LIFE CYCLE ASSESSMENT OF MATERIALS USED FOR PORTAL FRAME PRODUCTION

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Abstract
The construction sector plays a crucial role in global environmental impacts, making accurate life cycle assessment essential for sustainable decision making. This research evaluates the environmental impacts of timber, steel, and concrete in industrial portal frame structures using life cycle assessment. Timber shows the highest impact on land use but lower contributions to climate change and ecotoxicity. Steel has moderate climate impacts but the highest potential for freshwater ecotoxicity, while concrete is the most carbon-intensive, contributing most to climate change. The results highlight the importance of evaluating multiple impact categories for sustainable material selection.

Introduction
Buildings contribute significantly to environmental impacts, accounting for 35% of global energy use and 19% of energy-related greenhouse gas emissions in 2010, potentially doubling or tripling by 2050 [1]. Assessing the environmental impacts of building designs, particularly their role in climate change and environmental degradation, is a key motivation for this research [2]. Several studies emphasize timber construction's environmental benefits. Liang et al. (2020) [3] found a 12-story mass timber building reduced global warming potential by 18% and eutrophication by 47% compared to concrete. Guo et al. (2017) [4] showed cross laminated timber residential buildings in cold climates used 9.9% less energy and emitted 13.2% less carbon than concrete. Chen et al. (2020) [5] found a 12-story cross laminated timber building used 33% less material and emitted 70% less embodied carbon. Hegeir et al. (2022) [6] confirmed timber's lower environmental impacts in industrial buildings, mainly due to carbon storage.
The starting point of this research was the study by Hegeir et al. (2022) [6] where foreground data was used (Environmental Product Declarations), and in this research background data was used (Ecoinvent 3.7 database) [7]. The aim of this research is to compare the environmental impact of timber, steel, and concrete used in portal frame structures for industrial buildings by conducting a comprehensive LCA.

Experimental
A standardized LCA (ISO 14040:2006; ISO 14044:2006) [8,9] was performed, with environmental impacts calculated using openLCA software (version 2.3), a widely recognized tool for conducting LCA.

Goal and scope

The goal of the LCA is to evaluate potential environmental impacts associated with materials used for portal frame production in industrial buildings. Materials are timber, steel and concrete. The functional unit is kg/m^2 area. The area of the hall is 250 m^2, the total quantities of frames are 10 m span and 25 m span. In this research, the calculations refer to a 10 m span. This research uses cradle to gate system boundaries. The geographic scope of this research is the Global (GLO) region, representing an average worldwide context for data. Fig. 1 presents system boundaries. Fig. 2 presents 3D drawing of the portal frames: (a) timber frames; (b) steel frames; (c) reinforced concrete frames [6]

Figure 1. System boundaries

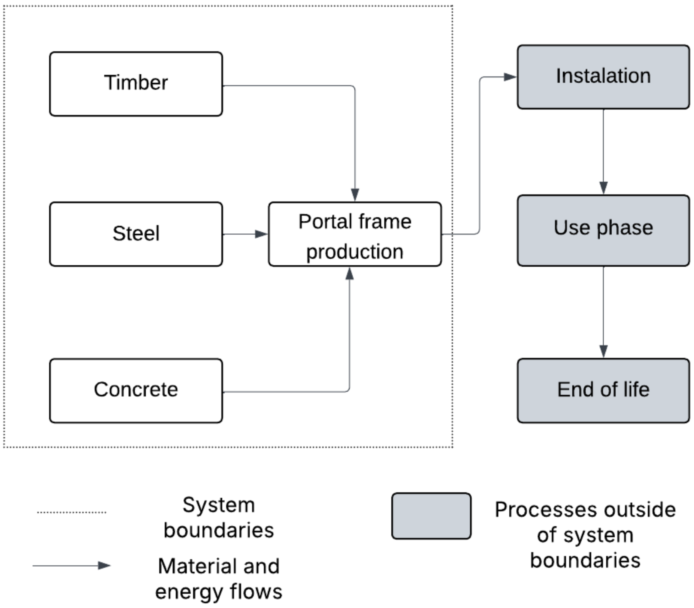
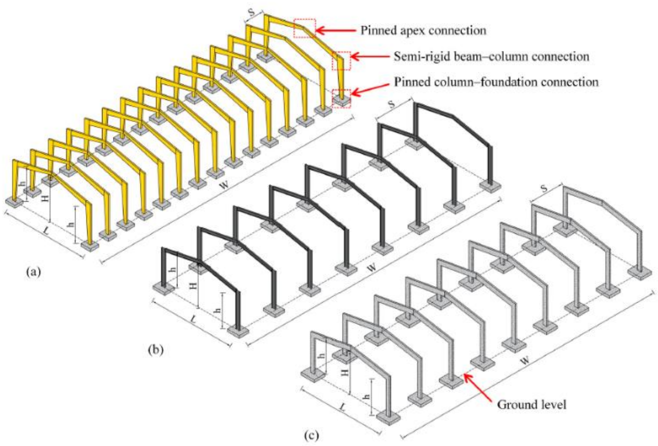


Fig. 2. 3D drawing of the portal frames: (a) timber frames; (b) steel frames; (c) reinforced concrete frames [6]



Assumptions and limitations:

The chosen Life Cycle Impact Assessment (LCIA) method focuses on midpoint indicators. This assumes that assessing impacts at the midpoint level (e.g., climate change, acidification) is sufficient to inform decision-making, even though endpoint assessments (e.g., damage to health or biodiversity) could offer more integrated views.

