COMPARATIVE ANALYSIS OF THE ENVIRONMENTAL PERFORMANCE OF DIFFERENT BUILDING ENVELOPE SOLUTIONS, CONSIDERING THE INFLUENCE OF CERAMIC TILES.

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ABSTRACT

Life cycle analysis (LCA) is an exhaustive, laborious and highly complex process, given that numerous factors need to be taken into account for its application; it is also time-consuming and requires professional skills which are normally incompatible with the conditions in which the architect works. It is precisely this scenario which has led to the use of a simplified LCA methodology for calculating the environmental impacts of buildings. The objective of this study is to estimate the environmental impacts of different building envelope solutions by applying a simplified LCA methodology. Our aim is to obtain enough data so that we can analyse and compare different alternatives for the design of the building envelope and evaluate the influence of ceramic tiles on the environmental performance of buildings.

There are different ways of approaching this problem and all of them entail finding a way to access better information about the options available at the beginning of the design process and obtaining preliminary estimative results as soon as possible.

Rather than trying to achieve highly accurate results, our intention is to obtain information that will enable us to lay the groundwork and contribute to the development of an environmental rating tool, which, by means of indicators, can help the designer, during the initial phase of design, to select building solutions with good environmental performance.

1. INTRODUCTION

Since 1987, when the Brundtland report for the UN was published and the term "sustainable development", defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (1), was used for the first time, environmental protection has become a global necessity and the inclusion of sustainability principles into all our production processes is becoming increasingly urgent.

Construction is responsible for a very high percentage of environmental pollution, according to the UNEP (United Nations Environmental Programme) and the OECD (Organization for Economic Cooperation and Development), and built environments account for an energy consumption of 25 to 40%, a solid waste burden of 30 to 40% and a greenhouse gas emission burden of 30 to 40%. It is vital for building to become sustainable and, to do this, it will be necessary to incorporate mechanisms for quantifying and preventing the impacts produced as a result of using different building solutions, taking into account their life cycle as a whole (3).

One of the key aspects in the entire building process is design. The designer or architect, the person who lays the cornerstone, as it were, for the subsequent development or construction of a building, must be able to control the choice of materials and the building solutions employed in his project effectively (4). To do this, he needs to take into consideration a series of variables, which will oblige him to make decisions during the design phase that will affect the viability of the product and the final result. To be sustainable, a building must try to achieve high energy efficiency through careful design of the building envelope, which will enable the use of central heating and air conditioning systems during its useful life to be reduced.

2. OBJECTIVE

- Our objective is to quantify the environmental impact of different building envelope solutions in order to determine the influence of ceramic tiles on this impact.

- We intend to analyse the environmental behaviour of different design alternatives for the building envelope, comparing conventional building solutions with other much more innovative solutions which include ceramic tiles in their composition and, in each case, to evaluate multiple variables.

- Our aim is to obtain data related to all the life-cycle stages so that we can compare the impacts produced during the manufacturing and construction (hereafter execution) phases with those produced during the use phase of a building, which might be linked to the building envelope solutions that were adopted.

- We would like to provide better information about the options which exist at the beginning of the design process in order to help the designer during the preliminary design phase.

3. BACKGROUND

Theoretical studies on environmental impacts based on LCA of materials or building solutions, which also include data about the reduction of the energy demands of buildings during their use phase, have been published by other authors (6), (7), (8),(9), (10), (11) and (12).

The components, materials and building systems implicated in the design process should perform optimally, in accordance with our expectations and the requirements of durability and useful life. Design should not be directly affected by building regulations but by the design criteria of the architect; thus, the final design will depend on the discretion of the designer (13).

As a result, the information required for the architectural design and building processes of a project must be derived from reliable sources and information that can be verified.

4. METHODOLOGY

A simplified LCA methodology was applied to determine the environmental impacts of building envelopes.

4.1. DESCRIPTION AND JUSTIFICATION OF THE APPLICATION OF A SIMPLIFIED LCA METHODOLOGY FOR BUILDINGS

The application of LCA to complex products, in which the limits of the system apply to a wide range of activities, may be incompatible with reliable Life Cycle assessments. This is the case in building, in which the level of complexity is self-evident.

