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Article

Sustainability Assessment of a Wooden Multi-Storey Building Compared with an Equivalent Reinforced Concrete Alternative Using ToSIA: Finnish Perspective

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ABSTRACT

The aim of this study was to conduct a sustainability impact assessment (SIA) on a wooden multi-storey building and compare this to an equivalent reinforced concrete building using ToSIA (Tool for Sustainability Impact Assessment). The SIA considered the material flows and processes along the respective supply chains in Finland and included environmental, economic, and social indicators. The greenhouse gas savings of various wood-based materials of the buildings were also compared with concrete elements. The boundary of the quantitative analysis was cradle-to-construction site and included the structural support system of the building. Primary data was collected from the material supply chain and manufacturing facilities and were used to develop the life cycle inventory database. Secondary data were also referenced for the selected indicators. The results indicated that the wood frame structure provided greater environmental benefits, being responsible for only one-third of the greenhouse gas emissions and two-thirds of the non-renewable energy consumption during building material sourcing to the construction site gate, compared to the reinforced concrete alternative. In terms of socio-economic sustainability, the reinforced concrete alternative had higher production costs, but a lower labour intensity than wood. It was also found that non-fatal accidents occurred more often in the concrete supply chain, especially at the manufacturing facility, indicating that work safety was higher in the wood-alternative. In addition, the avoided greenhouse gas emission calculation showed that 159 $kgCO_2$ m^{-2} could be avoided and 101 $kgCO_2$ m^{-2} could be stored by replacing concrete frame building with wood. Such information can be useful for constructors, designers, and public bodies in making informed choices during building design and future construction. Future studies may extend the system boundary and include

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end-of-life scenarios and the cascading use of wood to find further greenhouse gas emissions savings.

KEYWORDS: sustainability impact assessment; multi-storey building; wood and concrete materials; carbon stock; emission saving

INTRODUCTION

The building sector is currently responsible for ca. 40% of global greenhouse gas (GHG) emissions [1] and is thus significant in driving climate change. Efforts are urgently needed to reduce this impact, not only by improving the service life energy-efficiency of buildings, but also by using materials that have low embodied carbon emissions associated with their manufacture [2]. This latter point is important, since it has been estimated that the careful selection of building materials could reduce total carbon emissions by up to 50% [3]. Wood is widely used in the manufacture of building products and has significant potential to become a sustainable future solution because of its ability to store carbon in finished products, and to substitute functionally equivalent materials with a higher carbon footprint, such as concrete and steel. It has even been speculated that the widespread adoption of wood-based materials in the construction of mid-rise, multi-storey buildings could help the building sector become a carbon sink, rather than a source [4].

The many wood-based products used in building construction, such as sawn timber, cross-laminated timber (CLT) and laminated veneer lumber (LVL) each have different environmental impacts and carbon storage capacities. In many countries, such long-lived wood products have traditionally been used in the construction of single-family houses, though until recently little attention has been paid to their use as structural elements in modern multi-storey buildings. However, with the development of innovative engineered wood products like the aforementioned CLT and LVL, as well as glue-laminated timber (GLT), wood becomes a viable alternative to concrete and steel in many construction projects, and for this reason an increase in multi-storey wood construction is being witnessed [5], albeit at a slow rate. This suggests that there is the possibility to increase the use of wood products in construction yet, whilst Finland is one of the most afforested countries in the world, only ca. 10% of the total volume of harvested roundwood ends up in long-lived products like sawnwood and plywood [6].

In Finland, the annual increment of stem wood is nowadays, on average, around 107 million m^3, whilst the yearly harvesting (which has been up to 87 million m^3 annually in the last few decades) is lower than this figure [7]. For the ten-year period 2015–2024, Natural Resource Institute of Finland estimated that the maximum sustainable felling potential of forests throughout the whole country was 84 million m^3 of roundwood per year [8]. According to roundwood harvesting statistics, on average 86% of this potential is used and most is processed locally at industrial facilities. The major share of these processed products (such as sawnwood, wood-based panels, pulp, and paper) are exported to foreign markets. Since 2017, for example, more than 95% of paper and paper-based products and almost 75% of sawn timber have been exported, accounting for one-fifth of Finland's total goods exports [8]. Finland's ambitious goal of having 45% of new buildings constructed from wood by 2025 [9] might influence exports; however, whilst the demand for domestic wood may increase, a lack of understanding about, and the unknown cost structure of, wood construction, due to inconclusive prior research [10], may affect this target.

At present, the primary barriers to the use of wood are recognized as being the inadequate distribution of information, a limited number of industry actors, and inefficient policy measures [11]. However, since Finland strives to become climate-neutral by 2035, and some cities have even more ambitious targets, it is continuously promoting the use of wood in construction through various initiatives and updated policy regulations. A recent development in this regard is the adoption of the "Wood Building Program, 2016–2021" [12]. The goal of this program is to promote industrial wood construction and to increase long-term carbon storage in timber structures, as well as support the responsible use of forest resources. The share of wood currently used in the construction of apartment buildings accounts for less than 3% [10]. This contrasts strongly with residential single-family houses and terraced houses which are predominantly built of wood. Thus, to help meet carbon neutrality targets, there should be a greater focus on the long-lived application of wood in the structural systems of multi-storey residential buildings. This goal would be encouraged by assessing the potential role of the carbon hand printing of wood as a building material in relation to the Finnish low carbon construction initiative [13]. To date, though, Finland's construction industry has been hesitant to invest in wood construction since wood is not as well-known as a construction material [14].

The sustainable use of wood to mitigate climate change is a complex issue. Wood use in multi-storey buildings has a long chain of processes, considering its whole life cycle, and covers activities in the forest, supply chain and logistics, manufacturing and use in construction. Whilst there has been much emphasis on research into wood buildings and life cycle assessment (LCA) during the last decade, the major focus has been on environmental aspects (e.g., [15,16]), with several comparative assessments of wood and concrete buildings having been conducted [3,17]. One shortcoming of comparative LCA studies is that they often exclude the sourcing of the various materials used to make them truly comparable with each other. Ensuring that material sourcing and the first conversion chains are considered and calculated using the same method and system boundaries, makes the comparison more meaningful. Furthermore, studies relating to sustainability assessment from both an environmental and a socioeconomic perspective, over the life cycle of a building are limited (e.g., [18,19]), though, it might be argued, are essential if widespread wood construction is to be rapidly introduced. ToSIA (Tool for Sustainability Impact Assessment) considers material flows and processes along respective supply chains, considering environmental, economic, and social indicators, thus enabling such a comparison to be made [20], thereby addressing the limitations of comparative LCA studies and the lack of socioeconomic perspectives.

