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LIFE CYCLE CARBON FOOTPRINT ANALYSIS OF CROSS-LAMINATED TIMBER MULTI-STOREY BUILDING: IMPACT OF MATERIAL OPTIMISATION AND SUBSTITUTION STRATEGIES

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ABSTRACT: Cross-laminated timber (CLT) is increasingly proposed as a low-carbon alternative to steel or concrete in mid-rise multi-storey structures. In this study, the embodied carbon footprint of a CLT multi-storey building is analysed in a life cycle perspective, and strategies to optimise the carbon footprint are explored, based on CLT panel thickness optimisation and insulation material substitution. The analysis shows that the product and construction stage account for 72% of the life cycle embodied carbon footprint, and the effective post-use management of the materials arising from the end-of-life stage can give a significant climate benefit. A reduction of up to 5% of the life cycle carbon footprint can be achieved when employing the material optimisation and substitution strategies. This, together with effective post-use management of the building materials, results in a reduction of up to 20% of the life cycle carbon footprint of the studied CLT building. The study also emphasises the significance of service life in achieving a low carbon footprint for CLT buildings. Overall, this study shows that the life cycle embodied carbon footprint of a CLT building can be further reduced through material-related strategies.

KEYWORDS: Cross-laminated timber buildings, service life, life cycle analysis, carbon footprint, material optimisation, material substitution.

1 – INTRODUCTION

The 2030 Agenda for Sustainable Development emphasised the need to strengthen effort to mitigate climate change [1]. Moreover, the Paris Climate Agreement requires keeping global warming well below 2°C and pursuing efforts to limit the global average temperature rise to1.5°C, above pre-industrial levels [2]. To meet these targets, global carbon dioxide (CO_2) emissions should be halved by mid-century compared to 1990 levels [3]. Fossil fuels account for about 80% of the global energy mix, with coal, oil, and fossil gas contributing 41%, 32%, and 21% of global fossil CO_2 emissions, respectively [4, 5].

The European Union (EU) has set targets to reduce greenhouse gas (GHG) emission by at least 50% below 1990 levels by the 2030, towards achieving climate neutrality by 2050 [6]. This demands substantial improvement in all sectors, including in energy and material productions systems. The building sector accounts for 36% of GHG emissions and 40% of energy consumption in the EU [7]. Thus, the building sector is crucial for climate change mitigation [8]. The sector offers significant potential to reduce energy use and GHG emissions through measures such as reduced heating demands, increased efficiency in energy supply chains, greater use of renewable resources for materials, and increased use of less energy- and carbon-intensive resources for fuels and materials.

1.1 ROLE OF WOOD-BASED MATERIALS IN CLIMATE CHANGE MITIGATION

Greater use of wood-based materials from sustainably managed forests is increasingly identified as an effective means to reduce fossil energy use and GHG emissions [9]. This is highlighted by the European Commission [10], which reported increased use of wood products as part of its portfolio of measures to tackle climate change. The climate benefits of wood-based buildings, in contrast to non-wood alternatives, are highlighted in the literature, e.g., [11, 12]. Comparatively less fossil energy is used for the manufacture and processing of wood-based materials

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compared to non-wood alternatives such as concrete and steel, resulting in lower fossil GHG emissions [11]. Peñaloza et al. [13] investigated long-term strategies for climate change mitigation through new construction and concluded that increased use of wood-based construction systems is an effective approach to reduce CO_2 emissions of the Swedish building stock.