The few LCA studies which are performed on buildings in Spain have had to simplify the methodology they use, as well as making adaptations and approximations with respect to the data available in information sources, most of which come from other countries. These simplified studies are known as LCA summaries (14) and, despite their abbreviated form, in comparison with the methodology developed for complete LCA studies, they are very useful for evaluating environmental impact tendencies.

4.2. OPTIONS FOR SIMPLIFICATION IN THE APPLICATION OF LCA TO BUILDINGS

According to the recommendations of CEN 350, any system which is to be analysed should include the following stages: manufacture, execution, use and maintenance, and final disposal or demolition.

That said, it is possible to conduct a life cycle study if we use at least two stages: The manufacturing stage and the stage of use. (15). To conduct this study the following phases were selected:

- Manufacturing and execution phases, in which CO2 emissions, primary energy consumption, water consumption, and the hazardous and non-hazardous waste that was produced were evaluated.

- Maintenance phase of the building envelope during the entire useful life of the building.

- Use phase, primarily owing to the emissions and consumption of the building installations, which may be affected by building envelope solutions.

We also performed an economic assessment of the solutions that were evaluated; this involved calculating the investment costs of the manufacturing and execution phases, and the maintenance costs during the use phase of each of the building solutions included in the analysis.

4.3. SELECTION AND JUSTIFICATION OF THE DATABASES AND ANALYTICAL TOOLS

The TCQ2000 software tool and its environmental management module, TCQGMA, were used to analyse the impacts of the manufacturing, execution and maintenance phases of the study building. It was chosen because it was developed in a national context where the information it provides is accessible. It is also easy to access the program itself, as there are agreements which allow it to be used by students and researchers at little cost. The TCQGMA module of the TCQ2000 application provides environmental information about materials and building systems. This tool also enables water consumption to be estimated during the manufacturing and execution phases.

The impacts which are evaluated in the manufacturing and execution phases are as follows:

- Energy consumption during the manufacture and execution of the building materials.
- CO_2 emissions released as a result of the manufacture and execution of building materials.
- Hazardous and non-hazardous waste, surplus materials and packaging waste
- Water consumption.
- Investment and energy costs of the manufacturing and execution phase.

With respect to the databases, ISO 14040 establishes the general quality requirements, including the weather conditions that apply, technological and geographical scope, accuracy, level of detail and representativeness. The BEDEC database provides environmental information which can be compared and completed using other databases, such as Ecoinvent.

For the analysis of energy consumption and CO_2 emissions during the use phase of the building, the LIDER and CALENER energy simulation tools were selected. Keeping certain parameters fixed and performing different simulations, in which values related exclusively to materials and/or building envelope solutions, and/or climatic zones were changed, we obtained estimation results related to:

- Energy consumption for central heating and air conditioning.

- CO_2 emissions during the use phase of the building.

Calculations will be made for a building selected as a case study, combining the result of the impacts obtained for different building envelope solutions and analysing different orientations of the building and different climatic zones.

4.4. DESCRIPTION OF THE CASE STUDY

A real project will be used as the case study. It is a house built on a geometrically simple plot with two stories and a patio at the back. The house has two façades, one that looks out onto the street and the other opposite façade facing the patio. It is a terraced house so ventilation is only possible through the façades (Figure 2).

The interior layout is as follows:

- Ground floor: lounge/dining room, kitchen, a double bedroom and bathroom.
- First floor: two bedrooms, a bathroom and a passage.

5. APPLICATION OF THE SIMPLIFIED LCA METHODOLOGY TO THE CASE STUDYO

According to the methodology proposed by the ISO 14040 standard, the LCA can be divided into four phases as follows:

- Definition of objectives and scope.
- Inventory analysis.
- Impact evaluation.
- Interpretation of Results.

