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Massive timber building vs. conventional masonry building. A comparative life cycle assessment of an Italian case study

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Abstract. This work aims to investigate the environmental friendliness of building materials, and in particular the benefit of using biogenic products as replacement of conventional materials. The sustainability of wood as a construction material is a complex issue since the environmental impacts are strongly related to forest management, service life and, finally, to end-of-life scenarios and waste treatment processes. In this study, a Life Cycle Assessment (LCA) comparison was carried out between a semi-detached house out of cross-laminated timber (CLT) and a conventional building with similar geometric characteristics and equal thermal performance (U-value), out of light-clay bricks with a reinforced concrete structure. Particularly, the environmental impacts from raw materials supply, transportation and product processing (cradle to gate) were investigated and the Recipe mid-point method was adopted for the impact assessment to compare the environmental burdens of the two equivalent buildings. The positive environmental values resulted in the massive timber building are mainly connected to the replacement of the reinforced concrete mass used in the structure. The outcome, in terms of global warming potential, show that the use of wood as a building material instead of conventional materials results in a reduction of greenhouse gas emissions of roughly 25%. This material replacement, if extended on a large scale, could give a valid contribution on achieving the community goals of reducing emissions from the construction sector.

1. Introduction

The construction sector plays a decisive role in the achievement of the European targets for the reduction of energy consumption and carbon emissions. With this aim, European and, consequently, Italian standards mainly addressed the decrease of the environmental impact during the use phase through reducing the demand for operating energy [1]. As a consequence, the energy performance of buildings has been improved, mitigating the environmental impact of the operation phase. However, the

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importance of the other life cycle stages has increased due to higher material inputs [2]. As a matter of fact, the (fossil) carbon emitted when manufacturing the materials and during the construction stage might significantly affect the carbon savings from operational energy [3]. Building materials selection strongly affects the overall environmental impact of a building; in particular, the choice of the materials for the structural frame and the building envelope (foundation, exterior wall and roof) has a major influence [4].

This work presents the results of a study conducted with the aim of assessing the benefits, in terms of environmental impact, deriving from the use of construction technologies based on wood instead of traditional materials for the construction of residential buildings. Specifically, a Life Cycle Assessment (LCA) comparison was carried out between a semi-detached residential building with a load bearing structure made of Cross Laminated Timber (CLT) panels and a building of the same size and similar architectural and performance characteristics composed of a reinforced concrete load bearing structure and light-clay bricks. More precisely, the environmental impact deriving from the production cycle of the materials and products used for the construction of the two buildings has been assessed.

2. Methodology

The assessment of the environmental impacts of the two buildings was carried out according to the European standard EN 15978:2011 [5], which divides the life cycle of a building into different stages: the product phase (A1-A3), the construction process phase (A4-A5), the use phase (B1-B7), and the end of life phase (C1-C4).

The LCA analysis presented in this study was limited to the product phase (A1-A3) and it is used, specifically, to assess the environmental impact of materials and products used for the construction of the body of the two buildings. This phase includes the following activities: extraction of raw materials (A1), transport of the materials to the production company (A2), and production of the finished packed product up to the factory gates (A3).

For the comparative study of the two buildings, the construction technologies described in the technical documentation provided by the construction company were analyzed. Specifically, a list of all the materials necessary for the construction of the main structural and envelope elements was drawn up and the environmental impacts of these materials were calculated using the datasets available in the Ecoinvent 3 database [6]. Finally, the results for the two buildings were compared.

The methodology of LCA analysis is uniquely defined by the international standards ISO 14040:2006 and ISO 14044:2006 [7]. These standards provide the general principles, requirements and guidelines to properly conduct the analysis and define a scientific framework to assess the environmental load of products and processes allowing a comparison between them.

