Economic and Environmental Scenario Analysis of a Finnish Wood-based Case Building

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ABSTRACT

The construction industry is a major contributor to Greenhouse Gas (GHG) emissions, highlighting the need for more sustainable building practices. While building costs often drive project decision-making, environmental impacts from material production to building operation are considered equally significant. Wood has emerged as a viable alternative to traditional construction materials, offering reduced carbon emissions and potential cost savings. This study aims to assess the environmental and economic performance of a wooden-framed educational building in Finland, with a focus on life-cycle carbon emissions and cost-effectiveness. The case building is a single-story structure with glulam external walls, beams, and columns. A Life Cycle Assessment (LCA) and cost analysis has been conducted using LCA tools provided by the Finnish Ministry of Environment, alongside a comparative scenario analysis involving alternative structural materials. Three alternative scenarios have been designed with different materials utilized for external walls and the structure, i.e., beams and columns. The findings reveal that wood-based structures can achieve substantial reductions in carbon emissions while remaining cost-competitive, particularly in early life-cycle stages compared to conventional reinforced concrete options. The results of this study partially challenge the widely recognized barrier to adopting greener building practices, namely the incremental cost of sustainable construction. Additionally, scenario analysis highlights the potential for hybrid structural systems to balance environmental benefits with economic feasibility. This research contributes practical insights into how contractors and policymakers can adopt wood and hybrid materials to support low-carbon construction goals.

Keywords-life cycle assessment; greenhouse gas; timber construction; low-carbon material; cost analysis

I. INTRODUCTION

The construction industry contributes approximately 30-55% of the total human-induced GHG emissions and accounts for 40% of the global energy consumption [1-3]. The UN Paris Climate Agreement (PCA) aims to reduce GHG emissions to prevent rising global temperatures more than 2 °C. All 195 UN-recognized sovereign states, including United States who rejoined on January 20 of 2021, have committed to this agreement, which has been effective since 2016. Under the PCA, the European Union committed to have achieved carbon neutrality by 2050. Individual countries aim to hit this target earlier: Finland by 2035, Sweden by 2045, and both France and the United Kingdom by 2050. Finland's target is largely supported by its natural carbon sinks as 75% of its land area is covered by forests. Specifically, the capital city, Helsinki, intends to have achieved the target by 2030. Having achieved carbon neutrality, Finland plans to achieve carbon negativity through the use of carbon offsetting and Carbon Capture and Storage (CCS) technologies [4].

The environmental impact and carbon footprint of construction projects are not yet entirely understood or commonly monitored and regulated. In 2019, the Finnish Ministry of the Environment introduced a Microsoft Excel-based tool for pilot use. The tool calculates the carbon footprint of construction projects by accounting for the entire life-cycle of a building, including material production, construction, operation, and demolition phases. This kind of assessments are expected to become essential to construction projects [4].

Based on various calculations, the life-cycle of a building is assumed to span around 50 years [5]. Throughout the building's life-cycle, different phases are of interest to different stakeholders [6]. The emissions from the design and production phases are estimated to account from 10% to 50% of the building's total life-cycle emissions, with the majority of the remaining emissions arising from energy consumption during the operational phase [3, 7]. However, the significance of material choices and structural components in reducing emissions is expected to grow as operational energy increasingly shifts toward sustainable sources and building technologies become more energy-efficient [8].

Contractors' business models are primarily focused on the revenues generated during the production, design, and construction phases of a project, with the investment periods typically ranging from 1 to 5 years [9]. However, the time horizon has a significant impact on the cost-effectiveness of green investments in construction. Researchers in [10], demonstrated that profitability increases substantially when the investment period extends to 10-25 years, as compared to 1-10 years, depending naturally on the interest rate level. Encouraging environmentally friendly decisions during production, design, and construction requires understanding the stakeholder motives. Helping contractors manage and reduce their carbon footprint in an economically viable way benefits all real estate development parties and promotes environmental sustainability.

Wooden structures outperform other materials in terms of environmental impact [11-15]. On the contrary, a number of studies examining the economics of sustainable construction identify higher construction costs as the main obstacle to adopting less carbon-intensive materials [4, 16]. Nevertheless, literature also exists suggesting that wood as a framing material can be more cost-effective than alternative options [17, 18].

For instance, in [11], a cradle-to-gate LCA was conducted comparing a traditional cast-in-place reinforced concrete frame with a laminated timber hybrid design for a typical North American mid-rise office building. The laminated timber design utilized engineered wood products, such as Cross-Laminated Timber (CLT) and glulam. The study found that the cumulative embodied energy of construction materials was higher for the timber design at 8.2 GJ/m² compared to the concrete design 4.6 GJ/m². However, the timber design stored a significant amount of carbon within the building materials, highlighting its potential for carbon sequestration.

Authors in [13] analyzed the variability in energy and CO_2 balances between wood and concrete building materials. The wood-framed buildings consistently exhibited lower CO_2 balances than concrete-framed buildings. The use of demolition and wood processing residues as biofuels substantially improved the energy and CO_2 balances of wood-based construction materials. In addition, authors in [12] conducted a comparative life cycle study focusing on alternative materials for Australian multistorey apartment building frame constructions. The research assessed both environmental and economic perspectives, providing insights into the performance of various construction materials in terms of sustainability and cost-effectiveness.