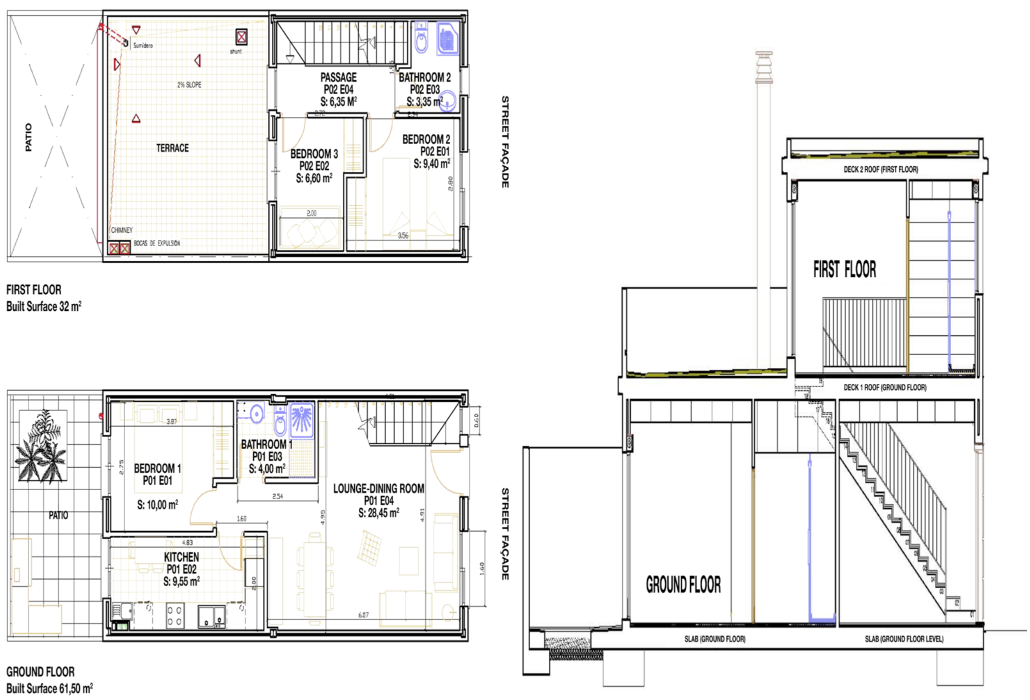


Figure 2. Floor plans and cross section of the house used for the case study.

5.1. DEFINITION OF OBJECTIVES AND SCOPE

Various factors which determine the limits of the system are established below, including the predicted application of the study, the hypotheses it proposes, the exclusion criteria, the economic data and limitations and the user it is intended for:

The objective of the study is to quantify the environmental impact of different building envelope solutions in order to determine the influence of ceramic tiles on this impact.

The results will enable us to compare the environmental impact data for the different building envelope solutions which are analysed, taking into account the energy consumption and CO2 emissions produced during the use phase, which will be obtained by applying energy simulation programs.

In terms of its scope, the LCA will be performed using the type of building selected for the case study. It will evaluate two opposite orientations and two climatic zones for different building envelope solutions and combine various types of roof with different types of façade and joinery. The building envelope solutions which will be analysed in each climatic zone comply with CTE (Spanish Technical Building Code) regulations.

5.2. CALCULATION HYPOTHESIS

VARIABLES

CLIMATE ZONES

Following the same criterion employed in other impact studies, for this study, two opposite climate zones have been selected.

- Zone B3 (Warm and humid climate, for example Castellón).
- Zone E1 (Cold and dry climate, for example Ávila).

ORIENTATION

The behaviour of the building will be calculated for the following orientations:

α= 45º orientation NE α= 135º orientation SE.

BUILDING SOLUTIONS

The building envelope solutions in the analysis are as follows:

Conventional roofing solutions (Figure 3):

- C1 Warm, flat roof, continuous and accessible, and protected with ceramic tiles.
- C2 Flat, ventilated roof, accessible and protected with ceramic tiles.

- C3 Flat, inverted and non-accessible roof protected with gravel.

Innovative roof solution (Figure 4):

- C4 Flat, partially ventilated roof with oriented strand board insulation and ceramic tile protection mounted on PLOTS.

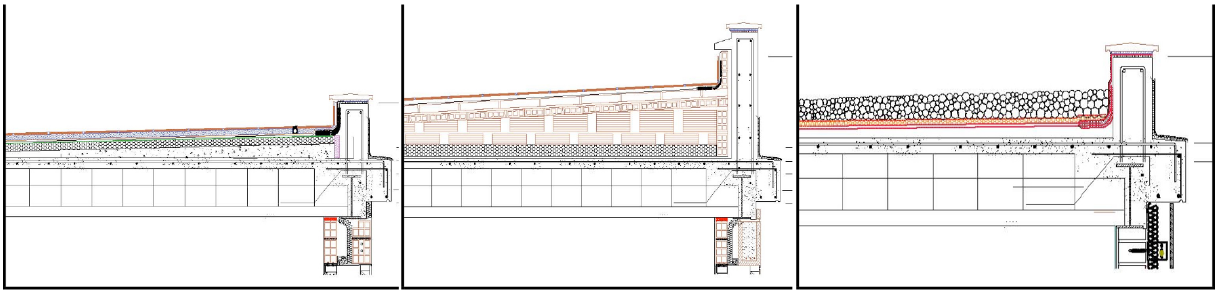


Figure 3. Cross sections of a traditional roof.

