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A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate

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A B S T R A C T

The construction industry is one of the less sustainable activities on the planet, constituting 40% of the total energy demand and approximately 44% of the total material use and the generation of 40–50% of the global output of greenhouse gases. The biggest environmental impact caused by buildings is generated during their operational phase due to the energy consumption for thermal conditioning. Hence, in order to reduce this energy consumption, insulation materials must be used and from a life-cycle perspective, the use of insulation materials reduces the building impact over time. This paper develops a comparative life cycle assessment (LCA) of different insulation materials (polyurethane, extruded polystyrene, and mineral wool) to analyse the environmental profile of each insulation material type in the Mediterranean continental climate. Significantly, all three insulation materials demonstrated a net positive benefit over a fifty-year life span due to the reduced heating requirements of the building. Results showed that the highest environmental impact was associated with the polystyrene insulation material and the best environmental performance was for the mineral wool. Moreover, regarding the consumption, polyurethane and mineral wool had similar thermal performance during the whole year. Furthermore, the environmental payback period shows that the cubicles with insulation material are environmentally efficient, if they are used for at least 7 years (for mineral wool), 10 years (polyurethane), and 12 years (extruded polystyrene). The results of this research give new insights into the effect on building insulation materials.

Contents

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1. Introduction

Addressing climate change is one of the greatest environmental challenges since energy demand is increasing significantly worldwide, especially in the buildings sector with its different purposes (residential, commercial, offices, etc.) [1,2]. This increasing energy demand has led to the necessity of directing energy research trends towards the use and development of renewable energy sources in order to replace the non-renewable fossil ones that are depleting in time and generate harmful emissions to the environment [3]. However, before conditioning a building, reducing its energy demand should be addressed. The use of insulation materials reduce the heat flow in buildings and, accordingly, their use to reduce their energy demand gained great interest recently [4,5]. Therefore, any improvements to this sector can have significant impacts on the reduction of energy use and consequently greenhouse gas emissions.

Therefore, a sustainable approach in the design of buildings involves guaranteeing the interior thermal comfort of the occupants throughout the year, since the properties of storage and insulation of the envelope have a fundamental role [6,7]. In the building sector, thermal insulation continues to receive significant attention in the literature as there is well-established knowledge about the strong correlation between the energy consumption of a building and the characteristics of the building envelope [4]. One of the key features by all insulation materials employed in building applications is their low thermal conductivity, λ, usually lower than 0.1 W/m·K [5,8] Using a high performance insulation material can significantly mitigate thermal losses throughout the building walls and roof and increasing its energy efficiency.. Moreover, significant cost savings can be achieved by properly insulating buildings. On a wide perspective, insulating buildings also helps the environment and reduces air pollution [9].

Fig. 1. Experimental set-up located in Puigverd de Lleida (Spain).

As buildings become more energy efficient, there has been a shift to a more holistic life cycle analysis of buildings [10]. The concept of life cycle has become widely accepted as a paradigm for assessing the environmental effect of products and services. Hence, LCA is also commonly used to describe the climate change mitigation benefits associated with alternative products and services [11,12]. This means that the assessment of the performance of buildings assessment should be extended to all stages of the life cycle and should be supported by a LCA methodology approach, that allows the identification of the hot-spots in the buildings' life cycle [13]. In this context, LCA is a growing methodology to assess the environmental impact from material extraction and production, through the construction and use stages to the waste treatment and end-of-life of the product [14]. In the building sector this methodology became more and more important during the last decades, in order to take into account the whole energy used starting from the construction up to the demolition [5].

In an experimental set-up that consists of house-like cubicles located at Puigverd de Lleida, Spain (Fig. 1), research studies have been continuously carried out since a decade ago in order to investigate the thermal performance and the potential energy savings that can be achieved using different insulation materials that served as a starting point to carry out this paper. The insulation materials used were polyurethane, extruded polystyrene and mineral wool. Significant energy savings, within the range of 37% in winter and 64% in summer, were obtained in comparison to another cubicle that was not insulated [9]. Similar studies can be found in literature; for example, Soubdhan et al. [15] investigated the use of insulation materials on the roofs in comparison with radiant barriers in terms of different heat transfer modes, where insulation materials such as fibreglass and polystyrene show significant heat flux reductions through building roofs. Farhanieh and Sattari [16] used integrative modelling to simulate energy consumptions in Iranian buildings, showing energy savings up to 35% when insulation materials are used. Pargana et al. [17] evaluated the environmental impact and the consumption of renewable and non-renewable primary energy on the stage manufacturing of five conventional insulation materials; in that study extruded polystyrene showed the worst performance of all materials evaluated and presented a similar environmental impact to polyurethane. Multiple studies about the selection and the optimization of insulation material thickness can be found as well [18–21]. The optimum insulation thickness of insulation materials used in buildings were analysed using mathematical modelling, as well as a life cycle cost (LCC) analysis [22]. A similar approach was taken by Ucar and Balo [23] who analysed energy cost savings and payback periods for different insulation materials and energy resources with the objective of choosing the optimum insulation thickness. Similar studies were conducted also using an LCC approach [18,19,24].

The effect of the location and distribution of the insulation materials on energy savings is a point of interest to some authors. For example, Al-Sanea et al. [25] studied the distribution of insulation layers within building walls, verifying that distributing the insulation material among three layers of the building wall (interior, middle, and exterior layers) was the most favourable solution with respect to the dynamic thermal characteristics parameters (time lag and decrement factor), and the peak cooling and heating loads as well. A similar study recommended that in order to get the maximum benefit of insulation with respect to time lag and decrement factor, it should be distributed between the outer and middle layers of walls [26]. However, in another study that considered high rise buildings in Hong Kong, Bojic et al. [27] showed that the best insulation position is at the inner layer of walls. The difference in the conclusions in the previous cases can be attributed to the nature and purpose of using the intended building, the building and insulation materials used, the climate conditions, and the regional location of each building.

Traditional insulation materials (polyurethane, polystyrene, etc.), although helping in reducing the energy demand, also have high impact on the environment, particularly during the manufacturing phase which encompasses the industrial and chemical processing of raw materials. This high impact is represented in different emissions and wastes that affect the human health and the ecosystem quality [28,29]. Though significant, these studies are not broadly applicable or comparable, due to the location and process-specific data used. To address the missing body of knowledge about the environmental impacts of different insulations materials, a new study is presented in order to benchmark assemblies.