A comparative carbon footprint analysis of residents living in wooden versus non-wooden houses was carried out in Finland, providing valuable data on the environmental impacts of different housing materials and offering insights on how material choices affect carbon footprints [14]. Another study explored the concept of cities acting as carbon sinks through the classification of wooden buildings [15]. The results suggest that the annual captured CO_2 by future building construction in Europe will range between 1 and 55 Mt, which is equivalent to 1% and 47% of CO_2 emissions from the European cement industry.

The barriers and drivers for sustainable building were investigated, highlighting elevated construction expenses as a primary impediment to the adoption of less carbon-intensive materials [16]. Their study offered a comprehensive analysis of the economic challenges and potential incentives related to sustainable construction practices. Authors in [17] examined the costs associated with mass timber construction, introducing the concept of the Total Cost of Project (TCP). Their findings revealed that when accounting in construction speed and labor efficiency, mass timber could prove to be a more cost-effective framing material compared to traditional options. Furthermore, an overview of wood construction practices in Europe through the LeanWOOD project is provided in [4], offering insights into the state of wood construction and discussing both the advantages and challenges of adopting wood as a primary building material in European contexts.

However, it is necessary to consider technical aspects in addition to environmental and economic factors. An innovative construction approach for bungalows, traditionally single-story dwellings primarily built with wood is explored in [19]. The authors introduced a design utilizing S235 grade steel, emphasizing its superior durability and higher modulus of elasticity compared to wood. The design features a hexagonal floor plan and leverages prefabricated modular steel components to facilitate mass production and ease of transportation to construction sites. The evaluation focused on parameters, such as displacement, modal analysis periods, and self-weight. The study found that steel and wood had similar structural performance, but steel structures were significantly lighter offering durability and weight advantages over traditional wooden structures.

Despite the increasing interest in sustainable construction, there remains a lack of comprehensive studies that evaluate both economic and environmental trade-offs in wood-based building projects. While prior research has demonstrated that wooden structures generally have a lower carbon footprint compared to concrete and steel alternatives, studies that integrate real-world cost data from contractors remain limited. Additionally, existing literature often focuses on single-variable analyses, either carbon emissions or cost, without a holistic scenario-based approach that captures the interplay between different structural choices and economic feasibility. Given the growing emphasis on carbon neutrality goals in Finland and the need for cost-efficient sustainable solutions, there is a critical need for research that provides quantitative insights into the cost-carbon relationship for decision-makers in the construction industry.

This study aims to offer practical understanding on how contractors and policymakers can incorporate wood and hybrid materials to advance low-carbon construction objectives. It examines the potential benefits and challenges of utilizing these sustainable materials in building projects, providing insights to help drive the adoption of more environmentally-friendly construction practices.

II. METHODOLOGY

The research was conducted in two key stages. First, an economic and environmental analysis was performed on a case building located in Finland. This analysis is focused on evaluating the building's life cycle, including material costs and carbon footprint, to determine the most cost-efficient and environmentally friendly options. In the second stage, three alternative scenarios were developed, each involving a change in building materials. These scenarios were then compared with the original case building to assess the impact of the material changes on both cost and carbon emissions.

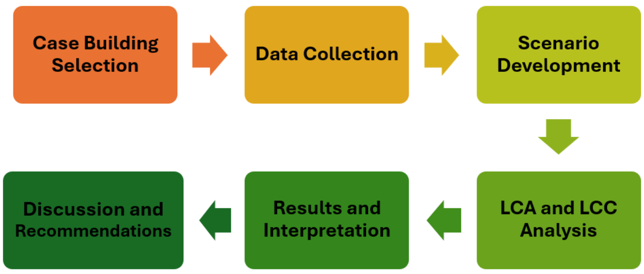

Fig. 1. Framework of the study.

The carbon footprint of the case building is evaluated using a draft carbon footprint assessment tool developed by the Finnish Ministry of Environment in 2019. The corresponding cost data will be obtained from the production management software utilized by the case contractor and developer, Jatke Oy. For comparison, cost and quantity data from a more conventional Steel-Reinforced Concrete (SRC) framed building with sandwich panel exteriors will be gathered from another project completed by the same case contractor. To ensure comparability, the case building's exterior walls, beams, and columns were hypothetically altered to a corresponding SRC frame with sandwich panel exteriors.

A. Case Study

In [4], it was concluded that educational buildings, which are often at least partially publicly funded, represent an ideal building type for introducing requirements to declare and eventually monitor emission levels. The Public Procurement and Concessions Act 29.12.2016/1397 in Finland, reformed in 2016, includes a provision that allows and encourages public procurers to incorporate environmental considerations and life-cycle costs as criteria or preconditions in the evaluation process (Act 1397/2016). Furthermore, Technical Research Centre of Finland (VTT) steering method number one, proposes that starting with publicly funded, and technically "simple and comparable" projects would lead the industry and suppliers toward more sustainable options while mitigating risks for smaller operators.

The case building analyzed in this study is a school and sports hall located in the municipality of Myrskylä, in the Uusimaa region of Southern Finland, approximately 95 kilometers northeast of Helsinki [20]. The building is a single-story structure featuring glulam external walls, beams, and columns. Half of the roof is constructed with Laminated Veneer Lumber (LVL) elements, while the other half consists of sawn timber roof trusses covered with sheet metal roofing. Aboveground, reinforced concrete is employed for the base elements, ground, and intermediate floors, which include the theater stage structure, ventilation engine rooms, and the on-site cast air-raid center. Two ventilation engine rooms are located in lofts, one serving the sports hall and the other serving the remaining areas of the school, with the loft structures being implemented using steel beams and columns. Wood is used extensively for most partition walls and as an interior surface on other material walls to create a cohesive aesthetic. Additionally, hardwood interior flooring is installed in places where acoustic requirements and the purpose of the room permit its use.

