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Low-Carbon Emissions and Cost of Frame Structures for Wooden and Concrete Apartment Buildings: Case Study from Finland

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Abstract: To date, the existing literature lacks any studies that compare timber and concrete apartment buildings in the Finnish context regarding their carbon footprint, handprint, and the cost of frame structures. This study rigorously analyzes and calculates the carbon footprint, carbon handprint, and costs associated with various structural solutions in a proposed multi-story building located in Laajasalo, Helsinki, Finland. While the primary focus is on wooden frame construction, exploring both its challenges and opportunities, this study also includes a comparative assessment with concrete frame construction. In Finland, regulations require a sprinkler fire extinguishing system to be installed inside. Also, weather protection is typically added to the top of building in connection with the construction of wooden apartment buildings. When the costs of a sprinkler system and weather protection are taken into account, the cost of achieving positive climate effects through a concrete frame is 290% higher than that of a solid wood frame. Our findings will provide a robust basis for assessing the sustainability and feasibility of construction methods, offering valuable insights into environmental and economic considerations for decision-makers in Finland and beyond as regulations evolve and awareness of climate impacts grows.

Keywords: low carbon; carbon footprint; carbon handprint; wooden apartment building; concrete apartment building; Finland

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Citation: Laitinen, M.; Ilgın, H.E.; Karjalainen, M.; Saari, A. Low-Carbon Emissions and Cost of Frame Structures for Wooden and Concrete Apartment Buildings: Case Study from Finland. *Buildings* **2024**, *14*, 1194. https://doi.org/10.3390/buildings14051194

Academic Editors: Miroslav Premrov, Vesna Žegarac Leskovar and Nerio Tullini

Received: 26 March 2024
Revised: 14 April 2024
Accepted: 20 April 2024
Published: 23 April 2024

1. Introduction

In the realm of low-carbon construction, the assessment of environmental merits and drawbacks spans the entirety of a building's life cycle [1]. The favorable ecological influence is quantified as a negative carbon handprint, while the adverse impact is gauged as a positive carbon footprint, with both conveyed in units of kg $CO_2e/m^2/a$. This measurement signifies the quantity of carbon dioxide equivalents per square meter of the building's heated space annually [2]. Specifically, carbon handprint is indicated by a negative numerical value, whereas carbon footprint is represented by a positive number. A construction is deemed low-carbon when it demonstrates a minimal carbon footprint coupled with a substantial carbon handprint [3].

In the 2020s, Finnish building regulations are integrating the evaluation of low-carbon considerations, with the finalization of regulations for climate assessments and material descriptions expected by 2023 [4]. A draft regulation outlining thresholds and their corresponding impact assessment is scheduled to be developed in 2024. These thresholds play a pivotal role in guiding construction practices toward low-carbon methodologies, ensuring that calculations encompass both the environmental drawbacks and benefits throughout the entire life cycle of a building [5]. The planned introduction of thresholds in 2025 is perceived as a dynamic process, with regular updates synchronized with the carbon neutrality target set for 2035 in Finland [6,7].

The selection of building materials plays a crucial role in influencing the overall life cycle carbon footprint of a building [8]. To strategically address and mitigate climate impact, it is essential to target the reduction in emissions associated with these materials [9]. This reduction can be accomplished by implementing measures such as adopting manufacturing processes with lower emissions or substituting environmentally unfriendly materials with eco-friendly alternatives [10]. By concentrating on the emissions embedded in building materials, substantial progress can be achieved in making a positive impact on the climate within the construction industry [11].

Strategies such as bio-based carbon capture and storage, timber construction, and the utilization of wood products emerge as crucial measures for mitigating net greenhouse gas emissions [12]. Timber construction, specifically, holds the potential to sequester carbon within buildings, thus contributing to the expansion of Finland's existing carbon sink and facilitating progress toward national carbon neutrality [13]. Presently, only approximately 3% of raw timber employed in domestic construction serves as a prospective long-term carbon store or sink [14]. Maximizing the effectiveness of this carbon sink necessitates preventing the release of carbon dioxide into the atmosphere during the demolition of old structures [15]. Techniques like biochar production from demolition wood, coupled with the incorporation of biochar into the soil, can effectively curb CO_2 emissions, establishing a continuous carbon sink and nearly permanent carbon storage in the soil [16–19].

In Finland, timber is predominantly used in constructing single-family homes (constituting 80% with wooden frames) and row houses (making up 60% with wooden frames) [20]. Despite the established tradition of timber construction and abundant forest resources in Finland, the utilization of timber in multi-story buildings like apartments is still in the early stages, with relatively low market share [21–23]. Nevertheless, there is growing momentum and support for the adoption of wooden multi-story buildings as an innovative building technology, receiving attention from both the public and political spheres in Finland and other forest-rich European countries [24].

There is rising interest in assessing and mitigating environmental impacts related to climate change and other adverse environmental factors. The focal point at this juncture revolves around the challenge of quantifying and minimizing environmental burdens [25]. In recent times, scholars, organizations, and various stakeholders have been actively engaged in formulating concepts and methodologies to gauge environmental sustainability. The environmental footprint, a significant topic addressed at the Habitat Conferences [26,27], has gained prominence and is playing a crucial role in sustainability assessments and research [28,29]. Environmental footprints serve as quantitative metrics for human utilization of natural resources [30]. These footprints are categorized into environmental, economic, and social dimensions and can also be combined to form integrated environmental, social, and/or economic footprints [31]. The foundational idea of the footprint concept stems from the ecological footprint introduced by Rees [32] and Fang et al. [33]. Notably, in recent years, the carbon footprint has been predominantly utilized as an indicator for environmental protection, e.g., [34–37].

Numerous studies have investigated the life cycle assessment (LCA) and carbon footprint of timber in contrast to conventional construction materials like concrete, such as [38–42]. Currently, there is a noticeable absence of studies in the existing literature that specifically examine the carbon footprint, handprint, and frame structure costs of timber and concrete apartment buildings within the context of Finland. The objective of this study is to address this gap by analyzing and calculating the carbon footprint, carbon handprint, and costs associated with wooden and concrete structural solutions in a proposed multi-story building located in Laajasalo, Helsinki.

Notably, hybrid construction is intentionally omitted from this investigation, guided by prior research findings suggesting that hybrid buildings may potentially exhibit higher carbon intensity than concrete construction [43]. In this paper, the term 'hybrid building' denotes a structure primarily constructed with reinforced concrete load-bearing elements, except for the top floor, which is framed with timber. Additionally, the exterior facade of the building is composed of timber framing and cladding. The deliberate exclusion of hybrid construction underscores a concentrated examination of wooden and concrete frame constructions. It is also important to note that this article does not address the implications of design choices on future repair needs or the potential reuse of structural elements post-demolition [44].

2. Materials and Methods

This study revolves around scrutinizing and computing the low-carbon characteristics and corresponding costs of structural alternatives for multi-story building construction in Laajasalo to provide a thorough comprehension of the intricacies and subtleties associated with low-carbon construction, evaluating two alternative structural solutions: a concrete frame and a massive wood frame.

To ensure the objectivity and comparability of results, the structural design, cost estimations, and quantity calculations for both frames were delegated to a third-party consulting service. This outsourcing strategy was implemented to uphold a standardized and unbiased approach to the assessment. The evaluations concentrated on the primary structure of the building, maintaining consistent content across both alternatives to facilitate precise and meaningful comparisons.