From this point, the main aim of this study was to evaluate the environmental performance of different insulation materials through a holistic approach. Therefore, in this paper the following key aspects are highlighted:

- This study was addressed through the development of a detailed life cycle assessment (LCA) cradle to grave.
- The environmental impacts of the selected insulation materials are calculated and compared to highlight the role of the life cycle approach for selecting the most effective options during the design process of buildings.
- Using a functional unit of 1 square meter of a wall system allow future comparisons as well as future analyses that would account for operational considerations among other typical wall assemblies.
- Additionally, to better understand the lifetime impacts, the operational energy savings were also calculated in order to estimate the payback periods of different options.

2. Methodology

2.1. Insulation materials: selection and properties

Insulation materials can be categorized based on various properties and characteristics, mainly density, thickness, and thermal conductivity [5]. The most important properties of the insulation materials used for this study are shown in Table 1. Both polyurethane and extruded polystyrene present a very similar thermal diffusivity, while mineral wool presents the lowest [9]. Conventional insulation materials can offer thermal conductivities in the range 19–46 mW/m·K [4,9].

Mineral wool is a porous material that traps the air, making it one of the best insulation materials. The porous and elastic structure of the wool also absorbs noise. Mineral wool is incombustible and does not fuel fire or propagate flames. Moreover, is produced by melting at 1600 °C several kinds of rocks, such as dolostone, basalt and diabase, obtaining fibres that are then bound together using binders, usually resins, food-grade starches and oils. Stone wool is commercialized as panels, felts, pipe sections, or rolls [5]. These commercialized materials are usually characterized by its low cost in the market and can be easily handled by operators without losing thermal performance. In addition to values of thermal conductivity ranging from 0.033 to 0.040 W/m·K. Research studies demonstrated that the thermal insulation performance of stone wool materials for building application is negatively affected by water vapour condensation [5,30]. On the contrary, it can be recycled and therefore reintegrate in the productive cycle [31].

The extruded polystyrene (XPS) is manufactured by melting the polyester grains into an extruder, with the addition of a blowing agent [5]. XPS is characterized by higher specific heat (between 1.3 and 1.7 kJ/kg·K). Moisture affects negatively the values of thermal conductivity [32]. Recycling process of these materials is achieved by specialized industries, because these materials are easily flammable and burning releases dangerous gases, a fire retardant is often added in the manufacturing process [5].

Polyurethane (PUR or PU) is manufactured through an exothermic reaction between di- or poly-isocyanate with a polyether polyol [5]. It has a thermal conductivity ranging from 0.022 to 0.040 W/m·K, density from 15 to 45 kg/m^3 and its specific heat is between 1.3 and 1.45 kJ/kg·K. The thermal conductivity is affected by the cell size and decreases when the cell size decreases [33]. Regarding recycling, it presents the same problems described for XPS [5].

2.2. Case study

This study was located at the experimental set-up in Puigverd de Lleida (Spain), where 22 house-like cubicles tested different active and passive building heating and cooling technologies and materials during the last decade (Fig. 1) [34]. It is important to highlight that this LCA is a case study in Lleida, Spain. That means that all the data was taken considering Spain as the region of the study.

In the case of our study, four house like cubicles were analysed, in which differed only the insulation material which was used: a reference cubicle without insulation (REF), a cubicle insulated with polyurethane (PUR), a cubicle insulated with extruded polystyrene (XPS), and a cubicle with mineral wool (MW). The construction system of those cubicles had the following layers on the walls (Fig. 2): perforated bricks, plaster, hollow bricks, and cement mortar; and a roof based on a concrete precast beam, 5 cm of concrete slab, plaster, insulation material, cement mortar, and double asphalt membrane [35]. The internal dimensions of the cubicles are 2.4 m × 2.4 m × 2.4 m, with an external surface of 9 m^2. The description, justification, and construction process (Fig. 3) of this experimental set-up is not detailed in this paper, is based on a previous study [9].

A heat pump installed in each cubicle to provide both cooling and heating was used. The electrical energy consumption of the heat pump was registered at 5 min interval for each cubicle. The energy consumption of the cubicles was compared using a set

Table 1
Thermal and physical properties of the selected insulation materials [4,9].

Insulation materials	Thermal conductivity (W/m·K)	Density (kg/m^3)	Thickness (cm)	Thermal diffusivity (m^2/s)
Mineral wool	0.035	100	5	3.5×10^{-7}
Polystyrene XPS	0.034	48	5	7.08×10^{-7}
Polyurethane PU	0.028	35	5	8×10^{-7}

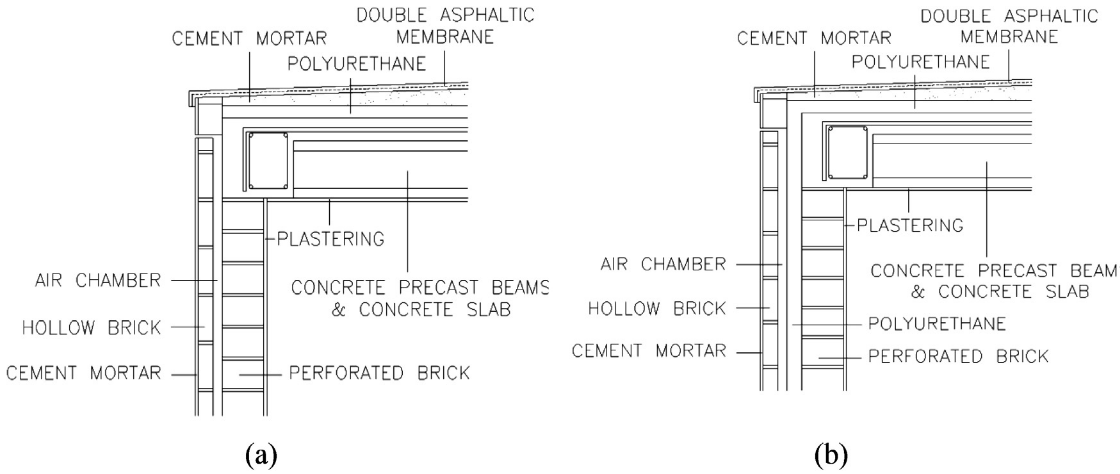

Fig. 2. Section of the construction system [9]: (a) Reference cubicle; (b) Insulated cubicle.

