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## CONSTRUCTION HISTORY AND PRESERVATION

## CONSTRUCTION AND BUILDING PERFORMANCE

**BUILDING AND DESIGN TECHNOLOGIES**

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# FORBEST PRODUCTS IN CONSTRUCTION: A COMPARATIVE LIFE CYCLE ASSESSMENT OF AN ITALIAN CASE STUDY

Giuliana Iannaccone, Francesco Pittau, Giovanni Dotelli

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**Highlights**

The environmental benefits of using forest products as a replacement for conventional materials for construction were assessed.
Timber building provided a lower impact for many environmental categories compared to the conventional option.
Forestry and agricultural activities negatively affect Marine eutrophication, Photochemical oxidant formation, Terrestrial ecotoxicity, and Ionising radiation.
Impacts related to land use are higher in timber due to the land occupation needed to grow long rotation species.

**Abstract**

This work aims to investigate the environmental consequences of using forest products as a replacement for conventional construction materials. A cradle-to-gate Life Cycle Assessment (LCA) was carried out to compare a semi-detached timber house located in Italy versus an equivalent building with conventional construction technologies (concrete and bricks). As a result, most of the ReCiPe environmental indicators resulted more favorable for timber alternative, which is mainly connected to replacing the reinforced concrete volume in the structure, while the pressure on the land resulted as a critical consequence for timber alternative.

**Keywords**

Wood, Timber construction, LCA, Concrete, Construction materials.

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## 1. INTRODUCTION

The built environment is one of the most significant contributors to carbon emissions, affecting climate change and the unsustainable pressure on the natural environment and its ecosystems. Thus, the construction sector plays a decisive role in achieving the carbon neutrality targets by 2050 of the Union as set in the European Green Deal. The Global Status Report [1] identifies reduction paths of embodied energy and greenhouse gas (GHG) emissions as a priority for action but does not present evidence of systematic and coordinated action in this area. With continuing global population growth and increased urbanization, the global floor area has grown in the last decade to more than 2.6%. Future projections show that this will result in a further doubling of floor area by 2050 [1]. European partners have made many efforts to reduce the carbon emissions from buildings during operation, while no particular attention has been paid to lowering the emissions of construction materials, whose contribution to climate change with new Nearly-Zero Energy Building (NZEB) requirements is becoming more and more significant [2]. Such emissions matter because they are not distributed over time but entirely occur at the time of construction, involving energy grids and supply chains that have still to be decarbonized to complete the transition to a carbon-neutral society [3].

A significant effort is needed to explore strategies for reducing embodied GHG emissions (or embodied carbon, EC) in all new buildings and their related contribution to reducing EC in the construction industry. There is now a growing interest in this issue from professional organizations, policy-makers, and building practitioners in general, who want to show their commitment to climate change and environmental consequences from materials selection. In particular, the choice of the materials for the structural frame and the building envelope, particularly the foundation, exterior wall, and roof, has a major influence on the overall impact caused by buildings [4]. Therefore, a better understanding of the environmental impacts of the structural systems and envelope components is crucial.

Mineral-based construction materials, such as metals, cement, and glass, are often considered finite resources requiring significant inputs from fossil fuels to be processed into engineered products required by the industry. Particularly, concrete and cement products are responsible for more than 8% of global emissions. The cement industry decarbonization is a priority in the political agenda that risks requiring heavy investments for structural changes or modifying existing standards if improvements and new synergies across the current value chain and involved stakeholders are not fast implemented [5]. Timber, by contrast, is considered a renewable material. Consequently, it is not a scarce material itself but requires anyway a relatively long time to be regenerated in the land [6]. Additionally, timber construction products physically embed carbon that existed in the form of atmospheric carbon dioxide (CO2) before the trees' intervention. Thus, it can be argued that the combined forestry, wood products, and construction systems can play a role in carbon sequestration strategy to mitigate climate change [7, 8]. Unfortunately, a large consensus on a recognized methodology to include the biogenic carbon effect on ordinary LCA climate change is not defined yet, and a warm debate is still ongoing within the scientific community [9]. The carbon physically stored in the timber in this way is different from the "embodied carbon" widely discussed in the literature and in the rest of this article, which is intended as "fossil carbon". GWP here refers to the greenhouse gas (GHG) emissions associated with the production of a material or product.

