Combining LCA and LCC in the early-design stage: a preliminary study for residential buildings technologies

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Combining LCA and LCC in the early-design stage: a preliminary study for residential buildings technologies

M C Dejaco[1], E S Mazzucchelli[1], F Pittau[2], L Boninu[1], M Röck[3], N Moretti[1], A Passer[3]

[1] Politecnico di Milano, Dept. of Architecture, Built environment and Construction engineering (ABC), Milan, I-20133, Italy
[2] ETH Zürich, Institut für Bau- und Infrastrukturmanagement (IBI), Chair of Sustainable Construction, Zurich, CH-8005, Switzerland
[3] Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, Graz University of Technology, 8020 Graz, Austria

mario.dejaco@polimi.it

Abstract. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) procedures are usually employed during the different building design phases. The first one is mainly related to the environment protection, while the second to the costs control and optimization. This paper aims to define a procedure to "translate" LCA results into an economic evaluation, typical of LCC. The goal is to support the decision-making process in the early-design phase for providing design guidance and monitoring, effectively and timely. This approach can lead to a comparison and choice among different structural technological solutions by focusing both on environmental impacts and on economic costs. LCA and LCC analyses have been carried out evaluating some construction solutions for residential buildings, considering the economic consequence of environmental impact (monetization of carbon emission). This article presents two methods: the first suggests a quantification from an economic point of view the carbon emission during the life cycle of building components through a "carbon tax"; the second one evaluates the "eco-cost" as a Virtual Pollution Prevention Cost (VPPC). Finally, the two methods were applied and compared on a case study, in order to define the possible outcomes on the building construction sector and on public policies.

1. Introduction

The construction sector is responsible for the 36% of global energetic consumption and for 40% of carbon dioxide emissions, with a steadily increasing trend. In this context, the sector has set itself the target of reducing its incidence by 80% by 2050 [1]. Through a transition to zero-carbon society, the challenge is to achieve a profound reduction of fossil carbon emissions, thanks to a combination of best available technologies and intelligent public policies.

Although today there is a growing awareness on environmental protection, and therefore the objective of reducing emissions into the atmosphere has been set, these issues cannot be separated from economic considerations, which is why in recent years more and more studies have focused on merging monetary and environmental impacts. Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) have been introduced to provide information for managing sustainable development.

Carrying out these studies in the preliminary phases of projects is fundamental, because it allows to obtain results in phases where there is a low level of detail. Therefore faster analysis and reasoning on the strategies to follow is essential to accompany this combination of cost/environmental impacts in all subsequent phases, when more and more variables come within the project. What is really important is to put it into practice and not let it remain a philosophy and a mere hope. That is the purpose of this paper.

2. Aim of the research

This research aims at supporting the decision-making process in the early-design phase this approach can lead to a comparison and choice of different technological solutions according to economic and environmental impacts. The choice fell on the early-design phase because it is fundamental for providing design guidance and monitoring the effects of design decisions: to support an efficient and user-friendly application of this phase, a simplified building model is proposed.

Four alternative construction technologies were assessed and compared: two timber prefabricated systems (timber frame and CLT), and two traditional systems, the first based on concrete structure and the second on light-clay blocks.

3. Methodology

3.1. Calculation model

Figure 1 and Figure 2 show that a specific calculation model was developed in this work, able to measure the economic and environmental consequences of the design in the preliminary phase.

