



Article Environmental Impact of a Mass Timber Building—A Case Study

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Abstract: The study focuses on a life cycle assessment of a wood-based residential building and evaluates the magnitude of individual construction components—foundations, flooring, peripheral wall, inner walls, ceiling, roof, windows, and doors—in terms of climate change; acidification; eutrophication; photochemical oxidation; depletion of abiotic elements and fossil fuels; and water scarcity categories within the system boundaries of the Product stage of the life cycle. The assessment was done using the SimaPro software and the ecoinvent database. The results pointed at the advantages of mass timber as a construction material and highlighted the significance in the type of insulation used. Foundations were found to bear the highest share of impact on photochemical oxidation (more than 25% of both), depletion of elements (responsible for 50% of that impact), and had about 60% impact on water scarcity. After adding up carbon emissions and removals, the embodied impact of the whole construction on climate change was detected to be 8185.19 kg CO₂ eq emissions which corresponded with 57.08 kg CO₂ eq/m² of gross internal area. A negative carbon composition of the construction was also set.

Keywords: mass timber; construction materials; life cycle assessment; environmental impact; sustainability; embodied impact

1. Introduction

The building sector accounts for relevant participation in general greenhouse gas emissions. Several climate declarations have been approved in a bid to reduce the climate impact from the building sector in everything that is built [1–3]. These focused climate declarations are a part of the shift towards a reduced climate impact from buildings from a life-cycle perspective, and they aim to drive developments towards more sustainable construction.

Cross-laminated timber (CLT) is a widely used engineered timber product in constructions, applicable as a full-size wall and floor element as well as a linear timber member, through the orthogonal laminar structure [4]. CLT is "a prefabricated engineered wood product consisting of at least three layers of solid-sawn timber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element" [5] (Figure 1). According to Karacabeyli and Brad [6], it is suitable as a structural or non-structural material for constructing walls, floors, ceilings, roofs, etc. Due to the cross-orientation of layers, CLT has a structural capability of a two-way span, desirable for floor applications.



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Figure 1. Cross-laminated timber panel.

CLT is a construction material in the building which represents a sustainable way of construction with minimal environmental impact [7,8]. CLT is a relatively new progressive but proven technology that can replace environmentally more encumbering building materials in many building applications.

International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) both have sets of standard documents defining the environmental assessment process for construction materials and buildings. Life Cycle Assessment (LCA) is an analytical method evaluating the impact of products, services, and organizations on the environment under the conditions set by ISO 14040 and 14044 [9,10] through several categories, of which global warming or climate change are the most common. Specific standards for LCA in the construction sector include CEN's EN 15978 [11] as a part of standards for assessing the environmental performance of a building and ISO 21931-1 [12] dealing with buildings sustainability.

By Robertson et al. [13], increased availability of readily accessible potential energy stored within the building materials of the timber alternative is indicated in a comparative cradle-to-gate life cycle assessment of building construction alternatives (Laminated Timber or Reinforced Concrete). Regarding a cradle-to-grave assessment by Liu et al. [14] replacement of masonry structure with CLT panel led to a reduction of energy consumption by more than 30% and decrease of CO_2 emission by more than 40%. As reported in an environmental product declaration (certificate needed for a building materials market) [15], a CLT frame manufactured by Södra can reduce carbon emissions by up to 80 percent compared with a similar concrete frame.

The study by Pierobon et al. [8] focused on the environmental benefits of using hybrid CLT structures in midrise non-residential constructions. The results showed that an average of 26.5% reduction in the global warming potential is achieved in the hybrid CLT building compared to the concrete building. Moreover, the non-renewable energy (fossil-based) used in the hybrid CLT building is 8% lower compared to that of the concrete structure. As global warming is the most frequently used impact category to determine building environmental performance, other categories are rarely stated. By the study of Chen et al. [16], the mass timber building had 18, 1, and 47% reduction in the impact categories of global warming, ozone depletion, and eutrophication, respectively, compared with a similar concrete building.

LCA environmental evaluation of CLT as a material itself is reported in several published studies [7,14,17,18], while logistics and wood species mix have an essential impact on the final assessment [19]. However, the generalizations in case studies on whole building life cycle assessment are limited by case-to-case type, exploitation, geometry (shape) of building [20], and the combination of materials in hybrid constructions.