1.2 CROSS-LAMINATED TIMBER (CLT) AS A LOW-CARBON BUILDING PRODUCT

Cross-laminated timber (CLT), as a structural composite panel product, is attracting increasing interest in mid-rise multi-storey building construction [9]. It is increasingly highlighted as a low-carbon wood-based alternative to conventional non-renewable structural frame materials for multi-storey construction, including reinforced concrete and steel [14, 15]. Life cycle assessment (LCA) considering the entire energy and GHG flows can play an important role in identifying options to optimise the environmental performance of buildings. Literature on the LCA, including carbon footprint, of CLT-based building systems has been growing recently. Carbon footprint studies suggest that CLT building systems result in considerably lower climate impact than steel and concrete building system alternatives [16]. However, there are limited full LCAs of CLT buildings in the literature that address the service life and explore efficient end-of-life management [15]. For example, in a review of LCAs of CLT for building construction, Younis and Dodoo [15] observed that several studies overlooked the use stage impacts. Similarly, in evaluation of the life cycle impacts of buildings with CLT structural systems, Liang et al. [17] excluded the end-of-life management of CLT elements, whereas Durlinger et al. [18] assumed these elements would be landfilled. Assumptions regarding use and end-of-life scenarios can significantly influence the LCA outcomes for buildings and construction products, especially for wood-based products and systems [19].

1.3 AIM OF STUDY

This explores the life cycle carbon footprint of a mid-rise building with CLT structure and identifies strategies for reducing the carbon footprint of the building.

2 – METHODOLOGY

In this study, a process-based approach is used for the LCA, focusing on the Global Warming Potential (GWP) impact category for the carbon footprint analysis. GWP characterisation factors for a 100-year time horizon, from the IPCC [20], are used. The factors are 1 for carbon dioxide, 28 for methane, and 265 for nitrous oxide.

2.1 CASE STUDY BUILDING

This study is based on a CLT multi-storey building with 39 apartments and a total heated floor area of 2780 m², built in 2015 in Växjö (latitude 56° 52' N, longitude 14° 48' E), Sweden. A photograph of the building is shown in Figure 1. The building is part of the Vallen residential complex, comprising 26 terraced houses and 172 apartments spread across four- to eight-storey apartment buildings.

Figure 1. Photograph of the case-study CLT building, within the Vallen residential complex, in Växjö, southern, Sweden.

The mass of key materials comprising the building is presented in Table 1. Aggregate dominates the mass of materials and is used in the foundation and intermediate CLT floor slabs for stability. This is followed by concrete used in the foundation and CLT used for the exterior and interior walls, as well as for the intermediate floors. CLT, together with other wooden materials in the building, represents about one-fifth of the building material mass. The other wooden materials comprise plywood, glued laminated timber, chipboard, laminated wood flooring, wood decking, and wood used as lath and for doors. The non-wood materials listed in Table 1 include asphalt (6.0 tonnes), cellular plastic (4.5 tonnes), cement (4.0 tonnes), aluminium (0.9 tonnes), polyethylene (0.3 tonnes), and polypropylene (0.1 tonnes).

Table 1. Material mass balance of the building.

Material	Mass (tonne)	Share (%)
Aggregates	1091.8	33.9
Concrete	929.7	28.9
CLT	443.2	13.8
Gypsum board	225	7.0
Others wooden materials	175.8	5.5
Steel (connections)	84.4	2.6
Plaster putty	79.6	2.5
Insulation (mineral wool)	53.7	1.7
Coarse concrete	36.5	1.1
Rebars (recycled steel)	24.8	0.8
Window	20.4	0.6
Facade stones	19.6	0.6
Glass	19.6	0.6
Others non-wood materials	15.8	0.5

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2.2 CARBON FOOTPRINT ASSESSMENT

The carbon footprint of the building is assessed following the normative standards EN 15804 [21] and EN 15978 [22], which prescribe guidelines for LCA of construction products and buildings, respectively.

System boundary and sensitivity analyses

The system boundary for the analysis is shown in Figure 2 and encompasses the product, construction, use, and end-of-life stages, as well as the potential benefits and loads of the post-use materials. The life cycle modules considered in the use stage are (B1), maintenance (B2), and replacement (B4).