## 2. STATE OF THE ART

The environmental impacts of concrete and steel structural systems have been debated for the last twenty years [10]. However, engineered timber, e.g., glulam and cross-laminated timber (CLT), is increasingly recognized as a viable alternative, with examples of realized high-rise buildings up to 24 stories [11] and even taller buildings planned [12]. By going beyond the sporadic case study approach commonly presented in the literature, there is a clear need for a systematic life cycle assessment of different structural systems and construction technologies. Understanding the life cycle environmental impacts of buildings involves investigations at a range of levels from materials to buildings and developments. LCA of buildings offers insights into the relative importance of a wide range of building elements over a long period. This holistic and necessary viewpoint does, however, require support from tighter focus investigations, such as structure and materials, as discussed in this article on a case study.

Different types of construction systems have been much compared through LCA, focusing primarily on steel and masonry systems, but with increasing interest in the timber. Different approaches have been adopted for investigating the EC of buildings with different characteristics. These include like-for-like comparisons of pairs of buildings that differ only in the aspect of interest (e.g., the structural material), to sweeping searches for benchmarks and trends from large samples of buildings differing in function, location, scale, and very often in the methodologies and scopes of the studies. Several studies have found significantly lower EC values in timber than concrete or steel counterparts, without including biogenic carbon content in the account [13, 14]. When extending the assessment to include biogenic carbon according to the Guest method [15], the carbon emissions associated with the use of biomass outweighed the carbon benefit related to the storage, and the relative advantage of timber was actually reduced. Although concrete has lower EC than timber per unit of mass [16], there is much evidence to suggest that the use of timber results in buildings with lower EC [17].

In assessing functionally equivalent concrete and timber designs for a small road bridge in Sweden, the timber bridge resulted in 22% lower EC [18]. Taking a similar approach to residential buildings, a cradle-to-grave LCA results for a CLT-based home in 42% lower EC than its concrete alternative [19]. In both studies, the superiority of the timber variant was confirmed within parallel assessments using dynamic LCA. Some researchers have attempted to generalize the emissions benefits from substituting wood in conventional construction materials. In their meta-analysis, Sathre and O'Connor [20] found that, on average, for every tonne of wood used in construction, 3.9 $tCO_{2\text{-eq}}$ emissions are avoided, providing a rationale for substituting wood for other products. After converting to the equivalent units, this is towards the lower end of the range of displacement factors identified by Geng et al. [7] for construction timber, which is 0.25–5.6 kgC substituted per kgC in the timber. The wide range reflects the different contexts in which timber is compared to other construction materials and differences in the assessments' scope. The balance of the evidence discussed above points towards timber comfortably being the lower carbon option when modeled through LCA, certainly in cradle-to-gate analysis, and probably cradle-to-grave too, without relying on arguments around carbon storage.

This work aims to cover the gap existing in the comparison of timber solutions versus conventional construction systems in regards to the whole environmental burdens caused by materials production. In fact, most of the studies described in the literature are mostly focused on EC assessment or combined operational and embodied energy, while a complete systematic environmental assessment is still missing. Specifically, a Life Cycle Assessment (LCA) comparison was carried out between a semi-detached residential building with a load-bearing structure made of CLT and a building with the same size and similar architectural and thermal performance characteristics, made of a reinforced concrete load-bearing structure and light-clay bricks. Specifically, the 18 environmental impact categories according to ReCiPe assessment method were assessed for the production of materials and products used for the construction of the two buildings.

## 3. METHODOLOGY

The assessment of the environmental impacts of the two buildings was carried out according to the European standard EN 15978:2011 [21], 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 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 construction company's technical documentation 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 [22]. Finally, the results for the two buildings were compared.

LCA methodology is uniquely defined by the international standards ISO 14040:2006 and ISO 14044:2006 [23]. 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.