The gross floor area of the building is 3,416 m², of which 3,099 m² is net floor area. Approximately 2,250 m² is allocated to the school, and 850 m² to the sports hall. The building's net volume is 20,920 m³. The construction schedule spans from April 2020 to December 2021. However, the school portion of the building was operational for approximately 150 students, from pre-school to the end of elementary school by August 2021, that is, on time for the fall semester. From August to December, the finishing work on the sports hall and yard was continued. The plot area is 27,000 m².

B. Life Cycle Assessment Tool

The Finnish Ministry of the Environment has developed a calculation tool for assessing the life-cycle carbon footprint of buildings, which accounts for both operational and embodied carbon. The tool measures life-cycle emissions in terms of tons of CO_2-equivalent (CO_2-eq) and kilograms of CO_2-eq per net square meter per year (kgCO_2-eq/netm²/year), which serve as the unit of Global Warming Potential (GWP). Additionally, the tool assesses the carbon handprint, or the potential for carbon compensation, using the same units; however, the carbon handprint is not offset against the carbon footprint in the tool's assessment.

The tool allows users to input data related to building materials, energy consumption, and other relevant factors. It enables calculations for building materials using product-specific environmental declarations, emission values from the national emissions database, or emission values from other available generic databases. The tool aligns with the Finnish Ministry of the Environment's method for the whole life carbon assessment of buildings, ensuring consistency with national guidelines.

The GHG emissions of a building are referred to as its carbon footprint, with all emissions converted to CO_2-eq using the assessment tool. In the result section, the calculated carbon footprints are presented in total tons of CO_2-eq., as well as in terms of GWP, measured as tons of CO_2-eq per net square meter per life-cycle year. This study will specifically focus on prior-usage emissions, examining how material choices impact these emissions, the total carbon footprint, and their cost-effectiveness for contractors. However, life-cycle costs, operating costs, and operational emissions will not be further analyzed.

C. Cost Analysis

The costs throughout a building's life-cycle are typically distributed between the developer and/or contractor during the product and construction phases, A1 to A5 as presented in Table I. Initially, the material supplier is responsible for production costs; however, once the decision to build is made, the most significant and cost-intensive elements, such as the frame, are produced to order. In the use stage, from B1 to B7, the owner-occupier bears responsibility for the operational and maintenance costs.

There are several economic stakeholders involved throughout a building project's life-cycle. From the perspective of first-hand costs, stages A1 to A3 are covered by the supplier, followed by the contractor, and then the owner. In contrast, the use stages, namely B1, B2, B6, and B7 referring to the use of products, maintenance, operational energy use, and operational water use, are overseen and paid for by the owner-occupier. This fragmented distribution of first-hand costs is significant and must be considered when aiming to influence changes in the decision-making processes of suppliers and contractors.

TABLE I. LIFE-CYCLE STAGES OF A BUILDING AND ITS INCLUSION

Life-cycle stage	Description	Phase
A1-A3: Product stage	Extraction of raw materials, transportation to the production facility, and manufacturing of construction products (e.g., concrete, steel, wood, etc.).	Pre-Use
A4-A5: Construction process stage	Transportation of products to the construction site (A4) and the construction/installation process (A5).	Pre-Use
B1-B7: Use stage	Includes use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7).	Use
C1-C4: End-of-Life stage	Deconstruction/demolition (C1), transportation of waste materials (C2), waste processing (C3), and disposal of materials (C4).	Post-Use
D: Benefits and loads beyond the system boundary	Potential benefits from material reuse, recycling, or recovery after the building's life-cycle (e.g., recycling of steel, energy recovery from materials).	Post-Use

The original budget for the project was initially negotiated to be between €6.7 and €7 million. After further discussions, the target cost specified in the contract was set at €7.5 million, with a cost ceiling of €7.65 million. It is important to note that this contract and case study do not include the demolition of the previous school buildings on the site.

D. Scope of the Study

The contractor monitors the budget using the Finnish production management software Evry Jydacom (JD). All costs and payments related to the project are processed through the software and assigned to specific areas via coded entries. However, as the carbon footprint was calculated using the carbon footprint assessment tool developed by the Finnish Ministry of Environment, which follows the "House2000" transcription system, while the contractor utilized the "House80" transcription system, manual adjustments were required to align the division of costs with the carbon footprint data.

In the House80 transcription, there are a total of ten main codes. In this study, each main code's proportion of costs and carbon footprints will be referenced relative to the overall totals. The specific areas covered by these ten codes are detailed in Table II.

While considering a life-cycle of 50 years, this study focused on specific stages of the building's life-cycle to analyze both economic and environmental impacts. Table I outlines the entire building life-cycle, with the stages being considered in this study highlighted in bold. Some stages, such as the benefits and loads beyond the system boundary (D), were not included in the analysis due to their lesser relevance to the scope of this study.