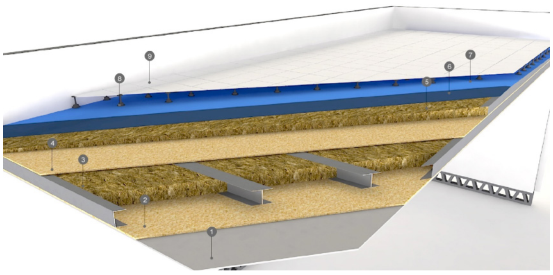


Figure 4. Cross section of an OSB roof finished with ceramic tiles.

Conventional façade solutions (Figure 5):

- F1 Conventional built façade with a non-ventilated air cavity, faced with solid brick, 5 cm-thick insulation.
- F2 Façade with non-ventilated air cavity, 5 cm-thick rendered insulation.
- F3 Ventilated façade, 5 cm-thick exterior insulation.
- F4 Lightweight curtain-wall façade.
- Innovative façade solutions (Figure 6):
- F5 Façade with non-ventilated air cavity, mounted on OSB boards, natural canvas insulation, external ceramic cladding system.
- F6 Ventilated façade mounted on OSB boards, natural canvas insulation, outer ceramic tile layer.

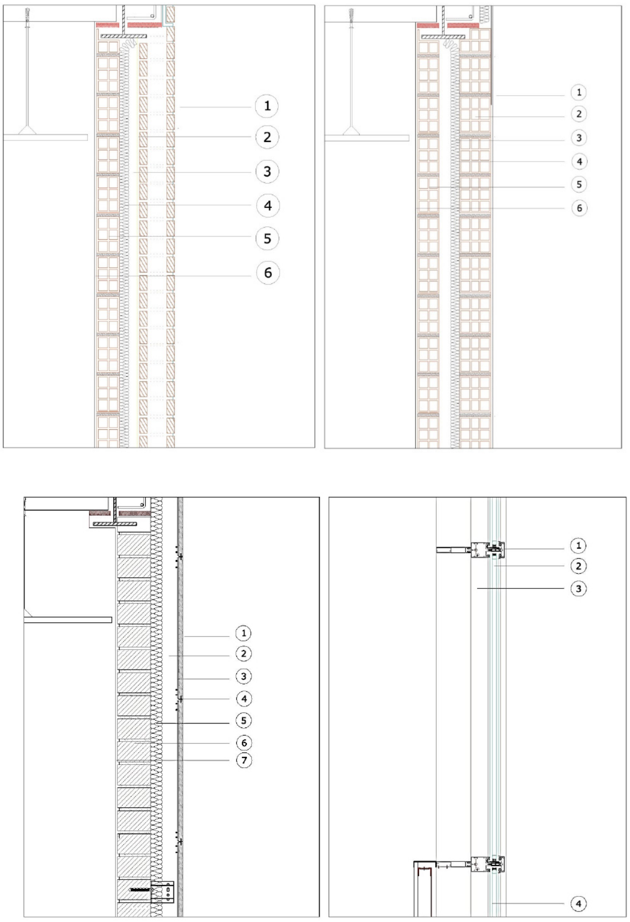


Figure 5. Face brick façade, rendered façade, ventilated façade and lightweight façade.

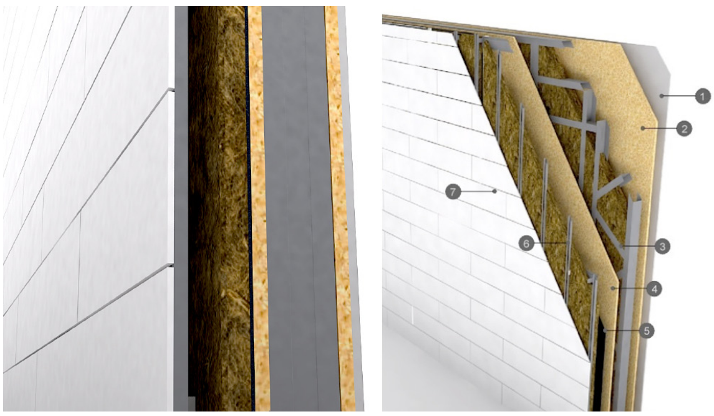


Figure 6. Non-ventilated and ventilated façades, OSB supporting structure, natural insulation and ceramic cladding.