### 3.1. DESCRIPTION OF THE CASE STUDY

The two case studies considered in the analysis are shown in Figure 2 and consist of two residential multi-family buildings built in the same period in the same northern Italian region. As shown in Figure 1, the buildings were built based on the same architectural design: similar geometric dimensions and internal layout characterize them; they have the same energy performances but are made of different construction systems. The first, Building A, was built by using a structural system with load-bearing walls made of cross-laminated timber. 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.

| | 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 |

Fig. 1. *Dimensional characteristics of the two buildings.*

## 3.2. PRELIMINARY ASSUMPTIONS AND LIMITATIONS OF THE ANALYSIS

The Functional Unit (FU) used to compare 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 raw materials' extraction 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 contractor's documentation, including graphs of the executive project, technical reports, and tender specifications.

## 3.3. INVENTORY ANALYSIS AND IMPACT ASSESSMENT

The LCA was used for the holistic investigation of the environmental impacts of the two alternative buildings. A range of 18 impacts were modeled, according to ReCiPe assessment method, with a particular focus on the 10 main affecting the ecosystems. The LCA was carried out according to EN 15978; an inventory of resource flows

Fig. 2. *On the left: Building A, built with a load-bearing structural system of cross laminated timber; on the right: Building B, built with a reinforced concrete load-bearing frame and brick walls.*

required for the creation of the functional unit of the products was compiled, namely 1 $m^3$ oven-dry timber, 1 $m^2$ of windows and doors, and 1 kg for the other materials, and then the impacts were assessed. The life cycle stages considered are shown in Figure 3.

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 [24]. SimaPro software (www.simapro.com) was used for the analysis. In the results, only the most main impact categories for the present case study are presented. Through the ReCiPe method (starting from the exchanges with the ecosphere provided by the Ecoinvent database), the unitary impacts of all materials and products used for the two buildings were calculated. Finally, the calculation of the two buildings' overall environmental impacts was performed considering the material intensity, expressed in kg/$m^2$ of the element, affecting the building. The main ten impact categories assumed in the assessment are the ones listed below.

### *CLIMATE CHANGE*

The greenhouse effect is defined as the trapping of heat from the earth's surface in the lower layers of the atmosphere (troposphere) due to the presence of water vapor, carbon dioxide, methane, nitrous oxide, and ozone able to absorb infrared radiation from the earth's surface.

The characterization factor chosen to assess the greenhouse effect caused by climate-altering gases is the Global Warming Potential (GWP). This is defined as the ratio between the radiative forcing agent due to the instantaneous release of 1 kg of a substance into the atmosphere and the one caused by releasing 1 kg of $CO_2$, integrated over a specific time interval.

### *OZONE DEPLETION*

The contribution of each pollutant to the depletion of the stratospheric ozone layer is estimated using the CFC-11 gas (trichlorofluoromethane) as a reference. To estimate the factor, the ozone molecule rupture reactions following the emission of one gram of CFC-11 compared to those of other substances have been evaluated.

### *TERRESTRIAL ACIDIFICATION*

For the acidification phenomenon, the characterization factor considered is the acidification potential expressed in kg of $S_{O2\text{-eq}}$. This factor considers the amount of $H^+$ ions released after the dissociation in the water of 1 kg of a substance compared to 1 kg of $SO_2$.

### *FRESHWATER EUTROPHICATION & MARINE EUTROPHICATION*

Eutrophication is a process of degradation of aquatic environments due to algal growth higher than normal

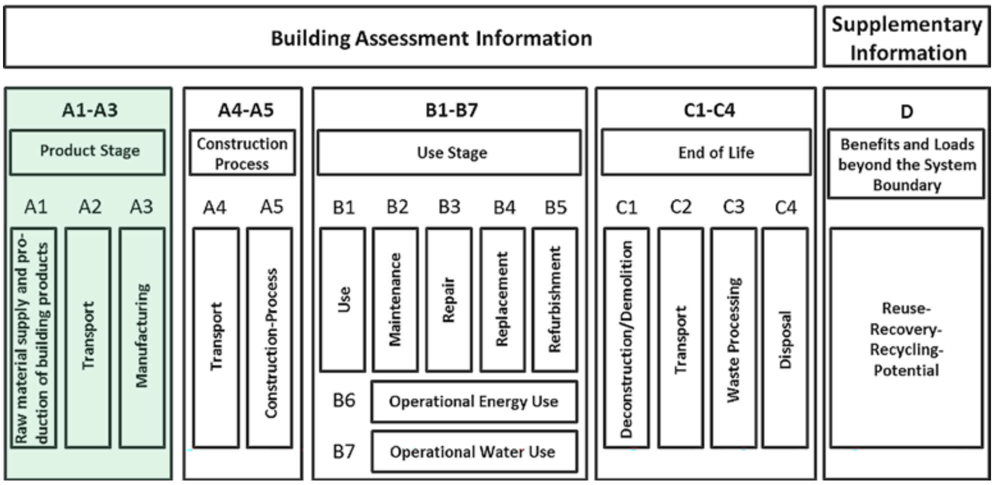


Fig. 3. *The life cycle phases of a building according to EN 15978:2011. In green, the life cycle phases considered in this work.*