TABLE II. HOUSE80- CODE DESCRIPTIONS

Main code	Description
0	Developer expenses
1	Site and ground works
2	Foundations and insulation
3	Frame and roof structures
4	Supplementary structures
5	Surface structures
6	Fittings, equipment, and appliances
7	HVAC works
8	Site operation expenses
9	Site joint expenses

A total of 66 codes were used for cost management in the case building, as recorded in the production management software, and as depicted in Table III. Table III is organized in descending order. The last column presents the proportional significance of each code in relation to the contractor's total costs. Codes highlighted in bold were included in the carbon footprint assessment. However, the cost comparison focuses on the overall building costs, providing a more realistic analysis of the economic impact on the contractor. Notably, the last four rows represent codes that had no costs allocated to them.

TABLE III. INCLUDED AND EXCLUDED CODES IN THE STUDY

Code	Code description	% €	Code	Code description	% €
71	**HVAC works**	**12.5**	86	On-site heating	0.4
30	**Log, glulam frame, and roof elements**	**10.7**	18	Equipment/external works on plot	0.4
12	**Excavations**	**7.5**	**22**	**Ground floor insulations**	**0.4**
73	**Electric works**	**6.4**	72	Sawdust removal	0.4
26	**Load bearing systems (foundation)**	**5.2**	85	Site utensils	0.4
21	**Footings and foundations**	**4.5**	44	Movable door system	0.3
37	**Attic and roof structures**	**4.4**	**35**	**External walls**	**0.3**
9110	Site supervision	3.7	9710	Kilometre allowances	0.3
56	**Internal floor surfaces**	**3.6**	96	Site insurances	0.3
45	**Non-load bearing partition**	**3.4**	**34**	**Stairs**	**0.3**
3	Designing and planning	3.2	42	Smoke evacuation system	0.2
43	**Doors**	**2.7**	8170	Site safety	0.2
9510	Additional works	2.4	**17**	**Pavements**	**0.2**
9511	Kitchen additional works	2.1	15	Underground draining	0.1
61	Fittings	2.1	55	External wall surfaces	0.1
92	Measuring	2.1	48	Roof inlets	0.1
51	**Roof**	**2.1**	9132	Data systems	0.1
53	**Internal ceiling surfaces**	**1.8**	94	Climate related additional works, winter	0.1
58	Painting, spreading and wallpapers	1.8	11	Clearance and demolition	0.1
25	**Civil defence centre**	**1.8**	63	Machines and devices	0.1
62	Equipment	1.6	47	Snowfall protection	0.1
14	**Piling**	**1.1**	46	Special partitions	0.1
52	**Internal wall surfaces**	**1.1**	9125	Site office	0
91	Site management	1.1	82	On-site installations	0
81	Site office buildings	1.1	97	Employees bonuses	0
84	Site machinery	0.9	9730	Utensil allowances	0
41	**Aluminium windows**	**0.7**	5	Public authority	0
87	Transportation/delivery	0.7	9750	Employees kilometre allowance	0
28	**External structures**	**0.6**	L	Non-coded costs	0
83	Site cranes	0.6	16	Filling, compression, and stabilisation	0
33	**Slabs and beams**	**0.6**	27	Special structures	0
9112	Per diem and kilometre allowance	0.5	78	Works for developers' acquisitions	0
9512	Av-cables additional works	0.5	6	Interfacing costs	0

E. Alternative Scenarios

Alternative structural systems were carefully selected from a building project that was constructed under similar conditions, including the same climate, timeline, and contractor, to ensure that the comparison would be as reliable as possible. The comparison data were sourced from a SRC office building in Helsinki, completed in August 2021 by the same contractor, Jatke Oy. The external walls of the office building were constructed using sandwich paneling elements made of sheet metal and mineral wool insulation. For acoustic purposes, the interior of these panels was framed, insulated, and finished with double layers of gypsum board on the inside.

The comparative project is a larger building, consisting of five floors with a gross net floor area of 14,200 m². In this building, wood was not used in the load-bearing structures. Notably, the structural frames for both the case building and the comparative project were tendered and invoiced during the 1st and 2nd quarters of 2020, ensuring consistency in the comparison of cost data. The accuracy of the cost data and the suitability of the selected comparative structures were verified in consultation with the Head of Production and Tendering and the Head of Design Management at the case company.

All comparative scenarios in the sensitivity analysis focus on the code 3, which relates to the exterior, frame, and roof elements. This code was the second most significant in terms of the total costs of the case building. The roof elements remain constant across all tested scenarios. Based on the attributes of the case building and conventional building solutions identified in the literature review, the comparative scenarios were selected as follows:

- **Scenario 1.1**. The exterior wall material is exchanged from glulam log to sandwich panels made of sheet metal and mineral insulation wool. In this scenario, the beams and columns remain glulam. All other materials and costs are assumed to remain constant.
- **Scenario 1.2**. Beams and columns are exchanged to more conventional SRC. In this scenario, the exterior wall material remains glulam log. All other materials and costs are assumed to remain constant.
- **Scenario 2.** In the final scenario, both assessed structures are changed at the same time. The exterior in this scenario is sandwich panel, and beams and columns are SRC.

III. RESULTS

A. Results from the Case Study

Using the tool developed by the Finnish Ministry of Environment, the total carbon footprint of the case building, from production to demolition, amounts to 3,822,000 $kgCO_2$-eq, while the carbon handprint, resulting from the use of materials with carbon storage potential, is -1,252,000 $kgCO_2$-eq. Table IV presents the values for different life-cycle stages. The distribution of emissions aligns with findings in the literature, indicating that embodied energy and material choices are becoming increasingly important for total life-cycle emissions [11].

