Monetizing environmental impacts can compensate for higher upfront costs of wood construction

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ABSTRACT

The transition toward low-carbon construction has renewed interest in engineered wood products (EWPs) as alternatives to traditional materials such as steel and concrete. While EWPs offer clear environmental advantages, their higher upfront costs often discourage adoption. This study investigates whether incorporating the monetary value of environmental externalities, or indirect costs not reflected in market prices, can influence the cost-effectiveness of material choices in construction. A life cycle assessment (LCA) is applied to compare the upfront emissions of two structural design alternatives of a Finnish public building, one based on EWPs and the other on steel-reinforced concrete elements. Monetary valuation was used to translate environmental impacts from four key categories (global warming potential, acidification potential, stratospheric ozone depletion, and tropospheric ozone formation) into indirect costs. Results show that, although the wood scenario had slightly higher direct costs (~4.4 %), it delivered substantial environmental benefits, particularly in the global warming potential category. Wood elements indicated net environmental gains and showed negative indirect costs, which reduced the total cost of the elements by approximately 33 %. By integrating both direct and indirect costs, this research demonstrates a more complete method for evaluating construction materials. This approach offers new insight for aligning financial decision-making with climate goals in the built environment.

1. Introduction

The building and construction sector plays a vital role in the economy, contributing significantly to global gross domestic product and employing approximately 220 million people worldwide [1]. Beyond its economic contributions, the sector is essential in addressing societal needs, including housing, infrastructure, and public services. However, the environmental impact of the built environment is substantial. The sector is responsible for over 34 % of global greenhouse gas emissions and 34 % of global final energy demand [2].

Despite several positive trends in renewable energy adoption, green buildings certification, and circular economy practices, the sector is not on track to meet the Paris Agreement targets [2]. To address these challenges in the built environment, climate policies and funding have primarily targeted operational greenhouse gas (GHG) emissions, the emissions created during the use phase of a building. Consequently, they are expected to decrease from 75 % to approximately 50 % relative to the total life cycle emissions of a building [3]. However, measures to address GHG emissions from material extraction, manufacturing,

transportation, construction, and renovation, so-called embodied emissions, have progressed more slowly.

Carbon-intensive processes of extraction and manufacturing traditional construction materials such as steel and concrete remain a large source of embodied emissions. One solution to address and mitigate these emissions is to incorporate more bio-based construction materials, in particular wood. As a scalable renewable resource, harvested wood products and subsequent engineered wood products (EWPs) (e.g., glued laminated timber, laminated veneer lumber (LVL), cross-laminated timber (CLT), etc.) offer environmental and structural benefits, making them promising alternatives to traditional construction materials. In addition to lower embodied emissions, an increasingly recognized benefit of wood construction is its capacity to act as a temporary carbon sink. EWPs retain the biogenic carbon absorbed during tree growth, thereby contributing to carbon storage over the building's lifetime. Recent literature shows substantial potential to increase the sustainable production and use of EWPs through improved plantation management, long-term forest maintenance, and more circularity initiatives [4]. Churkina et al. [4] estimated that if 50 % of new buildings in Europe

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were constructed with wood between 2020 and 2050, cumulative carbon storage could range from 45 to 484 Mt. This potential increases substantially under a 90 % wood-construction scenario, with estimated storage between 88 and 885 Mt. Similarly, Amiri et al. [5] projected cumulative storage of 22–67 Mt for a 5 % adoption rate of wood construction over a 20-year period, rising to 356–1067 Mt for an 80 % scenario. However, it is important to note that stored carbon is not permanently sequestered, as it may eventually be released back into the atmosphere at end-of-life stages or through improper waste management.

With the development of EWPs, it has become possible to build more structurally complex timber buildings. As a result, research has increasingly focused on comparing material choices, both in terms of embodied emissions and operational performance of wood versus concrete and steel. Earlier studies were mostly case-specific, as there were fewer built examples and limited data available for timber buildings. For instance, a study in Australia compared a timber building with a reinforced concrete one, focusing on greenhouse gas emissions during the construction stage, and found that emissions from materials were lower in the timber case [6]. Another study from Iceland compared concrete, optimized concrete, hybrid, and timber alternatives, concluding that the timber building performed best across all evaluated impact categories [7].

More recently, broader literature reviews have been compiled. One review from 2022 covering 27 life cycle assessment (LCA) studies of CLT buildings found an average reduction of about 40 % in carbon footprint compared to conventional concrete and steel multi-storey buildings. The authors noted, however, that differences in climate conditions, building codes, and service life complicate direct comparisons [8]. Another review of 62 LCAs of wood buildings reported that the embodied GHG emissions of reinforced concrete buildings are on average about 42 % higher than those of wood buildings. These studies also showed that wood buildings generally achieve lower global warming potential and primary energy demand over their life cycle compared to concrete and steel alternatives [9].

The growth of the wood construction industry has progressed slowly relative to its potential to support economic growth and innovation [10,11]. Literature on the subject discusses at length possible barriers to the development of the industry, as well as potential solutions [12]. Amongst the challenges, one of the most frequently discussed remains the cost concerns of wood materials compared to traditional ones. Similar to the industry at large, EWPs often come with higher upfront costs due to limited economies of scale, less mature supply chains, and the need for specialised design and construction expertise, making them appear less competitive despite their environmental benefits [13]. In this context, contractors emerge as key stakeholders as they are often involved in the early stages of design and development for new construction [14]. However, their business models are predominantly shaped by the revenues generated during the early stages of a project (e.g., design, production, construction). Their investment periods are generally short-term, ranging from one to five years [15,16], which significantly affects how sustainability considerations are weighted in decision-making. Typically, the cost-effectiveness of green investments matures over longer time spans [17,18], which might discourage contractors from adopting more sustainable materials and practices.

To align stakeholder financial interests with environmental goals, it is essential to consider and quantify the environmental impacts and direct costs of a project, as well as indirect costs upon the environment resulting from the project's environmental impacts. Direct costs refer to the actual expenses associated with material, labour, and construction costs. While the indirect costs, also referred to as environmental externalities, are the unintended side effects of production or consumption, not reflected in market transactions [19]. These can be negative, such as the long-term effects of GHG emissions on climate change and human health [20], or positive, such as improved air quality resulting from urban green spaces. The term has been widely used in welfare economics

and later, environmental economics, which broadly argue that markets fail to allocate resources efficiently when private costs diverge from social costs. When left unaddressed, such externalities can lead to significant market failures, resulting in overproduction of harmful goods and underinvestment in beneficial public goods [21].

This principle is especially relevant in the built environment, where decisions regarding construction materials and energy use shape long-term environmental impacts. These impacts should be internalised, meaning they should be systematically incorporated into economic assessments and decision-making processes. The internalisation of externalities, through e.g., taxes, subsidies, or environmental valuation methods, can reveal the hidden costs of unsustainable choices and support more informed decision-making. For example, research as far back as 2006 showed that if the indirect costs of fossil fuel combustion were included in energy pricing, several renewable technologies would have become financially competitive with coal-based electricity generation [22].