FUNCTIONAL UNITY OF THE SYSTEM

Functional unity defines the quantification of the identified functions of the product to provide a benchmark. Its purpose is to provide a standard for data entries and output. The functional unity which is selected must be defined and measurable. As our point of reference, we used 1m^2 of usable living space and we regarded the function performed by the different building solutions to be that of an envelope or sheath designed to ensure comfortable living conditions.

USEFUL LIFE PERIOD USED FOR THE ANALYSIS

To establish the useful life period, we consulted the literature and used the criterion adopted in other similar studies: most of the research studies we analysed, in which consumption values and CO2 emissions were taken into account during the use phase, were based on a useful life period of 50 years.

5.3. EVALUATION OF IMPACT IN EACH PHASE OF THE ANALYSIS: DATA ENTRY AND USE OF PROGRAMS

Manufacturing and execution phase

The TCQ2000 application was used to determine the environmental impacts produced during the manufacturing and execution phase.

To carry out this part of the study, the four roof solutions, six blind façade solutions and three joinery solutions were selected. Measurements were based on the initial case study project. When entering data into the program fields, each of the proposed solutions was treated as if it were a chapter of the building project. Results were obtained for 1m2 of built surface for each of the elements that make up the building envelope.

The methodology that was used links each simple element in the ITeC (BEDEC) database to the type and quantity of constituent materials of which it is composed. So, for example, for each building element we can directly obtain the quantity of materials used, the cost of the investment or the amount of water consumed.

We later calculated the total surface area of the case study envelope and weighted each square metre of envelope, taking into account the proportional part of each building element per square metre of usable space. The resulting coefficient was included in the general table of results, bearing in mind the fact that this figure will vary for each individual building project and will therefore need to be entered in each case by the architect concerned.

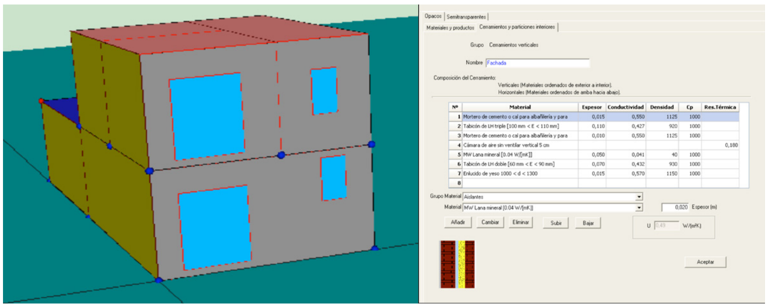
Maintenance phase

The impact of a particular material, depending on the number of times it has to be replaced during the useful life of a building, must be taken into account using the refurbishment factor (RF) concept, in accordance with the recommendations of the Impro-Building study (Nemry et al., 2008). To do this, each component was assigned a refurbishment factor or RF, depending on the number of times the material would need to be replaced throughout the useful life of the case study building, in other words 50 years. So, for example, if we assign a refurbishment factor of one, it means that the building element will be replaced once during the entire useful life of the building and, if a material has a durability of 10 years, it will be assigned a refurbishment factor of 5, in other words it will be included 5 times in the impact inventory.

Using the data entered using the TCQ2000 application, the TCQGMA program analyses various environmental impacts caused by building materials: to be specific, energy consumption, CO_2 emissions per unit of weight, and hazardous and non-hazardous waste generated during the manufacturing and execution phases, directly correlating technical, economic and environmental aspects of the project and, of course, building solutions.

Use phase

To evaluate the energy demand of the building, the official version of the LIDER program for the verification of the Limitation of Energy Demand (HE1) requirement will be used.



STREET FAÇADE

Figure 7. Data input using LIDER and CALENER.