3. Case study analysis

The two case studies considered in the analysis are two residential buildings built in the same year in the same area in northern Italy with similar features and dimensions, but built with different construction technologies. The first, Building A, was built using a structural system of load-bearing walls made of cross laminated timber, while the second, Building B, was built using traditional construction technologies (i.e. a load-bearing frame of reinforced concrete and walls made of light clay bricks).

The objective of the analysis was to compare the environmental impacts of the two buildings, broken down with respect to the materials and components used for the construction of the two buildings.

Figure 1. Building A, built with a load-bearing structural system of cross laminated timber.

Figure 2. Building B, built with a reinforced concrete load-bearing frame and brick walls.

Table 1. Dimensional characteristics of the two buildings

	Year of construction	Gross floor area *(m^2)*	Number of floors	Number of apartments
Building A	2016	820	3	8
Building B	2016	814	3	8

3.1 Preliminary assumptions and limitations of the analysis

The Functional Unit (FU) used for the comparison of the two buildings is 1 m^2 of heated floor area. An LCA analysis of materials was carried out from a "cradle-to-gate" perspective (i.e. from the extraction of the raw materials to the factory gate).

The following assumptions were made for the analysis:

- Only elements of the buildings that differ between the two scenarios were included in the analysis. For above ground elements, vertical and horizontal external structures and closures were considered, while installations, finishes (coatings, paints) and fixtures, which are assumed to be the same for both buildings, were excluded. For the same reason, all underground structures were excluded, including the lower horizontal closure (ground floor);
- Non-load-bearing internal partitions (partitions and doors) inside the apartments were excluded since they may vary according to the needs of space distribution;
- 10 kg/m^3 of steelwork and hardware were considered for the wooden building;
- 150 kg of steel bars were assumed to be used per cubic meter of reinforced concrete.

For each building an inventory of all the materials and components was compiled according to the documentation provided by the contractor, which included graphs of the executive project, technical reports, and tender specifications.

3.2 Inventory analysis and impact assessment

Secondary data from the Ecoinvent database were used for the inventory analysis. On the other hand, the characterization factors and the impact categories considered by the ReCiPe Midpoint method were considered to assess the potential environmental impacts of the two buildings [8]. Finally, the SimaPro software (www.simapro.com) was used for the analysis. In the results, only the most meaningful impact categories for the present case study are presented.

4. Results

4.1 Impact assessment of the whole buildings

'Figure 3' compares the potential environmental impacts of the two building scenarios assessed with the ReCiPe method. Figures are expressed in percentage terms, where the worst case for each impact category is set to 100% in order to simplify the comparison.

The wooden building proves to have a lower potential impact for many environmental categories, while it results comparable to a building with a reinforced concrete frame and masonry infill panels in the others. Only in one environmental impact category (i.e. marine eutrophication), the wooden house shows larger potential impacts.