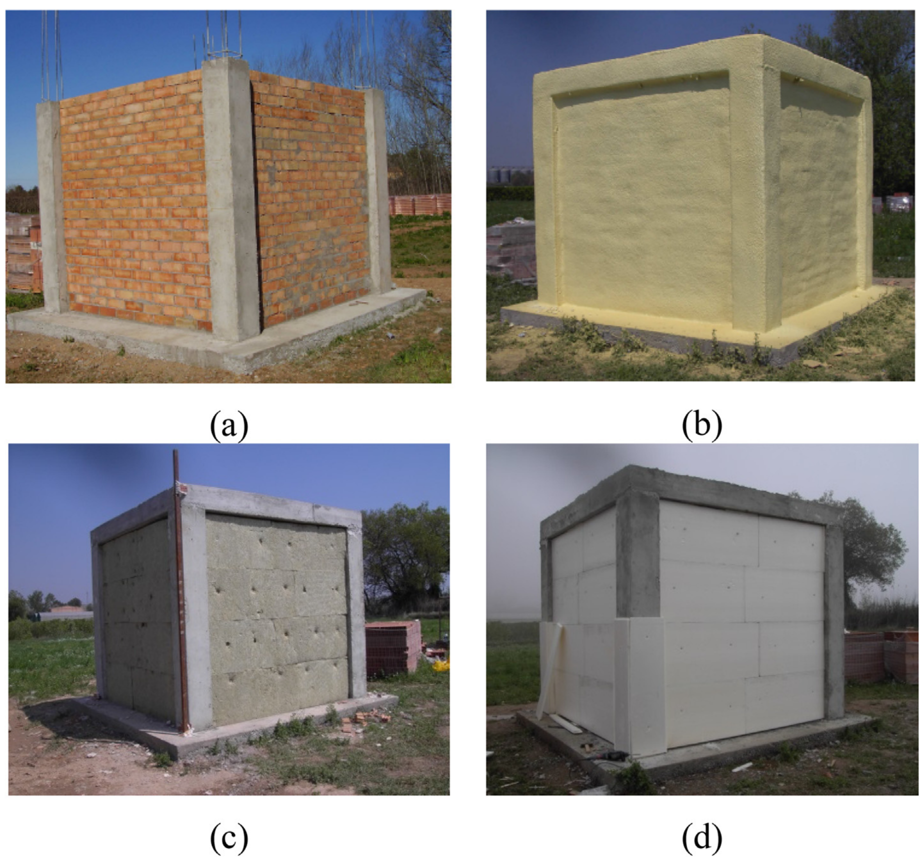

Fig. 3. Construction process of the cubicles [9]. (a) Reference cubicle; (b) cubicle insulated with polyurethane; (c) cubicle insulated with mineral wool; and (d) cubicle insulated with polystyrene.

point of 24 °C for the summer period (2018) and 21 °C for the winter period (2019).

2.3. LCA methodology

Life cycle assessment (LCA) is a tool that is used to evaluate and assess the potential impact of products or processes on the environment [37]. A LCA study considers a system through its entire life cycle; in most cases, the life cycle of a product system includes the manufacturing phase (extraction of raw materials, handling and processing), operational phase (the normal and intended use of the product) and the disposal phase (the end of the product service) [38,39].

The LCA of our experimental set-up is based on the impact assessment method ReCiPe and GWP, extracted from the database Ecoinvent [40]. The adopted method, ReCiPe is the successor of EI99 and CML-IA [41]. The primary objective of the ReCiPe method [41] is to transform the long list of life cycle inventory results, into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. In ReCiPe indicators are determined at two levels, eighteen midpoint indicators and three endpoint indicators. Midpoint indicators

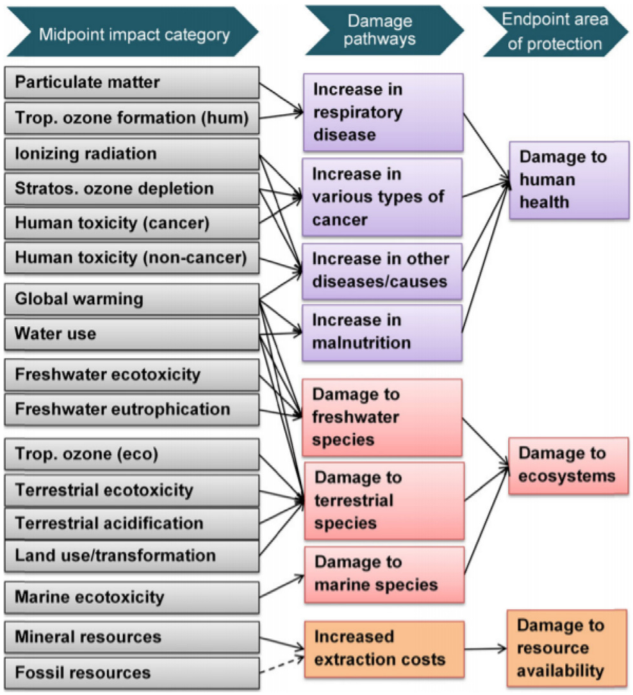

Fig. 4. Overview of the impact categories that are covered in the ReCiPe2016 method and their relation to the areas of protection [42].

focus on single environmental problems. Endpoint indicators show the environmental impact on three higher aggregation levels: effect on human health, biodiversity, and resource scarcity [42]. Converting midpoints to endpoints simplifies the interpretation of the LCA results (Fig. 4).

Moreover, ReCiPe employs three archetypes being used to describe the three groups of considerations and assumptions [43]. Individualist (I) considers the short-term impact due to the most relevant chemicals. On the other hand, egalitarian (E) is based on the precautionary principle that considers the long-term perspective and involves more risk. Hierarchism (H) is a balanced perspective based on the common policy principles [44]. In this study, the balanced term (H), which is recommended as a default choice, was adopted.

2.3.1. Definition of goal and scope

The aim of this study was to conduct a LCA for four house-like cubicles which are based on Mediterranean constructive solutions incorporating hollow bricks, perforated bricks and different insulation materials, being this difference the characteristic to assess. As mentioned in the previous section, the energy savings based on the results of previous studies were satisfying using traditional insulation materials like polyurethane foam and mineral wool [8].