The information obtained using LIDER will subsequently be transferred to the official Building Energy Rating program (CALENER VYP), which will be used as a simulation tool to determine the energy demands of central heating and air conditioning systems, final and primary energy consumptions and CO_2 emissions for the case study building.

For this study the following variables were selected:

- Thermal transmittance (U-factor) of materials (LIDER program database)
- CF Solar correction factor for façade openings: 1
- SF Shade factor: 1.
- $g\perp$ Solar factor for glazing: 0.5 to 0.7.
- Surface temperature (3).
- Humidity grade (3).
- hour = Air flow/ Volume = 1.5 h^{-1}.
- Percentage of openings in the main façade 24.50 % and in the façade facing the patio 30%.
- Permeability of joinery: ≤ 27 $m^3/h\ m^2$.

COLLECTION OF RESULTS

It must be remembered that the LIDER and CALENER* applications employ relative values, comparing the energy demands of the building, depending on the different solutions that are adopted, and only modifying the components of the thermal envelope, the climatic zone in which it is located and its orientation.

The results obtained by applying the CALENER software application, grouped for each climatic zone and each of the orientations that were analysed, are shown below:

*Given that the algorithms for ventilated roofs are not included in Lider v1.0, we used the method proposed in regulation UNE-EN ISO 6946 [12] to enter the data for the ventilated roof and façades. This regulation indicates that the total thermal resistance of a building element which contains a well-ventilated air cavity is calculated by ignoring the thermal resistance of the air cavity and other layers between the layer of air and the outer atmosphere and including an external surface resistance corresponding to stationary air.

DISTRIBUTION OF RESULTS

The program works with relative values, comparing the energy demands of the building, which will depend on the different solutions that are adopted, and only modifying the components of the thermal envelope, the climate zone in which it is located and its orientation. Data related to impacts, which will vary depending on the different building solutions defined for the envelope in each of the climate zones, must then be collated, establishing a useful life period of 50 years.

6. INTERPRETATION OF RESULTS

Some of the results obtained in the study are interpreted below:

There are impacts which are produced primarily in the initial life cycle phases, such as water consumption and the generation of waste, and they have less effect in the maintenance and use phases. These impacts primarily depend on the building solutions which are evaluated and do not vary as a result of orientation or climate zone

-**In terms of water consumption**, the solutions that combine a lightweight or ventilated façade with a ventilated roof consume less water during the manufacturing phase. The joinery which is selected does not influence water consumption during the manufacturing phase. In general, combinations that include concrete or mortar in their execution phase consume less water and the same is true for combinations which include prefabricated solutions.

-**In terms of the production of waste which is inert and non-hazardous**, solutions that combine a lightweight façade with an inverted roof generate less waste during their manufacturing and execution phases.

Combinations which include a continuous warm roof generally generate more hazardous waste during the manufacturing and execution phase.

The difference between the solution that generates the most hazardous waste and the one that generates the least is 0.12 kg of hazardous waste per m^2 of usable space.

-As for energy consumption (kWh/m^2) and CO_2 ($kg\ CO_2/m^2$) emissions, these are impacts which are produced during all the life-cycle phases, in other words during the manufacturing and execution phase, the maintenance phase and the use phase.