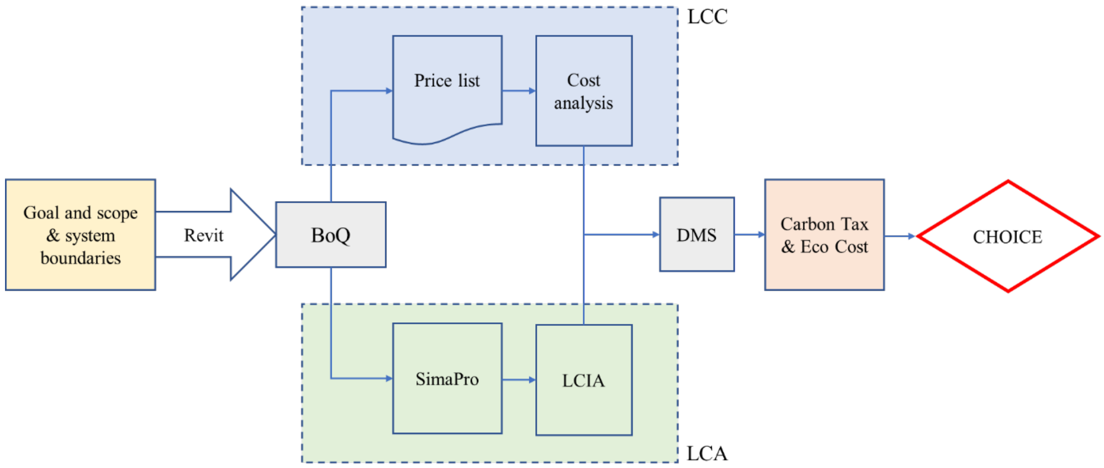

Figure 1. Schematic diagram of the adopted methodology.

As shown in Figure 1, the first step was to create a 3D model of the building with Revit software [2], through which it was possible to export the quantities of each material. These were then ordered into a Work Breakdown Structure (WBS) whose components were broken down into elements of increasing detail as follows: construction technology, technological units, technical elements and finally each layer with its relative dimensions. Each layer was then associated to its function. Subsequently, a waste category was associated with each material present in the building and different types of end of life scenarios were identified. Then, it was possible to introduce SimaPro Software [3] and it was set up the Ecoinvent v3 database [4], so each layer has been associated with a material of the database. In order to have a return of the environmental impacts for each material, the Global Warming Potential (GWP) indicator was considered. Finally, once obtained the environmental impacts per product unit, they were multiplied by the quantity, obtaining the final values of the impact of each layer.

3.2. Environmental impact's monetization

The carbon tax is a system of incentives for companies to develop technologies that allow to reduce the costs of cutting emissions, thanks to financial incentives that allow to reduce carbon emissions into the atmosphere. The taxation tool in this research work focused on the use of the Austrian scenario, which objective is to limit global warming by 1.5 °C by 2050 [5] and was finally applied to the life cycle CO_2 emissions of the building. This taxation has an impact of 5% on total life-cycle costs, which is interesting but does not have a relevant impact on decision-making. Therefore, the emissions' negative externalities have been economically evaluated through the eco-costs of emissions (Virtual Pollution Prevention Costs - VPPC) [6]. The Intergovernmental Panel on Climate Change (IPCC) estimates the damage of CO_2 emissions into the environment, quantifiable in 135 €/tCO_2 equivalent (IPCC 2007, GWP100) [7]. This methodology has led to considerable outputs: the average impact on the initial investment is 20%, which has a strong relevance in the decision-making (see results below).

3.3. System boundaries of LCA and LCC

The EN 15804:2012 standard regulates the calculation method, based on LCA and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment, defining four life stages as A1-3 Product, A4-5 Construction process, B1-7 Use, and C1-4 End of life [8]. In this work the whole life cycle was included into the system boundaries, except the use phase (module B), of which only the replacement (B4) was taken into account. This assumption was strategic because the excluded phases refer mainly to activities on building elements not considered in the analysis (e.g. cleaning, small repairs, etc.). Therefore, being these unchanged among the different technologies, they wouldn't make a difference for the decision-making purpose.

A building reference service life of 50 years was assumed for this study, on which all the economic and environmental analyses carried out are based.

Regarding the LCC, the following life cycle stages were included into the system:

- construction phase: construction site's direct and indirect costs;
- use phase: components repair and replacement, cleaning;
- end of life phase: disposal/demolition.

4. Case study

The case-study is a detached-house, a residential building composed by 3 residential units structured on three floors, with a total net-floor area of 350 m^2.

The challenge of comparing the economic and environmental performance of different technological solutions for the same building led to focus the attention on the choice of a functional unit that has been set as the U-value of the building components. In fact, the thickness and material's choice of the exterior envelope were set so as to ensure that their transmittance did not exceed 0,26 W/(m^2K). Therefore, a specific composition of the elements was defined in order to fulfil the expected thermal requirements.

As shown in Figure 3, the four envelope systems chosen for the comparison are:

- *masonry (poroton)* (with structural frame in reinforced concrete and brick-cement slabs);
- *prefabricated concrete panels* (with light-clay concrete slabs);
- *cross laminated timber (CLT)* panels (with CLT slabs);
- *timber frame wall system* (and lightweight wood slabs).

