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Comparative Life Cycle Analysis of Timber, Steel and Reinforced Concrete Portal Frames: A Theoretical Study on a Norwegian Industrial Building

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Abstract: The construction industry is a big contributor to greenhouse gas emissions, which has a negative environmental impact. Several studies have highlighted the possibility of using timber to reduce the environmental impact of construction. Most of these studies have focused on residential buildings, but little attention has been devoted to industrial buildings. In this paper, an attempt is made to compare the environmental impact of using timber, steel, and reinforced concrete in industrial buildings using life cycle assessment. The system boundary was set to cradle-to-gate with transportation to construction site due to the limitation of data, and only the quantities of the main structural system are considered. Portal frames with variable spans were designed using the three materials to meet similar load carrying capacity. Reinforced concrete was used in the foundation of all frames. The results of the comparative study show that timber has, by a good margin, better environmental impact than reinforced concrete and steel, due to the carbon stored in the wood. The results also show that reinforced concrete and steel alternatives have similar environmental impacts. The findings of this study agree with the findings of other studies on residential buildings.

Keywords: LCA; GHG emissions; CO_2 emissions; industrial buildings; timber; concrete; steel; portal frame

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1. Introduction

The world population is constantly increasing [1], implying a higher need for urbanization. However, the construction industry is a big contributor to worldwide greenhouse gas (GHG) emissions. In 2010, 19% of the total global energy-related GHG emissions were related to the construction industry [2]. GHG emissions are linked to the serious problem of climate change and its negative environmental impacts, such as extreme temperatures, heavy rains, and droughts [3]. Given the need for urbanization and the need for reducing the GHG emissions within the construction industry, the choice of construction material is of significant importance.

Timber is a good alternative to concrete and steel as a construction material, due to the high strength/weight ratio. Comparative life cycle analysis (LCA) studies highlight the positive environmental impact of using cross laminated timber (CLT) instead of reinforced concrete in multistorey buildings [4–9]. Skullestad et al. [10] performed LCA on buildings up to 21 floors and concluded that timber buildings have 34–84% lower climate change impact than reinforced concrete buildings with the same load capacity. Dodoo et al. [11] pointed out that the use of low-energy multi-storey timber buildings can further reduce carbon emissions by 8–9% compared to conventional multi-storey timber buildings. Dodoo et al. [12] studied the carbonation in the post-use phase of concrete and concluded that it does not change the validity that timber buildings have lower carbon emissions than concrete buildings. Gong et al. [13] performed LCA on concrete, steel, and timber residential buildings, the results show that the energy consumption over the life cycle of the timber building is approximately 30% lower than the concrete and steel buildings. According to Börjesson et al. [14], the efficiency of using timber as a construction material in a building highly depends on how timber is handled after the demolition of the building.

Industrial buildings, such as factories or warehouses, are traditionally constructed using structural steel as the main structural material. The structural system of such structures can vary depending on the span of the structural system. The most commonly used systems in practice are portal frames and trusses. The truss system is preferred over the portal frame system when the cross sections of the portal frame system become very heavy and non-economic [15]. Trusses can be built using timber or steel. However, the truss system is not common if reinforced concrete is to be used, due to the difficulty of the formwork and, thus, portal frames are usually used.

Previous studies have shown that using timber as a construction material instead of structural steel or reinforced concrete can result in reduced GHG emissions and, therefore, more environmentally friendly construction [4–14]. However, the focus was mainly on multistorey residential buildings, and less focus was given to industrial buildings. The material demands for multistorey buildings are different from industrial buildings and not linearly proportional. One example is, e.g., the amount of concrete in the foundations, which depends on the number of storeys, or the weight of the structure, but not linearly. Moreover, when it comes to timber buildings, different criteria are likely to govern the structural design of multistorey buildings (serviceability limit state) [16–19] and industrial buildings (ultimate limit state). The possibility of using timber as a structural material in industrial buildings to reduce the environmental impact of the construction process has not been investigated. This paper is an attempt to highlight the possibility of reducing the environmental impact of constructing industrial buildings by using timber as a construction material.