caused by the increased concentrations of nutrients. Human activities, affecting the nitrogen and phosphorus cycle through the use of fertilizers and concentrated discharges, can enhance this phenomenon.

The eutrophication characterization factors are expressed in:

- $PO_{3\text{-eq}}$ for eutrophication related to freshwater;
- $NO_{3\text{-eq}}$ for seawater eutrophication.

### *PHOTOCHEMICAL OXIDANT FORMATION*

The production of photochemical smog, consisting essentially of ozone in the lower atmosphere with negative impacts on human health and vegetation, is due to emissions of nitrogen oxides, volatile organic compounds (VOCs), and carbon monoxide in the presence of sunlight. Characterization factors for this impact category are expressed in terms of NMVOC (non-methane volatile organic compounds). The results for this category can vary significantly in time and space, so the results should be considered as an approximation.

### *PARTICULATE MATTER FORMATION*

The formation of fine particulate matter represents the emission into the environment of a complex mix of organic and inorganic substances with a diameter of less than 10 μm (expressed in kg $PM_{10\text{-eq}}$), very harmful to human health.

### *WATER DEPLETION*

Water consumption is an indicator that expresses the amount of water used in a given process and is expressed in $m^3$.

### *METAL DEPLETION*

The consumption of metals/minerals is expressed in kg $Fe_{eq}$.

### *FOSSIL DEPLETION*

The consumption of fossil energy resources is characterized according to the calorific value of the resource used. Generally, the characterization factor is expressed in terms of tons of oil equivalent (t $oil_{eq}$).

## 4. RESULTS

### 4.1. IMPACT ASSESSMENT OF THE WHOLE BUILDINGS

Figure 4 shows the potential environmental impacts of the two building scenarios assessed with the ReCiPe method. All the following figures are expressed in normalized values, where the worst case for each impact category is set to 100% to simplify the comparison. The timber 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 5 categories: Ozone Depletion, Terrestrial Acidification, Particulate Matter Formation, Water, and Fossil Depletion. Marine eutrophication, Photochemical oxidant formation, Terrestrial ecotoxicity, and Ionising radiation resulted in higher values than the conventional building. This difference can be justified as a consequence of forestry and agricultural activities [25]. Similarly, all impacts related to land use are higher in the case of timber building due to the land occupation needed to grow long rotation species.

Climate change resulted in being one of the categories where the timber building shows the most considerable impact saving. In fact, more than 25% of the greenhouse gas emissions could be saved if timber is used instead of reinforced concrete. This difference could be even higher if the additional benefits related to the storage of biogenic $CO_2$ in construction products were included. In fact, wood can absorb carbon dioxide from the atmosphere and store it in construction products. If the forest is managed correctly, the carbon stored in forest products can be regenerated in the land contributing to “negative” emissions (carbon uptake). Generally, forest regeneration requires a long-time horizon since an ordinary rotation period of coniferous forests in Europe is between 60-90 years, depending on the forestry model. Nevertheless, these emissions were not included in the assessment since a 0/0 method was applied according to the standard methodology outlined by ISO 14040:2006 and 14044:2006 and the Intergovernmental Panel on Climate Change (IPCC) guidelines.