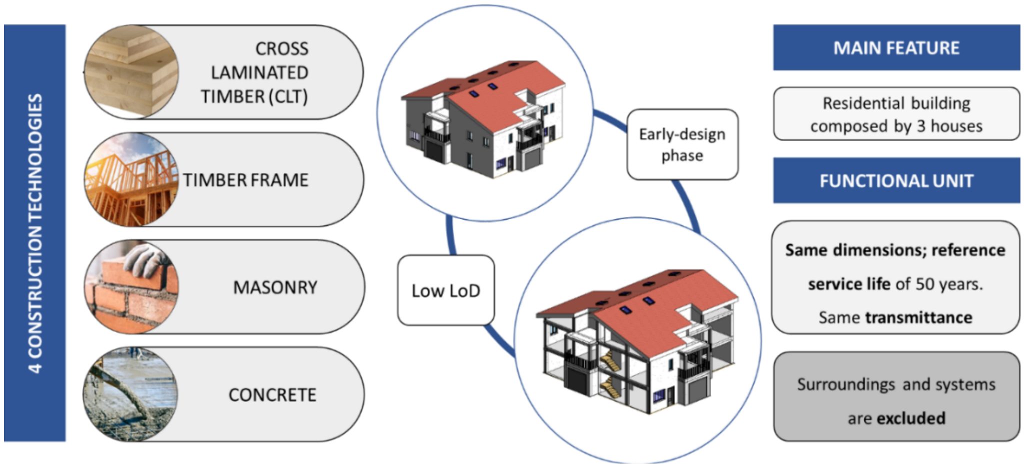

Figure 2. Case study characterization. The central figure shows the analysed building's 3D model. As explained above, this is an early design phase of the project, it means that the Level of Detail (LoD) is low, all the architectural elements are represented with their appropriate size, shape, location and quantities, but there are no finishes and systems in the building model.

5. Results

5.1. LCA and LCC output

The results of the LCA and LCC calculation are presented in Figure 4, which highlights the results obtained for each technology: in the left axis there are the cumulative costs, while in the right axis the cumulative tons of CO_2. The concrete technology has the highest cost and at the same time the greater impacts generated through its life cycle. The opposite trend has been identified by the timber frame solution, but a controversial path could be seen for CLT and Poroton: while CLT has greater life cycle cost, it accounts for almost 50% less of CO_2 tons with respect to the Poroton.

In general, the direct construction cost accounts for over the 60% of the total cumulative cost, while the second most impacting cost is due to the maintenance activities.

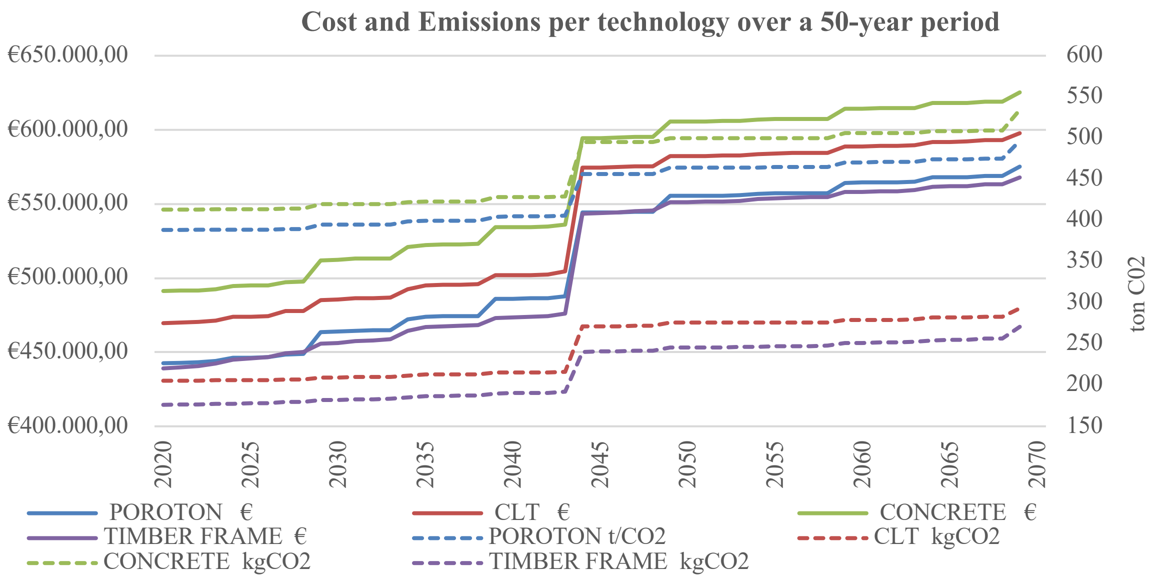

Figure 3. LCA and LCC results for each alternative construction solution.