In this paper, the environmental impact of using timber, structural steel, and reinforced concrete in the construction of industrial buildings is compared using LCA. The focus of this paper is given to the portal frame as a structural system, since it is easily constructable using all three different materials of concern. The study is conducted on an imaginary industrial building located in Oslo. The load-bearing structure is calculated for all three materials (in accordance with the relevant Eurocodes) giving material volume for the LCA.

2. Methodology

2.1. Structural System and Layout

The structural system of this study is to cover a rectangular area of WxL plan dimensions, as shown in Figure 1. The portal frame was designed based on timber, structural steel, and reinforced concrete; all the three alternatives are shown in Figure 1. All frames have concrete foundations, as shown in Figure 1. Steel dowels and bolts are used in the connections of timber frames. Illustrative drawings of the column–foundation connection, apex connection, and beam–column connection are shown in Figure 2. The out of plane spacing S between adjacent portal frames varies depending on the material to achieve economic design of each material. The slope of the roof is assumed to be 1:5 for all frames. Two variations of the span are chosen for each material, one short span of 10 m and one long span of 25 m. This is mainly to study the effect of the span and to capture any non-linearity in the results caused by the span. The dimensions are summarized in Table 1.

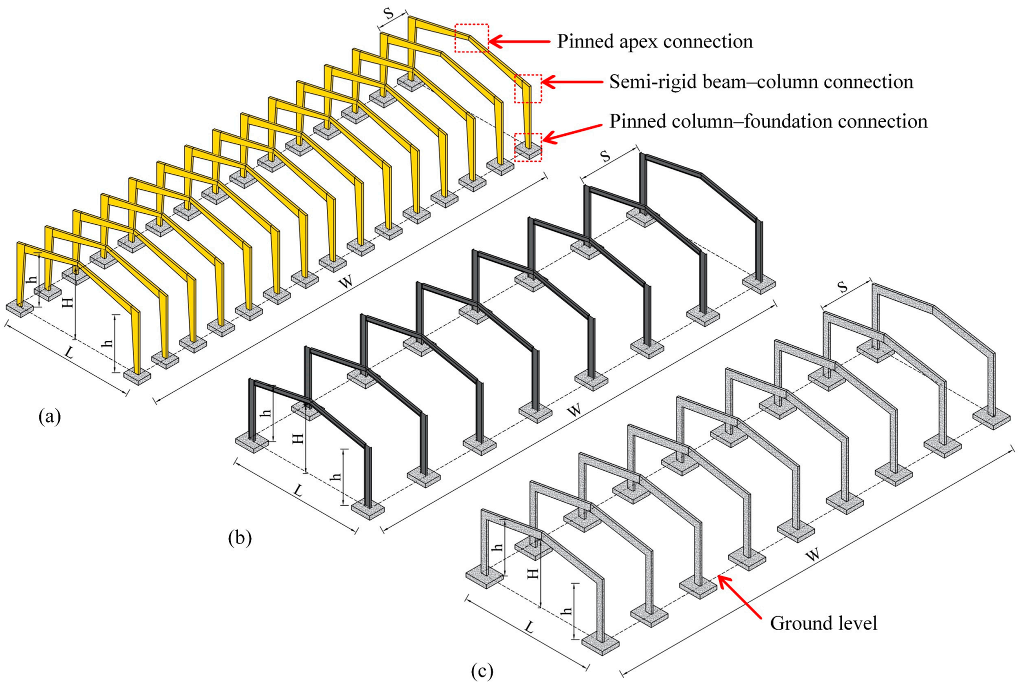

Figure 1. 3D drawing of the portal frames: (**a**) timber frames; (**b**) steel frames; (**c**) reinforced concrete frames.

