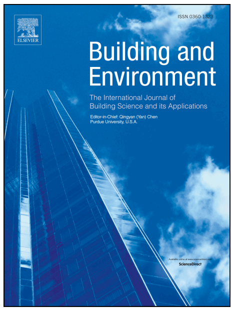


Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house

Carla Rodrigues, Fausto Freire

PII: S0360-1323(14)00217-0

DOI: 10.1016/j.buildenv.2014.07.001

Reference: BAE 3757

To appear in: *Building and Environment*

Received Date: 26 February 2014

Revised Date: 26 June 2014

Accepted Date: 2 July 2014

Please cite this article as: Rodrigues C, Freire F, Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house, *Building and Environment* (2014), doi: 10.1016/j.buildenv.2014.07.001.

Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house

Carla Rodrigues, Fausto Freire*

ADAI – LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

*corresponding author; email: fausto.freire@dem.uc.pt, Tel: +351 239790739, Fax: +351 239790701.

Abstract

Building retrofit plays an important role in reducing environmental loads associated with the building stock. The main goal of this article is to perform a comprehensive energy and environmental life-cycle assessment (LCA) of the roof retrofit of a Portuguese single-family house integrating thermal dynamic simulation. A life-cycle model was developed to assess 27 alternative retrofit scenarios combining three types of insulation material (rock wool, extruded polystyrene and polyurethane foam), three insulation levels (40, 80 and 120 mm) and three types of frame material (wood, light steel and lightweight concrete). The functional unit selected for this study was1 square meter of living area over a period of 50 years. Life-cycle (LC) impact assessment results were calculated for six categories showing that wood scenarios had the lowest impacts (all categories). The use phase accounted for 60 to 70% of the LC impacts in all categories. The results also showed that for insulation thicknesses of 80 mm or more, the reduction in operational energy, due to a further increase of 40 mm, is not significant (5% or less), while the embodied impacts increase from 6 to 20%. This article shows the importance of addressing the entire life-cycle of building retrofit to reduce environmental impacts by quantifying the marginal LC benefit of additional insulation levels and provides recommendations for optimal insulation levels for Mediterranean climates.

Keywords: Building Retrofit; Environmental Impacts; Life-Cycle Assessment (LCA); Thermal Insulation Materials; Thermal Dynamic Simulation

1. Introduction

European Union regulations were developed [1]–[3] to address the high contribution of the building sector in energy use and environmental impacts. They are focused on reducing the operational energy use of buildings (new and existing buildings), but disregard the environmental impacts associated with the entire life-cycle [4], [5]. The construction of new (low-energy) buildings has a great impact in the long term, but not much effect in the building stock overall energy use in the short term, since the rate of construction of new buildings in Europe is low [6], [7].

According to the EU Report on Energy Roadmap 2050 [8], building retrofit plays an important role in reducing the environmental loads currently associated with the building stock, thus appropriate techniques are needed to fulfill current demand for comfort and high standards of energy, as well as environmental efficiency. In order to reduce energy use and environmental impacts related to buildings, it is fundamental to introduce a design approach based on environmental sustainability, following a life-cycle (LC) perspective. Life-Cycle Assessment (LCA) can be used to identify the most critical components of the environmental performance of existing buildings and to evaluate the potential benefit of different retrofit measures.

LCA has been implemented to residential buildings, with different goals. A range of studies compared different types of buildings [9]–[11], in different locations [12]–[14], or with different envelope solutions (exterior walls [15]; roofs [16], [17]). Other studies focused on comparing conventional and low energy houses [18]–[22]. Although most studies concluded that operational energy is by far the most important contributor to LC impacts of conventional buildings [9], [18], [19], [23], [24], Blengini and di Carlo [25] claimed that progressing towards low-energy buildings may change the relative importance of the different LCA stages (construction, operation and end of life). According to Sartori and Hestnes [19], the construction phase becomes increasingly significant as measures are implemented to reduce operational energy requirements. Stephan et al. [26] showed for a passive house in Belgium, using input-output-based hybrid inventory data, that embodied energy can represent more than 70% of the total energy use (embodied and operational). Ghattas et al. [27] highlighted the importance of identifying the tipping point where LC impacts are minimized, as well as the balance between embodied and operational requirements when increasing energy efficiency in buildings.