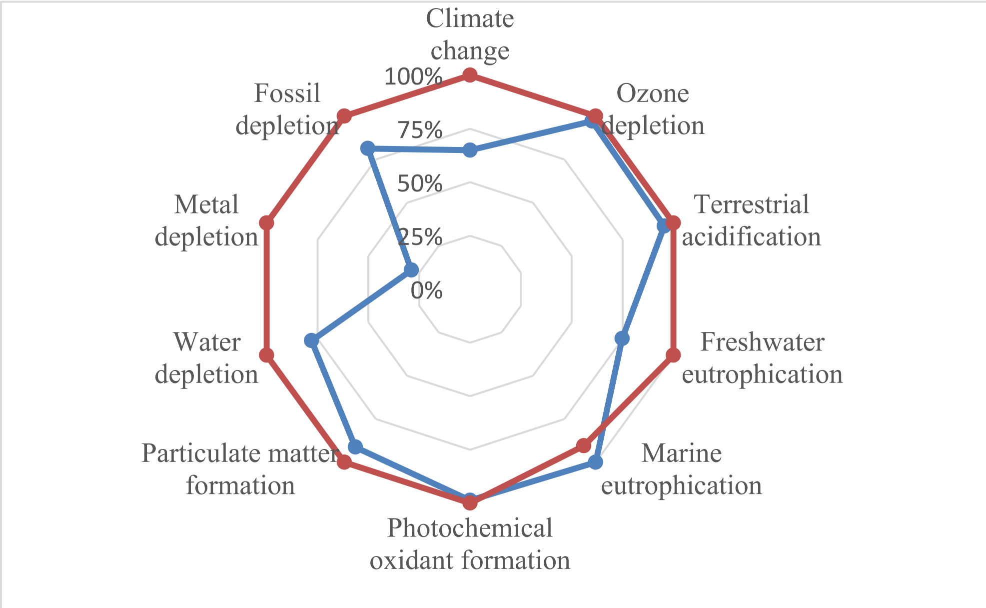

Figure 3. Comparison of results calculated using the ReCiPe method and the ecoinvent database. Blu line states for Building A (CLT), red line states for Building B (reinforced concrete).

Climate change results to be one of the categories where the timber building shows the highest impact reductions. In fact, more than 25% of the greenhouse gas emissions could be spared if timber was used instead of reinforced concrete and masonry. This difference could be even higher if the additional benefits related to the storage of biogenic CO_2 in construction products was included. In fact, wood can absorb carbon dioxide from the atmosphere and store it in the construction products. If the forest is properly managed, the carbon cycle can be defined as "neutral" since the biogenic CO_2 withdrawn is totally reabsorbed by the regrowth of the forest during the useful life of the building (i.e. 90 to 100 years). Nevertheless, these emissions were not included in the assessment since they are outside the scope of the study, given that they belong to the use phase of the life cycle of a building (i.e. B1-B7 modules in the EN 15978:2011 standard).

Moreover, the wooden building ensures a significant reduction in the consumption of non-renewable natural resources such as water, metals and fossils. Although it uses hardware to connect the various pre-shaped parts, the wooden building requires much less metal elements than the reinforced concrete counterpart, which uses large quantities of metal for the reinforcing structural elements. This results in a significant reduction in the impacts associated to energy usage as well, considering the high energy-intensity of metals production processes.

The use of wood, on the other hand, shows higher marine eutrophication impacts. The higher impacts are related to the management of the forest and the emissions of nitrates from fertilization.

For the remaining environmental impact categories, the two buildings do not exhibit significant differences.

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4.2 Impact assessment of the buildings per FU

According to the design documentation, Building A (timber structure) has a gross floor area of 820 m^2, while Building B (reinforced concrete structure) 814 m^2. Total impacts were divided by the respective gross surfaces of heated floor to obtain the environmental impacts per functional unit. As the two overall surfaces are almost identical, results do not significantly differ from the results shown for the entire buildings. Results per FU are reported in 'table 2'.

Table 2. Results calculated using the ReCiPe method and the Ecoinvent database per functional unit (i.e. 1 m^2 of heated floor area).

	Climate change *(kg CO_2eq)*	Ozone depletion *(kg CFC-11eq)*	Terrestrial acidification *(kg SO_2 eq)*	Freshwater eutrophication *(kg Peq)*	Marine eutrophication *(kg N eq)*
Building A	2,24E+02	2,29E-05	1,29E+00	7,98E-02	7,01E-02
Building B	3,46E+02	2,35E-05	1,35E+00	1,07E-01	6,35E-02

	Photochemical oxidant formation *(kg NMVOC)*	Particulate matter formation *(kg PM_{10} eq)*	Water depletion *(m^3)*	Metal depletion *(kg Fe eq)*	Fossil depletion *(kg oil eq)*
Building A	1,39E+00	7,78E-01	2,65E+00	2,86E+01	6,80E+01
Building B	1,40E+00	8,53E-01	3,40E+00	9,91E+01	8,36E+01

4.3 Environmental impacts of each technical building component

In this section, the environmental impacts were divided into classes of technical elements (walls, roof, structure) and the results are presented in 'fig 4, 5'. For both buildings, "walls" and "roof" include all the materials and components that are part of the vertical and horizontal envelope that do not have a load-bearing function. On the other hand, the "structure" category include all the structural components with load-bearing functions. For Building A, all the materials used for the structure were considered: the internal load-bearing walls in XLAM, the beams and the joists, the slabs, the OSB panels in the internal floors, the stairs, the EPDM gaskets, and the metal joints. Conversely, for Building B, the "structure" includes the columns, the beams, the slabs and the stairs.