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Since this stage it is possible to draw up a ranking of the technologies with respect to the construction costs, starting from the most expensive: concrete, CLT, masonry and timber frame. For each of them the highest cost is related to the external and internal vertical envelope.

5.2. The influence of carbon tax and Eco-Cost

The application of an eco-tax such as the Carbon Tax fails in obtaining significant results in terms of incidence on total costs as it is not yet able to tax in a decisive way the most impactful phase of the life cycle, i.e. production. The Carbon Tax will only find a significant place in the parameters of choice between various types when it is able to cover the greater investments required in the face of clearly reduced emissions. This type of situation is dictated by the fact that the rising costs forecast by the carbon tax do not reflect the real monetary value of the ecological impacts generated.

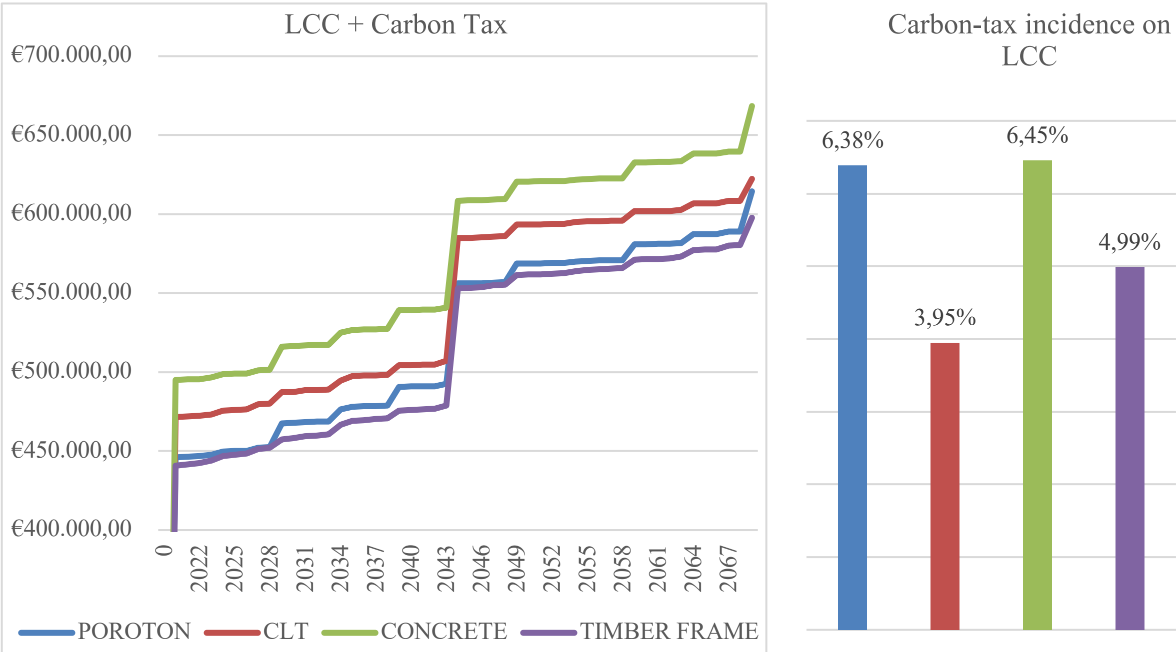

Figure 4. Total cost of each construction technology obtained summing up LCC and Carbon Tax and, on the right, Carbon Tax's incidence on LCC

The World Council for Sustainable Development (WBCSD) defines the eco-efficiency as *"the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity, throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity"* [9]. This purpose could be achieved by the introduction of the concept of Eco-cost, that allows to measure the environmental load of the LCA indicators in monetary terms. As shown in Figure 5, for CO_2 emissions a specific Eco-Cost of 135€/t CO_2 has been expressed [7]. Thanks to an investment equal to the eco-cost, linked to each production chain in different sectors, on technologies systems and other prevention measures for reducing CO2 emissions, significant results can be obtained for our planet. This cost is not a real indicator that is part of the cost estimate in the production and trade phase but must be seen as a hidden cost. The eco-cost is expressed in monetary value in order to create comparisons between different technologies and materials used and expressed with respect to the monetary value of 2007.