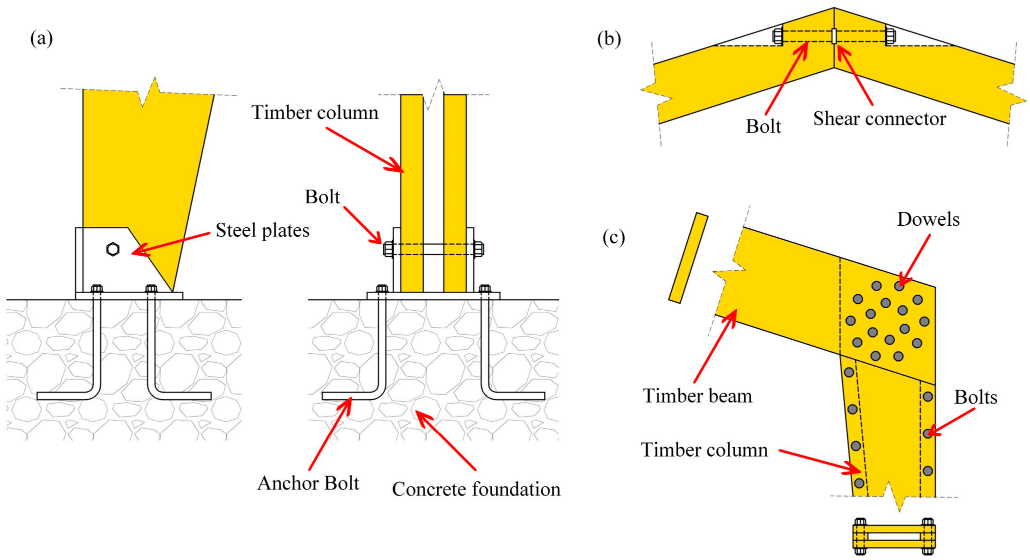

Figure 2. Illustrative drawings of connections in timber frames: (**a**) pinned column–foundation connection; (**b**) pinned apex connection; (**c**) semi-rigid beam–column connection.

Table 1. Summary of the dimensions of the main system.

Material	Width *W* (m)	Length *L* (m)	Spacing *S* (m)	Height at Apex H (m) *	Height at the Corner h (m) *
Timber	42.00	10.00/25.00	3.00	6.00/7.50	5.00
Steel	42.00	10.00/25.00	6.00	6.00/7.50	5.00
Concrete	42.00	10.00/25.00	5.25	6.00/7.50	5.00

* Measured from the ground level shown in Figure 1.

2.2. Assumptions and Simplifications

In this study, the following assumptions, simplifications, and limitations apply:

- For all frames, the design is performed such that the clear height at the corner is 5 m;
- All secondary elements were not included in the structural design; therefore, their own weight was assumed to be 0.30 kN/m^2 for all frames, this is to facilitate the comparison;
- All frames are subjected to a uniform live load of 0.40 kN/m^2 at the roof as recommended by EN1991-1-1 [20];
- The peak wind pressure is 0.65 kN/m^2, this corresponds to the Oslo area ($V_b = 26$ m/s) with terrain category of II as defined by EN1991-1-4 [21];
- The characteristic snow load is 2.80 kN/m^2, this corresponds to the Oslo area with altitude of less than 100 m EN1991-1-3 [22];
- The columns were assumed pinned to the foundations for timber, steel and concrete frames;
- The corner and apex connections of steel and concrete frames were assumed rigid. The apex connection of timber frames was assumed pinned, and the corner connection of timber frames was assumed semi-rigid (refer to Figure 2);
- The foundations of all frames are isolated footing and made of reinforced concrete;
- The concrete used in reinforced concrete frames and the foundations of all frames is C30/C37 (30 MPa cylinder strength or 37 MPa cube strength) and the reinforcing bars are of quality B500C available in the Norwegian market (500 MPa yield strength). The maximum aggregate size is 20 mm. The exposure class is XC3. The design life is 50 years. The previous assumptions result in a minimum cover of 35 mm, a maximum water content of 0.55, and a minimum cement content of 300 kg/m^3 [23];
- The structural steel used in the beams and columns of the steel portal frames is of quality S460, available in the Norwegian market (460 MPa yield strength);
- The timber used in the beams and columns of the timber frames is glulam of strength class GL30c defined by EN14080 [24];
- The steel dowels and bolts used in the connections of timber frames were assumed of a strength class 8.8 (800 MPa ultimate strength and 640 MPa yield strength) as defined by ISO 898 [25];
- The structural steel used in the connections of the timber frames is of quality S460 available in the Norwegian market (460 MPa yield strength);
- The load combination used in the design of all frames is the fundamental load combination defined by equation 6.10 in EN1990 [26] ($\gamma_G = 1.20$, $\gamma_Q = 1.50$, $\psi_0 = 0.70$ for live load and snow load, and 0.60 for wind load, as defined by the Norwegian National Annex);
- The structural design for all frames was performed based on the respective Eurocode for each material, EN1995-1-1 [27] for timber, EN1993-1-1 [28] for steel, and EN1992-1-1 [29] for concrete;
- All frames of the three materials are dimensioned to meet similar load carrying capacity;
- The structural design and the calculation of quantities were performed only for the main structural system, no secondary structural elements (purlins, slabs, etc.) or covering were included.