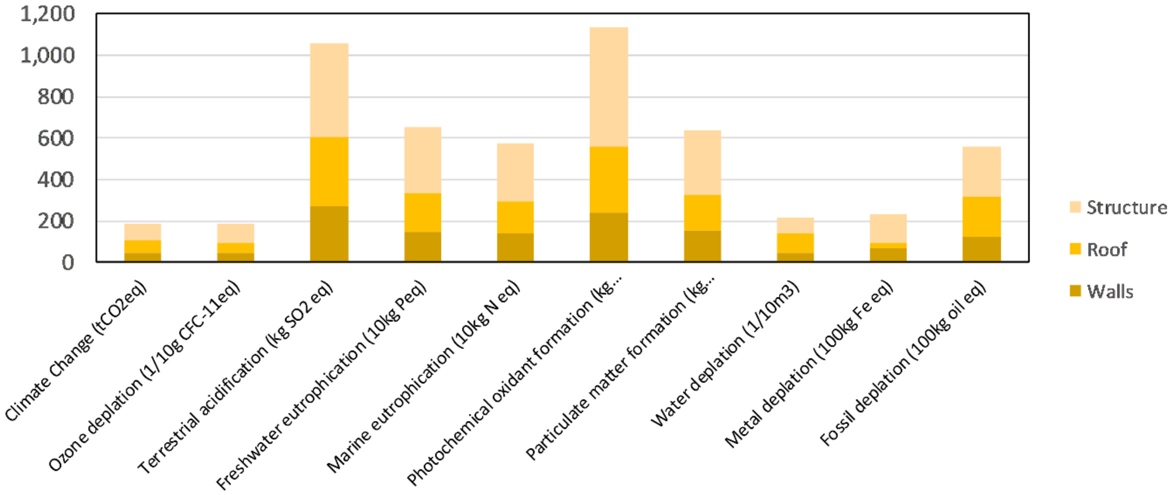

Figure 4. Results calculated using the ReCiPe method and the Ecoinvent database – Building A (timber structure)

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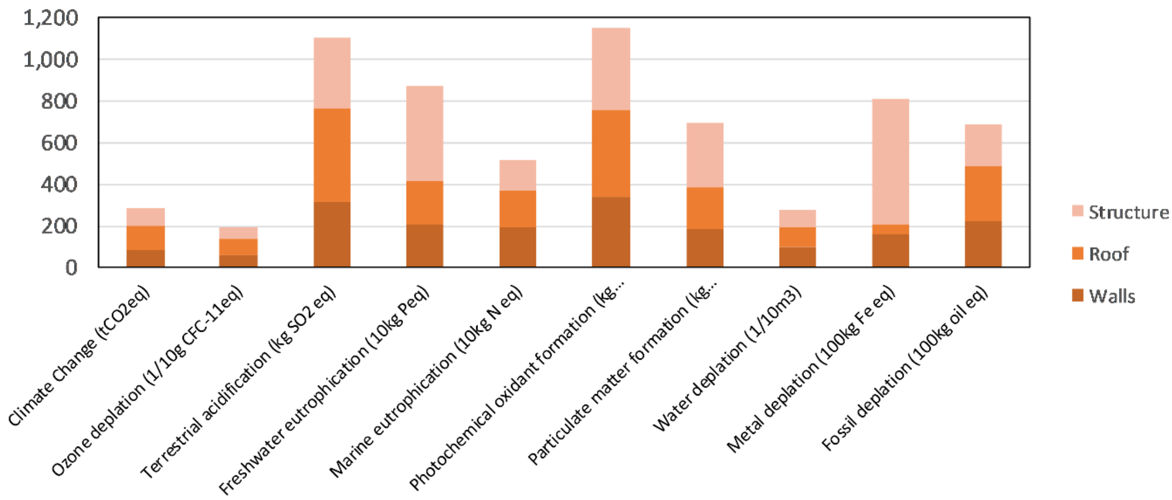