One approach to internalising these costs is through monetary valuation, which involves assigning economic values to environmental impacts [23]. Incorporating all three aspects, i.e., environmental impacts, direct, and indirect costs, into project evaluations provides a more comprehensive understanding of the true economic and environmental trade-offs in building construction. Doing so not only supports contractors' business decisions and future practices but also contributes to economic efficiency as well as mitigates embodied emissions in buildings and advances the climate targets of the built environment sector.

The purpose of the study is to assess the direct and indirect costs of two alternative building frame designs, i.e. wooden vs. concrete, and to evaluate whether the wood design option can offer lower indirect costs and thus emphasise the economic performance of the wooden, i.e., low-GHG, option. To this end, the current study presents a case study of a school building located in Myrskylä, southern Finland. The case study includes an LCA to measure and compare the upfront environmental impacts of two design scenarios: one using engineered wood products (hereafter referred to as 'wood scenario') and the other based on steel-reinforced concrete ('SRC scenario'). There is evidence that performing and using an LCA in the decision-making process of a new construction project supports the environmental performance of the project [24]. Thus, the use of an LCA in the current study can aid in comparing the environmental impacts of the two scenarios and highlight which construction choices contribute most to embodied emissions. In addition, direct and indirect cost analyses are carried out to capture both the construction costs and the environmental externalities associated with each option. Ultimately, this study aims to examine whether, and under what conditions, assigning economic value to environmental impacts could shift cost-benefit calculations in favour of more sustainable design alternatives.

2. Methodology

The methodology of this study centres on the monetary valuation of environmental impacts to explore the environmental and cost trade-offs in building design. By converting environmental impacts into monetary terms, the study offers a framework for potential construction stakeholders and decision-makers to better understand the full implications of material choices. This approach represents a novel contribution, as including indirect environmental costs in project cost evaluations remains uncommon in both academic literature and real-world construction practice.

This study followed a structured multi-step approach to assess and compare the environmental and economic performance of two alternative building designs (Fig. 1). Initially, a literature review was conducted to identify suitable monetary valuation coefficients for GHG emissions, enabling the conversion of emissions into indirect costs. These coefficients represent economic estimates of the societal and environmental cost of emissions and were used to monetise the embodied
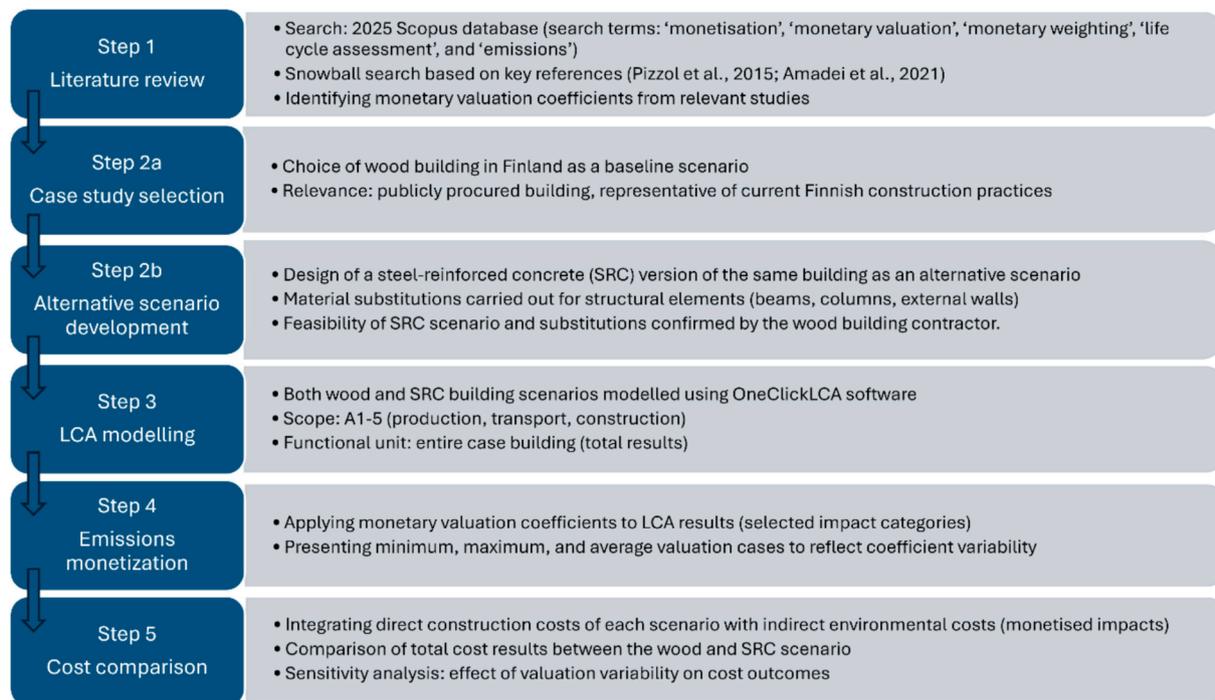
Fig. 1. Overview of the study design and workflow.

emissions associated with construction materials.

To apply the insights from the literature review, a case study was selected: a school building located in Myrskylä, Finland, originally designed using EWPs. An alternative design scenario was developed using SRC to enable a comparative analysis of structural systems. This allowed for the assessment of two building typologies under consistent functional and locational parameters. Analysing a public sector construction projects is relevant for advancing sustainable practices, as municipalities can act as early adopters and have the potential to influence the private sector [25]. Additionally, public procurement policies increasingly require environmental considerations [26], making public buildings important test cases for evaluating environmental and cost trade-offs. The public sector also offers the advantage of reliable and accessible data, which supports a more accurate analysis.

LCA modelling was then conducted for both designs using the One Click LCA software. The scope of the LCA covered the embodied emissions associated with material production, transportation, and construction stages. Subsequently, direct construction costs for both the wood-based and SRC-based designs were obtained. The emissions data from the LCA were monetised using the valuation coefficients identified during the literature review. This dual-costing approach, integrating both direct financial expenditures and the indirect environmental and societal costs of emissions, enabled a comprehensive comparison of the economic and environmental trade-offs between the two structural alternatives.

2.1. Monetary valuation coefficients

Monetary valuation has a long history in environmental economics research, as a practice of expressing societal and environmental impacts in monetary terms [23,20]. In the context of LCA, it has been adopted in the weighting phase of the life cycle impact assessment (LCIA), as one of the preferred methods to perform weighting [27]. In this study, the 'damage cost' monetary valuation method is used, which estimates the harm or 'damage' caused by an emission or an alteration to an ecosystem in monetary terms. The alternative method, 'abatement cost', estimates the potential cost of a replacement measure that prevents the emission or harmful ecosystem alteration [23]. However, the former was chosen

because it reflects real-world consequences more directly.

For the current study, a literature review was conducted in 2025 using Scopus to identify the monetary valuation coefficients. Using the terms 'monetisation', 'monetary valuation', 'monetary weighting', 'life cycle assessment', and 'emissions' to appear in all fields, restricted to the English language, 49 articles were identified, 14 of which were relevant to the aim and scope of the study. Given the wide variability in reported valuation coefficients for different impact categories (ICs), only those categories with multiple, well-supported coefficients were selected, following the publications above. The coefficients, covering global warming potential, stratospheric ozone depletion potential, acidification potential, and photochemical ozone formation, are detailed in

Table 1

Monetary valuation coefficients sourced from literature for selected environmental impact categories (Global warming potential, Depletion potential of the stratospheric ozone layer, Acidification potential, Formation potential of tropospheric ozone); units of measure converted to standard EU Level(s) units after [29]; coefficient values are presented in ascending order, with the average and median calculated on the last row.

