction (A4-A5), end-of-life (C1-C4) stages and the potential benefits and burdens from post-use building material recovery and management (D). The use stage and associated life cycle modules (B1-B7) are outside the scope of this study.

PRODUCT STAGE	A1	Raw material supply	X
	A2	Transport	X
	A3	Manufacturing	X
CONSTRUCTION STAGE	A4	Transport	X
	A5	Construction installation	X
USE STAGE	B1	Use	
	B2	Maintenance	
	B3	Repair	
	B4	Replacement	
	B5	Refurbishment	
	B6	Operational energy use	
	B7	Operational water use	
END OF LIFE STAGE	C1	Deconstruction/ Demolition	X
	C2	Transport	X
	C3	Waste processing	X
	C4	Disposal	X
POTENTIAL BENEFITS & LOADS	D	Reuse, recovery, recycling potential benefits beyond system boundary	X

Figure 3. System boundary of activities of the analysis, with considered life cycle modules marked X.

Product and construction stages

The environmental impacts during the product stage (A1-A3) are analysed based on the mass of materials in the building, considering emissions from extraction, transport, and manufacturing. Data mainly comes from product-specific environmental product declarations (EPDs) compliant with EN 15804 [29], supplemented by primary data from the company that constructed the studied building, and generic data. The details of the EPDs used are listed in [30]. Emissions from fasteners are calculated using data from IVL [31]. During the construction stage (A4-A5), emissions from transport and installation processes are calculated using EPDs and generic data. Transport emissions are based on diesel consumption rates of 0.07, 0.04, and 0.03 liters per tonne-km for local, long, and highway distances, respectively [30]. Primary data from the company which built the studied building is used to assess impacts from electricity (24,067 kWh), district heat (40,426 kWh), and fuel consumption during assembly. Wastage of material is accounted in the calculations.

End-of-life stage

Plausible scenarios are explored where the building is deconstructed by selective dismantling after a 50-year reference service life, followed by management of the end-of-life building materials. The end-of-life activities analysed comprise deconstruction/ demolition (C1), transport (C2), processing (C3), and disposal (C4). The potential environmental benefits and burdens linked with different circular economy practices (Table 1) for post-use CLT, and other wooden materials, concrete and steel are analysed. The post-use options include recycling, reusing and cascading. Cascading involves the sequential and consecutive use of resources. The concept is proposed as an effective strategy to guide material usage for creating added value within the circular economy [32]. According to Sirkin and ten Houten [33], cascading is an efficient strategy for using recovered wood. In this approach, the recovered wood is first repurposed for high-quality applications, such as reuse as lumber, then recycled or downcycled into other products, followed by additional suitable uses. Finally, the wood may be used for energy recovery through combustion.

Table 1. Options and processes considered in end-of-life stage analysis and avoided by implementation of circular economy practices.

Material	End-of-life option	Application and processes displaced
CLT	Recycling	Cruhed and chipped for particleboard, replacing virgin wood, forest operations, and landfilling.
	Reuse	Used as structural panels in new construction application, displacing new wood processing, forest operations, and landfill waste.
	Cascading	Reused in new construction application, then recycled into particleboard and recovered for energy. This displaces processes associated with reuse and recycling (above) and also displaces fuels for electricity via European average mix.
Concrete	Recycling	Recycled as concrete aggregate, avoiding landfilling, and extraction of virgin aggregate.
Steel (fasteners & reinforcement)	Recycling	Used as steel scrap, avoiding ore mining, smelting, and landfill waste.
Other wood (timber products [e.g. lath], plywood, parquet,)	Recycling	Cruhed and chipped for particleboard, replacing virgin wood, forest operations, and landfilling.

Based on the options in Table 1, three end-of-life scenarios towards circular economy are analysed in this study:

- Scenario 1: Recycling of CLT and other materials
- Scenario 2: Reusing CLT and recycling other materials
- Scenario 3: Cascading of CLT and recycling other materials.