2.3. LCA Background, Functional Unit, and System Boundaries

LCA is a standardized method used to quantify the environmental impacts of a product/service during the whole life cycle starting from material extraction up until disposal. The NS-EN ISO 14040:2006 [30] guidelines describe the principles and the framework of the LCA, while NS-EN ISO 14044:2006 [31] describes detailed requirements needed when performing LCA. For the case of buildings, NS-EN 15978:2011 [32] gives calculation methods to assess the environmental impacts of newly built and existing buildings.

The assessment of the environmental impacts is done using some environmental indicators. An environmental indicator is a numeric value that evaluates the environmental impact. According to NS-EN 15804:2012 [33], the core environmental impact indicator for climate change is the global warming potential (GWP), and the unit of the GWP is kg CO_2-eq. The functional unit in this paper is set to kg CO_2-eq. per square meter of the area (m^2), shown in Figure 1 by dotted line (LxW), to get a realistic comparison between the three alternatives.

According to NS-EN 15978:2011 [32], the system boundaries are divided into five stages: the product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B7), end of life stage (C1–C4), and benefits and loads beyond the system boundary (D). In this paper, since the main purpose is to compare the different alternative materials and due to the poor data availability, the system boundary is set to cradle-to-gate with the option of adding A4 (transportation to construction site) as defined by NS-EN 15804:2012 [33], which represents A1–A4.

2.4. Calculation of Emissions

To calculate the GWP, environmental product declarations (abbr. EPDs) are used. The EDPs provide the value of several environmental impact indicators, including GWP, for the different stages defined in NS-EN 15978:2011 [32]. In this paper, the EDPs retrieved from the Norwegian EPD Foundation [34] were used. In all calculations, the exact EDP of each product was used [35–39]. However, for dowels and bolts which are used in the connections of timber frames, the exact EDPs were not available, therefore, the EDP of threaded steel anchors was used for both [40].

3. Structural Design and Quantities

In this section, the details of the structural analysis and design of all frames are explained. The structural analysis of all frames is performed using CSI SAP2000 [41]. The structural design and dimensioning are performed using CSI SAP2000 [41] and Excel sheets developed by the authors. The quantities of all materials are also shown.

3.1. Timber Frames

The structural design is performed assuming glulam of strength class GL30c. Due to the moderate stiffness of timber, rigid connections cannot be achieved, therefore, the corner connections were assumed as semi-rigid in the structural analysis models. The connections of the timber portal frame were designed based on dowel-type connections as shown in Figure 2; therefore, steel is used in the connections and is calculated in the quantities. The structural design is performed using Excel sheets developed by the authors, since no design of timber available in CSI SAP2000 [41]. The total quantities of the timber frames, both the 10 m span and the 25 m span are summarized in Table 2.

Table 2. Quantities of the timber frames.

	The Portal Frame				Foundations	
Span (m)	**Timber CL30c (m^3)**	**Steel Dowels 8.8 (kg)**	**Steel Bolts 8.8 (kg)**	**Steel Plates S460 (kg)**	**Concrete C30/C37 (m^3)**	**Reinforcement B500C (kg)**
10.00	37.08	390.62	672.23	1180.41	7.68	338.75
25.00	94.91	1302.29	855.69	1757.46	18.75	651.03

3.2. Steel Frames

CSI SAP2000 [41] is used to perform the design of structural elements since it performs the design based on the EN1993-1-1 [28] together with the Norwegian national annex. The total quantities of the steel frames, both the 10 m span and the 25 m span are summarized in Table 3.