The main goal is to quantify the expenses related to the positive climate impacts associated with each of the structural solutions. This computation is guided by the results of both cost assessments and evaluations of low-carbon properties. The objective is to furnish a dependable and nuanced assessment of a construction approach that is not only environmentally sustainable but also economically viable.

2.1. Apartment Building Initial Information

The development of the residential complex in Laajasalo is a component of the Helsinki City's Developing Apartment Building initiative, designed to lead pioneering ventures in apartment construction and enhance the overall standard of apartment living. The site (Figures 1 and 2) is positioned within a residential apartment block zone established by the zoning plan ratified on 24 April 2019.

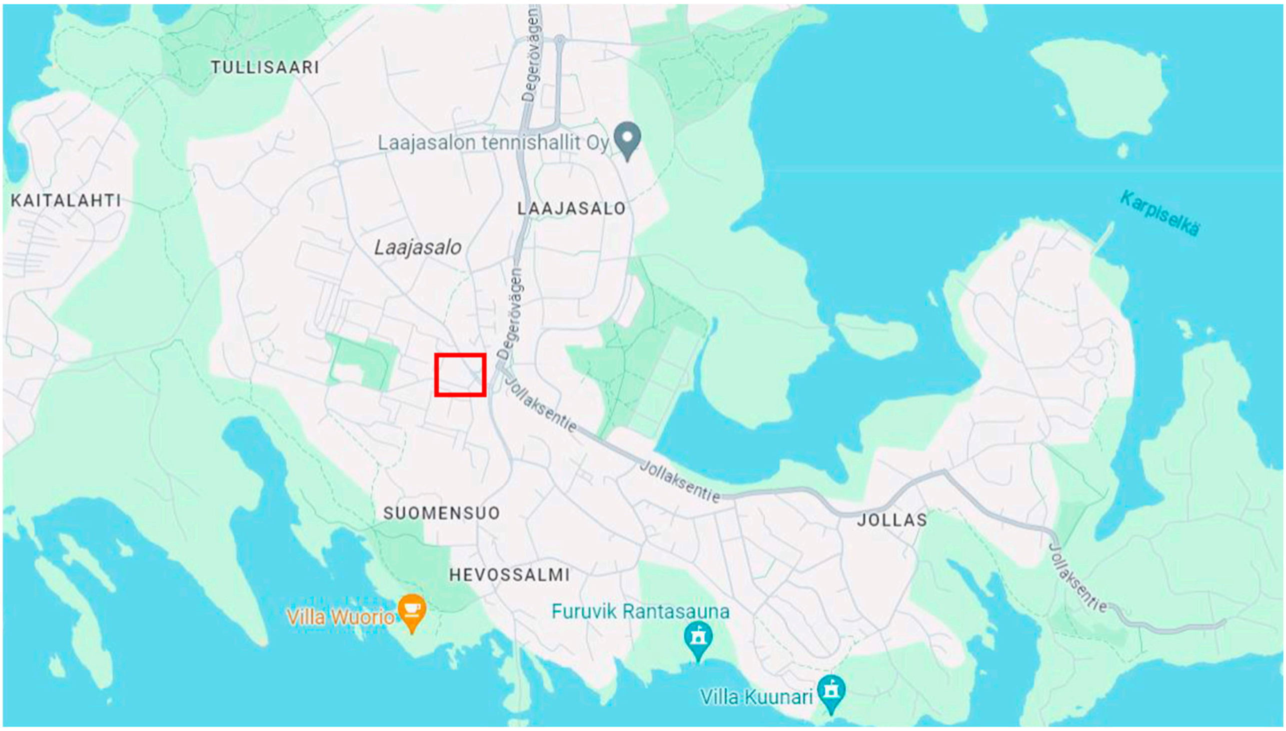

Figure 1. The location of the site in Laajasalo, Helsinki, on the map.

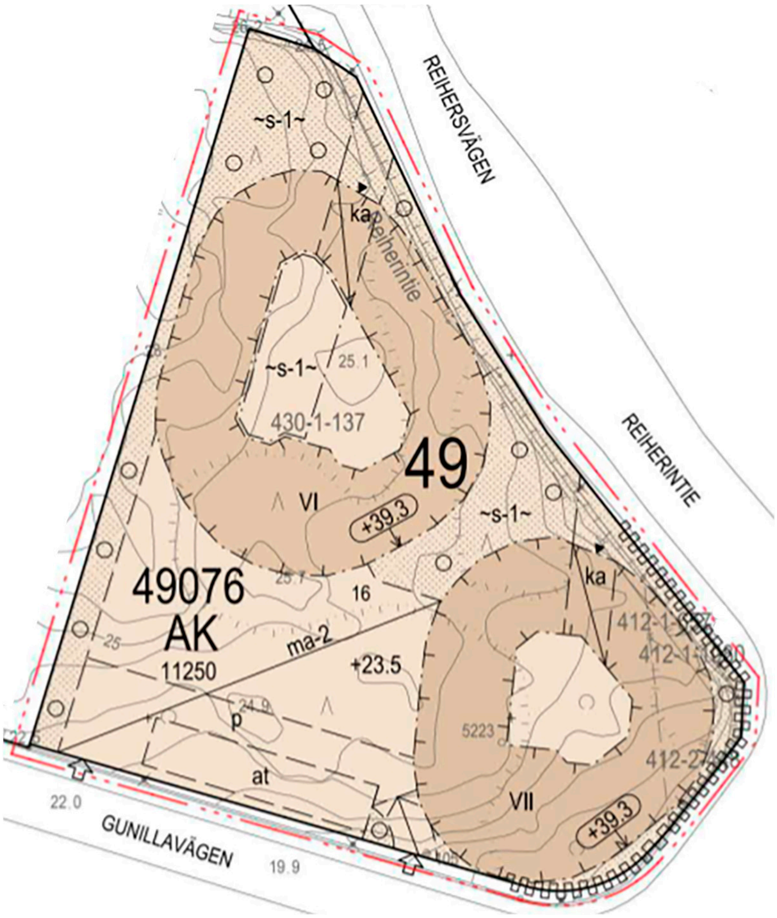

Figure 2. Map extract from the zoning plan (image by authors).

The building permit determined for the parcel is 11,250 m^2, and the number of floors allowed is 7. The distance to Helsinki's city center is approximately 10 km, and the existing public transport travel duration is about half an hour. A new tram route through Kruunusillat is presently under construction, with the commencement of operations between Laajasalo and Hakaniemi expected in 2027. This infrastructure improvement is foreseen to considerably improve transportation links between Laajasalo and the city center.

In contrast to the specifications delineated in the zoning plan, Figure 3 proposes a departure from the initial plan. Rather than building two separate donut-shaped apartment structures, the revised proposal introduces a more illuminated and expansive design that diverges from the prescribed zoning directives. The architectural concept for the Developing Apartment Building initiative incorporates the fusion of articulated and straight segments, resembling frames of bookshelves. Adhering to zoning regulations, the design includes a gallery on the side facing the courtyard.

The depiction of the building's street-facing facade emphasizes elements like glazed balconies and steel profiles, enhancing the overall visual allure of the structure. This alternative design aims to bring in a more luminous and expansive approach while maintaining compliance with zoning regulations, achieved through the incorporation of the gallery on the courtyard side.