In this analysis, 90% of each of the materials are assumed to be recovered at the building's end-of-life, following [34]. In scenario 1, all the recovered materials are recycled, following the options in Table 1. In scenario 2, 70% of CLT panels are assumed to be reused in new applications following Passarelli [35], with 20% of the CLT recycled along with all the other materials. In a documentation of experience in reusing CLT panels, Passarelli [35] indicated that the usable areas of the recovered panels decreased due to the previously used connections, and that about 30% of the recovered panels were lost during their reprocessing for the reuse. In scenario 3, 70% of the CLT panels are assumed to be cascaded with remaining 20% of the recovered CLT recycled along with all the other materials. The impacts, burdens and benefits of the end-of-life and post-use options are calculated using mostly the data in the specific EPDs, supplemented by generic data [31, 36]. The details of the EPDs are found in refs. [30] and [37]. The impacts due to the transport of the materials are calculated considering the distances to the waste processing and disposal sites and assuming an average diesel consumption of 0.071 l/km-tonne [31].

3 – RESULTS

Table 2 presents the total environmental impacts for the product and construction stages of the building. The product stage accounts for the highest contribution across all environmental impact categories. Compared to the transport and construction stages, the product stage accounts for approximately 65% of GWP, nearly 80% of EP, and over 95% of AP. Though the transport and construction stages contribute less, they still represent a notable share of the GWP.

Table 2. Total environmental impacts of the product and construction stages (A1-A5) of the building.

Life cycle stage	GWP ($kgCO_{2eq}$)	EP ($kgPO_4{}^{3}{}_{eq}$)	AP ($kgSO_{2eq}$)
Product (A1-A3)	2.2E+05	1.9E+02	1.1E+03
Transport & construction (A4-A5)	1.2E+05	5.0E+01	2.7E+01
Total	3.4E+05	2.4E+02	1.2E+03

Figure 4 shows the breakdown of the environmental impacts for the product stage. Steel is the most dominant material, followed by insulation and CLT, indicating their significant contribution to GWP. While this steel constitutes only 2% of the building mass (Figure 2), it represents about a quarter of the product stage GWP. For EP impact, CLT followed by insulation and doors are the biggest contributors, while for the AP impact, the biggest

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contributors are doors, CLT and insulation. Overall, CLT, steel and insulation are the materials with notable contributions across all three impact categories. CLT contributes 10% to GWP, 19% to EP, and 15% to AP. In comparison, steel accounts for 23% of GWP, 3% of EP, and 5% of AP, while insulation contributes 16% to GWP, 11% to EP, and 12% to AP.

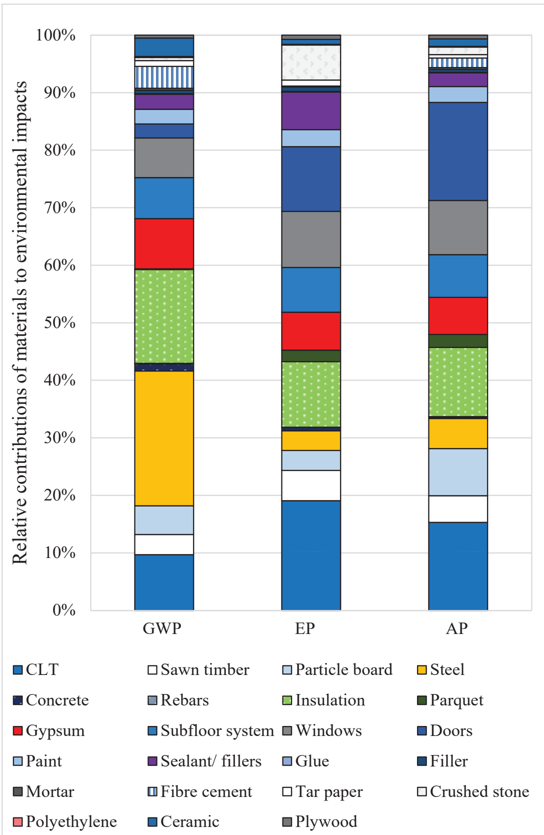

Figure 4. Relative shares of various materials and components to GWP, EP and AP impacts during the product stage (A1-A3).

Table 3 shows the building's environmental impacts at the end-of-life stage and also the post-use building material benefits. Processing of the post-use materials dominate the end-of-life GWP and EP impacts of the building while disposal dominates the AP impact. Table 4 presents the potential benefits from different post-use material management options for post-use CLT panels, and for recycling of other post-use wooden buildings materials, concrete and steel. Among the options for the CLT panels, cascading, entailing reuse of the panels, followed by recycling into chips for particleboard and lastly energy recovery of the end-of-life boards gives the biggest post-use benefits. Besides the options for the CLT panels, recycling of steel also provides notable potential post-use benefits. Overall, cascading of CLT combined with recycling of other materials (scenario 3) provides the most potential environmental benefits among post-use material options. This followed by the scenario involving reusing CLT combined with recycling of other materials (scenario 2). Cascading (scenario 3) give a GWP benefit of 70 $kgCO_{2eq}/m^2$. Comparatively, this benefit is 64% and 72% higher than that of the reuse (scenario 2) and recycling (scenario 1) options, respectively.