The main focus of LCA studies of buildings has been on new buildings. Few studies addressed the retrofit of residential buildings, primarily to evaluate energy efficiency measures, such as thermal insulation of the building envelope [11], [12]. The main goal of those studies was to improve the energy performance of buildings during the use phase, often neglecting embodied impacts during production and assembly of materials or constructive solutions (construction phase). Moreover, those studies were mainly developed for cold climates, where buildings have very different characteristics and energy requirements comparing to Mediterranean or hot climates [28], [29]. For instance, Fay et al. [30] demonstrated that, for a residential building in Australia, adding insulation represented a saving of less than 6% of the total embodied and operational energy of the building over a 100-year lifespan, concluding that there may be other strategies worth pursuing before additional insulation (the main strategy in cold climates).

LCA studies for buildings located in Mediterranean climates are rare and focused on new buildings [13], [20], [31]–[35]. In the Portuguese context, Monteiro & Freire [15] studied the influence of different exterior walls solutions for a new single-family house. Silvestre et al. [36] addressed the recent European standards in the LCA of different insulation materials in exterior walls. Addressing the entire building, Bastos et al. [37] performed a life-cycle energy and greenhouse gas analysis of three multi-family buildings types from the 1940s in a residential area in Lisbon, Portugal.

The occupancy level of a building influences the operational energy use and the contribution of the different phases to the overall life-cycle of a building [38], [39]. De Meester et al. [40] and Azar & Menassa [41] emphasized the need to properly account for occupancy during the design phase to provide more reliable building energy performance estimates. The integration of thermal dynamic simulation in LCA studies addresses the potential contribution of the occupants' preferences not only in the operational energy use of buildings, but also in the assessment of trades-offs between embodied and operational energy [39]. Several studies used thermal dynamic simulation for operational energy calculation, focusing only on the energy performance of buildings during the use phase [10], [13], [42]–[44]; however, more recently, LCA and thermal dynamic simulation have been integrated to assess constructive solutions for new buildings [45]–[48]. To sum up, very few publications addressed the life-cycle of new single-family houses in a Mediterranean climate, integrating thermal dynamic calculations for operational energy requirements, and none considered the retrofitting of existing buildings.

This article presents the environmental assessment of different roof retrofit scenarios of a Portuguese single-family house using an integrated life-cycle and thermal dynamic simulation assessment. A comprehensive analysis of alternative insulation materials and thickness levels was performed to identify optimal thickness levels minimizing life-cycle environmental impacts. This article is organized in four sections including this introduction. Section 2 presents the model and life-cycle inventory, detailing the components of the retrofit scenarios. Section 3 analyses and discusses the main results. Finally, Section 4 draws the conclusions together and provides recommendations.

2. Integrated LCA and Thermal Dynamic Simulation

An integrated life-cycle approach combining LCA and thermal dynamic simulation was implemented to assess energy and environmental performances of roof retrofit scenarios. LCA addresses the potential environmental life-cycle (LC) impacts and is organized in four interrelated phases: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and interpretation (ISO 14040:2006) [49]. Thermal dynamic simulation was implemented to calculate operational energy requirements for the inventory analysis.

2.1 Goal and scope definition

Roofs are a main priority in building retrofit, especially for buildings over 100 years old. The main goal of this study was to perform a comprehensive LCA of the roof retrofit of a Portuguese single-family house. The various life-cycle processes were characterized to identify improvement opportunities in the energy and environmental performance of the roof retrofit. Thus, different roof retrofit scenarios were compared, exploring the influence of the insulation material and thickness on the overall LC performance of the building.

A life-cycle model was developed for a semi-detached single-family house (with a living area of 279 m^2 organized in 4 floors) from the 1900s, located in Coimbra, central region of Portugal. The main features of the original building are massive stone walls (with 50 cm on average), single-glazed wood windows and a traditional wood frame roof. The roof retrofit process incorporates the replacement of frame material, interior and exterior coverings, as well as the incorporation of a thermal insulation layer. All scenarios assumed the replacement of the existing single-glazed windows by double-glazing and the exterior walls non-insulated due to their high thermal mass.