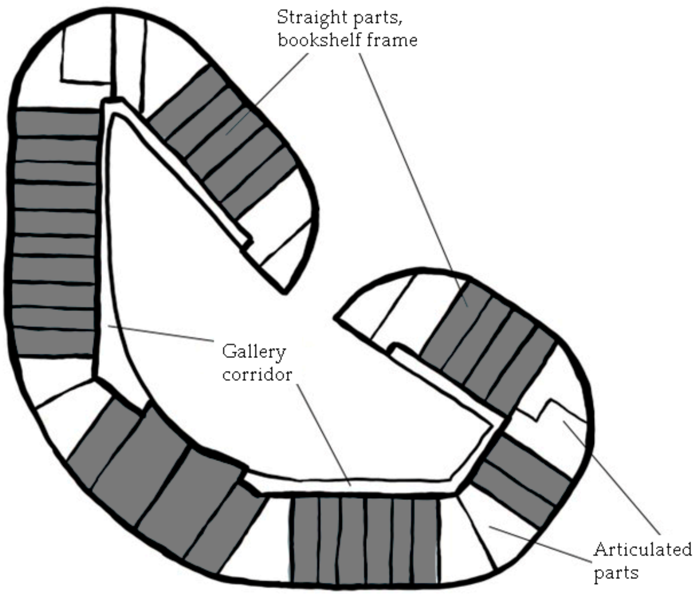

Figure 3. Structural principle of the Developing Apartment Building initiative (image by authors).

2.2. Alternatives for the Apartment Building's Structural Solution

Three structural alternatives for the ground floor of the apartment building in the early stages of project planning, as illustrated in Figure 4, underwent evaluation. It was recognized that a solution in line with the zoning plan requirements could be achieved through solid wood, frame construction, or traditional concrete methods. However, considering the project's ambition to lead innovations in apartment building construction, conventional concrete methods were deemed inappropriate for meeting the criteria outlined in the plot transfer conditions.

Figure 4. Apartment distribution diagram for the base floor of the studied apartment building (image by authors).

As a result, the decision was made to implement the Developing Apartment Building using timber construction, thereby creating an extraordinary pioneering project that considers structural innovations, floor plans, and a substantial potential for carbon sequestration. Although the apartment building could have been constructed using a frame structure, preference was given to a cross-laminated timber (CLT) structural solution due to its significantly higher capacity for carbon sequestration. It was recognized in the project planning phase that opting for a CLT-framed building would yield considerably greater climate benefits throughout the building's life cycle through the sequestration of carbon over an extended period.

2.3. Scope of Quantity, Cost, and Low-Carbon Calculations

As a crucial facet of the development process for the Developing Apartment Building initiative, the goal is to assess the environmental impact stemming from the selection of structural materials for the apartment building. In endeavors of this scale, the environmental consequences, encompassing both positive and negative aspects, are particularly significant. A comparative evaluation was carried out between the structural components and roof of a CLT apartment building, characterized by an identical floor plan design, and those of a conventionally designed concrete apartment building.

This analysis focused specifically on the structure and roof of the building, as these elements play a substantial role in carbon dioxide emissions during the product phase (A1–A3), which includes the extraction, manufacturing, and transportation of construction materials. Furthermore, emissions arising from on-site activities and transportation (A4–A5) during the construction phase are essential aspects of the evaluation. Through a detailed examination of these components, this study seeks to identify the environmental benefits and drawbacks associated with the selection of construction materials, considering their impact on the overall life cycle of the building.

2.4. Structural Design and Cost Estimation of the Structural Elements

The structural designs for both concrete and CLT structures were developed to replicate each other in terms of content and quantity, ensuring a meaningful foundation for comparison. A professional engineering and design firm was tasked with the responsibility of conducting the structural design for both alternatives, adhering to the primary principle of ensuring realistic constructability. Detailed information regarding the structural types, components, and quantities for both the concrete and CLT alternatives can be found in Appendices A–C.

To ensure consistency in this study, external entities were assigned the task of conducting cost assessments for the structural contracts. An experienced construction engineer carried out the cost estimation process for the concrete frame using the project planning-phase materials. Concurrently, another experienced consultant performed the cost estimation process for the CLT frame, also relying on the project planning-phase materials. The cost calculations were carefully harmonized in terms of content and carried out using a methodology for building component cost calculation.

The self-cost estimation for the concrete apartment building, which includes five floors and the roof structure, as per the cost estimate for the concrete frame's building components, is EUR 8,150,378 (Appendix C). In contrast, the self-cost estimation for the CLT apartment building, covering the same number of floors and roof structure, based on the frame cost estimate, is EUR 9,114,500. These cost assessments encompass various structural elements for the specified floors and roof, incorporating expenses for frame installation, labor and project management, element design, element installation work, crane operation, rental, and supplies. All calculations were performed with a 0% VAT rate.

2.5. Carbon Footprint and Handprint of Structural Elements

Assessing low-carbon impacts involved the use of building component estimates, structural designs, and quantity calculations for both timber and concrete frame contracts.

Microsoft Excel (Microsoft 365) was used to calculate quantities and masses of various construction materials, facilitating a comprehensive low-carbon assessment. Quantities of building materials were obtained from the basic cost calculation of building components. Material masses were then determined from these quantities to perform mass-based low-carbon calculations. Detailed information on the quantities of building materials and calculated masses is available in Appendix A (concrete frame) and Appendix B (wooden frame). The computation of material masses relied on values provided by material suppliers, expressed in kg/m^2 or kg/m^3.

Upon determining the material weights, carbon footprints, and handprints for the five floors and the roof, the Ministry of the Environment's building carbon footprint calculation tool was employed. Rather than relying directly on the tool's values, the calculations incorporated material data or more detailed figures sourced from the Finnish Environment Institute's construction emissions database version 1.01.000 (dated 29 June 2023) or values extracted from the environmental product declarations (EPD) of material suppliers. The specific sources and links for the refined emission values utilized in the calculation of each building material are comprehensively outlined in Appendices D and E. In the calculation process, refined values from the material suppliers' own EPDs or environmental product declarations were preferred when available; otherwise, refined emission values from the Finnish Environment Institute's emission database were utilized.

3. Results

The choice of the structural frame material for the apartment building stands as a pivotal element with extensive ramifications for the overall climate impact of the construction project. Figure 5 shows the scale of this impact, accentuating the substantial influence that the selection of building material wields in shaping the environmental footprint of the structure.