Figure 5. Results calculated using the ReCiPe method and the Ecoinvent database – Building B (reinforced concrete structure)

5. Discussion

The present analyses allowed to characterize the environmental impacts of the two houses both at the materials and the building level. As highlighted in other studies, the significant contribution of the structural elements to the total impacts was confirmed for both buildings, with a contribution of more than 50% compared to all the other technical elements for all the categories considered. Wooden building requires a lower amount of metal elements, and this results in a significant reduction of the potential impacts associated with the use of metals, which are particularly severe due to energy-intensive processes and typically long transports. The nearly total elimination of cement, used in the wooden building exclusively for the subfloors, also ensures a net reduction in the impacts. The production of cement, in fact, is one of the most impactful activities in the building industry, accounting alone in Europe for 55% of the CO_2 emissions of the entire construction industry. These impacts are particularly severe due to the clinker production process, which requires particularly high temperatures (around 1450 °C). In addition, large amounts of CO_2 are released as a result of the calcination reaction during the lime production process, which is also used in the preparation mixture of substrates and mortars. Nevertheless, it should be noted that part of the carbon dioxide emissions released during the production process can be reabsorbed during the useful life and end of life of the building due to the carbonation of the lime-based products. This process, however, is outside the boundaries of the analyzed system and it is not included in the assessment.

The use of wood is particularly beneficial for the Climate Change impact category compared to the use of reinforced concrete and masonry, thanks to the lower energy consumption during the extraction and production phases.

Moreover, the variation in insulation thickness can guarantee energy savings during the use phase of the building, but it is not so decisive in generating a significant environmental weight when compared to the contribution generated by the elements characterizing the entire building. This is partly due to the relatively modest masses of the insulating elements, which are typically rather light, and to the production impacts, which are not particularly heavy. Significant differences could be found in the use of alternative insulation materials, since moving from plant-mineral to synthetic materials can amplify the impact of some key indicators, such as Climate Change and Fossil Depletion.

6. Conclusions

Although life cycle assessment is becoming increasingly popular at the design level of buildings, there are still some methodological gaps due to the variability of the transformations involved in the building process. One of the main problems encountered is linked to the numerous uncertainties, at various levels, that characterise the several processes necessary for the production and assembly of the various building materials used in a building.

The sustainability of wood as a building material is a complex issue because from the point of view of the life cycle, the environmental impact is strongly linked to the management of the forest where the wood is sourced, to the durability of the building material, and, above all, to the end-of-life scenario. This study uses a standardised calculation methodology, based on EN-15978:2011, which allows comparison of the results of other works achieved with the same assumptions.

During the study it was necessary to establish some hypotheses and assumptions in order to clearly define the limits of validity of the results on the basis of the data currently available and provided by the contractor. In this context, the quantified contributions with purely economic values, the energy needed for the construction of the machinery, the energy provided by the workers and the energy spent on their transport to the workplace were neglected.

The positive environmental value measured in the wooden building is mainly linked to the replacement of the reinforced concrete masses used in the load-bearing structures. For instance, the use of wood as a building material instead of traditional materials leads to a reduction in greenhouse gas emissions of about 25%. The mere replacement of reinforced concrete and brick walls and floors with wooden panels guarantees a significant reduction in greenhouse gas emissions into the atmosphere, which, if extended on a large scale, could contribute on its own to the achievement of the EU Community objectives of reducing emissions from the construction sector.

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