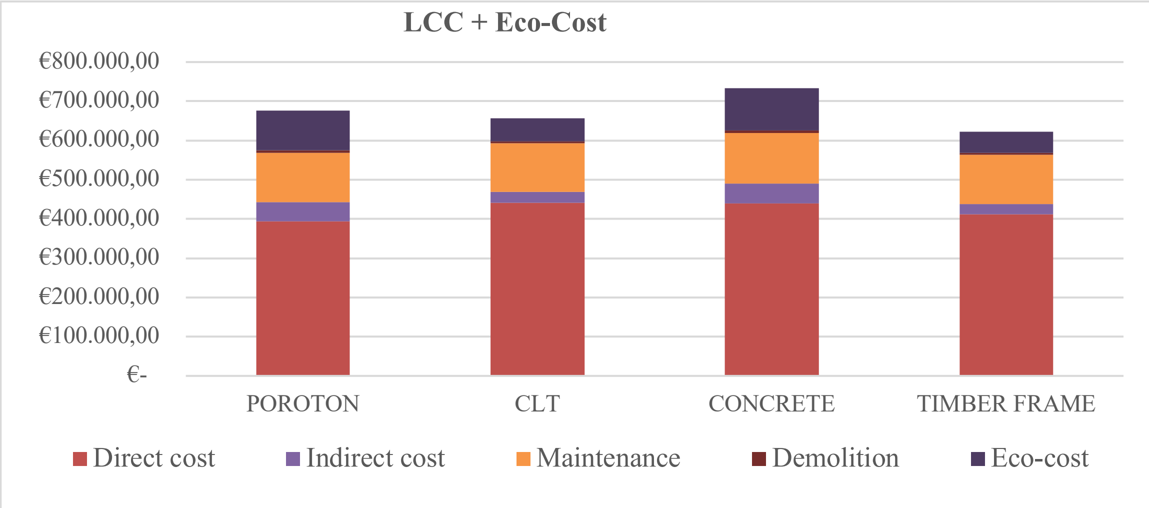

Figure 5. Total cost of each construction technology obtained summing up LCC and eco-cost

The indicator can therefore also be used in a panorama of LCC and combination with LCA to compare alternatives.

The difference of the Eco-cost incidence on Initial Investment compared to Carbon Tax is shown in Figure 6. The eco-cost identified for the two traditional solutions, masonry and Concrete, result 45% higher than that relating to wood technologies. This is a clear indication of how eco-cost can comprehensively identify the relationship between technologies with very different environmental impacts. Furthermore, the eco-cost impacts more sharply than the carbon tax, especially as regards the impact of the eco-cost on the total cumulative costs, both with respect to the initial investment.

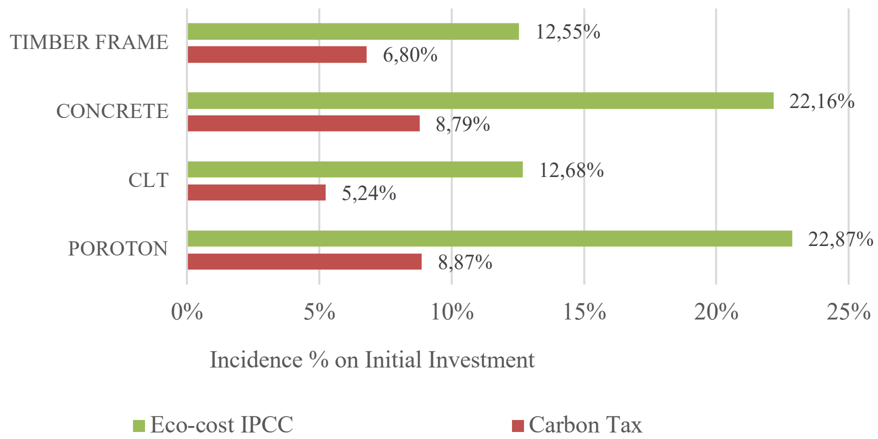

Figure 6. Eco-cost incidence on Initial Investment with respect to Carbon Tax.