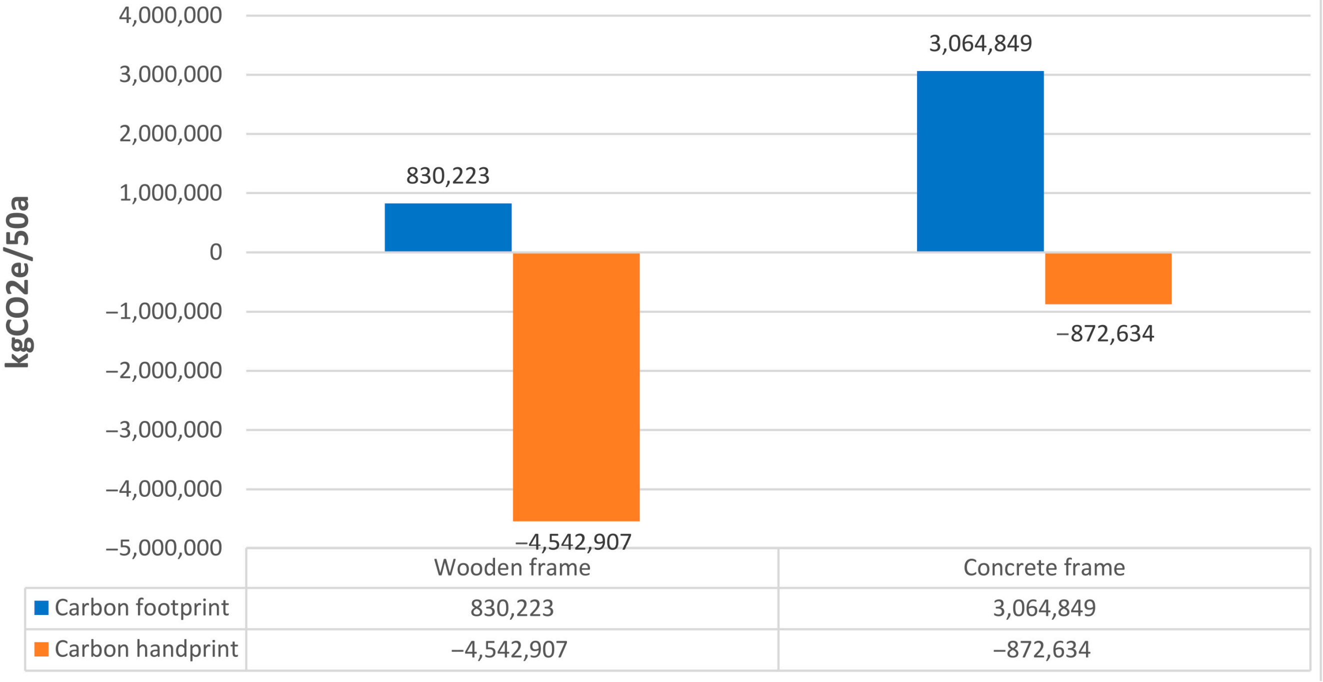

Figure 5. The impact of material selection for the load-bearing structure of a Developing Apartment Building initiative building on carbon footprint and handprint (image by authors).

Various structural materials, including concrete and wood, exhibit distinct carbon footprints and environmental implications across their life cycles, spanning extraction and production to construction and eventual end-of-life considerations. The choice of a specific material can impact factors such as carbon emissions, energy consumption, and resource utilization.

Choosing a concrete frame as the load-bearing structure for the upcoming apartment building yields immediate and environmentally adverse consequences. Over a 50-year analysis period, this decision contributes to over 2.2 million kilograms of carbon dioxide equivalent compared to opting for a massive wooden load-bearing frame. Precisely, the concrete frame in the Developing Apartment Building initiative building results in 3,060,000 kg CO_2e/50 years, representing a 270% increase in carbon dioxide emissions compared to the 830,000 kg CO_2e/50 years associated with a massive wooden CLT frame, as delineated in Equation (1):

$$\frac{3060000\ \mathrm{kg}CO_2\mathrm{e}/50\mathrm{a} - 830000\ \mathrm{kg}CO_2\mathrm{e}/50\ \mathrm{a}}{830000\ \mathrm{kg}CO_2\mathrm{e}/50\ \mathrm{a}} * 100\% = 270\% \quad (1)$$

This comparison underscores the considerable environmental advantages of selecting a wooden CLT frame over a concrete frame, particularly in terms of mitigating carbon emissions and advocating for a more sustainable and eco-friendly construction approach. The provided figures underscore the noteworthy influence that material choices can exert on the overall carbon footprint of a building over an extended period, underscoring the importance of integrating environmental considerations into construction decision-making processes.

From a low-carbon perspective, another crucial aspect to consider in selecting the structural frame material is the carbon handprint, which measures the positive climate impacts stemming from building construction. Choosing a CLT frame as the load-bearing structure for the upcoming apartment building leads to the creation of over 3.67 million additional kilograms of carbon dioxide equivalent in positive climate impacts over a 50-year analysis period compared to selecting a concrete load-bearing frame. The climate benefits associated with the massive wooden frame are, remarkably, 420% greater than the positive climate impacts caused by the concrete frame, as expressed in Equation (2):

$$\frac{-4540000\ \mathrm{kg}CO_2\mathrm{e}/50\mathrm{a} - (-873000)\ \mathrm{kg}CO_2\mathrm{e}/50\ \mathrm{a}}{-873000\ \mathrm{kg}CO_2\mathrm{e}/50\ \mathrm{a}} * 100\% = 420\% \quad (2)$$

This assessment highlights the substantial benefits of choosing a massive wooden CLT frame in terms of carbon handprint, signifying a noteworthy net positive contribution to climate mitigation. It reinforces the idea that the selection of construction materials extends beyond simply reducing negative environmental impacts; it can actively contribute to positive climate outcomes, aligning with sustainability goals and promoting environmentally responsible building practices.

Comparing the costs associated with these two distinct framing methodologies in relation to their positive climate impacts is of significance. According to the construction estimate for the concrete frame, the self-cost of the frame contract is EUR 8,150,000. Conversely, the self-cost of the frame contract for the CLT frame is EUR 9,110,000. By utilizing the cost estimates and low-carbon computations, we can juxtapose the cost per kilogram of carbon dioxide equivalent (kg CO_2e) sequestered between the implementations of concrete and massive wooden CLT frames.

The cost of positive climate impacts resulting from the construction of the concrete frame in the developing apartment building, per kilogram of carbon dioxide equivalent (kg CO_2e) over a 50-year analysis period, is EUR 9.34/kg CO_2e (=8,150,000 €/870,000 kg CO_2e). In contrast, the positive climate impacts associated with constructing the massive wooden frame in the developing apartment building, per kg CO_2e over the same analysis period, amount to $\frac{9110000\ €}{4500000\ \mathrm{kg}CO_2\mathrm{e}}$, resulting in EUR 2.01/kg CO_2e.

Consequently, the cost of positive climate impacts for a concrete frame is significantly higher, precisely 364.68% higher, compared to the cost associated with massive wooden construction. These calculations reveal that carbon sequestration in the building's structure and the positive climate impacts resulting from construction are approximately 365% more expensive with concrete construction than with the use of CLT in massive wooden construction.

It is worth noting that in Finland, regulations mandate the installation of a sprinkler fire extinguishing system in wooden apartment buildings, incurring construction costs of approximately EUR 100 per square meter of apartment space. Similarly, due to the country's climatic conditions, weather protection is typically added on top of the building frame during construction, also amounting to around EUR 100 per square meter of apartment space. Thus, the sprinkling system and weather protection will add an additional EUR 1,840,000 to the construction costs of this project. It means that when the cost of sprinkling and weather protection is considered, the cost of the positive climate effect of the concrete frame of the apartment building studied is 290% more expensive than the cost of a massive wooden frame.

4. Discussion

Presently, there is a growing interest in expanding the utilization of wood in the construction industry [45–47]. Various companies, ranging from large corporations to medium-sized enterprises in the construction sector, are diversifying their focus toward wood construction, indicating a strategic shift in their business approach. Drawing upon emission data and comparative analyses, it is observed that wood, when used as a structural building material, currently exhibits a reduced carbon footprint in comparison to alternative materials. As a result, the increasing prevalence of wood construction is considered a significant achievement in the realm of climate action.