2.3.2. Functional unit

The scope of an LCA should specify the performance characteristics of the system under study. The functional unit must be consistent with the objectives and scope of the system (according to UNE EN ISO 14040 and 14044) [45,46], since it determines the reference flow from which the inputs and outputs of the system are determined. Based on the functional unit, the results of the LCA will be expressed. In this study, the functional unit as a 1 m^2 of liveable floor per year was adopted, based on publications of LCA studies in the construction sector [35,47–51]. The entire cubicle also will be studied as a functional unit. The lifetime of the cubicles is assumed to be 50 years, which is consistent with most of the published case studies [36,50].

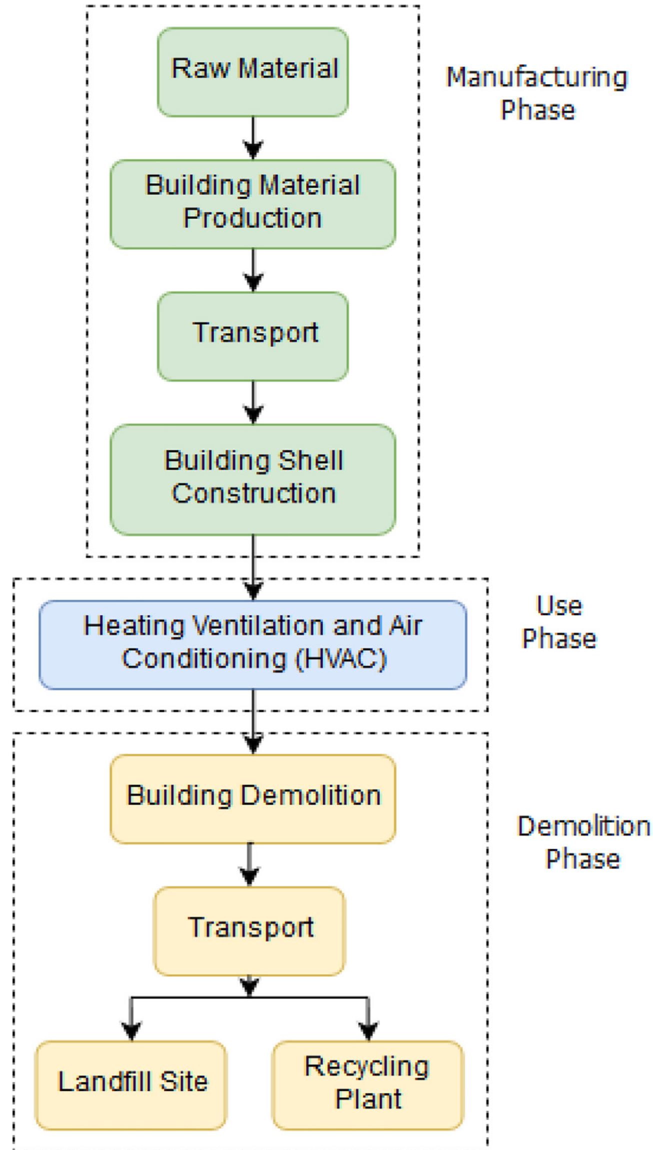

Fig. 5. System boundaries of the study.

2.3.3. System boundaries

The study accounts for the cradle to construction site portion of the life cycle and considers embodied environmental impacts. The system boundaries determine which unit processes are included in the LCA study. The system-building is broken down into process units, encompassing all the elements, materials, and components that constitute the building and are affected by flows of matter and energy during their life phases [48]. This model encompasses three distinct phases of evaluation (Fig. 5):

(1) Manufacturing phase:
- Materials production phase: extraction of raw materials, recovery of recycled materials, transportation to the factory, manufacturing processes.
- Building construction phase: transportation of materials from the factory to building site, components assembly and their possible replacement during the building lifespan, the

Table 2
Life Cycle Inventory and impact during manufacturing/dismantling phase.

Component	Mass used (kg)	ReCiPe		GWP 100a	
		Impact points	Impact/m^2 floor	(kg CO_2-eq)	Impact/m^{2}floor
Brick	5456	121.9	13.5	1340.3	148.9
Base plaster	518	10.9	1.2	119.1	13.3
Cement mortar	608	11.9	1.3	125.4	13.9
Steel bars	262	4.7	0.5	49.2	5.4
Concrete	1229	6.9	0.7	82.8	9.2
In-floor brick	1770	42.4	4.7	396.9	44.1
Asphalt	153	4.7	0.5	16.7	1.8
Polyurethane in roof	9	6.4	0.7	50.2	5.5
PU	63	43.3	4.8	335.3	37.2
XPS	99	45.4	5.1	371.9	41.3
MW	207	29.6	3.2	260.6	28.9
Disposal brick	5456	10.7	1.1	64.1	7.1
Disposal plaster	518	0.8	0.0	4.2	0.5
Disposal mortar	608	1.2	0.1	7.6	0.8
Disposal concrete + steel bars	1492	1.6	0.1	9.9	1.1
Disposal in floor brick	1770	3.6	0.4	22.2	2.4
Disposal asphalt	153	0.2	0.03	2.3	0.3
Disposal PU in roof	9	0.4	0.05	21.2	2.4
Disposal XPS	99	5.3	0.6	263.2	29.2
Disposal MU	207	0.2	0.03	0.9	0.1
Disposal PU	63	2.9	0.3	141.5	15.7

Table 3
Annual electricity consumption.

Annual electricity consumption (kWh)	REF	MW	XPS	PU
Summer period 24 °C	371.9	246.7	261.3	227.4
Winter period 21 °C	827.1	648.5	657.8	653.0
Total for a whole year	1199.1	895.2	919.1	880.4

energy consumption associated with the hydraulic digger used for excavation and transforming rural to urban-land, building discontinuous or continuous.

(2) Use phase: all activities related to the use of the buildings, including all operating energy for heating, cooling.

(3) End-of-life phase: dismantling and the demolishing the building components, their transport to the landfill site and/or to recycling sorting plants.