Table 3. Quantities of the steel frames.

	The Portal Frame	Foundations	
Span (m)	**Steel S460 (kg)**	**Concrete C30/C37 (m^3)**	**Reinforcement B500C (kg)**
10.00	7373.18	8.06	297.82
25.00	37630.66	22.04	670.44

3.3. *Reinforced Concrete Frames*

Together with Excel sheets developed by the authors, CSI SAP2000 [41] is used to perform the design of structural elements since it performs the design based on the EN1992-1-1 [29] together with the Norwegian national annex. The total quantities of the concrete frames, both the 10 m span and the 25 m span are summarized in Table 4.

Table 4. Quantities of the reinforced concrete frames.

	The Portal Frame		Foundations	
Span (m)	**Concrete C30/C37 (m^3)**	**Reinforcement B500C (kg)**	**Concrete C30/C37 (m^3)**	**Reinforcement B500C (kg)**
10.00	23.11	3776.48	10.08	374.74
25.00	120.65	22109.31	30.13	836.82

4. Results, Discussion, and Limitations

The quantities summarized in Tables 2–4 are used together with the respective EDPs provided by Norwegian EPD Foundation [34] to calculate the GWP/m^2 for all frames. The GWP extracted from the EDPs are summarized in Table 5. The results of the total GWP/m^2 are summarized in Table 6 and are shown in Figure 3.

Table 5. Summary of the GWP for different material [34].

Material	GWP (A1–A4)	Unit
Glulam (GL30c)	−597.70	kg CO_2-eq./m^3 timber
Steel dowels and bolts used for timber frames' connections (strength class 8.8)	2.90	kg CO_2-eq./kg steel
Steel plates (S460)	2.47	kg CO_2-eq./kg steel
Concrete (C30/C37)	212.26	kg CO_2-eq./m^3 concrete
Steel reinforcement (B500C)	0.40	kg CO_2-eq./kg steel
Structural steel I beams (S460)	1.21	kg CO_2-eq./kg steel

Table 6. GWP/m^2 for all frames.

Item	Span (m)	Timber	Steel	Concrete
		GWP (kg CO_2-eq./m^2)		
Main frame	10.00	−52.77	21.19	15.31
	25.00	−54.03	43.25	32.88
Foundations	10.00	4.21	4.36	5.45
	25.00	4.04	4.71	6.41
Steel fasteners and plates	10.00	14.27	0.00	0.00
	25.00	10.09	0.00	0.00
Total	10.00	−34.30	25.55	20.76
	25.00	−39.90	47.96	39.29