Our study underscores a deficiency in existing environmental certifications, revealing their inadequacy in adequately addressing the low-carbon attributes of buildings. These certifications primarily focus on energy efficiency and the carbon footprint throughout a building's life cycle, providing a limited perspective on low-carbon considerations. To enhance the significance of the findings, the suggestion is made that environmental certifications at various levels should include mandatory limits on carbon footprints.

As the importance of energy efficiency diminishes over a building's life cycle due to reduced emissions from energy production, it is crucial to implement stringent regulations, comprehensive accountability reporting, and sustainability reporting obligations for both companies and public entities. This approach aims to prevent greenwashing and promote a genuine and robust transition toward environmental sustainability. The proposal seeks to ensure that certifications go beyond superficial assessments and actively contribute to meaningful progress in reducing carbon footprints in the construction and building sectors.

As the transition progresses toward low-carbon and, ultimately, fully carbon-neutral energy production, the direct contribution of building energy use to emissions is expected to decline [48–50]. Instead, indirect impacts may arise from potential replacements of energy-related building components. Consequently, the forthcoming emphasis will shift toward the material phase (A1–A3) of building materials and the emissions stemming from construction transport and on-site activities (A4–A5). This shift is driven by the decreasing operational carbon dioxide emissions (B1–B7) over the life cycle.

It is argued that the implementation of mandatory limits for emissions during the building material phase (A1–A3) and construction transport and on-site activities (A4–A5) is unavoidable. Without these limits, the perpetual shifting of responsibility among financiers, clients, and construction companies cannot be halted. Limits are seen as the most effective means to systematically guide the reduction in buildings' carbon footprints. Diminishing the carbon footprint of construction, both during the construction process and throughout the building's life, is considered an essential measure to counteract the accelerating pace of climate change.

Recent research in the field provides significant insights into the environmental impact of structural materials in multi-story buildings [51–53]. A thorough analysis of comparative projects indicates that the carbon footprint (A1–A5) associated with concrete-framed buildings surpasses that of massive timber CLT-framed buildings by approximately 40%. This substantial difference highlights the considerable environmental advantage of opting for timber-based construction methods in the context of multi-story buildings.

Furthermore, a more detailed examination of carbon handprints in these structures reveals that CLT-framed buildings exhibit notably larger carbon handprints, ranging from 330% to 890%. The extent of this variation depends on various factors, including the specific structural solutions and foundation methods employed. This nuanced perspective underscores the multifaceted environmental benefits associated with choosing CLT-framed constructions over concrete-framed alternatives in the realm of multi-story buildings. The findings suggest that not only is there a reduced carbon footprint with timber-based construction, but there are also additional positive environmental implications that contribute to the overall sustainability of such structures.

Currently, wood construction stands out as the most economically viable and environmentally friendly option for low-carbon building practices [54–56]. In particular, the use of massive CLT for the building frame is highlighted as an exceptional choice, offering a compelling combination of advantages in terms of carbon footprint, carbon handprint, and carbon storage potential. This emphasizes the pivotal role of wood, especially massive CLT, in promoting a greener and more sustainable future for construction projects aiming to minimize their carbon impact.

A comprehensive analysis of an upcoming multi-story building project in Laajasalo, comprising five floors and a roof, indicates that selecting a concrete frame would have detrimental climate consequences, emitting over 2.2 million kilograms of carbon dioxide equivalent over a 50-year timeframe, 270% higher than the emissions associated with a substantial CLT frame. To thoroughly evaluate low-carbon and climate-friendly construction, it is essential to consider both the carbon footprint and carbon handprint. Choosing a massive CLT frame results in substantial positive climate impacts, exceeding 3.67 million kilograms of carbon dioxide equivalent over a 50-year period, 420% more than what would be achieved with a concrete frame. This underscores the critical significance of opting for construction methods that positively contribute to climate outcomes.

A thorough examination of the costs related to the positive climate impacts resulting from the adoption of these two framing methods reveals a significant economic disparity. When meticulously considering the financial aspects involved in the construction of a multi-story building, it becomes apparent that the expenses associated with the positive climate impacts incurred by a concrete frame are notably elevated. To be precise, the cost of positive climate impacts linked to a concrete frame construction is a staggering 370% higher compared to the construction of a massive CLT frame in this specific scenario. This sharp contrast underscores the economic advantage and affordability inherent in choosing environmentally sustainable and low-carbon massive wood CLT construction over the conventional concrete frame alternative. As was already pointed out in the results section, in Finland, regulations mandate the installation of a sprinkler fire-extinguishing system in wooden apartment buildings, incurring construction costs of approximately EUR 100 per square meter of apartment space. Similarly, due to the country's climatic conditions, weather protection is typically added on top of the building frame during construction, also amounting to around EUR 100 per square meter of apartment space. Thus, the sprinkling system and weather protection will add an additional EUR 1,840,000 to the construction costs in this project. It means that when the cost of sprinkling and weather protection is taken into account, the cost of the positive climate effect of the concrete frame of the apartment building studied is 290% more expensive than the cost of a massive wooden frame.

In the face of escalating climate change impacts and declining biodiversity, relying on future generations to bear the burden of significant carbon emissions from construction materials is considered unsustainable. Projections suggest that with increasing carbon dioxide emissions, natural carbon sinks on land and in oceans are expected to diminish. Consequently, there is an urgent imperative to promptly reduce carbon emissions.

The implementation of stringent regulations and laws becomes crucial to guide market economies toward low carbon intensity. Such measures are essential to ensure the potential for future generations to inhabit and thrive on this planet while fostering sustainable and environmentally conscious practices.

Moreover, there is a compelling need for an in-depth exploration of the relationship between calculated and actual emissions throughout the life cycle of building energy usage. Preliminary findings underscore significant divergences, especially in relation to electricity consumption. An essential avenue for further investigation involves a thorough examination of the use of local emission factors for district heating in carbon neutrality calculations. The integration of local emission factors is anticipated to align seamlessly with the low-carbon objectives of municipal and city district heating providers, enhancing the regional relevance of the results and extending their significance beyond reliance on national averages.

5. Conclusions

The findings of this study shed light on crucial aspects of construction methods and their implications for environmental sustainability, particularly in the Finnish context. Firstly, this study underscores the inadequacy of existing environmental certifications in capturing the full extent of low carbon content in buildings, highlighting a gap in current assessment methodologies. Secondly, it elucidates the evolving role of energy efficiency in mitigating carbon dioxide emissions across a building's lifecycle, emphasizing the need for nuanced strategies amid changing energy production landscapes. Notably, the comparison between conventional concrete and CLT structures reveals substantial disparities in carbon footprint and handprint, with CLT outperforming concrete in both categories. The stark contrast in emissions between the two materials underscores the significant climate benefits achievable through wooden frame construction. Moreover, the analysis of costs unveils a compelling economic case for solid wood frames, with the cost of achieving positive climate effects substantially lower compared to concrete frames, particularly when factoring in additional requirements such as sprinkler systems and weather protection.

These findings provide a robust foundation for decision-makers to assess the feasibility and sustainability of construction methods, offering valuable insights into the environmental and economic considerations inherent in building design and material choices. As regulations evolve and awareness of climate impacts grows, this study serves as a timely resource for guiding future construction practices toward more environmentally responsible and cost-effective solutions in Finland and beyond.