Despite certain similarities, each wood-based construction composition might be different depending on the used materials, which consequently affect the embodied impact of the building. Moreover, Bahramian and Yetilmezsoy [21] compared LCA studies on buildings over two decades. They identified numerous parameters such as life span, functional unit, life cycle stages, and impact categories to vary from study to study, making it difficult to compare buildings with each other.

This paper identifies the environmental performance of a typical wood-based reference residential building based on massive CLT as the frame construction material in terms of embodied impact on the environment. The structure is divided into construction sections—foundations, flooring, peripheral wall, inner walls, ceiling, roof, windows, and doors—and evaluated through climate change; acidification; eutrophication; photochemical oxidation; depletion of abiotic elements and fossil fuels; and water scarcity. The structure is also compared to a similar construction system replacing CLT for MHM (Massive Holz Mauer) panels. The study's outcomes provide information on the possible environmental impact of a massive timber building and might help designers, developers, and resellers in the building industry to critically assess the sustainability of natural-based construction materials.

2. Materials and Methods

2.1. Reference Unit and System Boundaries Description

The unit of the study was represented by the whole single-story residential building with a compact shape designed for a family of four to six members (Figures 2-4). The floor plan solution was ready-made by Inardex, Co. (Trenchin, Slovakia) [22] and the construction composition was adjusted by the authors to meet the passive building target values of heat transfer coefficient given by the Slovak Technical Standard [23]. The load-bearing structure consisted of a solid wood panel system based on CLT. The foundations consisted of a reinforced concrete ground slab. The gable roof structure was supported with trusses. Dimensions of the CLT panel were 120-mm thick in the peripheral wall and 80-mm thick in partitions. The material composition was composed mainly of natural construction materials, such as CLT panel, glued solid timber and oriented strand board. The thermal insulation consisted of wood fiberboards placed in a supporting grid of I-profile beams. The external layers of the structure consisted of a wood fiber thermal insulation contact system and wood cladding. The heat transfer coefficient of peripheral wall was calculated according to the Slovak Technical Standard [23] and equaled to 0.141 W.m⁻²K⁻¹. Aluminum frame windows with triple glazing were used. The measures of the construction were defined by the gross external area of 174.2 m²; gross internal area of 148.5 m², and net internal area of 142.1 m².



Figure 2. Floor plan of the construction.



Figure 3. Cross-section of the construction.



Figure 4. Front views of the construction: (a) western view; (b) eastern view; (c) northern view; and (d) southern view.

The object was assessed according to ISO 14040 and 14044 [9,10]. System boundaries (Figure 5) were chosen from A1–A3 by EN 15804 [24]. The evaluation was done using SimaPro 9.2.0.2 Analyst [25], developed by PRé Consultants in The Netherlands. Ecoinvent 3.7.1 database [26] was chosen as a source of input data for life cycle inventory. Calculation methods were chosen as follows: for the climate change (CC) impact category, IPCC 2013 GWP 100a (including CO₂ uptake) v1.00 method [27] was used; for the rest impact categories, EPD (2018) v1.02 method was selected [28].

For the assessment purposes, the construction was divided into foundations, flooring, peripheral walls, inner walls, ceiling, roof, windows, and doors. Description of construction materials within each component and specification of the input database are given in Table 1.



Figure 5. System boundaries.

Table 1. Description of construction composition and databases selected for the assessment of the building within life cycle stages from A1–A3.