2.3.4. Inventory analysis of the manufacturing phase

The life cycle inventory analysis (LCIA) is defined as a phase of the LCA involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle [52,53]. The LCI data was extracted from existing inventories that were selected according to their cradle to gate scope as well as Spain geographical context that resemble to the scope of this study.

The inventory list of all the materials used for the construction/dismantling phase of the four cubicles that span this study is shown in Table 2. Moreover, the impact points with ReCiPe and GWP100a per each material on the manufacturing phase area also presented.

2.3.5. Inventory analysis of the operational phase

To extend the scope of the analysis into a broader LCA perspective, the operational energy saving percentages as a result of implementing different insulation materials were also estimated. The energy consumption of the studied cubicles is crucial for the results of the LCA, since the type of energy source and also the amount of consumption is a key factor for the interpretation of the results [54]. The results also are quantified on the operational phase inventory as seen in Table 3.

3. Results and discussion

The interpretations of the results of the impact assessment are presented in this section. The results are interpreted demonstrating four aspects: the comparison between the impact scores of the studied cubicles, the damage categories for each cubicle, the building materials contribution percentage to the total impact score of each cubicle, and the environmental payback of the building system.

In order to keep the coherency and consistency with the previous LCA studies conducted on the same cubicles, the two phases (manufacturing and disposal) are added together and treated as a whole unit, then, the disposal impact contribution percentage to that will be highlighted separately. The normalization results sharing the same unit are hence comparable [44].

3.1. Comparison between the studied cubicles

In this section, the comparison of the results of the studied cubicles is presented. In order to compare the cubicles between each other, the functional unit was the whole cubicle

3.1.1. ReCiPe methodology

Results show that the highest environmental impact during the cubicles life cycle took place during the operating phase, approximately 68%–78% while the impact during the manufacturing phase was approximately 22%–32%.

Furthermore, as seen in Table 4 the total impact points of the MW cubicle were reduced by 17% compared with the non-insulated cubicle. The PU cubicle and XPS cubicle had a reduction of 16% and 14%, respectively, compared with the non-insulated cubicle. This reduction is due to the decrease of the energy consumption in the operational phase for the cubicles since the ther-

Table 4
Overall impact points ReCiPe for the manufacturing and operational period (50 years lifetime).

Total Summary	REF	MW	XPS	PU
Manufacturing	228.8	258.5	274.3	272.2
Summer period	248.8	165.0	174.7	152.1
Winter period	553.3	433.8	440.0	436.8
Total	1030.9	857.3	889.0	861.1

mal transmittance of its walls was lower due to the thermal insulation. Nevertheless, between MW, PU and XPS cubicles there were no significant variations in the total impact results because the impact savings achieved during the operational phase are balanced out with the high impact generated during the manufacturing phase. Moreover, as it was verified experimentally, the energy consumption required for heating is about three times higher than that required for cooling. These facts have to be taken into consideration when observing the insignificant variation that may occur in the global results. Generally speaking, if the concern is to reduce the environmental impact of a cubicle, then the attention should be focused on reducing, even more, the impact of the operational phase.

3.1.2. IPCC 2013 GWP20a and GWP100a

Table 5 shows the contribution to the Global Warming Potential indicator in kg CO_2eq or carbon dioxide equivalent, which is an indicator for measuring the carbon footprint, which refers to amount of carbon dioxide released to the atmosphere as a mixture of greenhouse gases.

In this analysis, the GWP 20a and GWP100a were assessed. Regarding the GWP100a indicator, it can be appreciated that when PU and MW is added to the cubicle, there is decrease of 12% of the total CO_2eq emissions compared to the non-insulated cubicle, while with XPS the decrease is 9% CO_2eq emissions.

3.1.3. Impact categories contribution

Contribution from the impact categories to the endpoint single score are presented in Fig. 6. At the endpoint level, the damage to the ecosystem is breakdown into the categories where two impact categories are found to be the most influential which are agricultural land occupation (for all the cubicles studied) followed by the climate change ecosystem. Regarding the damage to human health, the most influential categories are climate change followed by human toxicity. And finally, the two categories on resources (fossil depletion and metal depletion) have a significant impact.

The most affected category for the four cubicles is the fossil depletion category, which represents around 22% of the total impact. This category refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials like methane, to liquid petrol, to non-volatile materials like anthracite coal [55]. Moreover, the agricultural land occupation category is the second highest category, having an impact around 19% for all cubicles, which reflects the damage to ecosystems due to the

Table 5
Overall kgCO_2 eq. IPCC 2013 (GWP 20a and GWP 100a) for the manufacturing and operational period (50 years lifetime).

Total Summary	REF 20a	REF 100a	MW 20a	MW 100a	XPS 20a	XPS 100a	PU 20a	PU 100a
Manufacturing	2479.9	2312.4	2801.5	2573.0	3023.8	2684.3	2895.8	2647.7
Summer period	1504.5	1288.8	997.7	854.7	1056.8	905.3	919.6	787.8
Winter period	3345.4	2865.8	2622.9	2246.9	2660.7	2279.3	2641.1	2262.5
Total	7329.8	6467.0	6422.1	5674.6	6741.3	5868.9	6456.6	5698.0