Product Stage	Raw material supply	[A1]
	Transport	[A2]
	Manufacturing	[A3]
Construction Stage	Transport	[A4]
	Construction installation	[A5]
Use Stage	Use	[B1]
	Maintenance	[B2]
	Repair	[B3]
	Replacement	[B4]
	Refurbishment	[B5]
	Operational energy use	[B6]
	Operational water use	[B7]
End-of-life Stage	Deconstruction/ Demolition	[C1]
	Transport	[C2]
	Waste processing for reuse, recovery or	[C3]
	Disposal	[C4]
Potential Benefits and Loads	Reuse, recovery, recycling potential benefits beyond system	[D]

Figure 2. System boundary of activities in the analysis. The life cycle modules included are shown in deep blue.

Product and construction stages

Data for the calculations of the emissions from the product stage, including raw material extraction, transport, and manufacturing (A1-3), is from the Ecoinvent database [23]. The product stage carbon footprint is calculated using Ecoinvent energy values, with adjustments to reflect the Swedish electricity mix. The biogenic carbon of the wood-based material is accounted for using the -1/+1 method. Emissions from material transport are determined using Ecoinvent emission factors, accounting for distances between plausible material suppliers and sources and the building's construction site. The emissions for material transport (A4) are calculated based on truck capacities and associated fuel consumption, assuming a 30% empty return rate for the trucks when delivering the materials to the construction site [24]. In module A5, impacts of energy consumption for materials assembly and material waste during installation and assembly are assessed using material wastage factors from the Swedish National Board of Housing, Building and Planning climate declaration database [25], and construction site emissions data from Malmqvist et al. [26].

Service life stage

A 100-year building service life is analysed considering the use (B1), maintenance (B2), and replacement (B4) modules. In module B1, the carbon uptake from carbonation is accounted for, following Dodoo et al. [27]. The carbon uptake calculation considers the concrete to have limited exposure conditions, as the concrete is in the foundation. To help understand and determine the number of maintenance and replacement activities required during the building's service life, a web-based survey was conducted for modules B1 and B2. Details of the survey are in ref. [28]. Based on this and literature, in B2, walls and windows are assumed to be painted every 10 years within the 100-year service life. In B4, the mineral wool insulation, windows, and doors are assumed to be replaced after 50 years. Small parts of the gypsum plaster boards are assumed to be maintained or replaced. Parts of the exposed wood are also assumed to be replaced. The emissions from B2 and B4 were analysed based on the number of maintenance and replacement activities and using material emission data from the Ecoinvent database [23].

End-of-life stage

The building is assumed to be deconstructed after the service life of 100 years, with key materials recovered for reprocessing. The carbon footprint for the EOL stage (C1-4) and post-use benefits and burdens (D) is calculated using generic data from relevant Environmental Product Declarations (EPDs), detailed in ref. [28]. The transportation distance for the EOL material (C2) is assumed to match the material transport distance to the construction site (A4). Based on the EPDs, 100% energy recovery is analysed for the post-use CLT and wood products, while steel is assumed to be 95% recycled and 5% landfilled. Also, concrete is assumed to be 90% recycled and the remaining 10% landfilled.

Sensitivity analyses

Two sensitivity analyses are conducted in this study to explore strategies for reducing the climate impact of the building. The strategies are: i) substituting mineral wool insulation with cellulose fibre insulation; ii) optimising the thickness of the CLT panels for the walls, intermediate floors, and balconies. The details of the optimisation are described by Ali and Bozorgirad [28].

3 – RESULTS

Figure 3 compares the relative mass of the building materials to the corresponding carbon footprint during the product stage (A1-A3), which includes raw material extraction, transport, and manufacturing. This shows that the dominant materials by mass are significantly different from those contributing most to the carbon footprint. While steel accounts for a small share (3%) of the total mass, it represents the largest share (26%) of the total carbon footprint at the product stage. Insulation (mineral wool) accounts for 2% of the total mass and 9% of the total carbon footprint. On the other hand, aggregate constitutes the largest share of the mass (34%) but represents a minor share of the carbon footprint (1%). Concrete constitutes 30% of the total mass and 18% of the total carbon footprint.