Author Contributions: Conceptualization, M.L., H.E.I., M.K. and A.S.; methodology, M.L., H.E.I., M.K. and A.S.; software M.L. and H.E.I.; formal analysis, M.L., H.E.I., M.K. and A.S.; investigation, M.L., H.E.I., M.K. and A.S.; data curation, M.L., H.E.I., M.K. and A.S.; writing—original draft preparation, H.E.I.; writing—review and editing, M.L., H.E.I., M.K. and A.S.; visualization, M.L.; supervision, M.K. and A.S.; project administration, M.K. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no external funding.

Data Availability Statement: The data presented in this study are available in article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Quantities and masses of the concrete high-rise building frame and roof.

Structure	Name	Product; Structural Thickness	m^2	kg/m^2	Structure	Name	Product; Structural Thickness	m^2	kg/m^2
Exterior wall	Sandwich inner shell	Tb C30/37, XC4, XF1; 150 mm	4084	360	Intermediate floors	Plastering and leveling	Plan; 40 mm	10,189	80
	Stone wool insulation	Paroc cos 5 ggt; 220 mm	4084	12.1		Sound insulation	Step sound insulation board and filter fabric; 30 mm	10,189	2.6
	Sandwich outer shell	Tb C30/37, XC1; 70 mm	4084	168		Hollow-core slab intermediate floor	OL 320 seamless; 320 mm	10,189	400
Exterior wall	Sandwich inner shell	Tb C30/37, XC4, XF1; 80 mm	4782	192		Concrete element intermediate floor	TB slab C30/37 XC1; 260 mm	427	624
	Stone wool insulation	Paroc cos 5 ggt; 220 mm	4782	12.1		Concrete element intermediate floor	TB slab C30/37 XC4, XF1; 260 mm	3193	624
	Sandwich outer shell	Tb C30/37, XC1; 70 mm	4782	168	Roof structure	Roofing plywood	WISA-Kate Plus; 19 mm	3452	8.3
Partition wall between apartments	TB-element wall	Tb C25/30, XC1; 200 mm	5334	480		Roof trusses	NR purlin truss	3452	55
Load-bearing partition wall	TB-element wall	Tb C25/30, XC1; 200 mm	674	480		Mineral wool insulation	Blown stone wool insulation Paroc BLT 6; 460 mm	3452	16.6
Partition wall for balcony	TB-element wall	Tb C30/37, XC4, XF1; 180 mm	743	432		Hollow-core slab roof	OL 320 seamless; 320 mm	3452	400
Partition wall for a porch	TB-element wall	Tb C30/37, XC4, XF1; 180 mm	681	432	Stairs	Solid slab staircase	Rudus Element 9	36	2000

Appendix B

Table A2. Quantities and masses of the solid wood frame and roof of a mass timber apartment building.

Structure	**Name**	**Product; Structural Thickness**	**m^{2}**	**kg/m^{2}**	**Structure**	**Name**	**Product; Structural Thickness**	**m^{2}**	**kg/m^{2}**
Exterior wall	CLT panel	CLT 240 L7s BVI; 240 mm	3559	113	Interior wall	Gypsum board cladding	Gypsum Board GLF 18 Fireline RO; 18 mm	5334	14.8
Exterior wall	CLT panel	CLT 180 L5s VI; 180 mm	4084	84.6		CLT panel	CLT 100 C3s NVI; 100 mm	5334	47
	Wind insulation	Insulation Paroc Cortex; 50 mm	4084	4		Insulation	Paroc extra 50; 50 mm	5334	1.6
	Framing	Framing 28 × 98 at 600 mm spacing; 28 mm	4084	2.5		CLT panel	CLT 100 C3s NVI; 100 mm	5334	47
	Framing	Framing 28 × 98 at 600 mm spacing; 28 mm	4084	2.5		Gypsum board cladding	Gypsum Board GLF 18 Fireline RO; 18 mm	5334	14.8
	Stone board cladding	Flexit; 9 mm	4084	14.5	Load-bearing partition wall	Gypsum board cladding	Gypsum Board GLF 18 Fireline RO; 18 mm	674	14.8
Exterior wall	CLT panel	CLT 180 L5s VI; 180 mm	1223	84.6		CLT panel	CLT 180 L7s NVI; 180 mm	674	84.6
	Wind insulation	Insulation Paroc Cortex; 50 mm	1223	4		Gypsum board cladding	Gypsum Board GLF 18 Fireline RO; 18 mm	674	14.8
	Framing	Framing 28 × 98 k600; 28 mm	1223	2.5	Balcony partition wall	CLT panel	CLT 200 L7s VI; 200 mm	743	94
	Framing	Framing 28 × 98 k600; 28 mm	1223	2.5	Mezzanine partition wall	Gypsum board cladding	Flexit; 9 mm	681	14.5
	Exterior cladding	Exterior Spruce UYS 28 × 95; 28 mm	1223	12.6		CLT panel	CLT 180 L7s NVI; 180 mm	681	84.6

Table A2. *Cont.*

Structure	Name	Product; Structural Thickness	m^2	kg/m^2	Structure	Name	Product; Structural Thickness	m^2	kg/m^2
Interior floor	CLT panel	CLT 160 L5s NVI; 160 mm	8885	75.2		Gypsum board cladding	Flexit; 9 mm	681	14.5
	Lightweight frame	48 × 98 C24, k600; 98 mm	8885	3.8	Attic apartment	Underlay sheet installation	OSB4 18 1.2 × 2.7; 18 mm	2328	9.9
	Insulation	Paroc extra 100; 100 mm	8885	2.9		Insulation	Paroc BLT 6; 500 mm	2328	18
	Framing	28 × 48 ST/A, k600; 28 mm	8885	0.77		Roof trusses	NR purlin truss	2328	55
	Spring beam	acoustic spring hanger; 25 mm	8885	0.75		CLT panel	CLT 100 L3s NVI; 100 mm	2328	47
	Gypsum board cladding	Gypsum board 2 × 13 GEK; 26 mm	8885	19.8		Framing	42 × 98 ST/A, k600; 98 mm	2328	3.7
Entrance floor	CLT panel	CLT 140 L5s NVI; 140 mm	1304	65.8		Insulation	Paroc Extra 100; 100 mm	2328	2.9
	Gypsum board cladding	Plasterboard Siniat WD; 9.5 mm	1304	8.5		Framing	28 × 48 ST/A, k600; 28 mm	2328	0.8
	Framing	framing 48 × 48 ST/A, k600; 48 mm	1304	1.92		Plasterboard cladding	Plasterboard GEK 13 RO; 13 mm	2328	9.9
	Stone panel cladding	Flexit; 9 mm	1304	14.5	Roof terrace	Roofing underlayment	OSB4 18 1.2 × 2.7; 18 mm	442	9.9
Entrance floor	CLT panel	CLT 140 L5s NVI; 140 mm	1424	65.8		Insulation	Paroc BLT 6; 500 mm	442	18
	Gypsum board cladding	Gypsum board Siniat WD; 9.5 mm	1424	8.5		Roof trusses	NR purlin truss	442	55
	Framing	Framing 48 × 48 ST/A, k600; 48 mm	1424	1.92		CLT panel	CLT 100 L3s NVI; 100 mm	442	47
	Stone panel cladding	Flexit; 9 mm	1424	14.5	Attic loft	Roofing underlayment	OSB4 18 1.2 × 2.7; 18 mm	682	9.9
Entrance floor	CLT panel	CLT 140 L5s VI; 140 mm	1769	65.8		Insulation	Paroc BLT 6; 500 mm	682	18
Entrance floor	CLT panel	CLT 140 L5s NVI; 140 mm	427	65.8		Roof trusses	NR purlin truss	682	55
	gypsum board cladding	Gypsum board GLF 15 Fireline RO; 15 mm	427	12.8		CLT panel	CLT 100 L3s NVI; 100 mm	682	47