TABLE IV. CASE STUDY EMISSION DISTRIBUTION

Life-cycle stage	kgCO2-eq	kgCO2-eq/netm2	kgCO2-eq/netm2/year	% of total
Production A1-4	1,995,756	644	12.88	52.2
Construction A5	85,222.5	27.5	0.55	2.2
Reconstruction B3-4	148,752	48	0.96	3.9
Usage B6	1,489,069.5	480.5	9.61	39
Demolition C1-4	103,816.5	33.5	0.67	2.7

TABLE V. CASE STUDY COST AND INITIAL EMBODIED EMISSION DISTRIBUTION

Main code	Main code description	% of €	% CO2-eq (A1-A5)	%CO2-eq/ %€
0	Developer expenses	3.2	Not assessed	N/A
1	Site and ground works	9.4	12.2	1.3
2	Foundations and insulations	12.6	51.7	4.1
3	Frame and roof structures	16.3	12	0.7
4	Supplementary structures	7.6	5.7	0.7
5	Surface structures	10.5	10.9	1
6	Fittings, equipment, and appliances	3.7	Not assessed	N/A
7	HVAC works	19.3	3.3	0.2
8	Site operation expenses	4.3	Not assessed	N/A
9	Site operation expenses	13.1	Not assessed	N/A
	Site operations (A5)	No data	4.1	N/A

In terms of costs, the frame, main code 3 is the second most significant cost group, following HVAC works, main code 7, as seen in Table V. Together with main code 2, which covers the foundations and ground floor slabs, these components account for 28.9% of the total costs. However, the carbon footprint distribution deviates from the cost distribution, as identified by the carbon footprint assessment tool, which places much greater emphasis on main code 2, covering the majority of the concrete elements in the case building. More detailed information about individual materials within each code, their environmental and economic impacts, and their correspondence is shown in Table V. Main code 2 stands out, representing 51.7% of the carbon footprint, but only 12.6% of the total costs. At the opposite end of the spectrum, HVAC works account for nearly one-fifth of all costs, 19.3%, but contribute only 3.3% of the carbon footprint in the pre-use phase.

To highlight the relative significance of different codes to the overall outcomes, the percentage of CO2-eq emissions for each code was divided by the costs associated with that code. In theory, the higher this ratio is, the more potential there is for the contractor to reduce the carbon footprint by targeting the volume of materials linked to those codes. The upper half of the 22 codes accounts for 23.6% of the total building project costs but is responsible for 72.1% of the pre-use carbon footprint, as presented in Table VI. Conversely, materials appearing lower on the list are less carbon-intensive relative to their costs. This suggests that increasing the volume of these lower-ranking materials would decrease the carbon footprint but simultaneously raise the current project costs. The lower half of the codes represents 48.4% of the total project costs while contributing only 23.8% to the pre-use emissions. When the table was sorted in descending order based on this ratio, the results showed the following patterns.

B. Results from the Scenarios

1) Scenario 1.1

In this scenario, only the exterior material was modified, replacing glulam logwood with sandwich panels made of sheet metal, and mineral wool insulation. This alternative required the addition of gypsum boarding and some wooden framing for the interior side of the walls, while all other materials and costs remained the same as in the case building. The resulting total carbon footprint for this scenario was 3,894,000 $kgCO_2$-eq, with a carbon handprint of -918,000 $kgCO_2$-eq, attributed to the use of materials with carbon storage potential, such as wood.

TABLE VI. SCENARIO 1.1 INITIAL EMBODIED EMISSION DISTRIBUTION.

Life-cycle stage	$kgCO_2$-eq	$kgCO_2$-eq/netm^2	Kg CO_2-eq/netm^2/year	% of the total
Production A1-4	2,068,582.5	667.5	13.35	53.1
Construction A5	85,222.5	27.5	0.55	2.2

Table VII provides a detailed breakdown of the life-cycle emissions for this scenario. Notably, the highest percentage of CO2-eq per percentage of euro was in code 22 regarding ground floor insulation and received a value of 30.4, suggesting that ground floor insulation has a significant impact on the carbon footprint. On the other hand, the lowest percentage of CO2-eq per percentage of euro was observed in codes 28 and 73 translating to external structures and electric works, with a value of 0.1 for both cases indicating a relatively lower impact on the carbon footprint compared to other components.

2) Scenario 1.2

In this scenario, the material for the beams and columns was changed from glulam to SRC, while all other materials and costs remained unchanged compared to the case building. The total carbon footprint for this scenario amounted to 3,876,000 $kgCO_2$-eq, with a carbon handprint of -1,130,000 $kgCO_2$-eq due to the use of materials with carbon storage potential. The detailed distribution of emissions is outlined in Table VIII.

3) Scenario 2

In this scenario, both the exterior wall material was changed from glulam logwood to sandwich panels, and the beams and columns were switched to SRC. All other materials and costs remained constant, as in the case building. The total carbon footprint for this scenario was 3,948,000 $kgCO_2$-eq, while the carbon handprint was -514,000 $kgCO_2$-eq. The distribution of emissions for this scenario is detailed in Table IX.