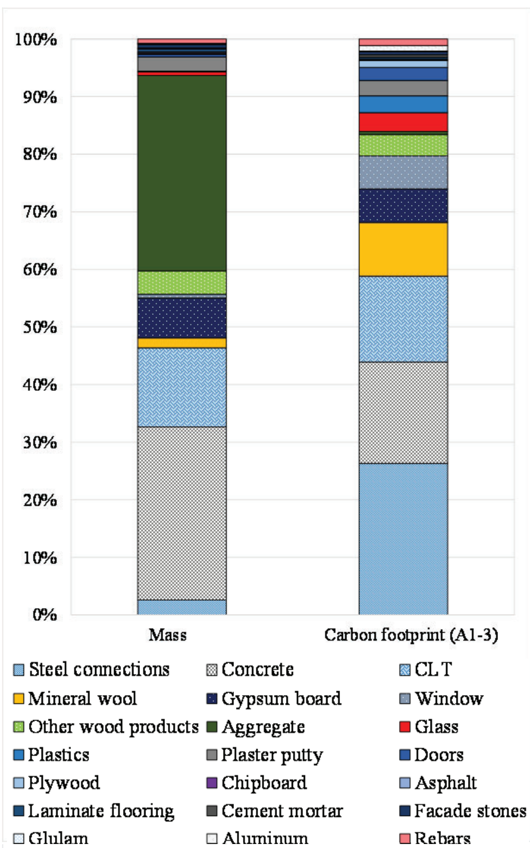

Figure 3. Relative distribution of building materials by mass and their corresponding product stage carbon footprint (A1-A3).

Figure 4 shows the product and construction (A1-A5) stages carbon footprint and indicates that steel, followed by concrete, CLT, and mineral wool insulation, dominate the impacts. The impact of material installation (A5) is noticeable, especially for steel connections, concrete, and CLT. The impact of material transport to the site (A4) is comparatively small for the materials and depends on the mass of the materials and the transport distance. Hence, materials with greater mass, e.g., aggregate and concrete, have noticeable transport emissions.

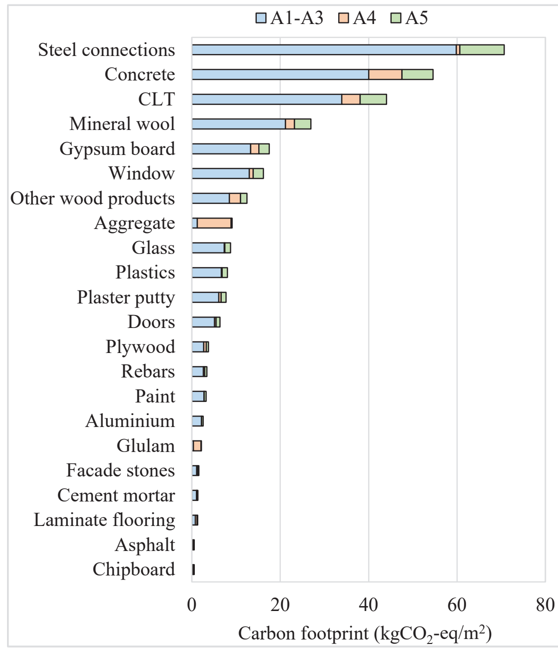

Figure 4. Carbon footprint of product and construction (A1-A5) stages.

Table 2 presents the carbon footprint of the service life activities over a 100-year period. The carbon footprint for module B1 is negative and is the carbon uptake for carbonation of concrete. The impact of maintenance (B2) is mainly from painting of the windows and walls, every 10th year within the 100-year service life. In module B4, replacement of insulation, windows, and doors, all after 50 years, contributes the most emissions.

Table 2. Carbon footprint ($kgCO_2eq/m^2$) for the service life activities during a 100-year building service life.