The aims of this study were to investigate the sustainability impact of a wooden multi-storey building using ToSIA and compare it with a more traditional concrete frame counterpart. The sustainability assessment was undertaken along the entire supply chain considering environmental, economic, and social indicators, ensuring that for both material types the same system boundaries and comparable assumptions were used. The results of such an analysis can be useful to building contractors, designers, and public bodies when making informed choices during building design and future construction.

METHODS AND MATERIALS

Overview

ToSIA was used to assess material flows along the supply chain and to compare the economic, environment and social impacts of buildings constructed from either wood or reinforced concrete elements. The study focused on the structural materials, and excluded the foundations, doors, and windows. It is to be noted that the building foundations of the two structures would be different due to the differences in the weight of the structures: concrete buildings are heavier than wooden buildings of the same size, and thus may require a thicker and stronger foundation. In practice, however, it is seldom done as it is easier for a wood building to specify the same foundations as for concrete because of a lack of knowledge about wood apartment buildings [21]. Gross floor area (m^2) was selected as the functional unit for the comparisons. The functionality, such as structural safety, was identical for both the wood and the reinforced concrete buildings. The structural system of the wood building was light-frame timber construction. The wall studs were of softwood sawnwood, and the floor joists were of LVL. The balcony slabs consisted of CLT. The concrete building consisted of sandwich walls (exterior walls), solid panels (interior walls, corridor floor slab and balcony slab) and hollow core slabs (regular floor slab).

The system boundary was set to "cradle-construction site gate". The process followed the standard for the sustainability of construction works and services, EN15804 [22]. In this case, this included:

- the extraction and supply of raw materials (A1): for wooden building, this included harvesting of trees in the forest to first conversion (sawmill, end products: sawlogs); for the reinforced concrete alternative it included the mining of ore and smelting to crude iron, the quarrying of stone and first conversion (production plant, end products: cement, steel, and stone-based materials)

- transportation to the manufacturing plant (A2): for wooden building this involved transport of sawlogs to the sawmill and LVL production plant; for reinforced concrete, transport to the concrete element production plant
- production of the structural elements (A3): for the wooden building this comprised the manufacture of LVL, CLT and sawnwood; for reinforced concrete internal and external wall panels, solid floor panels, and hollow core slab
- their delivery to the construction site (A4).

Supply chain models were built according to the buildings selected for this study. To assess the impacts of alternative material use, we defined and quantified six indicators (see section: Selection of sustainability impact indicators) related to the economic, social, and environmental sustainability. Details of the case study buildings, ToSIA, the supply chain model, and the methods for calculating the indicator values are presented in the following sections.

Case Study Buildings

The case study buildings were identified based on the feedback received from various stakeholders. The Federation of the Finnish Woodworking Industries suggested several buildings as potential case studies. One such suggestion was for two identical buildings. Both buildings are of four-stories, constructed either from reinforced concrete or wood as the main structural material. Several meetings were arranged with stakeholders including architects, an industry association, building contractors, all of which provided positive feedback about the two identical buildings suggested by the Federation of the Finnish Woodworking Industries. This was mainly because of their unique nature in terms of the construction and structural materials used, which would make a thorough analysis between concrete and wooden buildings possible (Table 1). For the wood building, materials for the whole structure were sourced from Finland. The concrete building is also in the same area, adjoining the wood building, in the Helsinki metropolitan area (Kuninkaantammi neighbourhood). The contractor, Reponen Oy, was responsible for both buildings which were completed in 2018. Both concrete and wooden buildings comprise three blocks (Block A, B and C). Block A is a separate building not included in our calculation, whilst blocks B and C, which were used in our analysis, are adjoining (Figure 1). The mass of the building foundations of the two buildings are quite similar (the estimated difference is about 2%).

Table 1. Summary information of case study buildings (wood and concrete building). Building information represents block A–C [23].

Components	Wooden building	Reinforced concrete building
Building owner	Owner X	Owner Y
No. of apartments	58	60
Surface area	3114.5 m^2	3132.5 m^2
Plinth	321 m^2	321 m^2
Outer wall	3273 m^2	3141 m^2
Roof	1378 m^2	1383 m^2
Base	903 m^2	903 m^2
Partitions	2841 m^2 (load-bearing wooden frame) 2813 m^2 (others)	4411 m^2
Floor	3593 m^2	3778 m^2
Windows & doors	700 + 779 m^2	700 + 779 m^2
Stairs	Wood	Concrete
Balcony	Cross-laminated timber (CLT)	Concrete

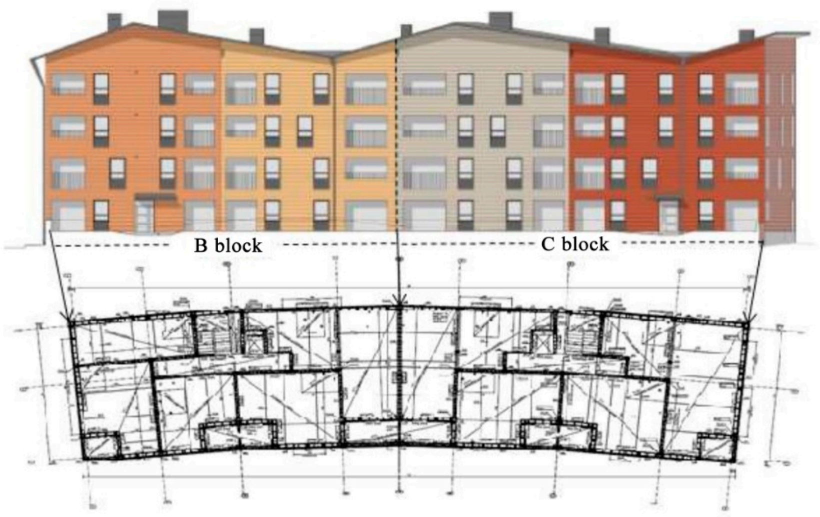

Figure 1. Facade and floor plan of the wooden building are shown as an example (Source: [24]). The concrete building has also similar plans.