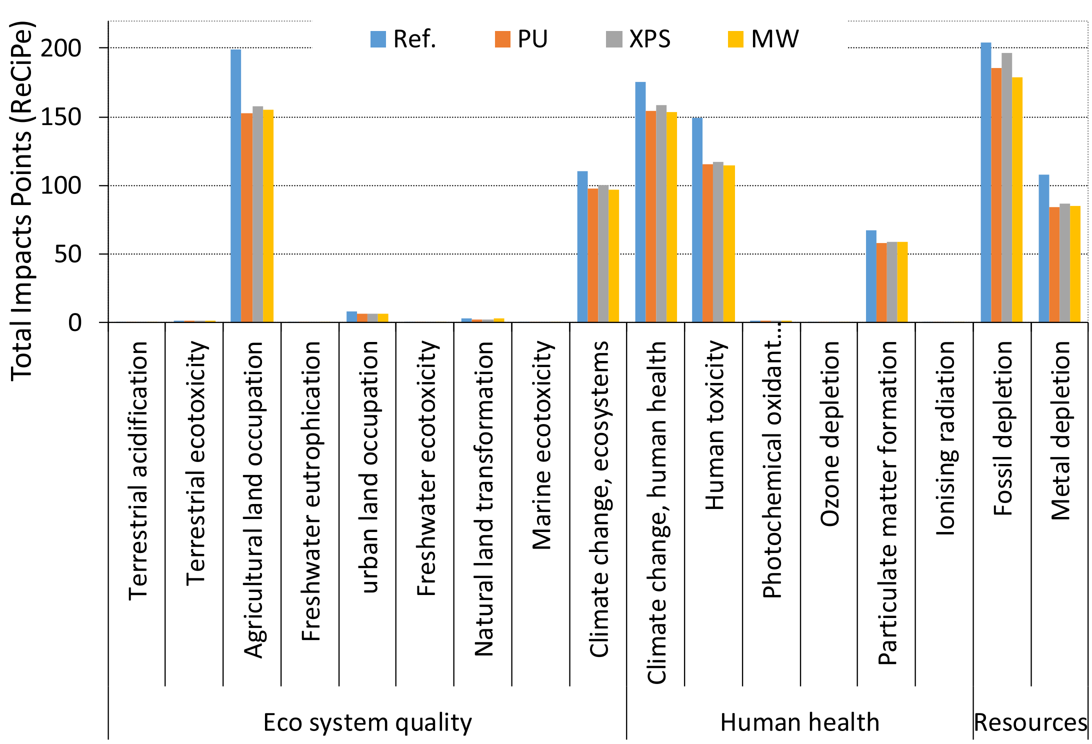

Fig. 6. Contributions from impact categories toward endpoint single score.

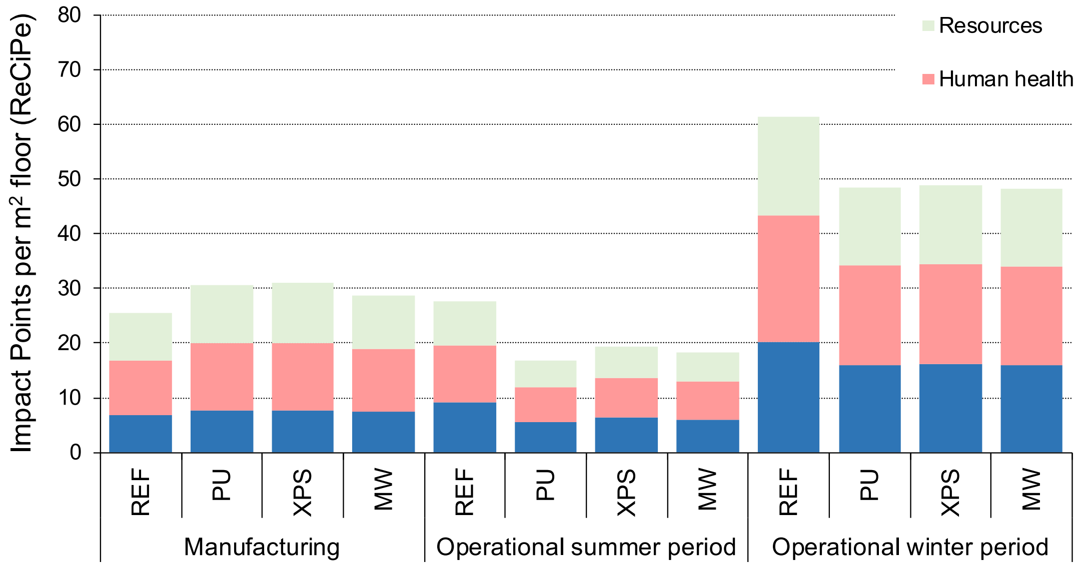

Fig. 7. ReCiPe indicator per m^2 of living floor.

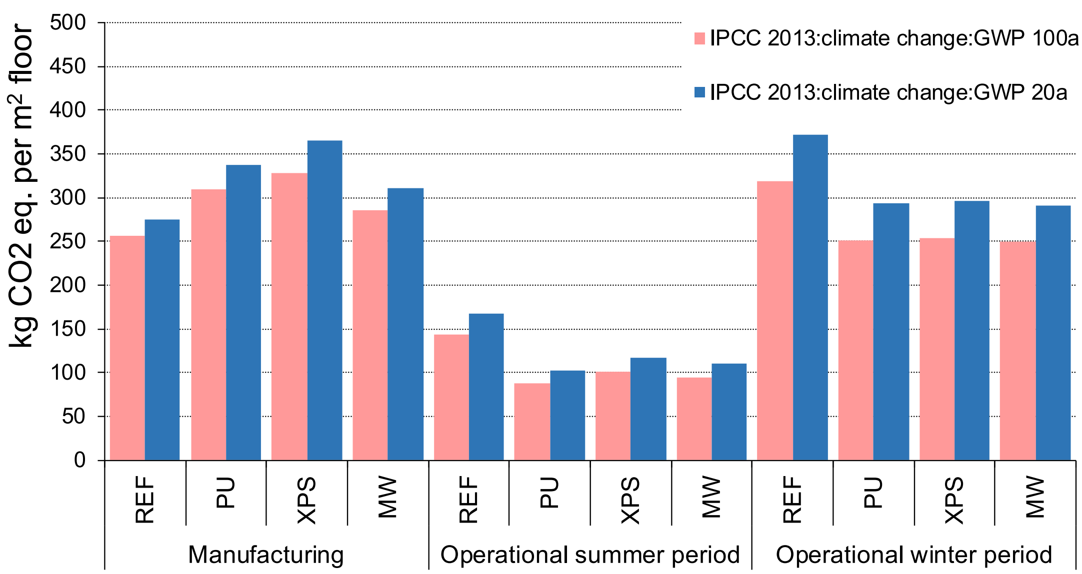

Fig. 8. $kgCO_2eq$ per m^2 of living floor.

effects of occupation and transformation of land. Although there are many links between the way land is used and the loss of biodiversity, this category is focused on the following mechanisms, occupation of a certain area of land during a certain time and transformation of a certain area of land [55]. Followed by human health and human toxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. These two categories contribute in more than 31% of the total impact in the cubicles.

Regarding the impact points to the damage categories shown in Fig. 6, it can be seen that the highest damage category is the human health both for manufacturing and operational phases, being the 38% of the total impact points in all cubicles; this is due to the electricity consumption and also for the use of bricks for the construction.