Building material / element	**Use (B1)**	**Maintenance (B2)**	**Replacement (B4)**
Concrete	-1.9	–	–
Mineral wool	–	–	26.9
Window	–	0.2	16.2
Door	–	–	6.4
Painting of walls	–	25.4	–
Gypsum board	–	0.2	0.2
Exposed wood	–	–	0.9
Total	**-1.9**	**25.8**	**50.6**

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Figure 5 shows the embodied carbon footprint of the life cycle stages and modules of the building as built. The carbon emissions are given in terms of fossil and biogenic sources. The product stage dominates the fossil carbon emissions while also providing significant climate benefits (negative number) due to the carbon storage in the wood materials. However, in the end-of-life stage, the biogenic carbon is released (in C1-C4), resulting in a net zero impact of the biogenic carbon. The post-use stage present carbon benefits, depicted by a negative carbon footprint, mainly from energy recovery of the wooden materials. Overall, the total life cycle carbon footprint is 465 and 392 $kgCO_2eq/m^2$ when the post-use benefit is not considered and considered, respectively. Thus, the life cycle carbon footprint is reduced by 16% when the post-use benefits are considered.

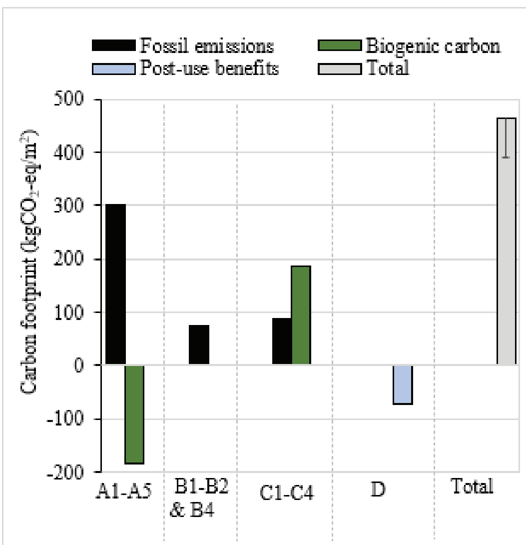

Figure 5. Fossil and biogenic carbon emissions over the life cycle of the as-built building. For the total emissions, the main bar represents values without considering post-use benefits, while the error bar indicates values when these benefits are included.

Figure 6 compares the building's total life cycle carbon footprint as built and when improved with material substitution and optimisation strategies, encompassing substituting the original mineral wool insulation with cellulose fibre insulation and optimising the thickness of the CLT panels (for the floor, interior and exterior walls, and roof structures). The substitution of the insulation resulted in a reduced carbon footprint of the product and service life stages, as the insulation has a 50-year reference service life and is thus also replaced once during the 100-year analysis period. Still, the product and construction stages dominate the life cycle impacts, even for the improved building, underscoring the importance of measures to reduce the impacts in these stages. Substituting the building's insulation reduced the building's product stage carbon footprint by 4%, while optimising the CLT panel thicknesses reduced the carbon footprint of the building by 1%. Together, these two material-related strategies reduced the product stage and the life cycle (A1-D) carbon footprint of the building by 5%. When excluding module D, the life cycle impact reduction is 3% for the material substitution and CLT optimisation strategies.

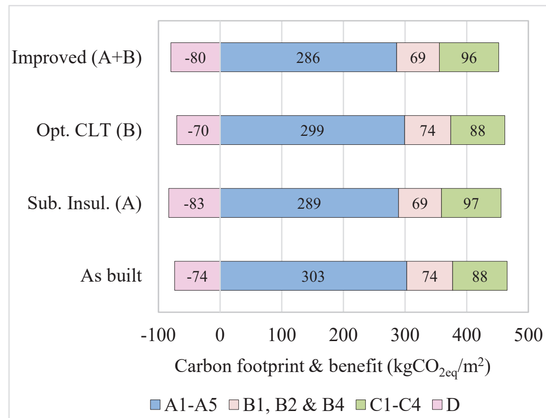

Figure 6. Carbon footprint and benefit of the building's life cycle with and without material substitution and optimisations. ''Opt. CLT'' denotes optimised CLT panel thicknesses, while ''Sub. Insul.'' denotes the substitution of cellulose insulation for the reference mineral wool insulation in the as-built building.