Tool for Sustainability Impact Assessment—ToSIA

ToSIA is a flexible, data driven tool which has been developed as a holistic framework for the comparative sustainability impact assessment of material supply (or process) chains. The tool was originally developed for applications in the forestry sector [20], but any value chain that can be described in a process-product topology with volume (cubic meter) or mass (ton) as the main material flow, can be calculated using ToSIA. This is useful for assessing the product chain of timber and non-timber (e.g., reinforced concrete) in building construction. Users gather all necessary data and create the database for all the products in the supply chain. ToSIA compiles and translates them into a comparable format. Thus, the tool differs from available LCA-based tools which are typically linked to some database(s). The application of the tool has been described in detail earlier (e.g., [19,25,26]). Therefore, only a short description of the tool is provided here.

ToSIA is primarily based on three concepts: alternative process chains (e.g., wood or concrete); material flows along the supply chain (e.g., wood, or other products) and indicators for each process. Thus, by comparing options, it assesses the sustainability impacts of alternative supply chains and differences in material flows and indicator values. The tool determines sustainability by analysing environmental, economic, and social sustainability indicator values for all the production processes along the material supply chains. The sustainability values are calculated as products of the relative indicator values (i.e., indicator value expressed per unit of material flow) multiplied by the material flow entering the process. The material flows are defined as chains of production processes and are linked to the final product in use. For wood products, as an example, this means that each process in the supply chain is linked as follows: raw material extraction (harvesting); transportation to mill; product manufacture; final use; disposal. The tool allows for the tracking of materials and their flows from source to the end-of-life of the products, but the system boundaries can be specified, depending on the study objectives. Figure 2 shows the workflow in ToSIA, indicating the steps in conducting a sustainability impact assessment.

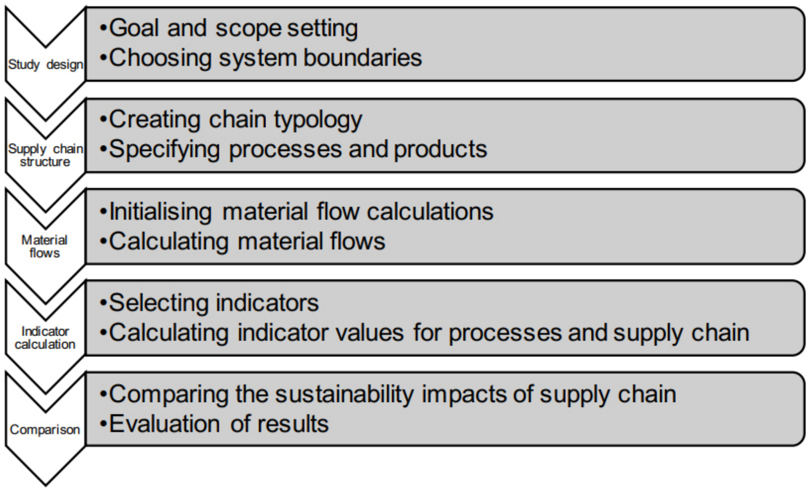

Figure 2. Outline of the ToSIA approach (modified from [20]).

Supply Chain Model for the Material Production Process

The supply chain model for the case study buildings was developed by interviewing relevant stakeholders and conducting a literature survey. A general supply chain model was first developed which included raw material supply to the transportation of usable materials to the construction site. This generic chain model is applicable for all materials especially in the case of concrete elements (Figure 3). Based on this, a supply chain for each element in the buildings was developed as shown in Table 2.

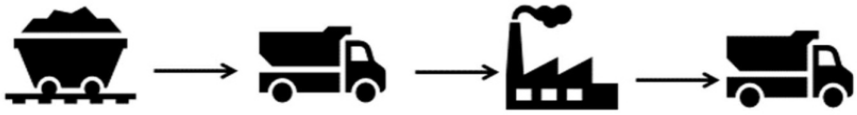

Figure 3. Generic material supply chain.

The concrete element supply chain includes the production of ballast, cement, and steel (A1), after which these raw materials are transported to the production facilities (A2). The production of the concrete elements (A3) begins with the preparation of the casting mould. It includes cleaning the casting platform and keeping the reinforcement steel in place. Fresh concrete is then poured onto the cast before curing and finalizing the elements. In the production of hollow core slabs, upper and lower base plates are connected by longitudinal cavities. The final usable elements are then transported to the construction site (A4).

Table 2. Structural element supply chain of wooden and concrete buildings.

Structural elements	Process A1 (Raw material)	Process A2 (Transport to production site)	Process A3 (Production)	Process A4 (Transport to construction site)
Wooden building				
Sawnwood	Harvest of logs	Transport of logs	Sawmilling & sawnwood	Transport of sawnwood
Laminated veneer lumber (LVL)	Harvest of peeler logs	Transport of peeler logs	LVL production	Transport of LVL
Cross-laminated timber (CLT)	Harvest of logs	Transport of logs and sawnwood	Sawnwood and CLT	Transport of CLT
Reinforced Concrete building				
External wall	Cement, steel and ballast production	Transport of raw material	Wall panel	Transportation
Hollow core slab	Cement, steel and ballast production	Transport of raw material	Hollow core slab	Transportation
Internal wall	Cement, steel and ballast production	Transport of raw material	Wall panel	Transportation
Solid wall	Cement, steel and ballast production	Transport of raw material	Wall panel	Transportation

The wood products supply chain is as follows: after harvesting (A1), the sawlogs or peeler logs are transported to the mill (A2), where the boards are cut (or rotary peeled for LVL), dried and the final products are manufactured into a useable form (A3). From here, a proportion of the boards are transported directly to the construction site (A4) as "sawnwood" and the remainder is transported to the CLT production facility (A2). There, the CLT is produced (A3) after which it is transported to the construction site (A4). Prefabrication of the panels (i.e., A5) was excluded. For LVL manufacture, the production and transport of adhesives was modelled as an additional process, due to the significant amount (27kg m^{-3}) of adhesive necessary in its manufacture. The adhesive costs were included within the LVL production process (A3). Due to the negligible amount of adhesive (3kg m^{-3}) required for CLT manufacture compared to LVL, in terms of environmental indicators the adhesive was not accounted for.