This article focus on the second floor, since the roof retrofit mainly affects this floor (the reduction of operational energy requirements due to roof insulation ranged from 25 to 35% in the second floor, but for the other floors was less than 5%). The floors plans, section and main façade are provided in Figure 1.

Fig. 1 goes about here

The functional unit selected for this study was 1 square meter of living area over a period of 50 years. The service life of a building is related to a range of factors, including the design of the building, construction methods and solutions, user behavior and maintenance strategy. Some of those factors are difficult to predict, so this article follows many other studies that have also assumed a 50-year lifespan for buildings. (e.g. [9], [50]–[53]).

2.2 Inventory analysis

There are three LCI methods: process, input-output (IO) and hybrid. The hybrid approaches have emerged to combine the strengths and minimize the limitations of both process and IO LCI methods. The process-based LCI method is a bottom-up approach and provides more detail at the product level, which allows the analysis of each individual process. However, process-based data suffer from some limitations, such as the so-called ’truncation error’, associated with the definition of a finite system boundary [54], [55]. The IO-based LCI method is a top-down approach that generally appears as a “black box” [56], without providing detail of individual processes for each model [57]. IO-based data can provide a practically complete system and describe economic activities in a macro level [57], but the use of national average data for each economic sector or the conversion from economic data to energy may lead to several limitations. According to Müller and Schebek [58], IO-based LCI data may underestimate specific emissions while overestimating sector-specific aspects. The hybrid approaches can be superior in terms of system boundaries definition [57]; however it can be difficult to implement if there are no IO data available.

This study implemented a process-based LCI to compare alternative processes within the same industry sector (inventories with the same level of incompleteness). Even though process-based LCI data can suffer from a systematic ‘truncation error’, comparative LCA studies can be considered as relatively insensitive to truncation error [57]. Moreover, classification and aggregation by sector used in IO-based LCI method does not allow modelling specific products or comparing similar products within one industry [54], [59], [60]. Both the IO- and hybrid-based methods require IO databases properly disaggregated to be used in process comparative analysis. Updated IO datasets are currently not available for Portugal.

Figure 2 presents the LC model which includes the following main processes: removal of the original roof components, construction phase of the new roof and use phase (heating, cooling and maintenance). The end-of-life phase of the new roof was not considered (more details in section 2.4). The model and life-cycle inventory were implemented using SimaPro 7 software (www.pre.nl). Operational energy requirements were calculated using Energy Plus software [61].

Fig.2 goes about here

2.2.1 Embodied requirements

The removal of the original components included dismantling and transport for recycling (roof tiles) or incineration (wood). The original wood frame roof was considered to have been completely removed and replaced by a new roof. The construction phase of the retrofit process included the production of materials and transport to the site, as well as on-site processes: carpentry/joinery, assembly of the wood/steel/concrete structure, insulation and tile placement and interior coating (gypsum plaster board or stucco). Twenty seven roof retrofit scenarios (based on solar passive measures) were defined combining three types of frame material, three types of insulation material and three insulation levels, as presented in Table 1. All the scenarios considered the same volumetric, slope and outer coat in ceramic tile, given that the character of the building, which dates from the early 1900s, is protected by municipal regulations and cannot be altered.

Table 1 goes about here

Table 2 presents the inventory for the alternative frame scenarios, per total roof area (84 m^2) and per square meter. Scientific literature [62] and technical data were gathered from producers and contractors in order to calculate the quantities of materials required in each scenario. An additional 5% of materials were considered to have been lost on site due to cutting and fitting processes. Material production was modeled based on Kellenberger et al. [63], which presented average

European LCI data. The main inventory data regarding material processing for the construction was obtained from Kellenberger; Spielmann; and Althaus [63]–[65].

The delivery of construction materials to the building site assumed lorry (3.5 – 16t) and van (<3.5t) transportation, with European fleet average characteristics. Inventory data were obtained from Spielmann et al. and Hischier et al. [64], [66]. The construction material weights and shipping distances for the alternative roofs are presented in Table 3. Transportation distances, from the building site to the recovery (recycling, incineration) sites, as well as from the production site to the building site, were calculated on the basis of the locations of local material producers and contractors, assuming the nearest locations to the building site.