Global Warming Potential		Depletion potential of the stratospheric ozone layer		Acidification potential		Formation potential of tropospheric ozone	
$€_{2020}$/kgCO$_2$ eq.		$€_{2020}$/kgCFC11 eq.		$€_{2020}$/ Accumulated Exceedance mol H + eq.		$€_{2020}$/kg NMVOC eq.	
Value	Source	Value	Source	Value	Source	Value	Source
0.03	[30]	32.00	[31]	0.002	[32]	0.002	[32]
0.05	[32]	32.00	[33]	0.35	[34]	0.17	[24]
0.06	[31]	46.10	[30]	0.35	[33]	1.18	[35]
0.33	[36]	52.00	[34]	0.57	[30]	1.21	[31]
0.69	[24]	115.00	[32]	1.43	[24]	1.21	[33]
Average: 0.23		**Average: 55.42**		4.00	[31]	13.90	[30]
Median: 0.06		**Median: 46.1**				**Average: 2.94**	
				12.14	[24]	**Median: 1.20**	
				Average: 2.69			
				Median: 0.57			

Table 1. By focusing on these more widely studied categories, the study aimed to increase comparability and reduce uncertainties. They were reported in euros (€) and converted to 2020 price references (the case study reference year) using the consumer price index (CPI) formula (*Formula 1*) [28].

$$Value_f = Value_i \times \frac{CPI_f}{CPI_i} \qquad (1)$$

where $Value_f$ represents the final value of the coefficient; $Value_i$ represents the initial value of the coefficient reported in literature; CPI_f is the consumer price index for the reference year (2020), while CPI_i is the initial consumer price index.

2.2. Description of case building

The case study examined in this research focuses on a recently completed school and sports hall complex in Myrskylä, southern Finland. The project was initiated in 2019 as a collaboration between the municipality and the construction company. Construction took place between spring 2020 and the end of 2021 on the site of the former school. The total cost of the project was €8.05 million, comprising €5.2 million for the school and €2.85 million for the sports hall, covering a combined net floor area of 3,099 m^2 [37,38].

The single-storey building uses wood across both structural and non-structural elements, wherever design requirements and safety standards permit. The main structural frame, as well as the exterior walls, are glued-laminated timber (glulam), while the roof combines sawn timber trusses with laminated veneer lumber (LVL) and sheet metal roofing. Internally, the design maintains a high use of wood in floors, partition walls, and ceilings, with exposed timber surfaces contributing to a warm, natural aesthetic. However, using steel and concrete was still necessary in certain areas due to functional and geotechnical requirements. These included the piling foundation (due to challenging soil conditions), as well as the base elements, floors in the theatre stage structure, ventilation engine rooms, and the air-raid centre.

For the current research study, the contractor provided their data on all costs and payments associated with the project, sourced from their production management software, *Evry Jydacom* (JD). The software processes costs for each item under a transcription system, which includes 10 code categories and follows a general breakdown of a project's lifecycle. The categories, along with their corresponding cost percentage shares, are presented in Table 2.

2.3. Description of alternative design scenario

An alternative design scenario was developed to assess the environmental and cost trade-offs associated with different structural material choices. Unlike the wood scenario, which uses EWPs for structural applications, this scenario is based on SRC. Based on the cost breakdown presented in Table 2, category 4 ('Frame and roof structures') represents the second largest cost share after 'HVAC works,' the latter of which is

not influenced by construction material selection. Therefore, it was determined that the frame of the building would be modified in the SRC scenario. The exterior wall material was replaced from glulam logs to sandwich panels composed of sheet metal and mineral wool insulation, while glulam beams and columns were substituted with steel-reinforced concrete elements (Table 3). Data for the SRC scenario was similarly provided by the contractor, who also reviewed and confirmed the feasibility of the proposed material changes. The hypothetical SRC scenario is based on an existing SRC-framed building, constructed by the same contractor at approximately the same time as the case building. This approach ensures consistency in construction methods, pricing assumptions, and overall comparability between the two scenarios.

2.4. Life cycle assessment method

LCA is widely recognised as an effective tool for evaluating the environmental impacts of construction projects because it provides a quantifiable method for identifying resource use, emissions, and environmental burdens across a building's life cycle. For example, legislation in several European countries already requires climate declarations based on LCA results for new construction projects or major renovations seeking a building permit [39]. In principle, a full building LCA follows a "cradle-to-grave" perspective (Fig. 2), assessing environmental impacts from raw material extraction through manufacturing, construction, use, maintenance, and end-of-life. However, the current study aims to evaluate the upfront embodied emissions of a building, so only stages A1-5 were considered, covering the product and construction stages.

The LCA was conducted using One Click LCA software (version 0.38.9). The parameters for materials calculations were set to the year 2021 in line with the project's timeline. The construction materials selection was structured as follows: i) matching each building component to the closest available product category in the One Click LCA database, ii) priority was given to materials with Environmental Product Declarations (EPDs) from Finland, iii) when not available, materials from neighbouring countries were selected, iv) when specific product data was not available, generic Finnish/Nordic materials from the Ecoinvent database were used. The construction company did not provide specific manufacturers' names. However, the selection process aimed to reflect realistic material options available on the market in Finland in 2021. A list of materials contributing most to the total mass of the project has been included in Appendix A (Tables A1 and A2) for both scenarios to provide transparency on the composition of the life cycle inventory.

As the analysis focuses on comparing two alternative building scenarios and material choices, the functional unit of the LCA was defined as the entire case building, expressed as total values. For the impact assessment phase of the LCA, the software applied the CML-IA 2012 methodology, consistent with the EN 15804 + A2 and EN 15978 standards [40,41] for Environmental Product Declarations and environmental performance of buildings, respectively.

Table 2
Cost categories of the building project provided by the contractor and the associated cost percentage shares for each category.

Category name		Cost percentage (%/total)
1	Developer expenses	3.2
2	Site and ground works	9.4
3	Foundations and insulation	12.6
4	Frame and roof structures	16.3
5	Supplementary structures	7.6
6	Surface structures	10.5
7	Fittings, equipment, and appliances	3.7
8	HVAC works	19.3
9	Site operation expenses	4.3
10	Site joint expenses	13.1

Table 3
Changes in the building frame between the case building and the alternative design.