Selection of Sustainability Impact Indicators

We compiled a list of public, private, and non-governmental organization stakeholders that have the greatest influence on the use of construction materials at the local and national levels in Finland. The stakeholders included, for example, major cities (Helsinki and Espoo), the Finnish Ministry of the Environment, associations (e.g., Finnish Associations of Architects and the Federation of the Finnish Woodworking Industries), wood industry enterprises and construction companies.

Table 3. Indicators used in this study in accordance with Data Collection Protocol (DCP) for ToSIA indicators. Indicators are accounted for in different processes, such as raw material supply, transporting, manufacturing structural elements, etc.

Indicator	**Description**
Economic	
Production cost, €	Production cost are the average cost for raw material, labour, and energy costs.
Environmental	
GHG emissions, $kgCO_2$	GHG (greenhouse gas) emissions from each process in the supply chains.
Energy use, MJ	Heat/Direct fuel/Electricity use from renewable/non-renewables sources in kWh (electricity) or MJ (heat, fuel) per reporting unit.
Biogenic carbon stock, $kgCO_2$	Total carbon stock in the building pool of wood product.
Social	
Employment, FTE (full time equivalent)	Number of employees per year from processes in the supply chains in full-time equivalent (FTE).
Occupational safety and health, accidents/1000 employees	Frequency of occupational accidents and occupational diseases for the administrative and management staff allocated to processes. It is measured by the absolute number of occupational accidents per 1000 employees per reporting unit.

A face-to-face meeting was conducted with each of the stakeholders to create a list of effective sustainability (economic, environmental, and social) indicators following the guidelines provided by Pülzl et al. [25]. At the beginning of each meeting, the project was introduced to the stakeholder. The stakeholder's opinion on various indicators was solicited by creating an interactive discussion. After each session, a list of indicators and other related information was itemized to process further when assessing the case study, from which a list of six indicators was compiled (Table 3).

Database for ToSIA

After defining the processes and selecting the indicators, data were collected for each process in the supply chains through an extensive literature study, by interviewing specific producers, experts, industry associations, and by consulting national statistics (see Supplementary Table S1 and S2). The goal was to identify not only single values for each indicator, but also to obtain them from several sources, in which case a mean value was used. Acquiring the most recent and reliable data applicable to the Finnish context was kept in mind during the data collection.

For the economic and social indicators, data were gathered from specific producers or national statistics. Depending on the source, data quality requirements could not always be entirely fulfilled, due to a lack of access to data. Sometimes only a single value from a specific producer was available, which does not represent the national average. This was true, especially for the economic data. The economic data was estimated based on literature and expert opinion for individual products e.g., for engineered wood products such as CLT and LVL. The average cost data for concrete elements were estimated using literature from the building information organisation of Finland [27], the consistency of which was confirmed by comparing with other sources (e.g., [28]).

For the environmental indicators, data from Ecoinvent 3.4 and element specific EPDs (Environmental Product Declarations) were used, though the values were adjusted to the case study buildings in the context of transportation distance and related matters. A conservative assumption was made that all environmental impacts were allocated to the products and not to the co-products.

Computation

Structural drawings of the wooden and reinforced concrete buildings were analysed to extract data about the structural elements of the building(s). A list of materials was then inventoried and archived with their name, dimension, and use. The data were thoroughly checked and assessed before a material flow analysis (MFA) was performed. The MFA had several steps and was first done backward from the building elements to the raw materials sourcing. Then the calculation is reversed along the supply chain from the source to the building construction to finalize the MFA. According to the ToSIA, the input data required for each process was calculated in volume (m^3) or mass (ton) for each process. This enables data to be fed into the ToSIA tool and, via specified conversion factors, to be converted between product and process units.

Since forests provide raw materials for many different industries in a single harvest, it was necessary to separate them in our calculation. About 37% of the harvested roundwood has been found to be associated with other wood product categories (i.e., pulpwood and logging residues), not of suitable sawmill quality. This means that roundwood (sawlogs or peeler logs) transported to a mill constitute about 63% of the total harvested wood [29]. Harvested roundwood was transported an average distance of 80 km utilising 40 tons of transportation capacity. However, the distance between the manufacturing plant and the construction site varied (329 to 559 km) depending on the location where the final product was produced. In all cases, a constant coefficient of 0.29 was used for determining driving with an empty truck for the return trip. It was assumed that no mass was lost during transportation. Manufacturing efficiency at the mill was assumed to be 60% for sawnwood, 70% for LVL and 82.6% for CLT [16,30]. The by-products produced from the processing of materials are often incinerated by the mills for energy generation. For simplification, the impact of the use of by-products was not included in this study. In the calculation, an average wood density of 400 kg m^{-3} was utilized for roundwood [31], while it was 460 to 510 kg m^{-3} for finished products—sawnwood, CLT or LVL [32–34].

For the reinforced concrete elements, the sourcing starts from the steel, cement, and ballast production. For transportation, the weighted average distance from the source of the raw materials to the factory gate was used. The distance between the manufacturer and the construction site was between 100 and 150 km. In the hollow core slab, the number of longitudinal cavities differs between the elements. This changes the weight of the element. In our calculation, an average weight of 485 kg m^{-2} for this element was used, with a thickness of 370 mm, width of 1200 mm and length of 5928 mm. The amount of waste materials and transportation losses ranged from 0.02 to 1% of the total mass and was not included in the calculation. Carbonation, which is considered a natural process occurring during the life cycle of concrete was not studied. In the calculation, the density of the reinforced concrete elements was assumed to be 2450 kg m^{-3}. The detailed parameters used in the calculation are summarized in Supplementary Table S1 and S2.