Table 2 goes about here

Table 3 goes about here

2.2.2 Operational requirements

The use phase included energy (heating, cooling, lighting and appliances) and maintenance requirements. A thermal dynamic simulation model was implemented to calculate the energy needs of the whole building. Each floor of the house was modeled as a thermal zone with different thermal behavior and a specific occupation pattern (internal heat gains and occupancy schedules). Kitchen and dining room are located on the basement floor (thermal zone 1); living room and office are located on the ground floor (thermal zone 2); and bedrooms are located on the first and second floor (thermal zone 3 and 4). As this research focused on the second floor, the operational energy considered was the heating and cooling requirements of this floor (thermal zone 4). The energy needs were calculated on an annual basis for the defined functional unit. A 12 kW heat pump, with a coefficient of performance (COP) of 3.6 for heating and 3.2 for cooling, was adopted for the heating and cooling system of the house. The heating season begins in November and ends in March and the cooling season begins in May and ends in September. The heating and cooling set-points were fixed at 20ºC and 25ºC, respectively, and a natural ventilation rate of 0.6 air changes per hour was considered, in keeping with Portuguese building thermal regulations [2]. The primary energy conversion factor used to convert delivered energy to primary energy was 2.65, as defined by the CED method (more details in section 2.3) for the Portuguese electricity mix.

The Portuguese climate is classified as a maritime temperate climate with a Mediterranean influence under the Köppen-Geiger classification system [67]. The building is located in the central region of Portugal where average temperatures in the winter range from 5ºC (night) and 15ºC (day). In the summer, the average temperatures range from 16ºC during the night and 29ºC during the day. Solar radiation levels in this city are about 1650 kWh/m^2/year (http://solargis.info/).

The main difference between a steady-state analysis and a dynamic approach is related to internal heat gains. A steady-state analysis usually assumes default values per area for internal heat gains (W/m^2) [2]. On the other hand, in a dynamic approach, the internal heat gains are computed taking into account the number of estimated persons in each thermal zone (occupancy density) and their metabolic activity, as well as the schedules defined for lighting and appliances. This level of accuracy may influence several time-dependent variables of the building. For instance, the effect of thermal mass may differ depending on the level of occupancy (intermittent or permanent occupancy) or on the convective or radiant heating system defined. If a building with high thermal mass stays unoccupied for several hours (as the one studied in this article), it is necessary to use more energy (and takes more time) to achieve indoor thermal comfort conditions than in a building with low thermal mass [68].Thermal dynamic simulation also provides several very specific output variable reports [69] that allow for modeling the building according to its specific needs.

A four-person family with a low occupancy level (representative of a Portuguese household) was considered, with loads mainly at night on weekdays and all day on weekends. This occupancy level consisted of an active couple who works outside the house during the day while their two children go to school. It was also assumed that they will receive a guest one weekend per month (with the same occupation pattern as the other users during the weekend). The heating and cooling systems were only partially activated during occupied hours. The schedule defined for the second floor was from 6 to 8 am and from 10 pm to 12 am within the defined set-points, with a drop in temperature to 18ºC at night during summer.

The internal gains used for the simulation were the number of people, lights and appliances. The number of people varied from none to five according to the occupancy schedule defined for each day of the year. Lights were estimated at 5 W/m^2 and appliances (computers, television, hair dryer and other small equipment) at 300 W (according to the schedule defined for each item of equipment). Hot water energy use was not considered since does not affect the thermal comfort of the house. Table 4 presents the energy requirements for the various insulation materials and thicknesses.

Table 4 goes about here

The main maintenance activities considered are associated with the conservation of the interior and exterior finishes of the building during the 50-year lifespan. The maintenance strategy is mainly corrective, i.e. the components were only replaced or repaired in case of deterioration or detection of anomalies. The maintenance activity schedule (service life of each component) for the roof was established based on data from Kellenberger et al. [63] and material producers. Table 5 presents the main assumptions for the inventory of maintenance activities, including interior painting of walls, varnishing of wood surfaces and plaster board replacement.