3.2. The impact of 1 m^2 of floor area

The results when considering the functional unit of 1 m^2 of living floor allows comparing results with the literature and extrapolating the values to other dimensions of buildings, therefore it guarantees future research.

Figs. 7 and 8 show the total impact points in the manufacturing phase, operational summer period, and operational winter period with them methodologies ReCiPe and GWP 20a and 100a, respectively. As it can be observed, results are proportional to the func-

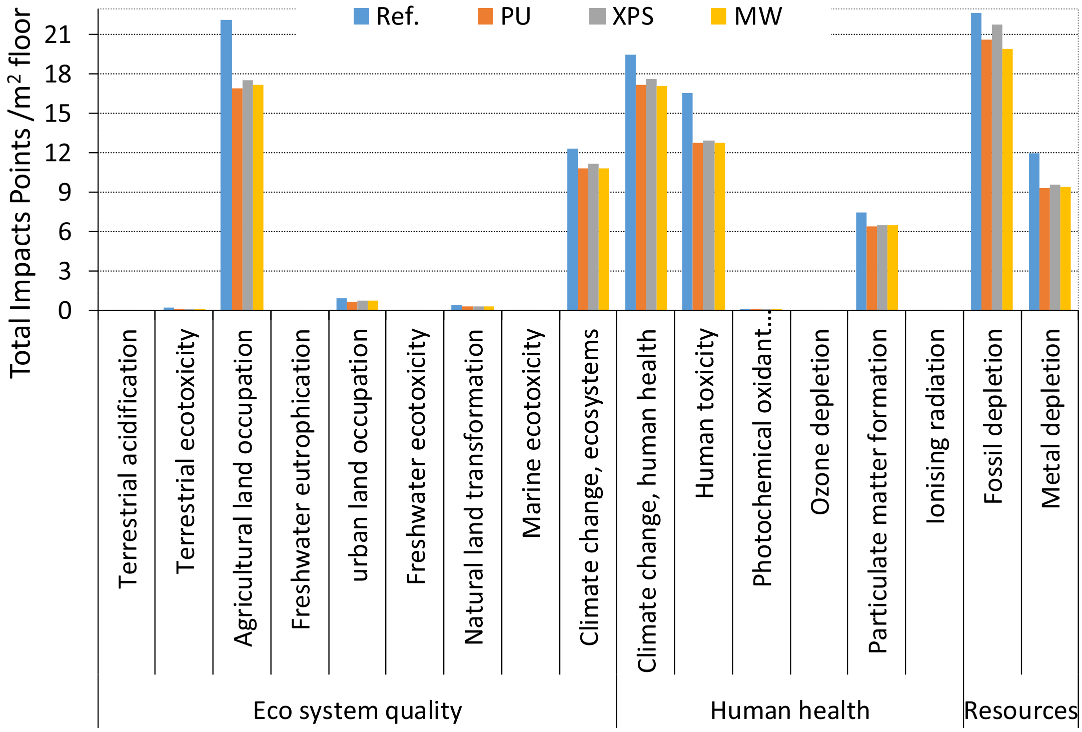

Fig. 9. Total impact points of damage categories per m² of living floor.

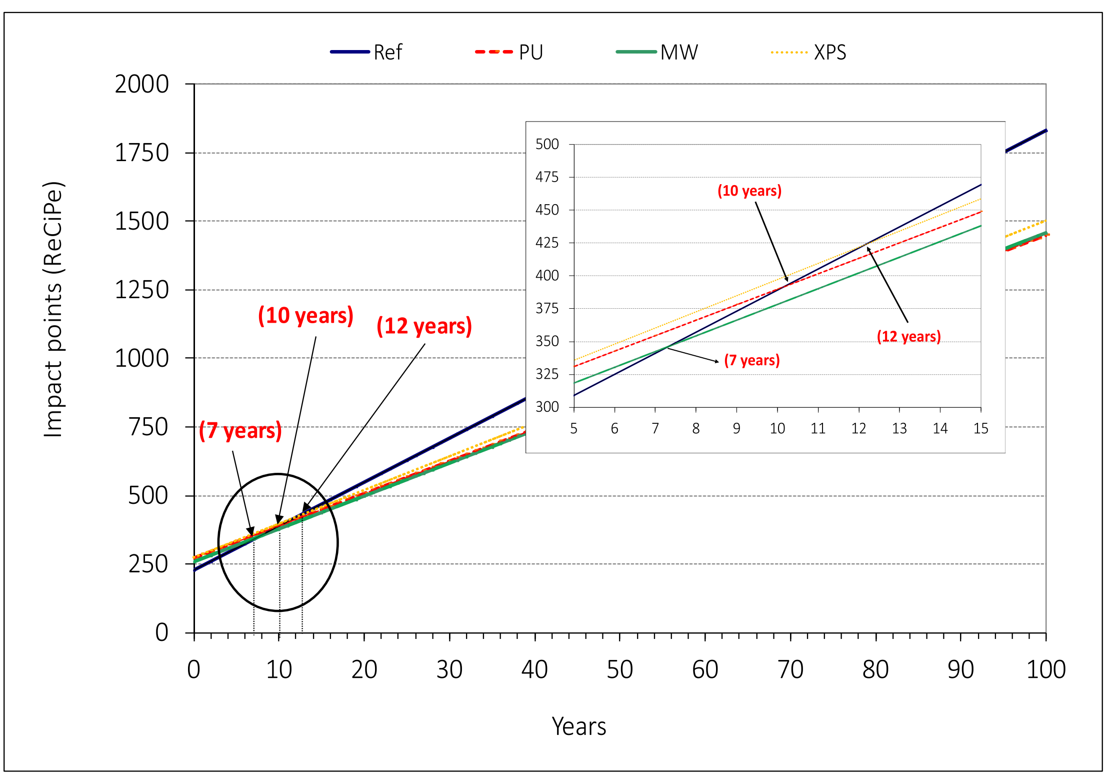

Fig. 10. Environmental payback for lifetime extended to 100 years: ReCiPe.

tional unit (the whole cubicle), which means that the interpretation of the results are the same to the previous section. The operational winter phase is still the most critical period because in winter the energy consumption is relevant in comparison with the summer period. Moreover, results of the total impact point of damage category are presented in Fig. 9.