Wood Scenario	
External walls	Glulam logs (275 mm x 275 mm)
Columns	Glulam columns (450 mm x 190 mm)
Beams	21 glulam beams (360 mm x 190 mm)

SRC Scenario	
External walls	Sandwich panel (230 mm + 50 mm insulation)
Columns	Steel Reinforced Concrete columns (380 mm x 380 mm)
Beams	16 Steel Reinforced Concrete beams (680 mm x 380 mm)

	Building Life Cycle Stages			
A1-A3 - Product Stage			**A4-A5 - Construction**		**B1-B5 - Use Stage**					**C1-C4 - End-of-life Stage**			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
Raw material supply	Transport	Manufacturing	Transport to site	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Demolition	Transport	Waste processing	Disposal

Cradle-to-gate
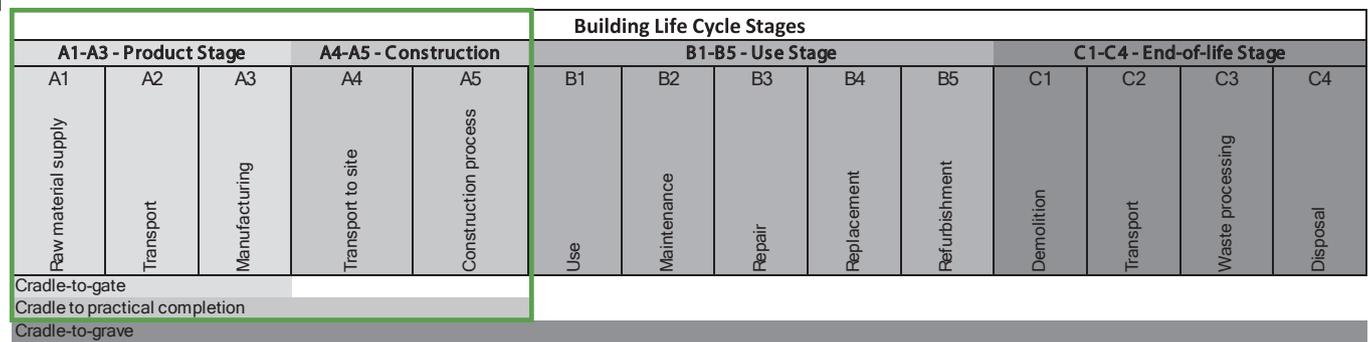Cradle to practical completion
Cradle-to-grave

Fig. 2. Overview of Building Life Cycle Stages included in Cradle-to-Gate, Practical Completion, and Cradle-to-Grave Assessments.

3. Results

3.1. LCA results

The results of the LCA for the wood scenario are presented in Table 4. The total Global Warming Potential (GWP) across stages A1–5 amounts to approximately 580,000 kg CO_2 eq. This value reflects the net effect after accounting for both fossil-based and biogenic carbon flows. The GWP fossil emissions, arising from fossil fuel use during material production, transportation, and construction, are significantly higher at approximately 1.6 million kg CO_2 eq. However, these emissions are substantially offset by the GWP biogenic value of -1 million kg CO_2 eq., reflecting the carbon stored in wood materials. This large negative biogenic contribution highlights the role of wood products as temporary carbon sinks. The emissions related to land use and land-use changes (GWP LULUC) are relatively minor, at approximately 4,000 kg CO_2 eq., suggesting that direct impacts on forestry and land transformation are limited in this case.

While the wood scenario shows substantial benefits in terms of biogenic carbon storage, it is important to recognize that increased demand for timber may also affect long-term carbon absorption capacity in forests. Unsustainable harvesting practices or deforestation could reduce the future ability of forests to sequester carbon, thereby diminishing some of the benefits observed in this study. However, the LCA results here only reflect upstream emissions (A1–5 stages) and do not account for such broader land-use dynamics.

In addition to GWP, other environmental ICs were assessed. The values for the acidification potential, eutrophication (freshwater, marine environments, terrestrial systems) indicate moderate nutrient pollution potential, particularly for terrestrial ecosystems. Regarding resource depletion, the abiotic depletion potential for non-fossil

resources (e.g., metals and minerals) was 460 kg Sb eq., while fossil resource depletion was 27 million MJ, reflecting the energy-intensive processes in material production and transport. Water use was also considerable, highlighting the importance of water management even in wood-based construction.

In the SRC scenario (results in Table 5), the total GWP amounts to 985,000 kgCO_2 eq. This value is considerably higher than that of the wood scenario. The GWP fossil emissions are also notably higher (1.6 million kg CO_2 eq.), reflecting the increased fossil fuel use associated with the concrete and steel production processes. Although a biogenic carbon uptake is reported at $-646,000$ kg CO_2 eq., it is smaller than in the wood scenario, which is expected given the reduced use of biogenic materials in the SRC design. The GWP LULUC remains relatively low at approximately 4,000 kg CO_2 eq., similar to the wood scenario, suggesting minimal additional land use pressure from the material supply chain.

The SRC scenario shows increased impacts in several other categories compared to the case building. The acidification potential and eutrophication impacts are slightly higher. The formation potential for tropospheric ozone is 13,000 kg NMVOC eq., comparable to the wood-based design, indicating similar contributions to photochemical smog. In terms of resource depletion, the abiotic depletion potential for non-fossil resources increases to 736 kg Sb eq., and fossil resource depletion rises to approximately 28 million MJ. Water use remains high, with minimal differences between the two scenarios. This similarity can be explained by the fact that both timber and concrete/steel supply chains involve water-intensive and energy-intensive industrial processes. These findings suggest that while material choice strongly influences certain categories (e.g., GWP, abiotic depletion), other categories are dominated by upstream industrial processes that show limited variation between materials.

Table 4
Results of the LCA for stages A1-5 in the wood scenario.

Wood Scenario				
Impact phase category	A1-3 Construction materials	A4 Transportation to site	A5 Installation process	TOTAL
Global Warming Potential − Total (kgCO_2 eq.)	383,345	77,649	117,959	578,954
Global Warming Potential − Fossil (kgCO_2 eq.)	1,416,314	77,647	98,161	1,592,122
Global Warming Potential − Biogenic (kgCO_2 eq.)	−1,036,749	–	19,442	−1,017,307
Global Warming Potential − LULUC (kgCO_2 eq.)	3,780	3	356	4,139
Depletion potential of the stratospheric ozone layer (kg CFC-11 eq.)	0.1	0.01	0.01	0.1
Acidification potential (Accumulated Exceedance mol H + eq.)	11,356	124	710	12,191
Eutrophication freshwater (kg P eq.)	34	5	3	42
Eutrophication aquatic marine (kg N eq.)	2,072	15	151	2,238
Eutrophication terrestrial (mol N eq.)	38,316	162	2,531	41,009
Formation potential of tropospheric ozone (kg NMVOC eq.)	12,388	68	681	13,138
Abiotic depletion potential (ADP-elements) for non-fossil resources (kg Sb eq.)	96	338	26	460
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (MJ)	23,670,989	1,746,087	1,572,618	26,989,694
Water use (m^3 deprived)	498,515,644	3	364,549	498,880,196

Table 5

Results of the LCA for stages A1-5 in the SRC scenario.