Table 3. Environmental impacts at end-of-life stage (C1-C4) and benefits of circular economy practices for post-use materials.

End-of-life activity	GWP ($kgCO_{2eq}$)	EP ($kgPO_4^{3}{}_{eq}$)	AP ($kgSO_{2eq}$)
Deconstruction (C1)	5.0E+03	8.6E-01	6.6E-01
Transport (C2)	1.0E+04	5.8E-01	3.2E+00
Processing (C3)	6.1E+04	2.2E+00	5.5E+00
Disposal (C4)	1.3E+03	1.2E+00	7.2E+00
Total impacts (C1-4)	**7.8E+04**	**4.9E+00**	**1.6E+01**

Table 4. Potential environmental benefits (negative numbers) of circular economy practices for post-use materials (D).

Post-use material options	GWP ($kgCO_{2eq}$)	EP ($kgPO_4^{3}{}_{eq}$)	AP ($kgSO_{2eq}$)
CLT panels:			
Recycling of CLT	***- 5 649.63***	***-1.26E+01***	***-6.82E+01***
Reusing of CLT	***-1.35E+04***	***-2.28E+01***	***-1.10E+02***
Cascading of CLT	***- 77 249.47***	***-6.32E+01***	***-3.98E+02***
Other materials:			
Recycling of wood [a]	-2.62E+03	-4.40E+00	-2.62E+01
Recycling of concrete	-1.81E+02	-5.88E-01	-5.38E-01
Recycling of steel	-1.98E+04	-2.55E+01	-8.17E+01
Sub-total for other materials recycling:	***-2.26E+04***	***-3.05E+01***	***-1.09E+02***
Scenario 1: Recycling of CLT + Sub-total for other materials recycling:	**-2.83E+04**	**-4.31E+01**	**-1.77E+02**
Scenario 2: Reusing of CLT + Sub-total for other materials recycling:	**-3.61E+04**	**-5.33E+01**	**-2.19E+02**
Scenario 3: Cascading of CLT + Sub-total for other materials recycling:	**-9.99E+04**	**-9.37E+01**	**-5.06E+02**

[a] This encompasses other wooden materials of the building other than CLT. This includes lath, plywood, and paraquet (see Figure 2).

Figure 5 compares the end-of-life stage impacts to those of the product and construction stages, while Figure 6 compares these stages to the post-use stage when combining cascading of CLT and recycling of other material (scenario 3). The end-of-life stage represents about 20% of the total material-related GWP impact. However, this stage constitutes a minor part of the total environmental impacts for acidification potential and eutrophication potential. The benefits from implementing the circular economy strategies (scenario 3) for post-use building materials more than offset the impacts from end-of-life activities across all impact categories. The benefits of efficiently managing post-use materials are just as significant as the impacts of transport and construction.

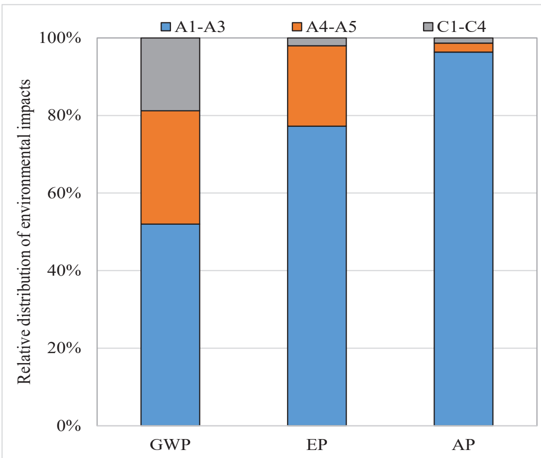

Figure 5. Relative distribution of environmental impacts across life cycle stages, including product, construction and end-of-life stages.