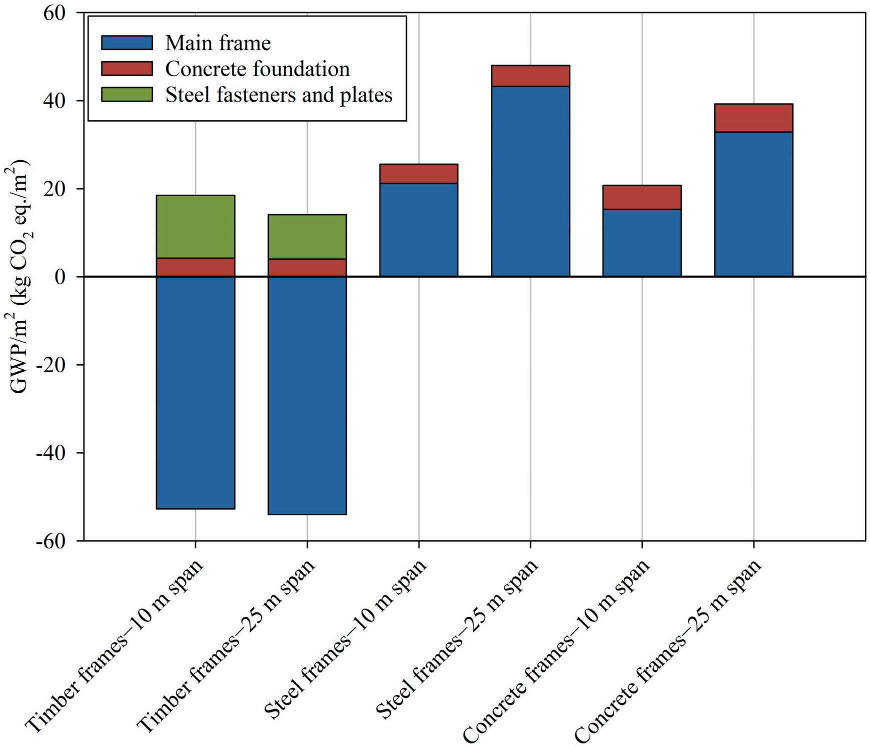

Figure 3. Comparison between the GWP/m^2 for all frames.

As shown in Figure 3 and summarized in Table 6, steel frames have a total GWP/m^2 (main frames, foundation, and steel fasteners and plates) that is higher than the concrete frames and much higher than the timber frames. This applies for both the 10-m span and the 25-m span frames. In the timber frames, although concrete is used in the foundations and steel is used in the connections, the net GWP/m^2 is negative due to the fact that timber stores CO_2. It is notable to mention that finetuning the design or using materials with lower GWPs, such as low-carbon concrete or recycled steel, might yield different results. However, such scenarios are not discussed in this paper. Furthermore, the end-of-life and circularity options (C and D) for timber, steel, and concrete frames should be taken into consideration.

As reinforced concrete is used for the foundation of all frames, it is also of interest to compare only the GWP/m^2 of the foundations. The results are shown in Table 6 and depicted in Figure 3. The foundations of timber frames have the lowest GWP/m^2 for both the small span and large span. This is because timber is a light material with good stiffness/weight ratio compared to steel and concrete and, hence, smaller foundations can be used. The GWP/m^2 for the foundations of the concrete frames are larger than the GWP/m^2 for the foundations of the steel frames for the small and large span frames. This is due to steel being lighter than concrete and having a higher stiffness/weight than concrete, which results in overall smaller foundations.

The use of different materials in the design and construction of the main structural system (portal frame) implies the possible use of different secondary structural elements, non-structural elements, insulation, etc. This will influence the total GWP/m^2 of the three alternatives (timber, steel, and concrete). However, in this paper, the focus is given to the main structural elements and other elements are assumed to be the same for the three alternatives. In some cases, and due to practical considerations, this assumption might not be valid.

5. Conclusions and Future Work

A portal frame with a small span of 10 m and a large span of 25 m was designed using timber, steel, and reinforced concrete to give the material quantities for LCA. A cradle-to-gate with the option of adding A4 (A1–A4) LCA is performed to compare the GWP of the three alternative materials. In performing the LCA, we could conclude that:

1. Considering the total GWP/m^2 (main frames, foundations, and steel fasteners and plates), the steel frames have a GWP/m^2 that is higher than the concrete frames and much higher than the timber frames for both the 10-m span and 25-span frames;
2. Considering only the foundations, the timber frames have the lowest GWP/m^2, while the concrete frames have the highest GWP/m^2 for both the 10-m span and 25-span frames.

Due to the limited data available, and to simplify the comparison, only the main structural elements were included in the LCA. This is done under the assumption that all other materials are the same, which in some cases may not be practical. There is a need for a more holistic LCA that includes the main and the secondary structural elements, and the non-structural elements to be able to fully judge the environmental impact of the different alternative materials. Furthermore, due to the limited data available for the operational conditions, demolishing, and disposal strategy, only cradle-to-gate with the option of adding A4 (A1–A4) was considered. To get a better understanding, it is worth including all stages in future studies to validate the findings of this paper. Since the focus in this study was given to portal frames, future work on different structural systems such as trusses or arches can be of interest.

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