In our study, the sustainability impact indicators (in section: Selection of sustainability impact indicators) were calculated as relative values (e.g., employment as full-time equivalents (FTE) per process unit (e.g., m^3 or ton of material handled in this process)). ToSIA then multiplies the material flow per process with the relative indicator value to give the overall impact of the process and then tallies them across the full chain to compare alternative chains. These values were then normalized against the gross floor area of a building unit and reported in the functional unit per m^2. In our case, the gross floor areas were 2798 m^2 for the reinforced concrete building and 2754 m^2 for the wooden building.

GHG emissions savings (avoided emissions) were calculated for the replacement of concrete materials with wood. This was done by estimating the differences in emissions between concrete and wood elements and reported per m^2 of building floor area. Due to uncertainty in emissions values, a sensitivity analysis was performed by changing the GHG emissions values of the concrete elements (details in Supplementary Table S2), increasing and decreasing them by 50%. The biogenic carbon stock, ($kgCO_2$) i.e., the amount of carbon stored in the wooden building was also calculated and reported.

RESULTS

Material Flow Analysis

Figures 4 and 5 summarize the ToSIA material flow chain topology for both the wood and the reinforced concrete buildings. A total of 371 m^3 wood products and 903 m^3 concrete elements were used in the structural parts of the wood and concrete buildings respectively. The wood building MFA shows that a total of 946 m^3 roundwood (sawlogs/peeler logs) were harvested to produce the three different wood product types (sawnwood, LVL and CLT) used in the construction. Of this, 597 m^3 were transported for further processing at the mill site. During the milling process, 226 m^3 of by-products (sawdust and residues) were generated and the remainder were the wood elements that were used in the building construction. Since we focused on the wood that was used in building construction, 371 m^3 was used for further assessment (Figure 4).

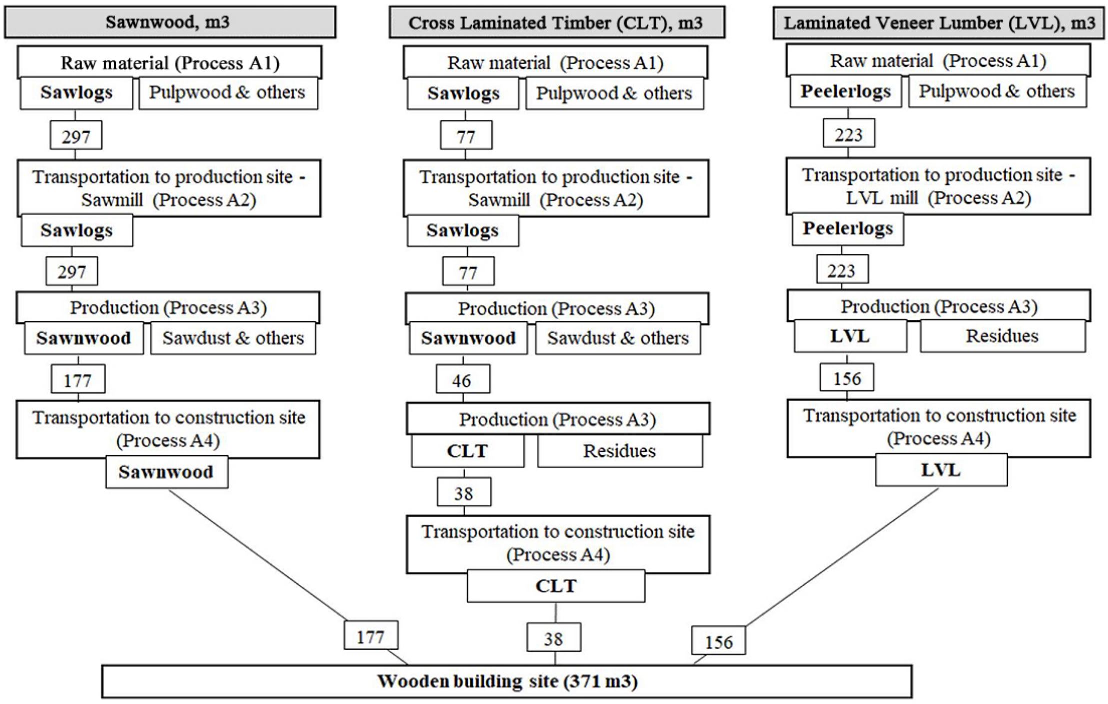

Figure 4. ToSIA material flow chain topology for the wooden building (values in the rectangular box are in m^3).

For the concrete elements, material analysis shows that 741 m^3 of stone-based minerals, 136 m^3 cement and 17 m^3 steel were needed to produce the 903 m^3 of structural elements (Figure 5). The amount of steel needed for the elements varied from 1 to 4%, whilst for ballast this share ranged from 78% to 85% and from 14 to 18% for cement.

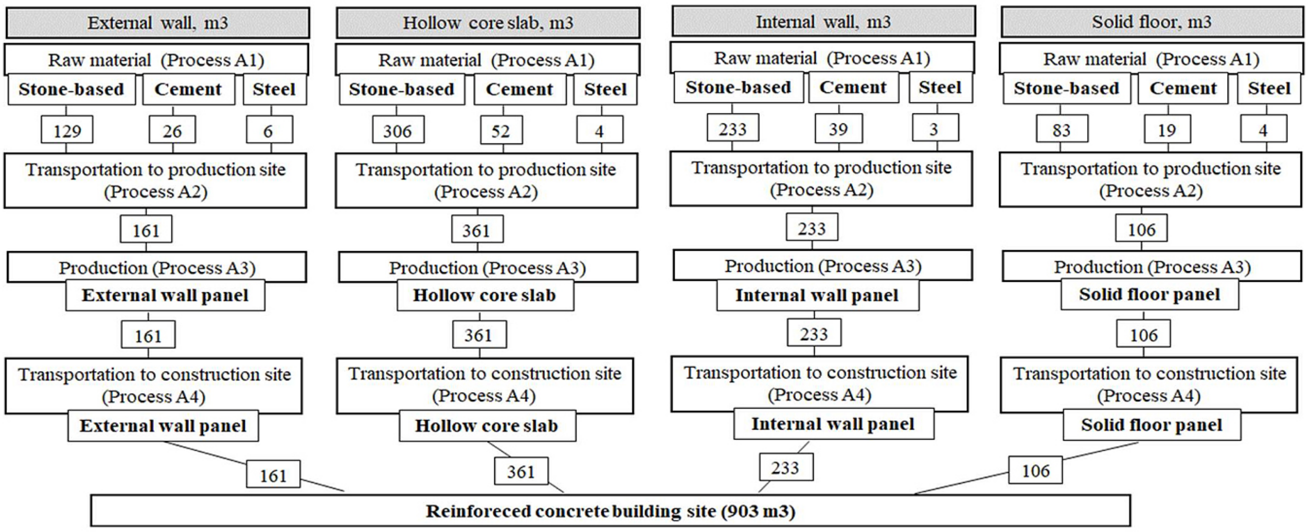

Figure 5. ToSIA material flow chain topology for the reinforced concrete alternative (values are in m^3, conversion factor used 2450 kg m^{-3}).