It is assumed that timber, steel, and concrete serve equivalent structural functions in portal frame applications, allowing for a direct comparison based on environmental impact per unit area. The research does not evaluate how material properties affect design efficiency (e.g., how much material is needed to achieve the same structural performance), potentially biasing results in favor of denser or more structurally efficient materials.

To assess the environmental impacts ReCiPe Midpoint (H) is used. This method is a widely used LCIA approach that translates environmental emissions and resource extractions into 18 impact categories, focusing on specific environmental problems (midpoints) to allow detailed and comparative sustainability assessments. The impact categories considered in this research for ReCiPe Midpoint (H) include: Agricultural land occupation (m^2/year), Climate change (kg CO_2 eq), Fossil depletion (kg oil eq), Freshwater ecotoxicity (kg 1,4-DCB eq).

Inventory analysis

Data for used materials were extracted from the Ecoinvent 3.7 database with cut-off system model (Wernet et al., 2016) [7], which provides life cycle inventory data on a wide range of materials and processes. The quantities of material and energy flows are taken from the study by Hegeir et al. (2022) [6] and shown in Table 1.

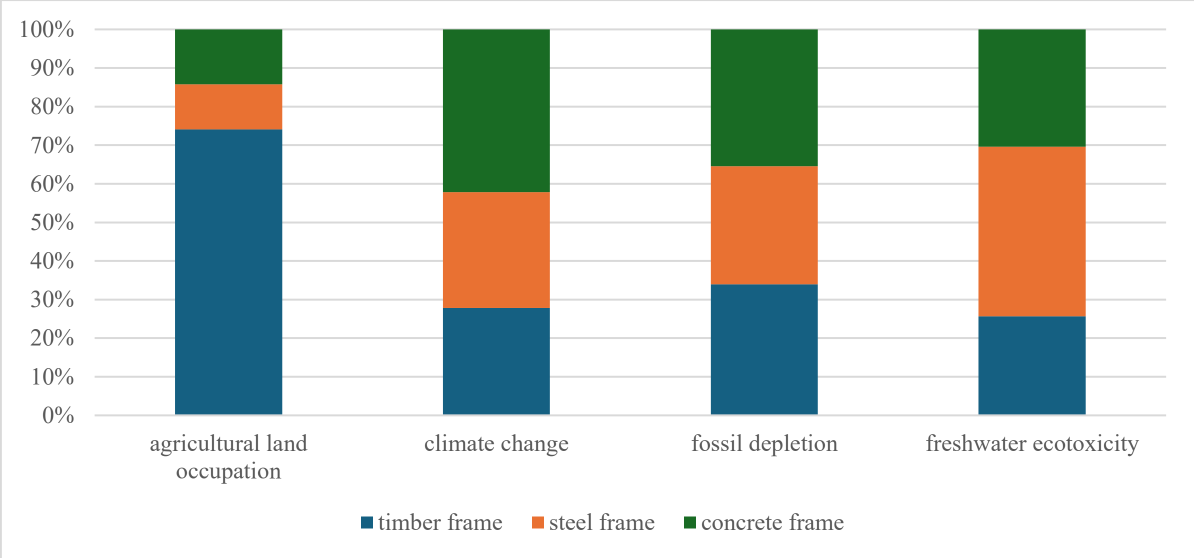
Table 1. Life cycle inventory for portal frame production [6]

Material/energy flow	Activity from Ecoinvent database	Location	Unit	Portal Frame production
timber, cross laminated	market for cross-laminated timber	RER	m^3	37.08
steel dowels	market for steel, low-alloyed	GLO	kg	390.62
steel bolts	market for steel, low-alloyed	GLO	kg	672.23
steel plates	market for steel, low-alloyed, hot rolled	GLO	kg	1180.41
steel low alloyed	market for steel, low-alloyed	GLO	kg	7373.18
concrete 30MPa	market for concrete, 30MPa	RoW	m^3	23.11
reinforcing steel	market for reinforcing steel	GLO	kg	3776.48

Results and discussion

Fig. 3 present comparison of the impact of different materials for frame production on different impact categories.

Fig. 3 Comparison of the impact of different materials for frame production on different impact categories



The timber frame dominates in the agricultural land occupation category, contributing roughly 75% of the impact. Steel and concrete have smaller contributions, around 12% and 13% respectively. This suggests that timber requires more land resources than the other materials. Concrete frames contribute the most in climate change category (around 42%), followed by steel (30%) and timber (28%). This indicates that concrete production is highly carbon-intensive, while timber has a lower contribution. Steel frames have the highest contribution to freshwater ecotoxicity. Steel dominates in freshwater ecotoxicity category (~44%), followed by concrete (~30%) and timber (~26%). Steel production appears to have the highest potential to cause freshwater ecotoxicity. Overall, timber is associated with high land use but lower contributions to climate change and ecotoxicity, steel has moderate climate impact but high ecotoxicity, and concrete has the highest climate change impact while being moderate in other categories. This highlights the trade-offs in environmental impacts depending on the choice of construction material.

Conclusion

This research highlights the diverse environmental impacts of timber, steel, and concrete in industrial portal frame structures. Timber, while often considered sustainable, shows the highest land use but lower contributions to climate change and ecotoxicity. Steel has moderate climate impacts but the highest potential for freshwater ecotoxicity, whereas concrete is the most carbon-intensive, contributing most to climate change while being moderate in other categories. These results emphasize the trade-offs in material choice and the importance of assessing a range of environmental impacts. This comprehensive LCA provides valuable insights for stakeholders to make more informed and sustainable choices in structural design. Future research should focus on refining life cycle inventory data, exploring regional variations in electricity mixes and material sourcing, and evaluating emerging low-impact materials and construction methods to further support sustainable decision-making in the built environment.

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