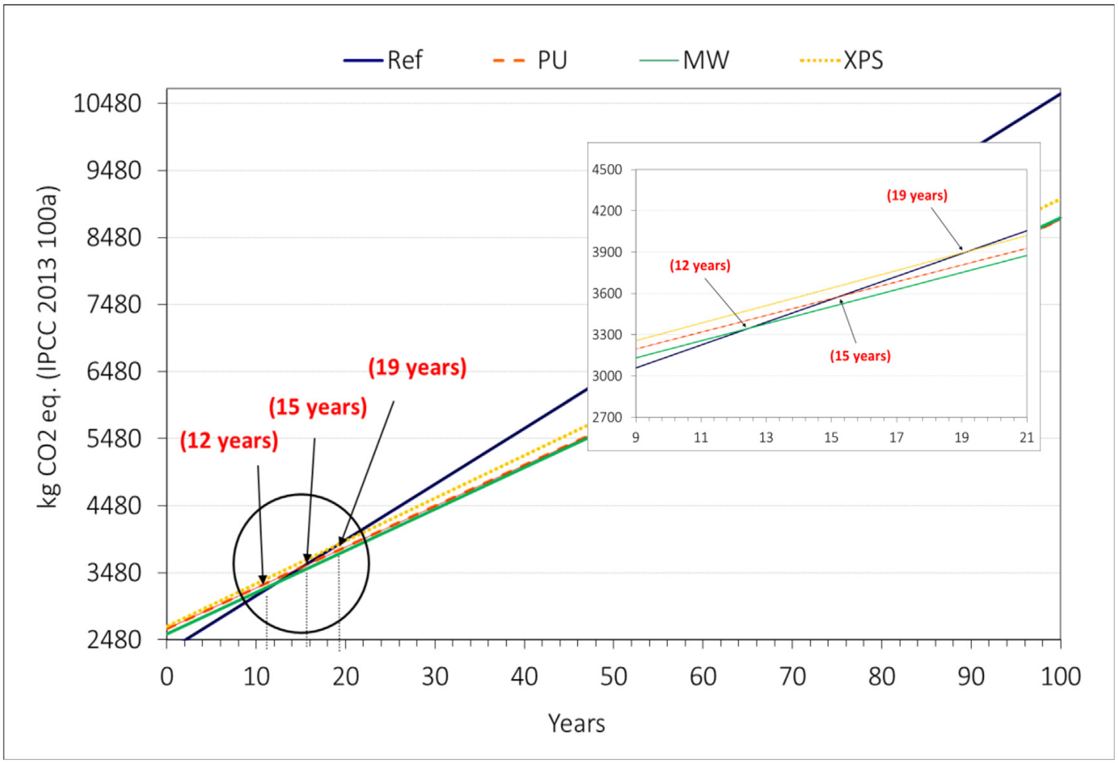

Fig. 11. Environmental payback for lifetime extended to 100 years: IPCC GWP100a.

3.3. Environmental payback. Extension of the cubicles lifetime to 100 years

Since the impact percentage of each phase, manufacturing and operation, within this system is significantly different, it was essential to carry out an environmental payback study.

The environmental payback is the time, measured in years, required for the system to compensate for the initial environmental impact, during its entire life cycle. This study provides the environmental impact year-by-year and it is used for assessing how efficient the system is [56].

As previously discussed, the cubicle with the studied XPS provided the highest environmental impact during the manufacturing/dismantling and operation phases, while the cubicles with the studied PU and MW presented similar environmental performance during manufacturing and operational phases.

A sensitive analysis of the lifetime up to 100 years is shown in Fig. 10. Results are very favourable for the three studied insulation materials compared to a non-insulated cubicle. It can be observed that the cubicle with MW is the most environmentally efficient if used at least during 7 years. This value is similar to the cubicles with PU and XPS; these presented an environmental payback of 10 years and 12 years respectively.

Regarding the $kgCO_2$ eq emitted during 100 years of lifetime for the four cubicles in question, Fig. 11 shows that the cubicle with the studied MW is environmentally efficient if used at least during 12 years, the environmental payback for the cubicle with the studied PU is 15 years, and 19 years for the cubicle with the studied XPS.

4. Conclusions

Insulation materials have proved to be a good technology to reduce energy consumption and hence to help achieving sustainability in buildings. This study focused on the most common thermal insulation materials available in the Spanish market, mineral wool, polyurethane, and polystyrene; the results showed in this study were for the insulation materials tested, with specific thermal properties. The environmental impacts of these materials was studied carrying out an LCA, where the manufacturing and operational phases were evaluated. The study was carried out using the two different methodologies of LCIA, ReCiPe (End-Point) and IPCC 2013 (GWP) and using the Ecoinvent v3.5 database to obtain the environmental impacts.

To ensure that the results were useful for further research, two different functional units were examined; the first one allows comparison within this study, since the whole cubicle is used as functional unit. The second one (floor m^2) allows comparing the results with the literature, i.e. whole buildings or other demo sites.

The main conclusions of this study are:

- PU presented the highest environmental impact during the manufacturing phase.
- XPS presented a similar environmental impact to PU, however, XPS presented the worst environmental performance of all materials evaluated.
- MW presented better environmental performance with the two methodologies used, ReCiPe and GWP.
- Insulation materials have proved to reduce electricity energy consumption in buildings. Results showed the cubicles with the studied PU, XPS, MW insulation material achieve an energy saving of 27%, 25%, 23%, respectively, in comparison to the non-insulated cubicle. Furthermore, it was observed that in the winter period the energy consumption is three times higher than in summer.
- The environmental payback of the three cubicles insulated with the studied MW, PU, XPS were 7 years, 10 years, and 12 years, respectively, when evaluated with the ReCiPe indicator. Moreover, when the GWP100a indicator was used, the environmental payback was 12 years, 15 years, and 19 years, respectively.

- It is important to highlight that these results cannot be generalised for all climates because of the specific building characteristics and microclimate conditions. Thus, further experimental research is needed to improve the knowledge about the thermal behaviour of insulation materials and their environmental impact.

The presented paper is part of a larger study that aims to evaluate the environmental impacts of different insulation materials from a cradle to grave perspective. The goal of the proposed methodology is to enable designers to understand the relative environmental impact implications of building component decisions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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