Structural Materials Used in Wooden and Reinforced Concrete Buildings

Laminated veneer lumber (156 m^3) was mostly used for the flooring, with minor amounts used in the internal and external walls, whereas cross-laminated timber (38 m^3) was used exclusively in the balconies (Table 4). The sawnwood used in external and internal walls amounted to 173 m^3. In contrast, the volume of concrete elements comprising the external and internal walls of the reinforced concrete alternative amounted to 400 m^3. The volume of the hollow core and solid floor slab was 418 m^3 and the balcony accounted for 85 m^3 (Table 5). A comparison of the wood and non-wood materials showed that the mass of the reinforced concrete was almost two-and-half times greater than the wood materials.

Table 4. Wood elements used in wooden building.

Volume (m^3)	External wall	Internal wall	Balcony wall	Floor	Balcony floor	Total
Sawn timber	83	89	-	4	-	177
Laminated veneer lumber (LVL)	5	8	-	143	-	156
Cross-laminated timber (CLT)	0	0	12	0	26	38
Total	88	97	12	148	26	371

Table 5. Wood and non-wood elements and the ratio of non-wood (reinforced concrete) materials to wood.

Elements	Concrete (m^3)		Timber (m^3)	Ratio
External wall	Sandwich wall	161	88	1.84
Internal wall	Solid wall	239	97	2.46
Floor slab	Hollow core	361	148	2.83
Corridor floor slab	Solid floor	57		
Balcony wall	Solid wall	37	12	3.14
Balcony slab	Solid floor	48	26	1.83
Total	-	903	371	2.44

Sustainability Impact Assessment

Figure 6 Shows the results for the sustainability impact assessment (indicator per square meter) for the wood and non-wood materials used in the buildings.

Economic indicator

The average production costs for all wood (sawnwood, CLT and LVL) and concrete elements are shown in Figure 6a. The cost was less for wood materials, corresponding to 63 EUR m^{-2}. The main costs for the wood materials were attributable to the manufacturing phase, A3. The costs for average concrete materials were 36% higher than the wood alternatives. It must be noted that the costs for the concrete materials are shown for all stages combined (A1–A4), due to a lack of separate data for the life cycle stages. In the calculation, the production costs of the adhesive were included for the CLT and LVL production.

Environmental indicator

Greenhouse gas emissions were 65 and 185 $kgCO_2$ m^{-2} for the wood and concrete materials, respectively (Figure 6b). The sourcing and production of the raw materials (e.g., cement production) (A1 phase) contributed the most to the emissions for concrete, whilst the emissions from the production phase were lower in comparison to the wood materials. Like the GHG, energy use (MJ m^{-2}) was higher in the concrete element than in wood per square meter of building production (Figure 6c). The share of non-renewable energy use was higher compared to renewables in both buildings. Non-renewable corresponded to about 60% in wood, whereas it was 88% for concrete materials (results not shown).

Social indicator

Employment was expressed in full-time equivalents (FTE) per year, a value of 1 indicated one person working full-time for a whole year (e.g., 2080 h). The major contribution for wood was found in A4 stage (transport of final material to the construction site) (Figure 6d). This was mainly because the manufacturing facilities were very far from the construction site and a long drive was needed for transportation. However, the manufacturing phase (A3) contributed a minor fraction due to the higher productivity rate at sawmills. Concrete, in contrast, showed the highest share in the manufacturing phase (A3) (Figure 6d).

Occupational accidents were reported only for non-fatal accidents and included A1 (raw materials extraction) and A3 (manufacturing) phases for both alternatives (Figure 6e). Wood materials resulted in fewer accidents in comparison to concrete materials. The main reason is that in the two production facilities no accidents were reported. For concrete, the highest value was found during manufacture (A3 stage), indicating that work safety was better in the wood-alternative.