Table 5 goes about here

2.3 Life-cycle impact assessment methods

Two complementary LCIA methods were applied: CED (Cumulative Energy Demand) measured the non-renewable life-cycle primary energy requirement, in order to address energy resource depletion, while ReCiPe [70] assessed climate change (CC), ozone layer depletion (OLD), terrestrial acidification (TA), freshwater eutrophication (FE) and marine eutrophication (ME). Environmental impacts are presented at midpoint level (problem-oriented) in order to avoid the high uncertainty associated with impacts at endpoint level (damage-oriented). A brief description of the environmental categories is presented in Table 6.

Table 6 goes about here

2.4 Model simplifications

Some simplifications were considered in the life-cycle model. The end-of-life scenario for the roof demolition assumed that i) residues were separated and treated in the same place, ii) waste was removed and transported to the incineration or recycling plant in only one trip. During the construction phase, appliances and transportation of workers to the construction site were not included, because they are expected to be minor in residential buildings [71]. The thermal resistance of insulation materials was assumed to be constant over the 50 years, since EU standards for thermal insulation products for buildings require that the aging process of the products is taken into account. The end-of-life phase of the new roof (dismantling scenarios and waste treatment) was not included because these are not accurately predictable and are considered of minor importance for single-family homes. Furthermore it represents less than 4% of the total environmental impacts of dwellings in southern European countries, according to one European study [71],

3. Results

The main results from the integrated assessment are discussed and presented in this section. A scenario analysis for the roof retrofit was performed for both frame (section 3.1) and thermal insulation materials (section 3.2). The balance between embodied phase “cradle to gate” and use phase was assessed, as well as the tipping point where total life-cycle impacts reach a minimum value. The results addressed the four phases: removal of the original roof, construction of the new roof, maintenance and operational energy (heating, cooling, lighting and appliances).

3.1. Frame material analysis

Three alternative roof retrofit scenarios with different frame materials [wood frame (W), light steel frame (LS) and lightweight concrete slab (LWC)], and the same thermal insulation solution (40 mm rock wool) were each evaluated to assess the contribution of individual processes in the construction phase. The various scenarios were defined to have the same heat transfer coefficient (U-value) and thus similar heating and cooling requirements. The frame material influenced material production (different material composition), transport (different weights for different materials) and maintenance activities.

Figure 3 presents LCIA results for the three frame materials. The results show that W is the scenario with the lowest environmental impacts among all categories. LWC is the scenario with the highest environmental impacts in four out of six categories. As far as eutrophication impacts are concerned, LS is the scenario with the highest environmental impacts, as a result of the galvanized steel process (steel with zinc coating).

Use phase is the largest contributor in scenarios W and LS, for all categories, accounting for 40 to 70%. For the LWC scenario, the construction phase is the most significant LC phase for three out of six categories, accounting for 30 to 65% of total LC impacts. Construction phase contribution is nearly half of use phase to terrestrial acidification and freshwater eutrophication and almost 20% for the other categories. The contribution of demolition (< 3%) and maintenance (< 15%) phases is much less significant (all categories).

Regarding primary energy, use phase accounts for 60% of total energy requirements in the W and LS scenarios, while LWC showed no significant difference between the energy requirements for construction and use phase (about 2%). These results provide a useful perspective on the influence of the frame material in the performance of the different LC phases. Depending on the frame material, the potential for reducing environmental impacts of building retrofit can shift from use phase to construction phase. Primary energy (CED non-renewable) results show high correlation with climate change (and to a less extent with terrestrial acidification and ozone depletion) but not with eutrophication (marine and freshwater). This is to be expected given that climate change, terrestrial acidification and ozone depletion impacts are mainly due to fossil energy use, which is itself characterized by CED non-renewable results.

Fig. 3 goes about here

Figure 4 details the contribution of the main processes and materials. The highest impacts are from transport, steel, concrete and zinc. Transport is the largest contributor to scenario W (25 to 50%) and to scenario LS (13 to 43%), followed by steel (10 to 30%). Lightweight concrete is the main contributor to the LWC scenario (26 to 54%), followed by steel (3 to 22%). The materials with the lowest environmental impacts are wood, oriented strand board (OSB) and stucco.