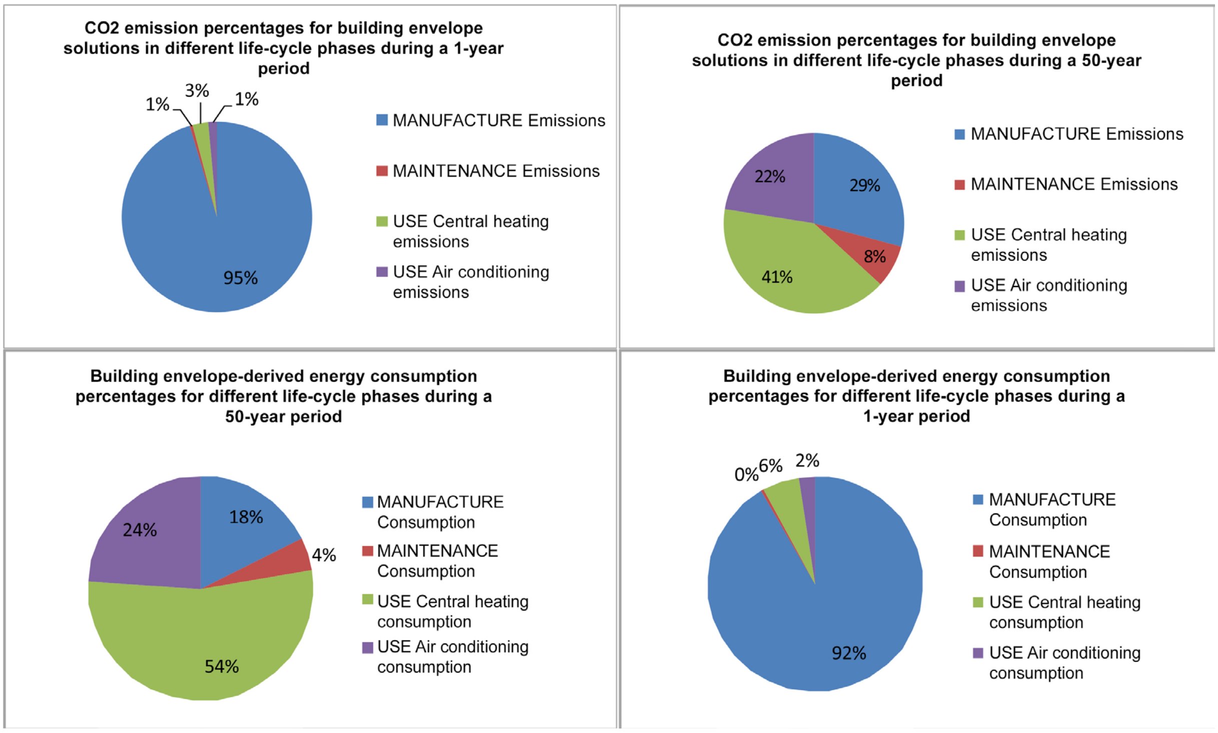


Figure 8 Comparison of CO_2 emission and consumption percentages during different life-cycle phases.

Logically, as we increase the life period being evaluated, the impacts produced during the maintenance and use phases become more important; that said, it is important to emphasize that the CO_2 emissions produced during the manufacture and use phases account for approximately 29% of the CO_2 emissions in a 50-year period. And energy consumption generated during the manufacture and execution phase accounts for approximately 18% of the energy consumption generated in a 50-year period (Figure 9).

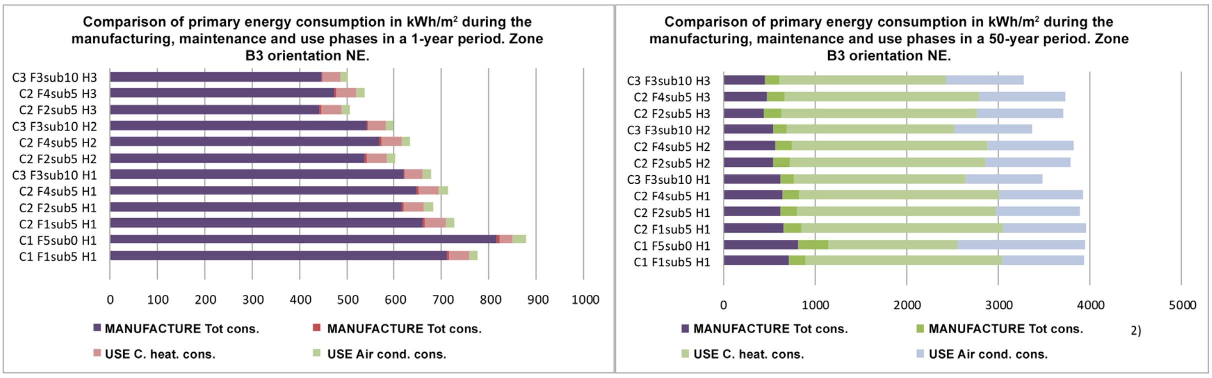


Figure 9. Table Comparing Energy Consumption Linked to Different Building Solutions in Zone B3 Orientation NE.

ESTIMATION OF THE ECONOMIC COST OF THE BUILDING ENVELOPE SOLUTIONS

To be able to make decisions about the sustainability of a particular building solution, we think it is very important to compare the cost of the impacts which are generated with the cost of the initial investment and the maintenance costs of the different building solutions. For a building to be really sustainable, it must cost the same or less than a conventional building and it must have lower maintenance costs.