4– DISCUSSION

This study investigated the embodied carbon footprint of a CLT building from a life cycle perspective. The findings reinforce previous studies, e.g. [14-16, 29], highlighting CLT's potential as a low-carbon alternative to conventional construction materials. The study also explored strategies for reducing the building's carbon footprint, focusing on optimised wood utilisation for CLT panels and material substitution by using cellulose fibre insulation instead of mineral wool insulation in the as-built building.

The results indicate that the product and construction stages (A1-A5) dominate the carbon footprint over the building's life cycle, accounting for about 72% of total life cycle GWP impact. The total carbon footprint of the product and construction stages (A1–A5) is 303 $kgCO_2eq/m^2$ (heated floor area). This is about 20% below the proposed limit value of 375 $kgCO_2eq/m^2$ for the carbon footprint of residential buildings under Sweden's climate declaration regulation, which comes into force in 2027 [30]. In a review of LCA studies comparing CLT buildings with alternative construction types, Dodoo and Younis [15, 29] found that, on average, CLT buildings have around 40% lower life cycle GWP impact. These findings highlight the potential of CLT as a low-carbon construction material.

The carbon footprint of the product stage (A1-A3) is 230 $kgCO_2eq/m^2$, representing 76% of the total impact of the product and construction stages (A1-A5). Among the materials used, steel, despite comprising only about 3% of the total mass, contributes significantly to the carbon footprint, representing 26% of the product stage (A1-A3) GWP impact. In contrast, aggregates, which constitute the largest proportion of the building's mass, contribute minimally to overall emissions. The other dominant materials in terms of the building's carbon footprint are concrete for the foundation, CLT for the building superstructure and mineral wool insulation. These three materials represent 42% of the total carbon footprint (18% for concrete, 15% for CLT and 9% mineral wool insulation). These results corroborate the findings of Dodoo et al. [31] and Al-Najjar and Dodoo [32] who also analysed CLT buildings of different design and building systems and stories. Strategies to reduce the carbon footprint of these key materials, particularly steel connections, can therefore contribute notably to reducing the overall embodied carbon footprint of CLT buildings.

The analysis showed that a combination of insulation material substitution and optimisation of CLT panel thickness can give meaningful climate impact reductions. The substitution of mineral wool insulation with cellulose fibre insulation resulted in a 6% decrease in the product stage (A1-A3) carbon footprint. This agrees with the findings of Tettey et al. [33], who showed that replacing mineral wool insulation with cellulose fibre insulation gives a carbon footprint reduction of 6 to 8% for a Swedish building. The CLT panel thickness can be optimised and reduced by an average of 7% while maintaining the structural integrity of the building [28]. In this study, a carbon footprint reduction of 1% is achieved with the optimised CLT panel thickness. These results are consistent with previous studies, which suggest that minimising material use while maintaining functional requirements gives environmental benefits [31, 32]. When both carbon reduction strategies were combined, the product stage carbon footprint was reduced by 7%, while the total life cycle carbon footprint saw a decrease of between 3% and 5%. Although these reductions are modest, they serve to demonstrate that careful design and material selection can contribute to making CLT buildings an even more low-carbon building system.

When considering the building's insulation material alone, the carbon footprint is about halved when replacing mineral wool with cellulose fibre. Hence, the selection of insulation presents an opportunity to improve the climate impact and resource efficiency of CLT buildings. Notwithstanding, the choice of insulation for a building may be governed by several factors besides the need to fulfil thermal performance requirements. Different insulations may vary in acoustical, fire protection, mechanical, and moisture performance, and changing a particular insulation material might impact other functions. This study illustrates the impact of insulation substitution from a climate impact perspective, and a more holistic evaluation might be needed before implementing such substitution, considering economic and other building physical and construction factors. In Sweden, mineral wool insulation is commonly used in CLT buildings, as in the studied building. However, experiences from a completed CLT building [34] show the suitability of using cellulose fibre insulation in highly insulated CLT buildings. For instance, in Estonia, a CLT building with cellulose fibre insulation has been built [35]. Also, studies [35, 36] indicate that using hygroscopic cellulose insulation offers benefits over mineral wool by stabilising indoor humidity levels and reducing the risk of mould growth. Hence, a plausible way forward for the CLT building industry would be to explore replacing the commonly used mineral wool insulation with cellulose fibre insulation, to further reduce the climate impact of CLT buildings.