Fig. 4 goes about here

3.2 Thermal insulation analysis

This section assesses the influence of the thermal insulation material (RW, XPS or PUR) and its thickness (40, 80 and 120 mm) on the total life-cycle impacts of the roof retrofit with a selected frame material (wood). Firstly, total LC impacts for the various insulation materials and thicknesses are analyzed, in order to identify a tipping point, for which total LC impacts are minimized. Secondly, LCIA results for rock wool (40, 80 and 120 mm) are presented for the purpose of understanding the contribution of the various LC phases of the roof retrofit. Lastly, a comparative assessment of the various thermal insulation materials with a thickness of 80 mm (where lower LC impacts were observed for most environmental categories) is presented.

Figure 5 presents total LC impacts (top line), as well as the impacts from both operational energy and the construction phase. Maintenance and demolition are not assessed in figure 5 since the insulation material does not influence them. A trend line (polynomial, order 2) was applied for total LC impacts (correlation between 95 and 98%, except for primary energy and marine eutrophication in PUR, around 90%). In all insulation materials there is a tipping point for climate change and primary energy that lies between 40 and 80 mm. This results from the high performance of the heating and cooling system (heat pump with COP=3.6) and from the Portuguese electricity mix, which has a large contribution of renewable energy. The tipping point for rock wool occurs for thicknesses less than 80 mm for all categories (less than 40 mm for ozone depletion, marine eutrophication and primary energy). The tipping point for PUR occurs for thicknesses of about 40 mm, as well as for marine eutrophication. In the XPS scenarios, it always occurs for thicknesses greater than 120 mm (except for climate change and primary energy), which are not commonly used in Mediterranean climates. XPS shows very high ozone depletion impacts that result from its production process, as discussed later in this section.

The comparison between embodied and operational requirements (excluding lighting and appliances) shows that embodied requirements are more significant (about 30 to 50%) in four out of six categories (climate change, ozone depletion, marine eutrophication and primary energy). For the two other categories, embodied impacts only account for 20 to 35% of total LC impacts. For XPS and rock wool thicknesses larger than 120 mm, the embodied requirements become higher than operational requirements (climate change and primary energy). For PUR, the contribution of operational requirements is always more than embodied requirements.

Fig. 5 goes about here

Total LCIA results for rock wool (40, 80 and 120 mm) are presented in Table 7, which shows the impacts in the main life cycle phases of the roof retrofit (construction and use phase). A contribution analysis was performed to assess the impact of a further increase of 40 and 80 mm in the insulation levels. LC impacts are dominated by the use phase (45 to 70% of total LC impacts) followed by the construction phase (20 to 40%). The main contributor to the use phase is the heating, which accounts for 70% of total operational energy. Cooling requirements accounts for only 8%, and lights/appliances account for 22%. Construction phase impacts for ozone depletion become more significant than operational energy impacts for thicknesses greater than 120 mm.

The results also show that for insulation thicknesses of 80 mm or more, the reduction in operational energy is not significant (5% or less), while the embodied impacts increase from 6 to 20%. The most important absolute benefit is obtained when a 40 mm insulation layer is applied to roofs with no insulation, leading to a decrease in energy use of about 30%. Thus, the energy efficiency benefit of increasing the insulation thickness may not always offset the increase of environmental impacts associated with production.

Table 7 goes about here

A contribution analysis was performed for each thermal insulation material with 80 mm thickness (the option with the lowest LC impacts in most environmental categories, as discussed previously).

Figure 6 presents the LCIA results per LC phase. The results show that the PUR option has the lowest LC impacts in four out of six categories. For the remaining categories (primary energy and marine eutrophication), XPS has the lowest LC impacts. Rock wool has the lowest environmental impacts in the construction phase for half of the categories (climate change, primary energy and marine eutrophication), while PUR has the lowest impacts in the use phase (all categories).

For the three insulation materials, the use phase results in the highest environmental impacts (55 to 80% of total LC impacts), followed by the construction phase (20 to 40%). The main differences between the alternative insulation materials are due to production and transportation.