The major problem encountered in the taxation of carbon has been identified in the inability to tax adequately the environmental impacts generated in phase A1-A3, the opposite consideration in the application of eco-cost. The eco-cost, although it should not be considered a real cost but a hidden economic value, can have a much greater influence than the total cumulative costs, thus managing to direct the choice and perception of the least impacting solutions as the equally most advantageous solutions to be used.

6. Discussion and conclusions

The primary aim of this work is to provide a decision-making support tool based on the LCA and LCC evaluation of different structural technological solutions of a residential building in the early-design phase. The main goal was to identify method able to compare environmental and economic aspects and attribute a monetary value also to the LCA, an issue that is often neglected; therefore, two types of proposals were made with the aim of encouraging companies to implement eco-sustainable corporate behaviours and policies. The first is the so-called carbon-tax, a policy to limit CO2 emissions into the atmosphere and reduce the increase in temperatures of the planet in the horizons of 2030-2050. It is a solution that turns out to be interesting and impacting from a decision point of view only in the future, when taxation will be increasingly consistent, but currently has an impact of about 5% on total costs during the life cycle.

It was therefore decided to propose an alternative solution, that is the application of eco-cost, the IPCC was able to demonstrate how, for some types of pollution, it is possible to obtain a corresponding estimate of future costs incurred by those responsible for the negative impact. In practice, the IPCC calculates the amount needed to remedy the environmental damage caused, based, for example in the case of climate change, on the index measuring the warming potential of greenhouse gases (GWP). It is an interesting measure that manages to monetarise the negative externalities caused by CO2 emissions into the environment, it can be called as "hidden" cost, being not really paid, but used in a sort of cost-benefit analysis aimed at making the best design choice and then to give a higher value to the more environmentally friendly option, unlike the carbon-tax, which is instead a real fee to be paid. Through this policy, the results are considerable, the environmental impact has a strong weight on the initial investment, about 20%, a substantial figure and certainly has a strong relevance in terms of decision-making.

However, it is necessary to find a way to measure the other environmental indicators in monetary terms, even if the GWP is certainly the most discussed. Many researchers are tackling this issue, but it is not easy to find a unified method, especially at a global level. The method proposed by the IPCC must be a real input that raises awareness and pushes for a change at a political level on the weight to be attributed to the environmental impact caused by products, not only in the world of construction, over the life cycle, and that also leads to the introduction of standards.

Another aspect important to be commented on concerns the availability of data for carrying out the LCA analysis. In this case was used the database Ecoinvent v.3, ecoinvent can be defined as a global leader in creating the most transparent life cycle inventory databases, but despite this, were found many difficulties in finding the materials present in the proposed project, even if they were very common building materials, especially in end-of-life scenarios. In this regard, it would be necessary to force industries to produce EPDs, as happens in France for example, because the current situation allows for analysis with a large margin of error.

Regarding the end of life, a subject widely discussed in recent times, currently there is not much documentation. Often, in fact, for both economic and environmental analysis, percentage values referring to the entire life cycle are taken as a reference, in general they impact about 3%, which is why it is not given particular weight. But on this subject, it is essential to investigate in a perspective of "from cradle to cradle", especially when it comes to prefabrication. Unfortunately, in this research work the end of life of materials has been treated in the same way in the 4 scenarios analysed, no distinction has been made between prefabricated technologies (the wooden ones) and others because we had to stick to datasets. This is a limit in terms of environmental impacts and certainly costs as the prefabricated elements at the end of their life can be recovered more easily than in cases where there is an undifferentiated demolition, even giving rise to scenarios of reuse and not only recycling.

In conclusion, the wooden buildings were the most environmentally friendly. In the current building industry, the aim should be to create projects that are not only aesthetically beautiful, but also functional and respectful of the ecosystem, through the recycling of materials, adopting technologies that exploit renewable and non-polluting energy. The wood in this context is the most suitable to achieve the defined technical characteristics, both from an environmental and from a technological point of view; indeed, it has considerable advantages: a reduction in consumption (for example energy) and emissions (CO2) has been the principle underlying the mitigation of environmental impacts so far. By optimizing the weak points (high energy incorporated) and maximizing the strengths (environmental benefits), the increased use of wood can improve the environmental profile of a building. Moreover, it is easily available thanks to the sustainable management of forests, which in Europe increases their surface every year.

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