Table A2. *Cont.*

Structure	Name	Product; Structural Thickness	m^2	kg/m^2	Structure	Name	Product; Structural Thickness	m^2	kg/m^2
Stairs	Staircase element	CLT-staircase element	36 (pieces)	208	Attic loft	Plasterboard cladding	Plasterboard Siniat WD; 9.5 mm	682	8.5
GLT	GLT	GLT	456 m^3	-		Framing	48 × 48 ST/A, k600; 48 mm	682	1.9
						Stone panel cladding	Flexit; 9 mm	682	14.5

Appendix C. Component-Based Cost Estimate for the Concrete Frame Structure

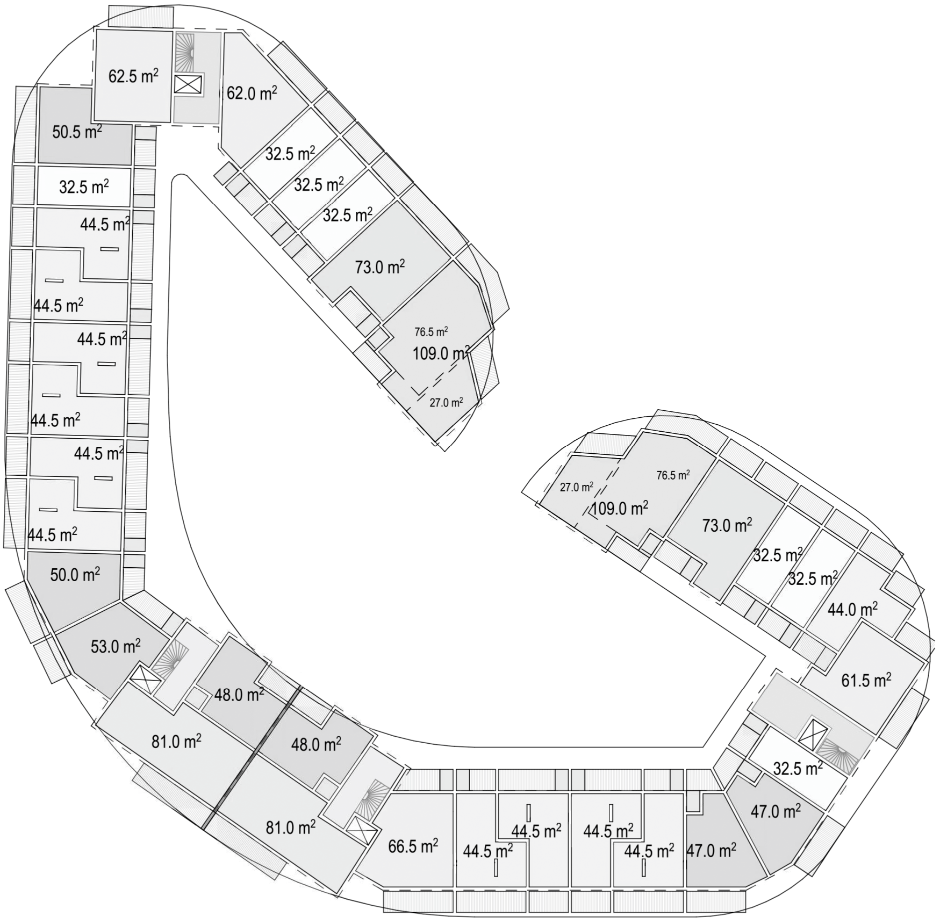

Figure A1. Apartment distribution diagram for the base floor of the studied apartment building (image by authors).

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Contents of Cost Estimate: Residential Apartment Building Timber Frame Contract, including CLT AKU and PALO surface structures indoors, as well as exterior cladding. Details of the cost calculation are provided below.
Estimated Total Price: Self-cost price is EUR 9,114,500, with VAT of 0%
Calculation content based on architectural plan drafts are dated 24 May 2023.
The basic floor area has been calculated for five levels, resulting in a total residential floor area of approximately 9677 m^2 in the timber-built floors.

The discrepancies in ground floor layouts and the spaces in concrete floors have not been accounted for. According to the architectural plans, the area is 8678 m^2 because part of the ground floor consists of other spaces.

Table A3. Exterior walls.

Construction Type	Structural Layer	Product
Balcony, 3559 m^2	CLT Exterior Claddings	CLT 240 L7s BVI Surface treatment only
Storehouse, 4084 m^2	CLT Insulation Battening Battening Exterior cladding	CLT 180 L5s VI Paroc Cortex 50 28 × 98, k600 28 × 98, k600 Stone panel cladding
Exit, 1223 m^2	CLT Insulation Battening Battening Exterior cladding	CLT 180 L5s VI Paroc Cortex 50 28 × 98, k600 28 × 98, k600 Spruce UYS 28 × 95 P+2xP

This does not include the procurement or installation of windows. There is no initial information about the quality/size/surface area of the windows.

Table A4. Partition walls.

Construction Type	Structural Layer	Product
Partition walls, 5334 m^2	Interior cladding panel CLT Insulation CLT Interior cladding panel	Plasterboard GLF 18 FireLine RO CLT 100 C3a NVI Paroc Extra 50 CLT 100 C3a NVI Plasterboard GLF 18 FireLine RO
Structural wall inside, 674 m^2	Interior cladding panel CLT Interior cladding panel	Plasterboard GLF 18 FireLine RO CLT 180 L7s NVI Plasterboard GLF 18 FireLine RO
Balcony VS, 743 m^2	Exterior cladding CLT Exterior cladding	Surface treatment only CLT 180 L7s VI Surface treatment only
Shed VS, 681 m^2	Exterior cladding CLT Exterior cladding	Stone panel cladding CLT 180 L7s NVI Stone panel cladding

Table A5. Intermediate floors.

Construction Type	Structural Layer	Product
Intermediate floors, 8885 m^2	CLT Frame Insulation Battening Interior Cladding Panel Insulation	CLT 160 L5s NVI 48 × 98 C24, k600 Paroc Extra 100 28 × 48, k600 Spring frame 25 mm + 2 × GEK 13 Vapor barrier
Intermediate floor entry alcove, 1304 m^2	CLT Wind barrier Battening Exterior cladding	CLT 140 L5s NVI Siniat Weather Defence 9.5 mm gypsum board 48 × 48 ST/A, k600 Stone panel cladding

Table A5. *Cont.*

Construction Type	Structural Layer	Product
Intermediate floor gallery corridor, 1424 m^2	CLT Wind barrier Battening Exterior cladding	CLT 140 L5s NVI Siniat Weather Defence 9.5 mm gypsum board Stone panel cladding
Intermediate floor balcony, 1769 m^2	Cladding Waterproofing CLT Exterior cladding	Balcony spaces Balcony membrane waterproofing CLT 140 L5s VI Surface treatment only
Intermediate floor stairwell, 427 m^2	CLT Interior cladding panel	CLT 140 L5s NVI Plasterboard GLF 15 FireLine RO

Table A6. Attic.