7. CONCLUSIONS

- During the initial phase of the life cycle of a building, CO_2 emissions and energy consumption are directly produced as a result of the effects of the manufacture and execution of building elements. During the corrective maintenance phase CO_2 emissions and energy consumption are directly produced as a result of the replacement of building elements throughout the useful life of the building. And, during the use phase, CO_2 emissions and energy consumption are produced by central heating and air conditioning systems, which we can regard as being linked to building envelope solutions.
  Both CO_2 emissions and energy consumption will vary, depending on the building solutions that are adopted, and the climate zones and orientations; but they will also vary as a result of other variables which have not been taken into account (as explained in the scope of the system), which is why the results which are obtained are regarded as reference values.

- -Based on a 50-year life cycle period, the combinations with the worst environmental performance are the ones that include a warm roof, a lightweight façade and aluminium doors and windows, and the combinations with the best environmental performance are those with an inverted roof and a ventilated façade.

- When we compared the different building solutions but only taking into account the type of façade, we noticed that the lightweight façade solutions (F4) generate less waste and consume less water; however, they produce more CO^2 emissions and consume more energy during the manufacturing phase than other building solutions. As we continue to analyse impacts throughout the life cycle, we can see that the solutions that include a lightweight façade perform less well in the use phase, owing to the emissions produced by air conditioning, and improve their performance substantially with regard to central heating emissions, which is why they are recommended in cold climates. This is because the glass cladding in these façades transmits heat much more easily than opaque solutions.

- We can also see that combinations that include a ventilated façade (F4 and F6) show good environmental performance in their use phase, owing to the reduction in emissions produced by air conditioning. Façade F4 behaves well in hot climates because of the protection it offers against heat, but it does not perform well with respect to heating demands in cold climates. However, in solution F6, in which the heat transfer of the supporting structure and insulation is substantially improved, the ventilated façade improves its environmental performance considerably in the use phase, even in cold climates. Currently, in Spain the demand for energy is greatest in the summer, due to the need for air conditioning, so a building envelope with a ventilated façade is advisable; that said, the innovative solutions which are evaluated in this study behave well in hot climates and their applicability is improved in cold climates, which makes them ideal for any climate.

- The impacts produced during the manufacturing phase, as a result of installing one or other insulation solution, account for an increase of 0.3%; the reduction in impacts will be approximately 7% in 50 years.

- If we analyse a life-cycle period of 50 years, the combination with the lowest investment and energy costs is the one that includes the inverted roof, rendered built façade and C3F3H2 wood joinery, whereas the highest investment and energy costs correspond to the combination with the hot roof, lightweight façade and C1F4H1 aluminium joinery. The final cost difference for these two combinations is 569.70 €/m^2.

We can see that sustainable design is not just a question of selecting materials or building systems. Instead, it constitutes a process by which the architect must define environmental performance objectives, which have been previously planned and agreed with the developer and which permit the evaluation and follow-up of the targets that have been reached in the different phases of the building we have designed. It is necessary to change the current development model to ensure that the use of resources does not mean they will disappear; in other words, it is essential to develop prevention policies for the protection of the environment, without forgetting other important factors, such as improving our well-being and quality of life.

In recent years, numerous international measures have been developed to improve sustainability and reduce the environmental impact of the building process as a whole; thus, for example, in many countries energy certification processes for buildings have been introduced. Their application is now also compulsory in Spain, in compliance with Royal Decrees 1027/2007 and 235/2013 based on European Directives 2002/91/CE, 2010/31/UE and 2012/27/UE. These measures are very important to ensure the improvement of the environmental performance of buildings; however, none of these certification processes take into account environmental impacts caused during the manufacturing, execution and maintenance phases of buildings, which, as we have seen, account for 30% of the impacts which are caused in some cases.

Sustainability is defined by limits, in the sense that we cannot exceed the total amount of resources at our disposal. This is why any Sustainability criterion or measure must be linked to its own limits. We need to have a method, which is accepted by government bodies and by everyone involved in the building sector (scientists, technicians, developers, builders and final users), so that we can establish limits on the impacts buildings have in every phase of their life cycle.

To do this, we need indicators that will enable us to make an objective appraisal of the environmental impacts produced by buildings throughout their useful life.

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