SRC Scenario				
Impact phase category	A1-3 Construction materials	A4 Transportation to site	A5 Installation process	TOTAL
Global Warming Potential − Total (kgCO$_2$ eq.)	788,881	80,878	115,264	985,023
Global Warming Potential − Fossil (kgCO$_2$ eq.)	1,453,042	80,875	93,885	1,627,801
Global Warming Potential − Biogenic (kgCO$_2$ eq.)	−667,690	−	21,074	−646,615
Global Warming Potential − LULUC (kgCO$_2$ eq.)	3,529	3	305	3,837
Depletion potential of the stratospheric ozone layer (kg CFC-11 eq.)	0.1	0.02	0.01	0.1
Acidification potential (Accumulated Exceedance mol H + eq.)	13,071	129	783	13,983
Eutrophication freshwater (kg P eq.)	35	5	3	44
Eutrophication aquatic marine (kg N eq.)	2,051	15	132	2,199
Eutrophication terrestrial (mol N eq.)	45,425	168	2,857	48,450
Formation potential of tropospheric ozone (kg NMVOC eq.)	12,371	71	628	13,070
Abiotic depletion potential (ADP-elements) for non-fossil resources (kg Sb eq.)	363	329	44	735
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (MJ)	24,529,137	1,768,844	1,587,074	27,885,055
Water use (m^3 deprived)	498,575,210	3	365,880	498,941,093

Tables 6 and 7 present the relevant LCA impact categories results only for those components that were modified between the two design scenarios (i.e., beams, columns, and external walls) covering stages A1-5. This approach allowed for a closer assessment of the environmental impacts from the material substitutions alone, leading to a more accurate comparison. As expected for the wood elements scenario, the GWP has a negative value at approximately –303,000 kg CO$_2$ eq., largely driven by biogenic carbon storage, which offsets the fossil-based emissions. The GWP in the SRC elements scenario is more than double in value at 103,000 kg CO$_2$ eq. However, in categories such as acidification and ozone formation, the SRC elements perform relatively better, with acidification impacts over four times lower than for the wood elements and slightly reduced ozone formation potential. These results reflect the potential trade-offs between materials: while wood excels in carbon performance, concrete has lower emissions for certain pollutants.

3.2. Monetary valuation for selected impact categories

The monetary valuation results were obtained by multiplying the results of each selected IC from the LCA by the corresponding monetary valuation coefficients. The minimum, maximum, and average values for the monetary valuation coefficients were chosen from Table 1 to provide the range of results. To support a more detailed understanding, the monetary valuation of environmental impacts was first applied to the specific structural elements that were modified (i.e., beams, columns, and external walls). The breakdown helps isolate the contribution of material substitutions before presenting the aggregated impacts at the whole-building level. By doing so, it becomes possible to distinguish which part of the environmental cost differences are directly attributable to the change from EWPs to SRC.

The results, presented in Tables 8 and 9, show that the wood-based elements actually generate a net environmental benefit under the average monetary valuation scenario, with a total indirect cost of –€66,394, compared to €31,367 for the SRC elements scenario. This contrast is driven primarily by the significant negative cost (i.e. benefit)

assigned to biogenic carbon uptake in the wood scenario, in addition to a lower GWP total. The differences are increasingly visible under the maximum valuation scenario. The SRC elements result in €105,678 indirect costs, while the wood elements generate a net benefit of –€193,365.

The whole-building indirect costs for the relevant impact categories are presented in Tables B.1 and B.2 (Appendix B). Looking at the average values, the total indirect costs for the wood scenario were estimated at € 204,253, while the SRC one reached a total of € 301,987. On average, the indirect environmental costs of the SRC scenario are approximately 30 % higher than those of the wood one. This difference is primarily driven by the GWP category, which accounts for the largest share of indirect costs in both cases, followed by the Acidification potential. The wood scenario shows lower average indirect costs from GWP (€ 132,754) compared to SRC (€ 225,866), highlighting the contribution of biogenic carbon uptake in the wood design. The wood case building shows a slightly higher tropospheric ozone formation potential than the SRC alternative. This is likely due to higher emissions of volatile organic compounds (VOCs) from adhesives and treatments used in EWPs, which contribute to ground-level ozone formation.

Another aspect of the results is the considerable variation between the minimum and maximum values across all relevant impact categories. For example, the total indirect environmental costs for the wood scenario range from €17,131 to €727,176, while the SRC one ranges from €29,131 to €1,026,142. This variation highlights how sensitive the results can be to the choice of monetary valuation coefficients.

3.3. Total direct and indirect cost comparison between building cases

The current study aims to provide a realistic comparison of direct and indirect costs associated with the two structural design scenarios. To maintain the focus on material-related differences, certain cost categories, such as interior fittings and equipment, were assumed to be equivalent between the two scenarios; therefore, they were excluded from the calculations. The value-added tax (VAT) was also excluded

Table 6

Wood scenario A1-5 LCA results for beams, columns, exterior wall elements for relevant impact categories.

Wood scenario − beams, columns, exterior wall				
Phase	A1-3 Construction materials	A4 Transportation to site	A5 Installation process	TOTAL
Global Warming Potential − Total (kgCO$_2$ eq.)	−315,941.4	1,529.7	11,512.2	−302,899.5
Global Warming Potential − Fossil (kgCO$_2$ eq.)	61,585.4	1,529.6	11,396.5	74,511.4
Global Warming Potential − Biogenic (kgCO$_2$ eq.)	−377,880.4	−	56.6	−377,823.9
Global Warming Potential − LULUC (kgCO$_2$ eq.)	353.7	0.1	59.2	413.0
Depletion potential of the stratospheric ozone layer (kg CFC-11 eq.)	0.01	0.001	0.001	0.01
Acidification potential (Acc. Exc. mol H + eq.)	485.1	2.6	89.8	577.4
Formation potential of tropospheric ozone (kg NMVOC eq.)	428.2	1.4	82.0	511.7

Table 7

SRC scenario A1-5 LCA results for beams, columns, exterior wall elements for relevant impact categories.

SRC scenario − beams, columns, exterior wall				
Phase	A1-3 Construction materials	A4 Transportation to site	A5 Installation process	TOTAL
Global Warming Potential − Total (kgCO$_2$ eq.)	89,594.5	4,758.1	8,816.8	103,169.4
Global Warming Potential − Fossil (kgCO$_2$ eq.)	98,312.7	4,757.9	7,119.7	110,190.4
Global Warming Potential − Biogenic (kgCO$_2$ eq.)	−8,821.2	−	1,689.1	−7,132.1
Global Warming Potential − LULUC (kgCO$_2$ eq.)	102.9	0.2	8.0	111.1
Depletion potential of the stratospheric ozone layer (kg CFC-11 eq.)	0.02	0.001	0.001	0.02
Acidification potential (Acc. Exc. mol H + eq.)	2,200.1	7.2	162.1	2,369.3
Formation potential of tropospheric ozone (kg NMVOC eq.)	410.8	3.9	29.2	444.0

Table 8

Minimum, average, and maximum indirect costs associated with relevant impact categories for the beams, columns, and exterior wall in the wood scenario.

Wood scenario − beams, columns, exterior wall		Indirect Costs		
Total Environmental Impacts A1-5	Unit	Minimum valuation	AVERAGE VALUATION	Maximum valuation
Global Warming Potential − Total	€$_{2020}$/ kgCO$_2$ eq.	−8,936	**−69,455**	−207,486
Global Warming Potential − Fossil	€$_{2020}$/ kgCO$_2$ eq.	2,198	**17,085**	51,040
Global Warming Potential − Biogenic	€$_{2020}$/ kgCO$_2$ −eq.	−11,146	**−86,635**	−258,809
Global Warming Potential − LULUC	€$_{2020}$/ kgCO$_2$ eq.	12	**95**	283
Depletion potential of the stratospheric ozone layer	€$_{2020}$/ kgCFC-11 eq.	0.3	**0.5**	1.1
Acidification potential	€$_{2020}$/Acc. Exc. mol H + eq.	0.9	**1,554**	7,009
Formation potential of tropospheric ozone	€$_{2020}$/kg NMVOC eq.	1.1	**1,507**	7,112
	Total (€)	−8,933	**−66,394**	−193,365

Table 9

Minimum, average, and maximum indirect costs associated with relevant impact categories for the beams, columns, and exterior wall in the SRC scenario.