Component	Material	Specification of the Chosen Database		
Foundations	Concrete	Concrete block {RoW} market for concrete block APOS, S Concrete, 20 MPa {RoW} market for concrete, 20 MPa APOS, S Concrete, 25–30 MPa {RoW} market for concrete, 25–30 MPa APOS,		
	Steel	Reinforcing steel {GLO} market for APOS, S		
	Gravel	Gravel, crushed {KoW} market for gravel, crushed APOS, S		
Flooring	Waterproof layer	Bitumen seal, Alu80 {RER} production APOS, S		
	Insulation	Polystyrene foam slab {GLO} market for APOS, S		
	Mortar	Adhesive mortar {RoW} production APOS, S		
		Cement mortar {RoW} market for cement mortar APOS, S		
	Wood floor	Three and five-layered board {KEK} market for three and five-layered hoard APOS_S		
	Tiling	Ceramic tile {GLO} market for APOS, S		
Peripheral wall	Timber	Cross-laminated timber {RER} market for cross-laminated timber APOS, S		
	Insulation	Glued solid timber {RER} market for glued solid timber APOS, S Joist, engineered wood {GLO} market for APOS, S Fibreboard, soft {RoW} market for fibreboard, soft APOS, S Polystyrene foam slab for perimeter insulation {GLO} market for APOS, S		
	Inner sheating	Gypsum plasterboard {GLO} market for APOS, S		
	Mortar	Cement mortar {RoW} market for cement mortar APOS, S		
	Steel joints	Steel, chromium steel 18/8 {GLO} market for APOS, S		
	Inner tiling	Ceramic tile {GLO} market for APOS, S		
	Plinth tiling	Shale brick {GLO} market for APOS, S		
	Outer sheating	Wood cladding, softwood {GLO} market for APOS, S		

Component	Material	Specification of the Chosen Database		
Inner walls	Timber	Cross-laminated timber {RER} market for cross-laminated timber APOS, S		
		Glued solid timber {RER} market for glued solid timber APOS, S		
	Sheating	Gypsum plasterboard {GLO} market for APOS, S		
	Tiling	Ceramic tile {GLO} market for APOS, S		
	Steel joints	Steel, chromium steel 18/8 {GLO} market for APOS, S		
	Mortar	Cement mortar {RoW} market for cement mortar APOS, S		
Ceiling	Timber	Glued solid timber {RER} market for glued solid timber APOS, S		
_	Sheating	Gypsum plasterboard {GLO} market for APOS, S		
		Oriented strand board {RER} market for oriented strand board APOS, S		
	Insulation	glass wool mat, uncoated, Saint-Gobain ISOVER SA {CH} market for		
	insulation	glass wool mat, uncoated, Saint-Gobain ISOVER SA APOS, U		
		Cellulose fibre {RoW} market for cellulose fibre APOS, S		
	Steel joints	Steel, chromium steel 18/8 {GLO} market for APOS, S		
Roof	Timber	Glued solid timber {RER} market for glued solid timber APOS, S		
		Wood cladding, softwood {GLO} market for APOS, S		
	Insulation	Stone wool, packed {GLO} market for stone wool, packed APOS, S		
		glass wool mat, uncoated, Saint-Gobain ISOVER SA {CH} market for		
		glass wool mat, uncoated, Saint-Gobain ISOVER SA APOS, U		
	Steel joints	Steel, chromium steel 18/8 {GLO} market for APOS, S		
	Root tiles	Root tile (GLO) market for APOS, S		
	Water drainage system	Aluminum, primary, cast alloy slab from continuous casting {GLO} market for APOS, S		
	Chimney	Autoclaved aerated concrete block {RoW} market for autoclaved aerated		
	enancy	concrete block APOS, S		
		Refractory, fireclay, packed {GLO} market for APOS, U		
	Window frame	Window frame, aluminium, U = 1.6 W/m2K {GLO} market for APOS, S		
Windows and doors	Glazing	Glazing, triple, U < 0.5 W/m2K {GLO} market for APOS, S		
willdows and doors	Outer door	Door, outer, wood-aluminium {GLO} market for APOS, S		
	Inner door	Door, inner, wood {GLO} market for APOS, S		

Table 1. Cont.

Note: APOS—Allocation at the point of substitution; S—System processes; U—unit processes; GLO—global data; RER—data representative for Europe; RoW—data representative for rest of the world.

2.2. Data Quality Statements

The selected structure was designed by the authors. Data on input construction materials were calculated based on the actual dimensions of the compounds and represent Europe's geographical region. All relevant input flows were included meeting the 1% cut-off rule. The data are representative of the current year.

3. Results

3.1. Weight and Volume Distribution

First, the weight and volume of the construction components were assessed (Figure 6). Foundations occupied the majority (76.68%) of the overall weight distribution. Peripheral wall (7.30%) and roof (6.70%) were the second and third heaviest, respectively. The rest component distribution was below 5%. By volume, the most significant share was represented by the ceiling (28.89%), followed by the peripheral wall (23.23%), foundations (19.25%), and flooring (14.12%). The contribution of other components reached a maximum of 6.39% in the case of the roof.