In this study, the thicknesses of the CLT panel elements were optimised based on structural considerations. However, the dimensioning of a structural element is influenced not only by structural safety but also by other factors, e.g. fire performance and acoustics. Fire safety is increasingly addressed with gypsum plasterboard and sprinklers in CLT buildings. Still, it is important to consider that installation and piping systems can be part of the wall and floor construction. Therefore, the dimensions of these systems also need to be considered when optimising panel thickness. Based on the scope of this study, the analysis of CLT panel optimisation did not account for how fire performance of exposed CLT elements, and also installation and piping systems might be affected when panel thicknesses are optimised. This aspect should be considered in future studies.

There is limited analysis of the impact of the service life in the LCA of CLT buildings. In this study, the impact of the service life is analysed partly based on surveys, material service life data, and assumptions in the literature. The analysis shows that the service life can represent a significant share of the life cycle carbon footprint of a CLT building for 100 years. In this analysis, the impact of the service life is estimated to be about a quarter of the impact of the product and construction stages, and about 16 to 19% of the total life cycle

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embodied carbon impact. However, this analysis is based on simplified descriptions of the building's service life, as service life data for CLT buildings are currently lacking. Future studies could focus on detailed modelling of the impact of service life, drawing insights from more stakeholders, and also using empirical data, if available.

The end-of-life stage showed a significant impact based on the EPD data used and may warrant further studies. The calculations showed that the end-of-life stage represents 19% of the building's life cycle embodied carbon footprint, including modules A1-A5, B1, B2, B4, and C1-C4. Other studies have shown similar trends. For instance, in an analysis of 10 buildings in Denmark, Balouktsi and Birgisdottir [37] found the end-of-life stage to represent an average of 23% of the life cycle carbon footprint, including modules A1-A5, B1, B2, B4, B6, and C1-C4. When comparing the impact of the end-of-life stage (C1-C4) to the production stage (A1-A5), this analysis showed that the end-of-life stage represents about 29% of the production stage impact, while Balouktsi and Birgisdottir [37] showed that the end-of-life stage represents about 42% of the production stage impacts (A1-A5). It is important to note that the estimated impact of a building's end-of-life can be quite variable, as this depends on assumed demolition practices, transportation distance to waste management facilities, waste processing methods and disposal practices, among other factors. Further studies on end-of-life practices and associated impacts are particularly vital for CLT buildings, which have largely yet to reach the end of their service life given that CLT technology is relatively young.

This study highlights the potential benefits of post-use materials management. In this analysis, the post-use benefits of recycling and energy recovery correspond to about a quarter of the impacts of the building's product and construction stages. In other words, about 25% of the climate impact of the product and construction stages can be offset by the GHG savings from efficient end-of-life management of the building materials. From a life cycle perspective, recycling of concrete and steel, as well as energy recovery from CLT components at the end-of-life stage, can contribute to a 16% reduction in the building's total carbon footprint. Efficient end-of-life material management is thus crucial to reduce climate impact.

5 – CONCLUSION

The findings of this study highlight the dominance of the product stage in the studied CLT building's carbon footprint, with steel fasteners and connections playing a disproportionate role despite their small mass. The study also emphasises the significance of service life and post-use management, showing that efficient end-of-life management can lead to significant climate benefits. Overall, the results support the potential of CLT as a low-carbon construction material, with opportunities for further improvements in engineering design, material selection, and post-use material management.

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