TABLE VII. CASE STUDY COST AND INITIAL EMBODIED EMISSION DISTRIBUTION

Code	Code description	Material	% of €	% CO2-eq (A1-A5)	%CO2 -eq/ % of €
22	Ground floor insulations	Expanded polystyrene (EPS)	0.4	12.3	30.4
21	Footings and foundations	Concrete	4.5	16.2	3.6
26	Other load bearing systems (foundation)	Concrete	5.2	18.5	3.5
33	Slabs and beams	Concrete	0.6	1.9	3.2
14	Piling	Concrete	1.1	3.6	3.2
25	Civil defence centre	Concrete	1.8	4.7	2.6
51	Roof	Cold rolled steel	2.1	4.3	2.1
17	Pavements	Concrete	0.2	0.3	1.9
56	Internal floor surfaces	Acrylic mass and concrete	3.6	5.2	1.4
41	Aluminium windows	Glass	0.7	1.0	1.4
45	Non-load bearing partition	Gypsum and hard board	3.4	4.2	1.2
12	Excavations	Gravel, sand, and stone	7.5	8.3	1.1
34	Stairs	Steel	0.3	0.3	1.0
37	Attic and roof structures	Wood (timber and LVL)	4.4	3.5	0.8
30	Exterior, frame, and roof elements	Wood (Glulam, LVL, and timber)	10.7	6.3	0.6
52	Internal wall surfaces	Ceramic tiles and timber	1.1	0.6	0.6
53	Internal ceiling surfaces	Veneer and gypsum	1.8	0.9	0.5
35	External walls	Parco fire protection board	0.3	0.1	0.3
71	HVAC works	N/A	12.5	2.5	0.2
43	Doors	Glass and steel	2.7	0.5	0.2
28	External structures	Wood (timber and LVL)	0.6	0.1	0.1
73	Electric works	N/A	6.4	0.8	0.1

TABLE VIII. SCENARIO 1.2 INITIAL EMBODIED EMISSION DISTRIBUTION

Life-cycle stage	kgCO2-eq	kgCO2-eq/netm2	kgCO2-eq/netm2/year	% of the total
Production A1-4	2,049,988.5	661.5	13.23	52.9
Construction A5	85,222.5	27.5	0.55	2.2

TABLE IX. SCENARIO 2 INITIAL EMBODIED EMISSION DISTRIBUTION

Life-cycle stage	kgCO2-eq	kgCO2-eq/netm2	kgCO2-eq/netm2/year	% of the total
Production A1-4	2,122,815	685	13.7	53.8
Construction A5	85,222.5	27.5	0.55	2.2

C. Cost Analysis

In Table X, both the life-cycle cost and the changes in emissions are presented. The outcomes are bold-regular to indicate their desirability. The bolded scheme highlights that none of the scenarios are the most optimal in terms of both carbon footprint and cost. All hypothetical scenarios result in an increase in the project's carbon footprint compared to the case building. Scenarios 1.1 and 2 show potential for cost savings, whereas Scenario 1.2 is expected to be more expensive by 0.5. However, Scenario 1.2 is identified as the most environmentally beneficial option among the three hypothetical scenarios. Despite its environmental advantages, Scenario 1.2 should be considered the least favorable alternative overall, as the case building outperforms it in both cost and carbon footprint.

TABLE X. COST AND INITIAL EMBODIED EMISSION CHANGE OF SCENARIOS COMPARED TO THE CASE BUILDING.

Scenario	% of total change to case €	% of structures change to case €	% of change to case CO_2-eq (A1-A5)	% of change to case structures CO2-eq
Scenario 1.1	**-4.2**	**-53.5**	3.5	120.8
Scenario 1.2	0.5	7.2	**2.6**	**91.1**
Scenario 2	-3.5	-46.3	6.1	212.0

These results suggest that Scenario 1.1 would be the most optimal choice for the contractor to pursue if the goal is to reduce hybrid structures, rather than fully wooden constructions, could offer a viable solution for the proactive adoption of greener approaches in the construction industry.

The fact that Scenario 1.1, which features glulam beams and columns, is the most feasible option, while Scenario 1.2, with a glulam log exterior, is the least feasible, aligns with the literature, suggesting that engineered wood is priced according to volume [21]. The massive glulam logwood exterior was significantly more expensive than its hypothetical alternative, with the alternative exterior estimated to cost only one-third of the price of the glulam log exterior. On the other hand, the SRC beams and columns were 30% more expensive than the glulam counterparts. This finding supports conclusions from several studies, which indicate that focusing on the proportional volume of wooden structures could facilitate the proactive adoption of low-carbon construction [22].

Regarding the most cost-effective scenario production stage, from A1 to A5, carbon footprint was only 3.5% higher than that of the case building, indicating that achieving the same carbon footprint with minor adjustments is a realistic possibility. Moreover, when considering the entire life-cycle, the difference in carbon footprint between the case building and Scenario 1.1 is just 1.9%. Although scenarios without a logwood exterior have significantly lower carbon compensation potential, the sharp impact of pricing on feasibility highlights that Scenario 1.1 is a more realistic option in terms of economic sustainability, particularly under the current regulatory framework.

IV. DISCUSSION

The results from the case study's four scenarios regarding carbon footprints were clear and consistent with the findings of the literature review. The analysis confirmed that concrete is a more carbon-intensive material compared to wood, with the results reinforcing this conclusion. Additionally, there is currently no carbon compensation potential when using concrete or steel, making timber structures the only viable option for compensating emissions through material choices. Even without factoring in carbon compensation, timber structures were found to be a significantly less emissive alternative. Given Finland's current legislative framework and the robust state of the forest industry, it would be environmentally advantageous to increasingly and proactively consider timber frames in construction projects.