CLT panels were only situated in the peripheral and inner walls. Total weight of the panels was 10,489.5 kg which corresponded to 4.62% of total construction weight whereas amount of the CLT panel in peripheral wall was only 1300.5 kg higher than that in inner walls.

3.2. Holistic Life Cycle Impact Assessment

Second, the impact assessment of the structure was performed. Table 2 summarizes the environmental impact of the whole structure. The climate change impact category was divided into fossil carbon emissions, biogenic carbon emissions, carbon uptake by vegeta-

tion, and carbon emissions resulting from land use and transformation. Biomass uptake of carbon was detected as the most represented part of the climate change category accounting for -87.96 t CO₂ eq. Carbon emissions from fossil sources, biogenic decomposition, and LUT activities reached 76.28 t, 19.86 t, and 291.41 kg of CO₂ eq, respectively.



Figure 6. Distribution of construction components within the whole construction: (**a**) weight distribution; (**b**) volume distribution.

Impact Category	Unit	Impact Per Whole Structure	Impact Per 1 m ² of GIA
CC—fossil	kg CO ₂ eq	76,279.05	513.66
CC—biogenic ¹	kg CO ₂ eq	19,861.54	133.75
CC—carbon uptake ²	kg CO ₂ eq	-87,955.40	-592.29
CC—LUT ³	kg CO ₂ eq	291.41	1.96
Acidification	kg SO ₂ eq	408.76	2.75
Eutrophication	kg PO $_4^-$ eq	130.84	0.88
Photochemical oxidation	kg NMVOC	346.11	2.33
AD—elements	kg Sb eq	3.31	0.02
AD—fossil fuels	MJ	837,548.89	5640.06
Water scarcity	m ³ eq	99,137.69	667.59

¹ involves biogenic emissions of carbon dioxide and methane with emission factors of 1 and 30.5 kg CO₂ eq, respectively. ² involves carbon dioxide captures with emission factors of $-1 \text{ kg CO}_2 \text{ eq}$. ³ involves emissions of carbon dioxide and methane connected with land transformation with emission factors of 1 and 30.5 kg CO₂ eq, respectively. Note: CC—Climate change; LUT—Land use and transformation; AD—Abiotic depletion; NMVOC—Non-methane volatile organic compounds.

To calculate the carbon balance (CC_{overall}), the following Equation was applied:

$$CC_{overall} = CC_{fossil} + CC_{biogenic} + CC_{uptake} + CC_{LUT}$$
(1)

According to Equation (1), by adding carbon emissions (fossil, biogenic, LUT) and removals (carbon uptake), carbon balance equaled 8185.19 kg CO_2 eq. The following subsections describe selected impact categories in more detail.

3.2.1. Impact on Climate Change

The subsection compares the impact of construction components within the CC impact categories (Figure 7). LUT category contributed the least to CC. Nonetheless, the greatest impacts were attributed to the peripheral wall (27.37%), roof (19.47%), windows and doors (17.04%), and ceiling (14.82%). Foundations, flooring, and inner walls contributed to the total LUT impact of approximately 7% each.



Figure 7. Impact distribution of construction components on climate change.

Nearly half of carbon emissions uptake is related to the peripheral wall (48.98%). Inner walls corresponded to 20.24%, and roof and ceiling reached 13.17 and 12.13% of the impact, respectively.

Peripheral wall also dominated in the biogenic carbon emissions (54.07%). Ceiling and inner walls were responsible for 20.02 and 10.48% of the impact, respectively.

Foundations reached 35.13% of the total embodied fossil carbon emissions, followed by the peripheral wall (18.01%); windows and doors (16.60%); roof (10.76%), and flooring (10.20%), respectively.

The impact of inner walls was the lowest in the LUT (7.05%) and fossil carbon emissions category (4.03%). Foundations were identified to have the lowest embodied impact in carbon uptake and biogenic carbon emissions equal to 0.42 and 2.39%, respectively.