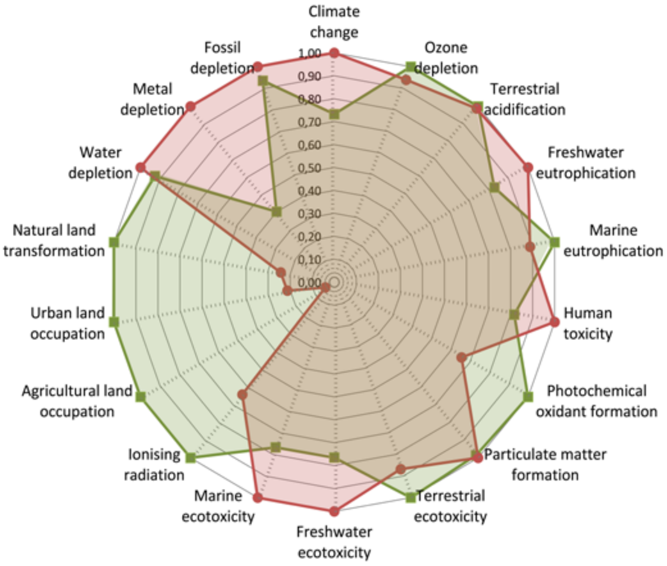


Fig. 4. *Comparison of results calculated using the ReCiPe method and the Ecoinvent database. The green line states for Building A (timber building), the red line states for Building B (conventional building).*

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 connectors and fasteners to connect the various pre-shaped parts, the timber building requires fewer metal elements than a reinforced concrete alternative, which uses large quantities of metal to reinforce the structural elements. This resulted in a significant reduction in the impacts associated with energy usage as well, considering the high energy-intensity of metals production processes.

The use of wood, on the other hand, showed higher marine eutrophication impacts. The higher impacts are related to the forest management and the penetration of nitrates into the soil due to fertilization.

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

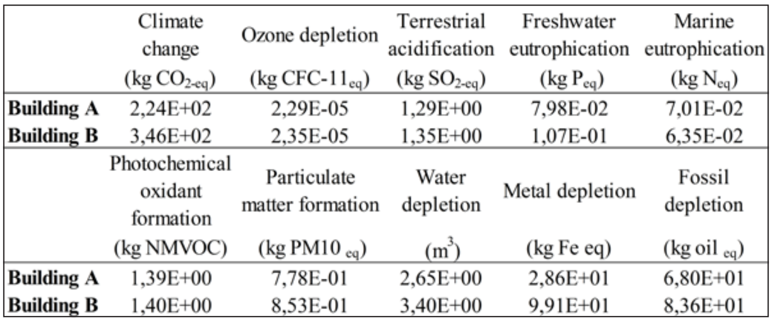
## 4.2. IMPACT ASSESSMENT OF THE BUILDINGS PER FU

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 heated floor respective gross surfaces to obtain the environmental impacts per functional unit (1 m$^2$). As reported in Figure 5, since the two overall surfaces are almost identical, results do not significantly differ from those shown at the building scale.

## 4.3. ENVIRONMENTAL IMPACTS OF EACH TECHNICAL BUILDING COMPONENT

In this section, the environmental impacts were divided into classes of technical elements, namely exterior walls, exterior floors, and structure, and the results are presented in Figures 6 and 7. For both buildings, exterior walls and floors include all the materials and components which take part in the vertical and horizontal envelope with no load-bearing function. On the other hand, the "structure" category includes 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 out of CLT, the beams and the joists, the slabs, the OSB panels in the internal floors, the stairs, the EPDM sealing, and the metal joints. Conversely, for Building B, the "structure" includes reinforced concrete columns, beams, slabs, and stairs.

As shown in the Figures, the contribution of the structure in Building A is always dominant for each impact category, while for Building B its relative contribution is



| | Climate change (kg $CO_{2\text{-eq}}$) | Ozone depletion (kg CFC-11$_{eq}$) | Terrestrial acidification (kg $SO_{2\text{-eq}}$) | Freshwater eutrophication (kg $P_{eq}$) | 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 PM10 $_{eq}$) | 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 |

Fig. 5. *Results calculated using the ReCiPe method and the Ecoinvent database per functional unit (i.e., 1 m$^2$ of heated floor area).*

less significant, moving from 30% for Climate change to around 50% for Freshwater eutrophication.