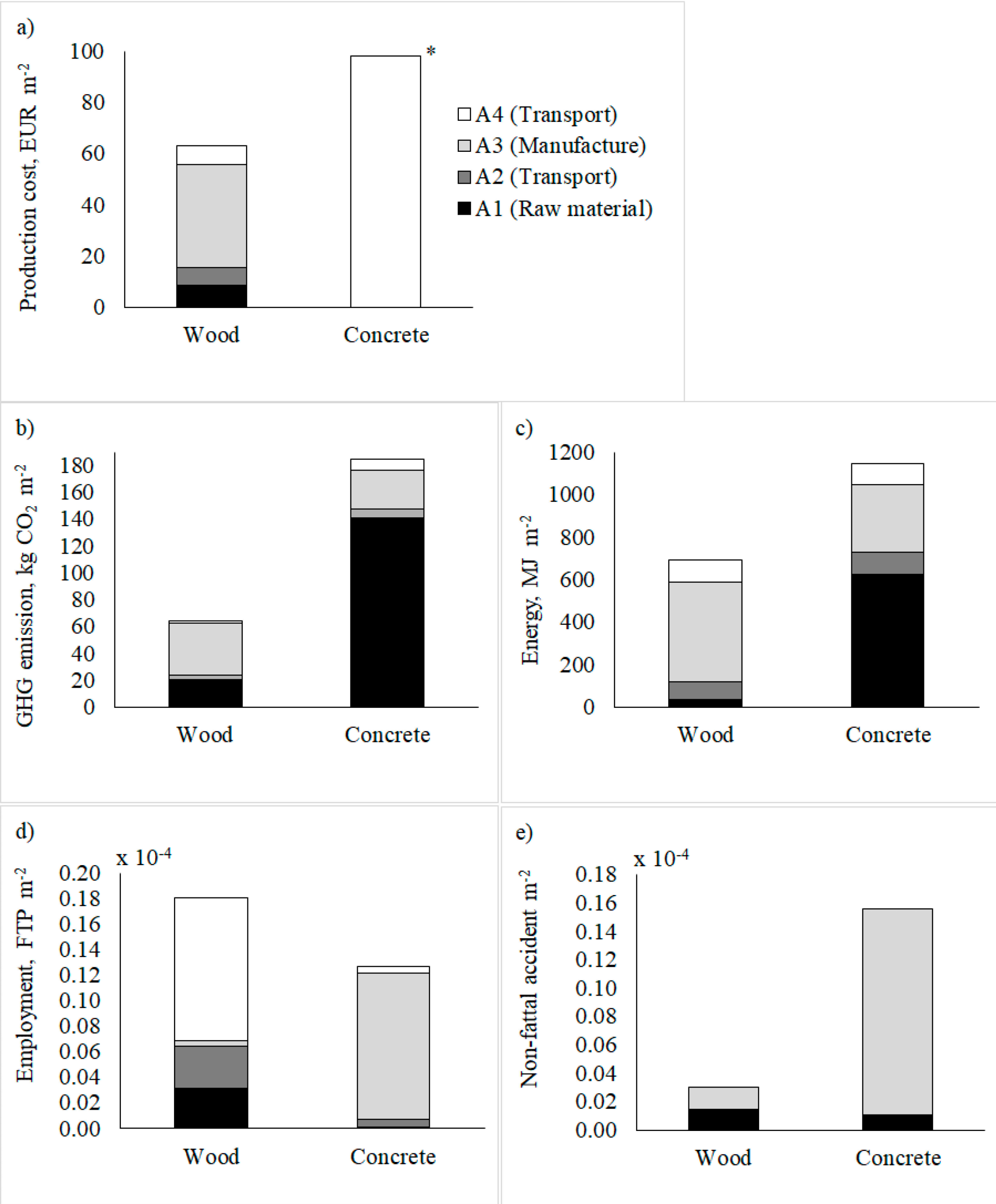

Figure 6. Sustainability assessment of the selected indicators. Production costs (**a**), GHG emissions (**b**), energy use (**c**), employment (**d**) and non-fatal accidents (**e**) for the wood and non-wood materials used in the buildings. * The production cost for concrete shows all four stages (A1–A4) combined.

Emission Savings and Carbon Stock of Building Products and Component

Figure 7 shows the GHG savings gained by using wood in place of reinforced concrete (Figure 7a) and the carbon stock (biogenic carbon) in the wooden materials (Figure 7b). The results are reported for various building components and wood versus concrete elements. Overall, wood was found to reduce emissions by 159 $kgCO_2\ m^{-2}$ when replacing concrete. The emissions savings ranged from 21 to 89 $kgCO_2\ m^{-2}$ depending on the building components (Figure 7a) and from 7 to 77 $kgCO_2\ m^{-2}$ for the wood products (Figure 7b). CLT was found to contribute the least to the emissions savings, whilst sawnwood, LVL and floor were found to save the most. The sensitivity analysis showed that when the emissions factor of the concrete elements was increased by 50%, the total emissions savings rose to 251 $kgCO_2\ m^{-2}$, whilst the value was 66 $kgCO_2\ m^{-2}$ when emissions were halved. On the other hand, the amount of carbon stored in the building components and materials ranged between 10–46 and 23–53 $kgCO_2\ m^{-2}$ respectively.

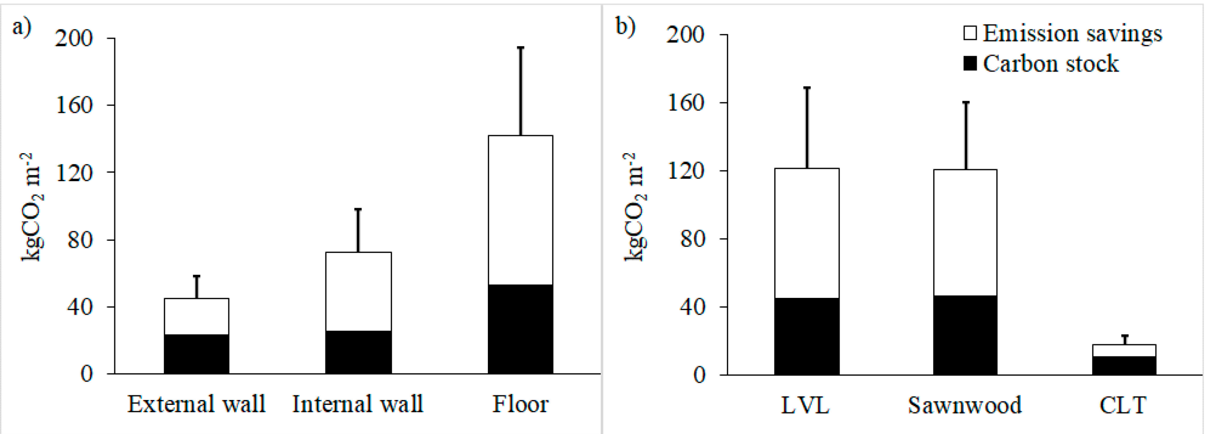

Figure 7. Biogenic carbon stocks and GHG emission savings for using wood against concrete separated for components (**a**) and materials (**b**) of building structure. The cap in the bar indicates the emission savings value for a 50% increase of emission factors for concrete elements. The magnitude of the result is the same when lower emission factors were used.

DISCUSSION

The objective of this study was to quantify and compare the sustainability (economic, social, and environmental) impacts associated with the use of alternative materials in the construction of typical Finnish mid-rise residential buildings. Using ToSIA, a tool that couples LCA with material flow analysis, a four-storey reinforced concrete frame building was compared with a wooden building, utilizing sawnwood and engineered wood products (LVL and CLT) in its construction. The system boundary for the assessment was cradle-to-construction site gate (A1–A4) and focused on the sourcing, manufacturing, and transportation of various raw materials in a comparable manner. The analysis included the structural and load-bearing support system of the building. The foundations and the building envelop, which included doors and windows, were excluded from the analysis since it was assumed that both buildings incorporated similar materials and amounts of materials in these categories.