3.2.2. Impact on Acidification and Eutrophication

The share of embodied impact on the above-mentioned categories was relatively balanced (Figure 8). The highest impact resulted from the peripheral wall (25.89; 27.02%), the second-worst component was detected to be foundations (22.73; 25.42%), followed by windows and doors (17.91; 14.62%), and roof (10.39; 9.95%) for both acidification and eutrophication impact categories, respectively. The share of inner walls on the overall impact was 4.53 and 5.24%, respectively.



Figure 8. Impact distribution of construction components on: (a) acidification; (b) eutrophication.

3.2.3. Impact on Photochemical Oxidation

The highest emissions contributing to photochemical oxidation (Figure 9) were identified for foundations (29.74%). The rest, precisely 23.26%, was bound to the peripheral wall; 12.86% resulted from windows and doors manufacture; 10.85% accounted for flooring, and 10.26% were connected to the roof. The share of inner walls was the least equaled to 5.75%.



Figure 9. Impact distribution of construction components on photochemical oxidation.

3.2.4. Impact on Water Scarcity

Most of the embodied water consumption was assigned to the peripheral wall (60.30%) (Figure 10). Ceiling accounted for 20.91%, and foundations were responsible for 9.12% of the impact, respectively. Other components reached less than 4% of the impact, each leaving the inner walls the least damaging part of the studied construction.



Figure 10. Impact distribution of construction components on water scarcity.

3.2.5. Impact on Abiotic Depletion

Abiotic raw material sources were divided into chemical elements and fossil fuels (Figure 11). The results showed 50.09% of elements depletion related to the peripheral wall. Ceiling and roof were responsible for 19.03 and 16.45% of the impact, respectively. Embodied impact of inner walls was the least, accounting for 2.57%.



Figure 11. Impact distribution of construction components on abiotic depletion: (**a**) depletion of elements; (**b**) depletion of fossil fuels.

The category of fossil fuels depletion was rather leveled in comparison with the previous one. A quarter of the impact was bound to foundations (25.26%), and a fifth related to the peripheral wall (20.03%). Flooring and windows and doors reached 18.00 and 15.90%, respectively, of the embodied impact. Similar to the previous categories, inner walls were found to be the best construction component reaching only 4.70% of the total impact on fossil fuels depletion.

3.2.6. Specification of the Most and the Least Contributing Construction Components

Up to this point, it was still not obvious which construction materials contributed the most to the specific environmental impact categories. Thus, an overview of components ranking within individual impact categories was performed (Table 3). Foundations and peripheral walls were the only components ranked in the first place represented with a ratio of 3:7, respectively. The last positions were occupied up to 80% by inner walls, and the rest was assigned to foundations. Other components were placed in between the stated ranks. Therefore, the above-mentioned components were selected for a closer impact assessment.

Table 3. Ranking of construction components according to their embodied impact within the impact categories.

Impact Category	Rank (No. 1 Refer to the Highest Contribution)						
I man and a second	1	2	3	4	5	6	7
CC—fossil	Found.	PW	W/D	Roof	Flooring	Ceiling	IW
CC—biogenic	PW	Ceiling	IW	Roof	Flooring	W/D	Found.
CC—carbon uptake	PW	IW	Roof	Ceiling	Flooring	W/D	Found.
CC—LUT	PW	Roof	W/D	Ceiling	Found.	Flooring	IW
Acidification	PW	Found.	W/D	Roof	Flooring	Ceiling	IW
Eutrophication	PW	Found.	W/D	Roof	Ceiling	Flooring	IW
Photochemical oxidation	Found.	PW	W/D	Flooring	Roof	Ceiling	IW
AD—elements	PW	Ceiling	Roof	Flooring	Found.	W/D	IW
AD—fossil fuels	Found.	PW	Flooring	W/D	Roof	Ceiling	IW
Water scarcity	PW	Ceiling	Found.	Flooring	W/D	Roof	IW

Note: Found—foundations; PW—peripheral wall; W/D—windows and doors; IW—inner walls.

First, an impact assessment of the peripheral wall was performed (Figure 12). In most of the impact categories, light density fibreboard (LDF; according to ecoinvent database it referred to Fiberboard, soft) was found to bear the highest embodied impact. The positive impact of CLT in carbon emissions removal was detected in the CC—carbon uptake category. Steel joints were the most emission contributing materials in fossil carbon emissions and the depletion of fossil fuels.