### 4.4. THE INFLUENCE OF THE MASS AND MATERIAL SELECTION

The timber building requires a lower amount of metal elements, resulting 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 exceptionally high temperatures (around 1450 °C). Besides, large amounts of $CO_2$ are released due to 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 diox-

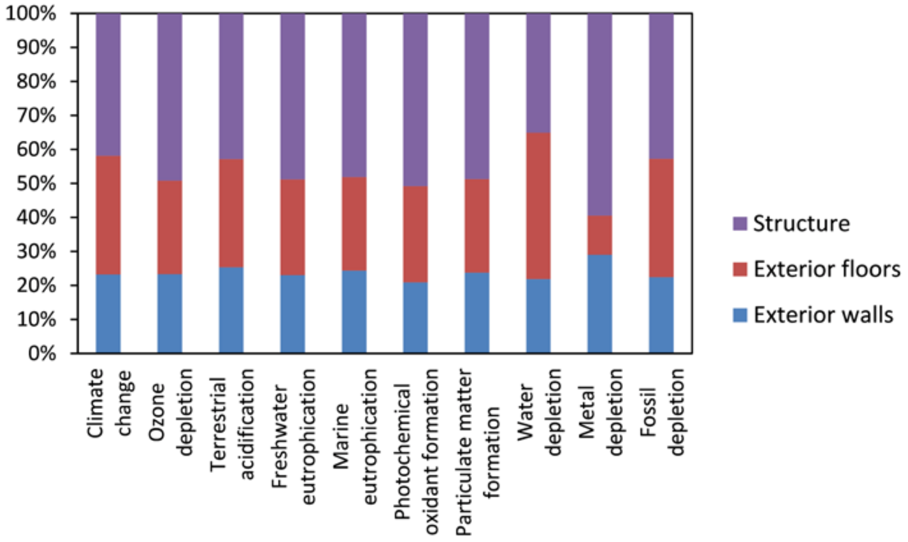


Fig. 6. *Results calculated using the ReCiPe method and the Ecoinvent database – Building A (CLT structure).*

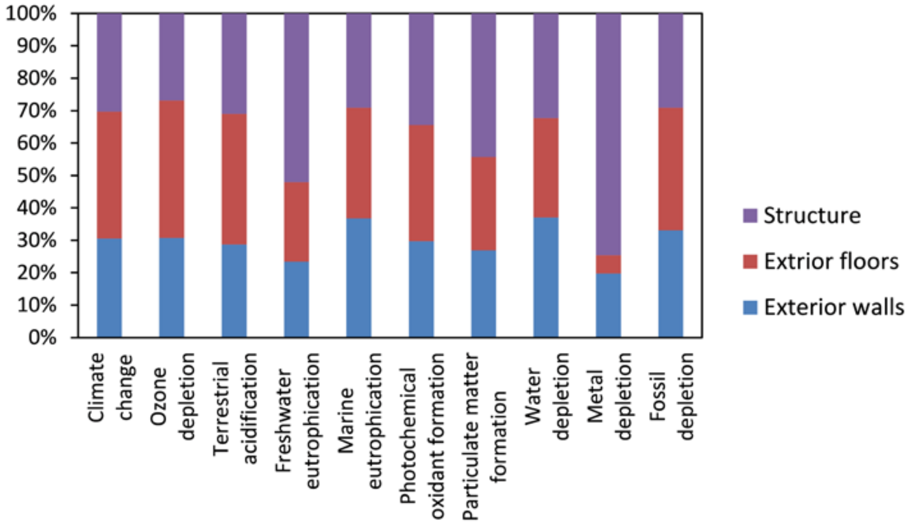


Fig. 7. *Results calculated using the ReCiPe method and the Ecoinvent database – Building B (reinforced concrete structure).*

ide 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. However, this process is outside the boundaries of the analyzed system and 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 relatively light, and to the production impacts, not particularly heavy. Significant differences could be found in using 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.

## 5. 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 characterize the several processes necessary for the production and assembly of the various building materials used in a building. Wood sustainability as a building material is a complex issue because, from the life cycle point of view, the environmental impact is strongly linked to the forest management where the wood is sourced, the building material durability, and, above all, the end-of-life scenario. This study uses a standardized calculation methodology, based on EN-15978:2011, which compares the results of other works achieved with the same assumptions.

During the study, it was necessary to establish some hypotheses and assumptions to clearly define the limits of validity of the results based on 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 workers' energy, 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 replacing the reinforced concrete masses used in the load-bearing structures. For instance, using wood as a building material instead of traditional materials reduces greenhouse gas emissions by 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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