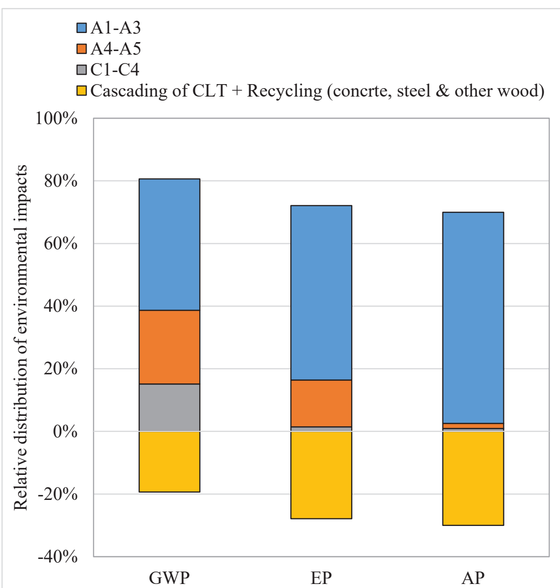

Figure 6. Contributions of life cycle stages to environmental impacts, and the benefits of circular economy practices for post-use building materials, encompassing Cascading of CLT and recycling of concrete, steel and other wood-based building materials.

4 – DISCUSSION AND CONCLUSIONS

In this study, the GWP, EP, and AP impacts of a CLT building are analysed from a life cycle perspective, focusing on the implications of circular economy practices for post-use materials at the end-of-life stage. These practices include reuse, recycling, and cascading. The analysis follows the life cycle of the building from the acquisition of natural resources through to the end-of-life of the materials.

Steel, insulation, and CLT made significant contributions to all three environmental impact categories. Despite constituting only 2% of the building mass, steel represents about a quarter of the product stage GWP. This highlights the need for strategies to minimise the impacts of these materials, including prioritising circularity strategies for CLT buildings after their service life ends. Concrete accounts for a notable part of the building's mass, but its estimated environmental impacts are particularly low. This is because high performance concrete with very low climate impact is assumed in this study. Thus, the GWP impact of concrete would have increased, e.g. by about factor 6 if conventional concrete based on normal Portland cement had been used instead, according to data from the Swedish climate declaration database [38].

The GWP impact of building's material production (A1–A3) is 2.2E+05 $kgCO_{2eq}/m^2$, which translates to about 150 $kgCO_{2eq}/m^2$. With the recycling options (scenario 1) involving concrete, steel, CLT, and other wooden materials, a GWP benefit of 20 $kgCO_{2eq}/m^2$ is realised. The corresponding GWP benefits for reuse and cascading are 25 and 70 $kgCO_{2eq}/m^2$, respectively. These represent 13% to 47% of the material production GWP impacts. The potential GWP benefit of cascading is therefore 3.5 and 2.8 times greater than that of recycling and reuse, respectively. In contrast to reuse and recycling, in the cascading scenario (scenario 3), CLT panels are used sequentially in different applications following the initial service life (see Table 1). The circular economy scenarios options also provide significant benefits for the AP and EP impact categories. For example, the benefits from the options (scenarios 1 to 3) represent 16% to 46% of the AP impacts, and 23% to 49% of EP impacts, both for material production stage.

While the product stage represents the dominant share of the life cycle impacts, the end-of-life stage makes a notable contribution to the building's overall environmental effects, representing about 20% of the total material-related GWP impact. This analysis shows that the benefits of circular economy strategies more than offset the impacts from end-of-life activities across all impact categories. This underscores the importance of a life cycle perspective in reducing a building's environmental impact, particularly its GWP impact.

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Despite the advantages of effective end-of-life management, several challenges hinder the reuse, recycling, and downcycling of materials after their initial use. A major barrier is that buildings are typically not designed and constructed to facilitate efficient material recovery at the end of their service life [39]. Moreover, building materials themselves are often not manufactured or installed in a manner that allows for easy reuse, energy recovery, downcycling, or recycling [40]. To facilitate efficient material recovery and support a circular economy, buildings need to be designed, constructed, and managed using strategies that minimise waste, and encourage material reuse and recycling [41]. Circularity approaches such as design for disassembly and design for adaptability enhances the integration of effective post-use materials and end-of-life solutions for materials in buildings by considering their recovery and reuse from the design phase [42, 43]. For example, designing for disassembly and adaptability has been reported to offer an 85% reuse potential for building materials compared to conventional design and construction solutions [44].

Overall, this study shows that implementation of circular economy strategies, including reuse, recycling, and cascading strategies, offers opportunities to reduce the life cycle environmental impacts of the studied CLT building, offsetting its end-of-life impacts.

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