Construction Type	Structural Layer	Product
Attic floor insulation layers, 2328 m^2	roof underlayment sheets insulation frame CLT battening insulation battening interior cladding panel	OSB4 18 mm 1.2 × 2.7 blow-in insulation 500 mm roof trusses installed, complex shape CLT 100 L3s NVI 42 × 98, k600 Paroc Extra 100 28 × 48, k600 plasterboard GEK 13 RO
Attic floor balcony, 442 m^2	roof underlayment installation insulation frame CLT exterior cladding	OSB4 18 mm 1.2 × 2.7 blow-in insulation 500 mm roof trusses installed, complex shape CLT 100 L3s VI Surface treatment only
Attic floor shelter, 682 m^2	roof underlayment installation insulation frame CLT wind barrier battening exterior cladding	OSB4 18 mm 1.2 × 2.7 blow-in insulation 500 mm roof trusses installed, complex shape CLT 100 L3s NVI Siniat Weather Defence 9.5 mm 48 × 48 ST/A, k600 gypsum board

Appendix D

Table A7. Sources of detailed emissions data for concrete structures.

Structure	Name	Product; Structural Thickness	Structure	Name	Product; Structural Thickness
Exterior wall	Sandwich inner shell	Tb C30/37, XC4, XF1; 150 mm	Partition wall of the storage closet	Tb-element wall	Tb C30/37, XC4, XF1; 180 mm
	Mineral wool insulation	Paroc cos 5 ggt; 220 mm	Intermediate floor	Surface leveling	Planar; 40 mm
	Sandwich outer shell	Tb C30/37, XC1; 70 mm		Sound insulation	Footstep sound insulation board and filtering fabric; 30 mm

Table A7. *Cont.*

Structure	**Name**	**Product; Structural Thickness**	**Structure**	**Name**	**Product; Structural Thickness**
Exterior wall	Sandwich inner shell	Tb C30/37, XC4, XF1; 80 mm		Hollow-core slab intermediate floor	OL 320 seamless; 320 mm
	Mineral wool insulation	Paroc cos 5 ggt; 220 mm	Intermediate floor	Concrete element intermediate floor	Tb-slab C30/37 XC1; 260 mm
	Sandwich outer shell	Tb C30/37, XC1; 70 mm	Intermediate floor	Concrete element intermediate floor	Tb-slab C30/37 XC4, XF1; 260 mm
The wall between the apartments	Tb-element wall	Tb C25/30, XC1; 200 mm	Upper floor	Roofing plywood	WISA-Kate Plus; 19 mm
Load-bearing partition wall	Tb-element wall	Tb C25/30, XC1; 200 mm		Roof trusses	NR-purlin truss
Partition wall for balcony	Tb-element wall	Tb C30/37, XC4, XF1; 180 mm		Mineral wool insulation	Blown stone wool insulation Paroc BLT 6; 460 mm
Stairs	Solid slab staircase	Rudus Elemento 9		Hollow-core slab roof	OL 320 seamless; 320 mm

Appendix E

Table A8. Sources of detailed emissions data for solid wood structures.

Structure	**Name**	**Product; Structural Thickness**	**Structure**	**Name**	**Product; Structural Thickness**
Exterior wall	CLT panel	CLT 240 L7s BVI; 240 mm	Entrance floor/level	CLT panel	CLT 140 L5s NVI; 140 mm
Exterior wall	CLT panel	CLT 180 L5s VI; 180 mm		Plasterboard cladding	Siniat WD plasterboard; 9.5 mm
	Wind barrier insulation	Eriste Paroc Cortex; 50 mm		Battening	48 × 48 ST/A, k600; 48 mm
	Framing	28 × 98 k600; 28 mm		Stone board cladding	Flexit; 9 mm
	Framing	28 × 98 k600; 28 mm	Attic floor	CLT panel	CLT 140 L5s NVI; 140 mm
	Stone panel cladding	Flexit; 9 mm		Plasterboard cladding	Siniat WD plasterboard; 9.5 mm
Exterior wall	CLT panel	CLT 180 L5s VI; 180 mm		Battening	48 × 48 ST/A, k600; 48 mm
	Wind barrier insulation	Paroc Cortex insulation; 50 mm		Stone board cladding	Flexit; 9 mm
	Framing	28 × 98 k600; 28 mm	Balcony floor	CLT panel	CLT 140 L5s VI; 140 mm
	Framing	28 × 98 k600; 28 mm	Balcony floor	CLT panel	CLT 140 L5s NVI; 140 mm
	Exterior cladding	Exterior. Spruce UYS 28 × 95; 28 mm		Plasterboard cladding	Plasterboard GLF 15 Fireline RO; 15 mm

Table A8. *Cont.*

Structure	Name	Product; Structural Thickness	Structure	Name	Product; Structural Thickness
Interior wall	Plasterboard cladding	Plasterboard GLF 18 Fireline RO; 18 mm	Ceiling/floor structure	Underlay boarding	OSB4 18 1.2 × 2.7; 18 mm
	CLT panel	CLT 100 C3s NVI; 100 mm		Insulation	Paroc BLT 6; 500 mm
	Insulation	Paroc extra 50; 50 mm		Roof trusses	NR purlin truss
	CLT panel	CLT 100 C3s NVI; 100 mm		CLT panel	CLT 100 L3s NVI; 100 mm
	Plasterboard cladding	Plasterboard GLF 18 Fireline RO; 18 mm		Battening	42 × 98 ST/A, k600; 98 mm
Load-bearing partition	Plasterboard cladding	Plasterboard GLF 18 Fireline RO; 18 mm		Insulation	Paroc Extra 100; 100 mm
	CLT panel	CLT 180 L7s NVI; 180 mm		Battening	28 × 48 ST/A, k600; 28 mm
	Plasterboard cladding	Plasterboard GLF 18 Fireline RO; 18 mm		Plasterboard cladding	plasterboard GEK 13 RO; 13 mm
Balcony partition	CLT panel	CLT 200 L7s VI; 200 mm	Balcony ceiling	Underlayment boarding	OSB4 18 1.2 × 2.7; 18 mm
Attic partition	Stone panel cladding	Slolid board; 9 mm		Insulation	Paroc BLT 6; 500 mm
	CLT-levy	CLT 180 L7s NVI; 180 mm		Roof trusses	NR purlin truss
	Stone panel cladding	Slolid board; 9 mm		CLT panel	CLT 100 L3s NVI; 100 mm
Intermediate floor	CLT panel	CLT 160 L5s NVI; 160 mm	Attic floor	Subroofing	OSB4 18 1.2 × 2.7; 18 mm
	Light frame	48 × 98 C24, k600; 98 mm		Insulation	Paroc BLT 6; 500 mm
	Insulation	Paroc extra 100; 100 mm		Roof trusses	NR purlin truss
	Battening	28 × 48 ST/A, k600; 28 mm		CLT panel	CLT 100 L3s NVI; 100 mm
	Spring slat	Acoustic spring slat; 25 mm		Plasterboard cladding	Siniat WD plasterboard; 9.5 mm
	Plasterboard cladding	Plasterboard 2 × 13 GEK; 26 mm		Battening	48 × 48 ST/A, k600; 48 mm
Stairs	Staircase Element	CLT Staircase Element		Stone board cladding	Flexit; 9 mm
			GLT	GLT	GLT

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