SRC scenario − beams, columns, exterior wall		Indirect Costs		
Total Environmental Impacts A1-5	Unit	Minimum valuation	AVERAGE VALUATION	Maximum valuation
Global Warming Potential − Total	€$_{2020}$/ kgCO$_2$ eq.	3,043	**23,657**	70,671
Global Warming Potential − Fossil	€$_{2020}$/ kgCO$_2$ eq.	5,102	**25,267**	75,480
Global Warming Potential − Biogenic	€$_{2020}$/ kgCO$_2$ eq.	−426	**−1,635**	−4,885
Global Warming Potential − LULUC	€$_{2020}$/ kgCO$_2$ eq.	36	**25**	76
Depletion potential of the stratospheric ozone layer	€$_{2020}$/ kgCFC-11 eq.	0.7	**1.1**	2.3
Acidification potential	€$_{2020}$/Acc. Exc. mol H + eq.	3.9	**6,376**	28,758
Formation potential of tropospheric ozone	€$_{2020}$/kg NMVOC eq.	1.0	**1,307**	6,171
	Total (€)	3,085	**31,367**	105,678

because it does not influence the relative difference between the two.

When both direct construction costs and environmental indirect costs are considered, the total cost differences between the wood and SRC scenarios become notably smaller (Fig. 3). The average total cost for the wood building is approximately €6,200,000, while the SRC building totals €6,032,000, resulting in a difference of 2.7 %. Under the low valuation scenario, the wood scenario appears 4.4 % more expensive, whereas under the high valuation scenario, the SRC building becomes slightly more costly, by approximately 0.5 %. These results indicate that including the indirect environmental costs can shift the perceived economic competitiveness of building materials, narrowing the cost gap and, in some cases, even reversing it in favour of the wood design.

This trend is also reflected at the component level, presented in Table 10. While the direct cost of the wood elements is almost double that of their SRC counterparts (€572,456 vs. €307,370), the gap narrows significantly when indirect environmental costs are included. Under the average valuation, the adjusted cost of the wood elements is €506,062, compared to €338,736 for SRC elements. In the maximum valuation scenario, the SRC elements become more expensive (€413,048 vs. €379,091), again showing how environmental externalities can influence total cost rankings.

These findings demonstrate that while SRC remains less expensive in terms of direct costs, incorporating environmental costs can meaningfully alter the assessment. For early-stage planning and public procurement, this suggests that the wood scenario may be more cost-competitive than traditionally perceived.

4. Discussion

The present research evaluated and compared the upfront environmental impacts, as well as the direct and indirect costs, associated with two alternative structural design scenarios for a public building. The existing structure used EWPs extensively across both structural and non-structural components, particularly in the beams, columns, and exterior walls. The alternative design scenario proposed replacing those structural elements with SRC. This study focused on the early life cycle stages of the building (A1–5), where most embodied emissions occur, and applied an LCA combined with monetary valuation methods to capture both environmental and economic dimensions of material choices.
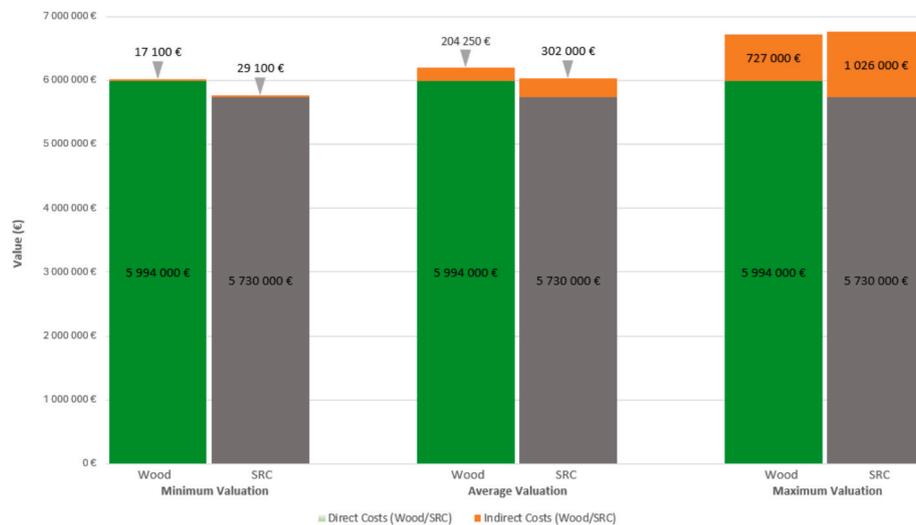
Fig. 3. Total direct and indirect costs associated with the whole building design for the wood and SRC scenarios.

Table 10
Total Direct and Indirect costs for the beams, columns, and exterior wall in the wood and the SRC scenarios.

Direct Cost		Direct + Indirect Costs		
Wood Scenario − beams, columns, exterior wall		Minimum	AVERAGE	Maximum
Beams & Columns	105,656	96,723	39,262	−87,709
Exterior Wall	466,800	457,867	400,406	273,435
Total Cost Elements	572,456	563,523	506,062	379,091
		−1.6 % (Compared to Direct Cost)	**−11.4 %**	–33.5 %
SRC Scenario − beams, columns, exterior wall				
Beams & Columns	146,782	149,831	**178,149**	252,460
Exterior Wall	160,587	163,636	**191,954**	266,265
Total Cost Elements	307,370	310,418	**338,736**	413,048
		1.0 % (Compared to Direct Cost)	**8.4 %**	18.0 %

Incorporating environmental impacts alongside both direct and indirect costs into project assessments enables a more holistic understanding of the true trade-offs involved in building construction. In particular, the indirect costs, representing environmental externalities are often excluded from financial evaluations, despite their relevance for long-term sustainability. By monetizing these externalities, the study provides additional information that can support early-stage decision-making by contractors and other stakeholders. This perspective not only improves the quality of cost-benefit analyses but also supports emissions reduction efforts, promotes economic efficiency, and contributes to advancing the climate goals of the built environment sector.

The results indicated primarily similar environmental impacts across most LCA categories between the two scenarios. However, the GWP category presented the most significant difference, highlighting the importance of material selection in reducing a building's carbon footprint. Economically, the comparison between the main structural components (i.e., beams, columns, and exterior walls) shows the wood scenario with higher direct costs, but a significant environmental benefit when indirect costs are included, 'reducing' the total cost of the wooden elements by approximately 33 % and becoming 9 % less expensive than the SRC counterpart, in the maximum valuation case.