Another key finding was that a significant portion of the case building's prior usage stage carbon footprint originated from the concrete foundations and ground floor elements, indicated with main code 2. Similar conclusions about the impact of foundations have been drawn [8]. The significance of main code 2 ranged between 49% and 52% across the scenarios. Despite the scenario testing, the significance of main code 3, which relates to the frame, varied between 8% and 17% in terms of its contribution to the prior usage carbon footprint. The significance of these codes for the entire life-cycle carbon footprint can be estimated by multiplying these percentages by 0.55, representing the proportion of stages A1-A5 in the overall life-cycle emissions.

The relative impact of individual materials on the overall carbon footprint was largely inconsequential. However, an interesting finding was that Expanded Polystyrene (EPS) ground frost insulation accounted for approximately 12% of the prior usage carbon footprint. This suggests that considering alternative ground frost insulation materials in single-story constructions with crawl space foundations could be a cost-effective strategy for contractors to reduce their carbon footprint. Additionally, exploring different structural solutions for the ground floor, such as slab-on-grade, could reduce the need for insulation and further decrease emissions.

The main finding regarding the contractor's costs was that glulam beams and columns were found to be 28% cheaper than the SRC alternatives. Additionally, the comparative exterior structure was found to be 65.6% less expensive than the logwood exterior. These findings lead to an important conclusion: for this building, an approach involving individual material procurement and a hybrid framing system would have been the most cost-efficient option for the contractor.

The results indicated that the exterior elements, beams, and columns accounted for 7.6% of the contractor's total costs in the case building, whereas in the most cost-efficient scenario (Scenario 1.1), this percentage was reduced to 3.7%. Across all scenarios, the structural elements' proportion of total building costs ranged from 3.7% to 8.1%. Notably, the second most cost-efficient option, Scenario 2, was only 0.7% more expensive than Scenario 1.1. Scenario 2 employed more conventional building materials, and as suggested in the literature, this small cost difference can act as a barrier to exploring less conventional materials. This is especially relevant when practitioners perceive differences in risk, quality, the availability of suppliers, and supply timelines.

The results of this study partially challenge the widely recognized barrier to adopting greener building practices—namely, the incremental cost of sustainable construction. This was disproven in the case of glulam beams and columns, which were found to be more cost-effective than SRC alternatives. However, incremental costs were observed for the logwood exterior. The literature review, however, revealed another economic barrier, split economic incentives. Studies indicate no significant return on investment for less carbon-intensive or energy-efficient buildings at the point of presale [10]. As a result, the costs incurred during the production phase, from A1 to A5, remain the primary factor influencing contractors' decision-making.

Literature has highlighted that the incremental costs of green investments and split incentives between stakeholders across a building's life-cycle are the primary barriers to achieving more carbon-neutral construction [23, 24]. This case study found the first barrier to be only partially true, as contractors could overcome incremental costs by proactively adopting less conventional and more cost-efficient procurement choices. Furthermore, the most carbon-neutral scenario in this study was not the least carbon-intensive one, and the least carbon-intensive option was identified as the second most expensive. Although the second barrier, namely split economic incentives, did not directly appear in this case study, it was recognized in the literature review. This barrier stems from longer returns on investment for greener construction and the green price premium, which is primarily driven by lower operational costs—an incentive that does not directly benefit the contractor.

This study sought to determine whether a contractor could make less carbon-intensive investments without incurring a profit loss. Interestingly, the codes included in the carbon footprint calculations accounted for 72% of the contractor's total costs. This implies that, regardless of the financial incentives for using greener materials, 28% of the costs are essentially fixed and not influenced by carbon-reducing measures. This gap highlights a significant constraint that should be recognized by decision-makers when encouraging the adoption of greener construction practices.

A. Barriers of Green Construction

An increasing number of studies are examining the economic feasibility of green, less carbon-intensive buildings. A phenomenon known as the green premium, which refers to the increased value of environmentally friendly solutions, is well recognized in real estate literature. However, most studies focus on the green premium of such buildings after they have become operational. These premiums are directly linked to lower energy costs, higher rents, greater occupancy rates, and increased market value, while indirect benefits include an improved corporate image, better health and comfort, and enhanced productivity. Nonetheless, research has shown that these positive premiums are more reliable once the building is in use and both direct and indirect benefits can be substantiated, such as through a proven record of lower heating and electricity costs [24].

The potential for achieving a positive green premium at presale remains uncertain. Generally, constructing more carbon-neutral buildings is considered to incur an incremental cost of 0-10% [23, 24]. Studies suggest that the green premium largely benefits the owner-occupant, meaning that for contractors, building more carbon-neutral typically results in only a 0-10% cost increase. If clearer evidence emerged showing cost-effective methods for carbon-neutral construction, it is anticipated that practitioners would adopt such practices swiftly. Consequently, in literature reviewing the state of sustainable construction, incremental costs are consistently identified as the primary barrier worldwide. This conclusion is supported by numerous studies conducted in Canada, New Zealand, Australia, the USA, China, and Singapore [25-27]. Therefore, there is an urgent need for empirical evidence and effective risk management strategies to reduce the carbon footprint without compromising business viability.