Figure 12. Impact assessment of peripheral wall construction materials.



If we assumed different concrete types in foundations as separate construction materials, reinforcing steel would be the significant impact contributor within each category (Figure 13). However, if the impact of concrete was added up, it would level or exceed the contribution of reinforcing steel.

Figure 13. Impact assessment of foundations construction materials.

Assessing the inner walls material contribution, CLT was found to bear most of the impact in all categories except depletion of elements led by glued solid timber (Figure 14). Ceramic tiles contribution in the stated category was the second highest.



Figure 14. Impact assessment of inner walls construction materials.

3.3. Sensitivity Analysis

As LDF and CLT were found to be the most impact contributing construction materials within peripheral and inner walls, a sensitivity analysis was conducted to completely substitute these materials. MHM panel was selected to replace the CLT panel within the whole construction. The new construction material differed from the original in manufacturing technology and dimensions. Instead of the CLT panels, which were glued, separate layers of MHM panels were nailed. The thickness of the peripheral and inner wall panels was adjusted to 170 and 120 mm, respectively. The design of the structure using MHM panels preserving the same gross external area reduced the gross and the net internal area of the construction, improving the thermal-technical properties of the peripheral walls, on the other hand. The heat transfer coefficient of the peripheral wall using MHM panel was $0.133 \text{ W.m}^{-2}\text{K}^{-1}$. Substitution of CLT by the MHM panel only changed the load-bearing structure. Structural layers remained the same. The change in the impact after substitution of CLT panel (Table 4) showed minimal differences in peripheral wall environmental performance. However, the impact of inner walls rose from 9.33–30.91% in fossil fuel depletion and biogenic carbon emissions, respectively. Water scarcity was the only category reporting a decrease of -12.17% of the impact. The most significant reduction of -16.16% in the impact of other components was noticed in the carbon uptake category.

Table 4. MHM panel instead of CLT panel-sensitivity analysis results.

Impact Category	Foundations	Flooring	Peripheral Wall	Inner Walls	Ceiling	Roof	Windows and Doors
CC—fossil	-1.05%	-1.05%	1.83%	12.08%	-1.05%	-1.05%	-1.05%
CC—biogenic	-8.67%	-8.67%	-0.31%	30.91%	-8.67%	-8.67%	-8.67%
CC—carbon uptake	-16.16%	-16.16%	1.05%	22.02%	-16.16%	-16.16%	-16.16%
CC—LUT	-5.23%	-5.23%	4.79%	30.03%	-5.23%	-5.23%	-5.23%
Acidification	-1.81%	-1.81%	1.77%	17.69%	-1.81%	-1.81%	-1.81%
Eutrophication	-2.42%	-2.42%	2.18%	19.99%	-2.42%	-2.42%	-2.42%
Photochemical oxidation	-3.07%	-3.07%	3.70%	22.94%	-3.07%	-3.07%	-3.07%
AD—elements	-1.19%	-1.19%	0.10%	19.97%	-1.19%	-1.19%	-1.19%
AD—fossil fuels	-0.91%	-0.91%	1.23%	9.33%	-0.91%	-0.91%	-0.91%
Water scarcity	0.32%	0.32%	0.00%	-12.17%	0.32%	0.32%	0.32%

According to the previous findings, insulation played a substantial role in the impact of peripheral wall concurrently affecting the whole construction. Therefore, for sensitivity analysis purposes, stone wool was chosen as a replacement for LDF—the most contributing construction material by embodied impact of the peripheral wall. The adjusted peripheral wall impact (Table 5) showed a reduction in all impact categories with the lowest change of -11.89% in carbon uptake up to -85.76% in water scarcity. The last-mentioned category also reported a remarkable increase in the impact of other components of 130.26%.

Table 5. Stone wool insulation instead of LDF—sensitivity analysis results.