At the whole-building level, the wood scenario is estimated at a direct cost (excluding VAT) of €5.99 million, which is 4.4 % higher than the SRC scenario (€5.73 million). This aligns closely with previously published findings. For example, Ahmed and Arocho, [42] reported a 6.43 % cost premium for a hybrid 18-storey residential wood building in Canada (including a concrete foundation and lower floors). The relatively smaller cost difference in the current case can be attributed to the specific characteristics of the project: a one-storey school building with highly reinforced foundations and substantial insulation, reflecting both site-specific constraints and the requirements of the Finnish climate. These factors likely decreased the cost differences as the amount of concrete used in both scenarios was substantial, limiting the capacity for comparison. Nevertheless, when both direct and indirect costs are considered together, the gap between the two scenarios narrows substantially. In the average valuation, the wood scenario is only 2.7 % more expensive overall. Under favourable conditions (maximum valuation coefficients), it even offers a 0.5 % cost advantage, suggesting that, depending on valuation assumptions and market context, wood construction may be economically competitive when the environmental externalities are fully accounted for. This reinforces the relevance of including indirect environmental costs in project evaluations to support informed decision-making in the construction sector.

To frame the results in the wider context, the current study finds 169.5 $kgCO_2$ eq/m^2 GWP total (including biogenic carbon) for the wood scenario and 288.4 $kgCO_2$ eq/m^2 for the SRC scenario. However, comparisons remain challenging, as LCA outcomes depend on the local context, such as location and climate, and also on methodological choices like system boundaries and the scope of the study. Reported values for GHG emissions vary considerably: Amiri and Junnila, [43] give a range of 40 – 1,170 $kgCO_2$ eq/m^2 for upfront emissions of wood buildings, with an average value of 293.3 $kgCO_2$ eq/m^2 and a median value of 220 $kgCO_2$ eq/m^2. Younis and Dodoo, [8] report an even wider range of 50 – 6,300 $kgCO_2$ eq/m^2 for CLT construction, with the average value for upfront emissions of 162.5 $kgCO_2$ eq/m^2 and a median value of 149 $kgCO_2$ eq/m^2 based on the studies reporting A1-5 stages. The results of the current study for the wood scenario are closely aligned with these lower-end averages and medians, suggesting that the case building represents a relatively efficient example among researched cases.

It is also important to contextualize the findings within the characteristics of the studied building type. In this case, the school building is a single-storey structure, yet it features a relatively robust foundation and substantial insulation, elements that would also be required in multi-storey buildings, particularly in cold climates such as Finland's. As a result, the contribution of these shared elements to the total

environmental impact reduces the relative difference between the two structural systems. In other words, because both scenarios already include these baseline components, the environmental advantages of the wood design, especially in terms of GWP appear more modest than they might in other building contexts. It is equally important to ensure structural efficiency from the outset, since design choices directly affect material demand and the size of required foundations. Hassan et al., [44] mention that CLT's weight is one-sixth that of concrete, making wood buildings lighter than SRC alternatives. This reduction in weight would translate into lighter foundation systems where the soil and climate conditions allow.

In multi-storey buildings, however, the quantities of structural materials such as concrete, steel, or engineered wood increase substantially, while the foundation and insulation systems do not scale up at the same rate. This means that a greater share of the total environmental burden in taller buildings comes from the structural frame itself. Under such conditions, the lower embodied emissions of wood products would likely have a more significant impact on the overall GWP and other environmental indicators. Therefore, the differences observed in this study may underrepresent the potential environmental benefits of wood construction in taller buildings, suggesting an even stronger case for low-carbon alternatives in multi-storey applications.

The results of this study have important implications for policy and decision-making in the construction sector. In many cases, project costs are calculated without considering the environmental harm caused by greenhouse gas emissions. This can lead to choices that are less sustainable in the long term. By including the indirect environmental costs in the comparison, this study shows that low-carbon building materials, such as engineered wood, can be more cost-effective than they first appear. Public authorities could help promote more sustainable construction by including environmental impacts in their procurement and planning processes. This approach would support national and international climate goals and encourage wider use of environmentally friendly materials in the building industry.

Integrating monetary valuation within LCA frameworks provides valuable insights for comprehensively evaluating the environmental and economic trade-offs in building design. Expanding this approach to include additional impact categories for a holistic understanding of indirect costs, more case studies with a wider variety of building types and structural elements, as well as a more streamlined analysis framework, could be considered as future research.

A key issue in scaling up timber construction is the availability and sourcing of wood. Global demand for wood is already substantial, with annual roundwood use reaching 2,028 million m^3 in 2018, of which 1,943 million m^3 was consumed as fuel [45]. Redirecting timber from short-lived applications such as fuel toward long-lived applications such as construction can enhance climate change mitigation by extending carbon storage periods. This transition, however, requires careful planning and innovation, particularly in the production of engineered wood products. In parallel, reduced demand for carbon-intensive materials such as cement and steel would further lower emissions along the supply chain. Importantly, timber used in construction does not need to originate exclusively from natural forests; planted forests and agroforestry systems, especially those managed intensively, can deliver higher yields with lower environmental impacts [45].

Despite these opportunities, the expansion of timber construction raises ecological and technical challenges that must be carefully managed. Unsustainable harvesting and monoculture plantations may result in biodiversity loss and ecosystem degradation, potentially offsetting some of the climate benefits of wood-based construction. Ensuring that timber is sourced from sustainably managed forests that also protect biodiversity is therefore essential. At the building level, durability concerns must also be addressed, as wooden structures remain vulnerable to fire, moisture, insect damage, and decay. These risks necessitate context-specific design solutions and strict adherence to building codes. For example, Östman et al. [46] emphasize that fire safety in wooden buildings can be improved through structural fire resistance measures, fire space separation, and ensuring sufficient evacuation time for occupants. Addressing these ecological and technical issues should remain central to both future research and policy strategies supporting responsible timber construction.

4.1. Limitations of the study

Regarding the methodological choices, this study applied monetary valuation, which assigns economic values based on the potential harm caused by emissions, such as future damage from climate change. Nevertheless, current research remains limited both in scope and in the availability of peer-reviewed, high-quality sources, even within established categories such as GWP, Acidification, Eutrophication, and Photochemical Ozone Formation. The relatively wide gap between the average and median monetary valuation coefficients in these ICs indicates a skewed distribution. Further in-depth research into present ICs, as well as the inclusion of additional categories, is essential for enhancing the value and usefulness of monetary valuation frameworks.

Another limitation of this study is that it only accounts for the upfront life cycle stages (A1–5), without including the end-of-life, or beyond-life-cycle stages. This means that the potential release of biogenic carbon stored in wood products at the end of a building's life is not considered here. Previous studies have highlighted that while wooden buildings can act as temporary carbon sinks, the eventual release of stored carbon through demolition, incineration, or decay can offset these benefits if not managed through reuse, recycling, or carbon capture strategies. Therefore, the carbon storage results should be interpreted with caution, acknowledging that long-term benefits depend strongly on end-of-life practices and policies. There are relatively few examples in literature of multi-storey wood buildings that have reached demolition stage, thus that stage can only be modelled based on assumptions [9]. Nevertheless, carbon storage during the 50-year service life can be seen as a temporary contribution to climate goals for 2030 and 2050, since it delays emissions at a time when rapid reductions are most urgently needed.