The LCA method is recognized as a useful tool for identifying problematic areas and their proportional significance in a process. However, given that a building project involves multiple stakeholders, basing investment decisions solely on the LCA and LCC perspectives can be problematic and, in some cases, may even hinder the adoption of sustainable technologies [28, 29]. While the integration of green solutions is often accompanied by LCC analysis to assess economic viability, the challenge arises because costs and profits throughout the building's life-cycle are distributed among different stakeholders. A theoretically reduced LCC alone is not sufficient to persuade all parties. Reviews on the economic viability of reducing the carbon footprint in the building sector underscore that LCC calculations are limited, as they fail to reflect realistic market mechanisms, and the resulting economic benefits are often confined to a few market participants.

This presents a barrier to green building, where the split incentives between stakeholders prevent all parties from proactively pursuing less carbon-intensive options. This issue has been acknowledged as a distinct barrier, separate from the challenge of incremental costs [15, 27-29].

In [16], it was identified that scattered information and uncertain performance data regarding more carbon-neutral practices present a significant barrier for all participants in a building project. This lack of clear and reliable data hinders investors from demanding carbon-neutral techniques, prevents suppliers from providing high-quality information about their products, and consequently causes designers and contractors to struggle in both convincing others and being convinced about the reliability of new solutions. Several studies recommend that this issue of quality and uncertainty risk should be addressed by building authorities, who must take an active role in steering these practices [16, 30].

Another critical issue is the supply chain, which plays a pivotal role in the success of a construction project. In [17], it was estimated that the supply of engineered wood may struggle to meet the growing demand in both Australia and globally. Additionally, organizational and psychological barriers significantly impede the adoption of greener construction practices. Authors in [31] identified cognitive barriers at all levels, individual, organizational, and institutional. These barriers often stem from a fear of the unknown and the reluctance to adopt new methods, resulting in an underlying resistance to change across the industry.

Finally, a lack of knowledge and information significantly limits the advancement of greener building construction globally. In [24], it was found that many practitioners are not fully aware of what sustainability in buildings entails. Moreover, they observed that certifications or design documents alone are insufficient to demonstrate a building's environmental efficiency—owner-occupiers often require tangible proof, such as actual electricity bills. Additionally, authors in [16] concluded that carbon-neutral construction is further hindered by the absence of a common language and shared understanding across stakeholders, making collaboration and adoption of greener practices more challenging.

B. Further Research

Finally, as the quantity, carbon footprint, and cost data were collected from different platforms and manually integrated, there is an inherent uncertainty due to potential human error in this study. The carbon footprint tool required unit modifications, which were also performed manually. However, in the final comparison, the quantity, carbon footprint, and cost data align with the results from their original platforms. Nevertheless, the manual processes and associated uncertainties could have been minimized through the use of a Building Information Model (BIM) and a more integrated production management software for handling the cost data.

Throughout this study, the need for research focusing on the cost of greener construction became evident. While a substantial body of literature examines the green premium related to resale value or saved operational costs in less carbon-intensive buildings, the incremental costs of building green and the issue of split economic incentives remain the primary barriers to a more proactive adoption of carbon-neutral construction. Further research addressing this gap would benefit all stakeholders striving for a more sustainable construction industry.

In general, more research is needed on the overall performance of greener multistorey buildings, particularly those with timber-carrying floors, as floors constitute a significant mass percentage of a building. Further investigation is required to understand both the impact of timber floors on the carbon footprint and their effect on construction costs. Moreover, collecting additional data on greener buildings is crucial for overcoming barriers, such as perceived quality risks and the lack of knowledge surrounding less conventional practices among contractors. These data could help reduce uncertainty and build confidence in sustainable construction methods.

V. CONCLUSIONS

This case study revealed that, contrary to concerns expressed in the literature, the most cost-effective structural choice was not the most conventional one. Specifically, glulam beams and columns were found to be 28% cheaper and a more environmentally friendly solution compared to Steel-Reinforced Concrete (SRC), with the costs including both materials and labor. This finding is significant for practitioners aiming to reduce their carbon footprint in a cost-effective way. Additionally, the most expensive option, scenario 1.2, increased total construction costs by 5% compared to the most cost-efficient option, scenario 1.1. These results should encourage stakeholders in real estate and construction to consider tendering a variety of structural materials. Furthermore, the study found that nearly 30% of the contractor's costs are not accounted for in the carbon footprint assessment. This gap should be recognized by decision-makers when setting economic incentives to reduce embodied carbon in construction.

Focusing on the mass of a material, it is essential for maximizing carbon compensation potential and carbon handprint. Wooden structures generally have a lower carbon footprint compared to concrete or steel, while also storing carbon throughout the building's life-cycle. This study found that increasing the mass of wood within a specific code by 19.6% led to a rise in carbon storage impact from 18.8% to 27.4% for the case building's prior usage stages, from A1 to A5 and from 10.3% to 15.1% over the building's full life-cycle from A to C. This effect was observed when comparing the carbon compensation potential of code 30, which includes the log exterior, glulam beams and columns, and Laminated Veneer Lumber (LVL)-roof elements.

Finally, the carbon footprint of the production stage, from A1 to A5, was found to account for approximately 55% of the entire life-cycle's carbon footprint, even after testing various material selection scenarios for the exterior, beams, and columns. This significant proportion highlights the importance of focusing on reducing the embodied carbon emissions in the built environment, as this is essential for achieving the climate goals set for the future.

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