Impact Category	Foundations	Flooring	Peripheral Wall	Inner Walls	Ceiling	Roof	Windows and Doors
CC—fossil	4.21%	4.21%	-19.16%	4.21%	4.21%	4.21%	4.21%
CC—biogenic	44.87%	44.87%	-38.12%	44.87%	44.87%	44.87%	44.87%
CC—carbon uptake	11.42%	11.42%	-11.89%	11.42%	11.42%	11.42%	11.42%
CC—LUT	10.43%	10.43%	-27.67%	10.43%	10.43%	10.43%	10.43%
Acidification	11.70%	11.70%	-33.49%	11.70%	11.70%	11.70%	11.70%
Eutrophication	12.28%	12.28%	-33.18%	12.28%	12.28%	12.28%	12.28%
Photochemical oxidation	6.59%	6.59%	-21.76%	6.59%	6.59%	6.59%	6.59%
AD—elements	61.44%	61.44%	-61.22%	61.44%	61.44%	61.44%	61.44%
AD—fossil fuels	4.75%	4.75%	-18.95%	4.75%	4.75%	4.75%	4.75%
Water scarcity	130.26%	130.26%	-85.76%	130.26%	130.26%	130.26%	130.26%

By applying the results of sensitivity analyses to the overall impact of the construction (Table 6), it was found that change in the load-bearing system slightly increased the environmental performance of the structure, primarily visible in biogenic carbon emissions (9.49%). However, carbon uptake was improved by 19.27%, which enhanced the carbon balance to negative signs leading to the predominance of carbon removals over emissions.

This construction composition created a carbon-negative construction of embodied carbon emissions equaled to -5764.22 kg CO_2 eq respecting Equation (1) of carbon balance.

Table 6. Overall changes in the embodied impact of the construction after substituting the most relevant construction materials.

Impact Category	Original Impact	Change in Impact after Substituting CLT by MHM Panel	Change in Impact after Substituting LDF by Stone Wool
CC—fossil	100.00%	1.06%	-4.04%
CC—biogenic	100.00%	9.49%	-30.97%
CC—carbon uptake	100.00%	19.27%	-10.25%
CC—LUT	100.00%	5.52%	-9.44%
Acidification	100.00%	1.84%	-10.48%
Eutrophication	100.00%	2.47%	-10.94%
Photochemical oxidation	100.00%	3.17%	-6.19%
AD—elements	100.00%	1.21%	-38.06%
AD—fossil fuels	100.00%	0.92%	-4.53%
Water scarcity	100.00%	-0.32%	-56.57%

Substitution of LDF by stone wool reduced the impact of construction in all categories by 4.04% (fossil carbon emissions), and up to 56.57% (water scarcity). The outcome of the carbon balance regarding Equation (1) was 8228.71 kg CO₂ eq, which was approximately 3% lower than the original one.

4. Discussion

The study focused on the comparison of the embodied environmental impact of individual construction components. The initial evaluation was aimed at determining the weight and volume distribution within the construction. In terms of the first mentioned, 76.68% of the overall construction weight was concentrated in the foundations. Timber constructions consist of several construction materials. In addition, the weight of the inner walls was about 57% lower than that of the peripheral wall. That was caused by relatively simpler material composition and lower thickness of the inner walls (excluding insulation and outdoor cladding). CLT panels constituted only 4.62% of the total construction weight. The biggest component by volume represented ceiling (28.89%), which was about 5% higher than peripheral wall (23.23%). The components volume could be explained by the relatively large openings for windows and entrance door (34.5 m²) and the rather large ceiling thickness due to the insulation layer of 400 mm.

The impact assessment of the construction was set (Table 2). As one of the biggest concerns in the construction industry is focused on climate change mitigation [29], a carbon balance was calculated to measure the embodied carbon of the structure. The considered construction composition carbon balance was 57.08 kg CO_2 eq/m² of GIA, which agreed with the embodied carbon emissions of low-rise timber constructions [21].

After a primary analysis (Table 2), impact analyses on the share of the building components within the individual impact categories were carried out (Figures 7–11). Based on the findings, a table was created ranking the components from the most to the least burdensome (Table 3). Subsequently, the best and the worst components were chosen for a detailed impact assessment to identify materials responsible for such impact.