According to the results, wood has a clear environmental advantage over a similar building of reinforced concrete. During the sourcing, manufacturing, and building phases, wood structures result in about 65% less GHG emissions and consume 40% less fossil energy than comparable concrete structures. Generally, every cubic meter of manufactured reinforced concrete emits less carbon than wood, however, normalizing it by floor area (per square meter), to compare buildings made of lighter elements (such as wood) but providing similar function, a greater mass of concrete is required, leading to higher GHG emissions. In our case, a volume of concrete materials about two-and-half times greater than wood was needed to construct an equivalent building. In terms of carbon emissions, our results are within the range reported earlier [15,19,35]. These studies reported carbon emissions values of 287–550 $kgCO_2\ m^{-2}$ and 40–159 $kgCO_2\ m^{-2}$ for concrete and wood structures, respectively and for energy use, the values were 1.38–8.3 GJ m^{-2} for concrete and 0.74–8.17 GJ m^{-2} for wood. The discrepancy between the results arises from the system boundaries or the materials used in the construction. The buildings, for example, studied by Leyder et al. [19] involved a hybrid structure incorporating both wood and concrete. In our case, the structural elements used in the wood building did not include any non-wood materials.

When wood replaces more energy-intensive materials, or fossil fuels, average displacement factors for material and energy can be determined [36]. These are a measure in tons of carbon (tC) avoided per tC of wood product use (tC tC^{-1}). The most often used displacement factors for harvested wood products are in the range 0.5–5.6 tC tC^{-1}, with an average of 2 tC tC^{-1} [36–38]. Our calculation shows that for such a mid-rise, multi-storey wooden building, emissions can be reduced by 159 $kgCO_2\ m^{-2}$ compared to an equivalent concrete building. By applying the formula suggested by Sathre & O'Connor [36], the displacement factor in our case is 1.3 tC tC^{-1}, if we quantify the emission reduction achieved per unit of wood used in place of reinforced concrete. Our estimate is quite similar to the average displacement factor (1.2 tC tC^{-1}) reported by Leskinen et al. [38].

Often biogenic carbon stored in wooden components is not added to displacement factors [36] because it is argued that the carbon storage capacity of wood is temporary, and the stored carbon eventually returns to the atmosphere after use. However, wood products used in long-term structures like buildings, and especially in buildings which are designed for disassembly, make it possible to cascade the material after first use and thereby extend the carbon storage period (e.g., [39]). By extending the life of wood products in this way, and until the next generation wood is available for harvesting from the same land, it can be argued that stored biogenic carbon should be included in displacement factors, at least partially. If the biogenic carbon stored in wooden materials is added to the value above, a total of 260 $kgCO_2\ m^{-2}$ could be stored, and at the same time emissions avoided on a long-term basis. Converting this to units of $tC\ tC^{-1}$, it equates to a value of 2.1 $tC\ tC^{-1}$.

In Helsinki, the current emissions level is around 2300 $ktonCO_2$ annually, with the building sector accounting for about 10% of this [40]. Helsinki constructs about half a million square meters of residential floor area in new buildings annually [41], predominantly from concrete. If these were to be constructed from wood, as in our case study (0.13 m^3 wood products per m^2 of built floor area), it would require only a fraction of a percent of the wood harvested annually in Finland. By using our emission reduction value and applying it to 50% of newly built residential buildings, we calculate that there would be a reduction in emissions of 62 $ktonCO_2$ annually. This equates to a saving of around 25% of the current construction emissions. Future studies may extend the system boundary and include end-of-life scenarios and cascading use of wood to find new emissions saving values.

Wood-based construction is generally recognized as being significantly faster in comparison to reinforced concrete construction [14,42], but a clear cost comparison has not been established to date due to a lack of research. Our results show that the overall cost could be reduced by using engineered wood instead of concrete materials. The costs for all the materials combined could be reduced by up to 36% depending on the material used. Earlier Mallo & Espinoza [43] also showed that the use of CLT could potentially reduce the cost of structures by up to 22%. However, a study by Talvitie et al. [10] indicated that wood-based housing is almost 10% more expensive per square meter than concrete-based housing in the same area in Finland. This could be true since costs can be higher at earlier or later stages in building construction that are not considered in this study. For example, precise design modelling for controlled wooden component installation is currently less efficient than concrete [44], which could delay the planning time required for building production, leading to a rise in costs. But the most important aspect that increases the costs is the installation of sprinkler systems arising from regulations. However, if the price for carbon stored in the wooden components is accounted for in the future, the higher costs of wooden apartments now claimed (e.g., [14]) can be mitigated.

CONCLUSIONS

In summary, the wood frame structure was found to provide greater environmental benefits for the studied phases (A1–A4), with only one-third of the greenhouse gas emissions and two-thirds of the non-renewable energy consumption compared to the reinforced concrete alternative. In terms of socio-economic sustainability, the reinforced concrete alternative had higher production costs, but a lower labour intensity than wood. It was also found that non-fatal accidents occurred more often in the concrete supply chain, especially at the manufacturing facility, than in the wood-alternative, indicating that work safety was better in the wood-alternative. In addition, the avoided emissions calculation showed that 159 $kgCO_2.m^{-2}$ could be avoided and 101 $kgCO_2\,m^{-2}$ could be stored by replacing concrete framed buildings with wood. By replacing 50% of new residential buildings to be built in Helsinki with wood, a total of 62 $ktonCO_2$ emissions could be saved.

SUPPLEMENTARY MATERIALS

Supplementary Table S1: Parameter used for calculating sustainability impact indicator values [27,28,45–58]. Supplementary Table S2: Parameter used for calculating environment indicator values. Raw material for wood elements and transportation distance from site to site is adjusted according to the case study buildings. In concrete elements, the values after "±" sign indicate that it is added or deducted from the base value for the sensitivity analysis [32–34,59–63].

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

The original draft was prepared by AA and all other authors contributed to the revision and editing of the manuscript. All authors have also read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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