5. Conclusion

This study began with a review of existing literature to identify monetary valuation coefficients for greenhouse gas (GHG) emissions. A structured, step-by-step approach was used in order to compare the environmental and economic performance of two structural design options: one based on engineered wood products (EWPs) and the other on steel-reinforced concrete (SRC). The goal was to evaluate how including indirect environmental costs, calculated by monetising embodied emissions, could influence the overall cost comparison. The study showed that while the wood-based design had slightly higher direct costs, its lower embodied emissions significantly reduced total costs when indirect environmental impacts were included. Under the highest valuation scenario, the wood design became even more cost-effective than its SRC counterpart.

These findings suggest that including indirect environmental costs in construction project evaluations can lead to more informed and sustainable decisions. While this study focused on a low-rise building, the results indicate that the advantages of wood construction could be even greater in taller buildings, where structural material quantities are higher, but foundation and insulation requirements remain relatively similar. The study also points to a need for further research into impact categories and valuation methods, as well as stronger integration of environmental considerations into building policy and procurement practices. Overall, this research contributes to the growing body of evidence supporting the use of lifecycle thinking and monetary valuation in achieving climate goals in the construction sector.

CRediT authorship contribution statement

Oana Iliescu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Amiri:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Seppo Junnila:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
List of 15 largest material flows by mass for the wood scenario (percentages are calculated for each building material, excluding external yard works, which are not part of the building mass.).

Wood Scenario	Building Part	Material	Quantity (kg)	% mass of building
1	External areas	Gravel, 0–180 mm, 1625 kg/m3	15 975 495	*yard stabilisation works
2	External areas	Crushed stone, S-P-07875	7 884 640	*yard stabilisation works
3	Foundation and sub-surface	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	1 320 000	19,5 %
4	Floors and horizontal elements	Hollow-core concrete slab, C50, 200 mm, 245 kg/m2	1 118 974	16,5 %
5	Floors and horizontal elements	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	880 900	13,0 %
6	Columns and load-bearing walls (air-raid centre)	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	570 250	8,4 %
7	Foundation and sub-surface	Concrete piles, 200 × 200-450 × 450 mm, length: 3–16 m, C50/60	513 900	7,6 %
8	Foundation and sub-surface	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	506 047	7,5 %
9	Floors and horizontal elements (roof)	Softwood timber from spruce and pine, klin dried, planed, 478 kg/m3	354 330	5,2 %
10	External walls and facade	Glued laminated timber (Glulam), 470 kg/m3, moisture content 15 %	232 034	3,4 %
11	Floors and horizontal elements	Self-levelling dry screed based on fast-hardening cement	176 988	2,6 %
12	Internal and non-bearing walls	Gypsum plasterboard, 12.5 mm, 8.4 kg/m2, 672 kg/m3	128 345	1,9 %
13	Floors and horizontal elements	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	121 250	1,8 %
14	Finishes	Pumpable levelling screed	112 100	1,7 %
15	Columns and load-bearing walls	Glued laminated timber (Glulam), 470 kg/m3, moisture content 15 %	75 239	1,1 %

Table A2
List of 15 largest material flows by mass for the SRC scenario (percentages are calculated for each building material, excluding external yard works, which are not part of the building mass.).

SRC Scenario	Building Part	Material	Quantity (kg)	% mass of building
1	External areas	Gravel, 0–180 mm, 1625 kg/m3	15 975 495	*yard stabilisation works
2	External areas	Crushed stone, S-P-07875	7 884 640	*yard stabilisation works
3	Foundation and sub-surface	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	1 320 000	18,8 %
4	Floors and horizontal elements	Hollow-core concrete slab, C50, 200 mm, 245 kg/m2	1 118 974	15,9 %
5	Floors and horizontal elements	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	880 900	12,5 %
6	Columns and load-bearing walls	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	570 250	8,1 %
7	Foundation and sub-surface	Concrete piles, 200 × 200-450 × 450 mm, length: 3–16 m, C50/60	513 900	7,3 %
8	Foundation and sub-surface	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	506 047	7,2 %
9	Columns and load-bearing walls	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	495 661	7,0 %
10	Floors and horizontal elements (roof)	Softwood timber from spruce and pine, klin dried, planed, 478 kg/m3	354 330	5,0 %
11	Floors and horizontal elements	Self-levelling dry screed based on fast-hardening cement	176 988	2,5 %
12	Internal and non-bearing walls	Gypsum plasterboard, 12.5 mm, 8.4 kg/m2, 672 kg/m3	128 345	1,8 %
13	Floors and horizontal elements	Ready-mix concrete, C35/45, 16 mm, 2315 kg/m3	121 250	1,7 %
14	Finishes	Pumpable levelling screed	112 100	1,6 %
15	Floors and horizontal elements	EPS insulation boards, 0.033–0.039 W/mK, 18–18.5 kg/m3	74 561	1,1 %

Appendix B

Table B1
Calculation of monetary valuation for each relevant impact category for the whole-building wood scenario.

Wood scenario		Indirect Costs		
Total Environmental Impacts A1-5	Unit	**Minimum valuation**	**AVERAGE VALUATION**	**Maximum valuation**
Global Warming Potential − Total	€$_{2020}$/kgCO$_2$ eq.	17,079	**132,754**	396,583
Global Warming Potential − Fossil	€$_{2020}$/kgCO$_2$ eq.	46,968	**365,074**	1,090,604
Global Warming Potential − Biogenic	€$_{2020}$/kgCO$_2$ eq.	−30,011	**−233,269**	−696,855
Global Warming Potential − LULUC	€$_{2020}$/kgCO$_2$ eq.	122	**949**	2,835
Depletion potential of the stratospheric ozone layer	€$_{2020}$/kgCFC-11 eq.	4	**7**	14
Acidification potential	€$_{2020}$/Acc. Exc. mol H + eq.	20	**32,807**	147,966
Formation potential of tropospheric ozone	€$_{2020}$/kg NMVOC eq.	28	**38,684**	182,612
	Total (€)	**17,131**	**204,253**	**727,176**

Table B2
Calculation of monetary valuation for each relevant impact category for the whole-building SRC scenario.

SRC scenario		Indirect costs		
Total Environmental Impacts A1-5	Unit	**Minimum valuation**	**AVERAGE VALUATION**	**Maximum valuation**
Global Warming Potential − Total	€$_{2020}$/kgCO$_2$ eq.	29,058	**225,866**	674,741
Global Warming Potential − Fossil	€$_{2020}$/kgCO$_2$ eq.	48,020	**373,255**	1,115,044
Global Warming Potential − Biogenic	€$_{2020}$/kgCO$_2$ eq.	−19,075	**−148,269**	−442,932
Global Warming Potential − LULUC	€$_{2020}$/kgCO$_2$ eq.	113	**880**	2,628
Depletion potential of the stratospheric ozone layer	€$_{2020}$/kgCFC-11 eq.	4	**7**	14
Acidification potential	€$_{2020}$/Acc. Exc. mol H + eq.	23	**37,630**	169,716
Formation potential of tropospheric ozone	€$_{2020}$/kg NMVOC eq.	28	**38,485**	181,671
	Total (€)	**29,113**	**301,987**	**1,026,142**

Data availability

Data will be made available on request.

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