Foundations and peripheral wall were identified as the worst components. The impact contribution of foundations was caused by concrete and reinforcing steel. Except for water scarcity and depletion of elements, the contribution of foundations on individual impact categories was higher than 22%, which roughly matches the findings of Ondova et al. [30]. LDF was marked as the main environmental impact contributor of the peripheral wall component causing the majority of the impact on the depletion of elements and water scarcity (Figure 12). The CLT panel reported the greatest impact of the inner walls (Figure 14), which is understandable given that inner walls were composed of a low number of construction materials, and since the panel was the main element of the component. To determine the influence of another construction material selection as well as to find out if the CLT panel structure affected the total environmental impact more than the LDF insulation, a sensitivity analysis was performed. The CLT panel was replaced by an MHM panel, which retained the same orthogonal laminar structure and differed in the production technology and material composition (Table 4). The next analysis focused on applying stone wool insulation instead of LDF (Table 5). Afterwards, the comparison of the primary total construction impact and the two substitutions in construction was established (Table 6).

Sensitivity analysis showed that substitution of CLT by MHM panel led to carbonnegative embodied emissions of the construction ($-38.82 \text{ kg CO}_2 \text{ eq}/\text{m}^2$ of GIA), which might be partly caused by larger dimensions of the MHM panel. However, it should be stated that the manufacturing of the MHM panel was considered on the construction site and did not include auxiliary material and energy inputs for the prefabrication. Therefore, the actual impact of MHM panel manufacturing might be higher. The second analysis showed that the impact on each category was reduced as LDF was replaced by stone wool (Table 6). The most decreased impact was reported on the water scarcity category accounting for an overall construction reduction of -56.57% of the impact. The change in the depletion of elements observed was -38.06% of that impact. However, introducing abiotic insulation material lowered carbon removals, resulting in an overall carbon balance of almost 3% compared to the LDF alternative. Therefore, it can be concluded that natural-based construction materials might not be a sustainable solution that complies with the findings of other authors [31,32]. However, future studies might be focused on the application of bark-based panel insulation [33].

Each construction impact might be unique due to its use, specific construction materials, climate conditions, regional markets, etc. [34]. Moreover, the selection of calculation methods, modelling approach, as well as system boundaries vary from study to study [35]. Several limitations were found using this study for comparison purposes with other constructions. First, the assessment was done using attributional modeling based on allocation at the point of substitution [26] used for hot-spot identification of the system under study. Other types of modeling might report different results. Another point is that the study only considered embodied environmental impacts reflecting the burdens of the construction materials manufacture. Other life cycle stages, such as transportation, construction process, use of the building, and the end-of-life, were not assessed. The absence of the assessment of other stages might also be a disadvantage in an overall assessment of the construction while it would enhance or worsen the embodied impact performance when considering the whole life cycle.

5. Conclusions

Timber constructions are generally considered sustainable as they bind carbon dioxide in the wood structure and as it is relatively easier to manufacture wood-based construction materials instead of masonry buildings. Efforts to reduce the energy intensity of buildings shift the environmental impact from the operational stage to construction materials. Therefore, the environmental performance of construction becomes highly dependent on the construction materials involved.

The main findings of the paper could be specified as follows:

- The majority of the overall construction weight was located in foundations accounting for 76.68%. CLT panels constituted only 4.62% of the total construction weight. The biggest component by volume represented ceiling (28.89%) due to rather large ceiling thickness due to the insulation layer of 400 mm followed by the peripheral wall (23.23%) with the relatively large openings for windows and entrance door.
- Foundations and peripheral wall were identified as the worst components of the construction in terms of several impact categories. The impact contribution of foundations was mainly caused by concrete and reinforcing steel. LDF was marked as the main environmental impact contributor of the peripheral wall component causing the majority of the impact on the depletion of elements and water scarcity.

- The considered construction composition carbon balance was 57.08 kg CO₂ eq/m² of GIA. Sensitivity analysis showed that substitution of CLT by MHM panel led to carbonnegative embodied emissions of the construction (-38.82 kg CO₂ eq/m² of GIA).
- CLT panels were found to be one of the least negative impact contributing construction material. On the other hand, the study showed LDF to contribute the most to the environmental impact of the construction. Moreover, a properly chosen composition of construction materials might result in carbon negative embodied emissions of a building as it was in the case of MHM panels. Future studies might be focused on the application of bark-based panel insulation.

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