Regarding the XPS option, the use phase accounts for only 3% of the LC impacts, while the construction phase accounts for 96%. The important contribution of XPS for ozone depletion is caused by the agent used in the extrusion process, namely hydrofluorocarbon (HFC-134a). Recently some XPS producers have started to use CO_2 as the primary blowing agent as an alternative to HFCs [65], but this was not considered because no detailed inventory data was available for the XPS production process that is currently being used in Europe. Nonetheless, a preliminary analysis was performed, showing that the use of CO_2 as the primary blowing agent could reduce the impact of material production from almost 97% to only about 11%. However, the thermal insulation properties of CO_2 blown-foam would be significantly compromised [65].

Fig. 6 goes about here

4. Discussion and conclusion

This article assessed the environmental performance of the roof retrofit of a Portuguese single-family house using an integrated life-cycle assessment and thermal dynamic simulation. A life-cycle model was developed including the implementation of a comprehensive inventory. Twenty-seven alternative roof retrofit scenarios were assessed combining three types of frame material (wood frame, light steel frame and lightweight concrete slab), three types of insulation material: rock wool (RW), extruded polystyrene (XPS) and polyurethane foam (PUR), and three insulation levels (40, 80 and 120 mm). Primary energy and five environmental categories were evaluated to identify critical aspects of these scenarios, as well as to identify hot spots and improvement opportunities.

Wood frame scenarios presented the lowest environmental impacts in the construction phase. Lightweight concrete scenarios presented the highest environmental impacts in all categories, with the exception of freshwater eutrophication, where light steel frame scenarios had the highest impacts. The use phase (maintenance and operational energy) accounted for about 40 to 70% (depending on the scenario and impact category) of the LC impacts. PUR had the lowest LC impacts in 4 out of 6 categories. Rock wool had the lowest environmental impacts in the construction phase for climate change, primary energy and marine eutrophication.

The results quantified the influence of incorporating thermal insulation as a retrofit measure in existing buildings. There was a very significant benefit associated with the improvement of the thermal envelope just by adding 40 mm of insulation in the roof (a reduction of 30% in the operational energy of the second floor). For insulation thicknesses of 80 mm or more, the reduction in operational energy is not significant (5% or less), while the embodied impacts increase from 6 to 20% of.

The integration of thermal dynamic simulation in LCA provides more robust and representative results by considering a more realistic use of the building and avoiding overestimating energy needs. In the dynamic approach, the internal heat gains are computed taking into account the number of estimated persons in each thermal zone (occupancy density) and their metabolic activity, as well as the schedules defined for lighting and appliances.

Some of the assumptions and simplifications of this study led to several limitations. First, the results were based on a single building (representative of a significant number of buildings in historical city centers) located in a maritime temperate Mediterranean climate, which may not be representative of other locations or building types. Second, process LCI data was used for a detailed comparative analysis, which may underestimate the impacts calculated as compared with IO-based LCA studies. Third, uncertainty associated with inventory data was not addressed. Fourth, in the thermal simulation model, the schedule defined for occupancy represents a typical Portuguese family, but does not take into account variability due to user behavior. Fifth, the variability in external temperatures throughout the year (and differences between years) due to climate change was also not taken into account in the thermal simulation model. Finally, uncertainty associated with some geometric simplifications and the use of a specific system to calculate heating and cooling requirements was also not addressed.

The results can be useful for other real-life applications helping building designers, stakeholders (i.e., owners, operators), or policy makers to reduce energy and environmental impacts associated with building retrofit in Mediterranean climates. Drawing on the results, some recommendations can be provided to enhance the environmental performance of building retrofit, for instance the use of about 80 mm of insulation as a threshold in the roof retrofit of existing low occupancy buildings, such as family dwellings. Future work will follow the approach hereby presented to assess the influence of different occupancy patterns in buildings (residential and commercial buildings), to characterize the marginal LC performance of adding extra insulation and to identify adequate insulation thresholds.

Acknowledgements

The first author (C. Rodrigues) is grateful for the financial support provided by FCT (Fundação para a Ciência e a Tecnologia), under the program MIT Portugal – Sustainable Energy Systems, through the doctoral degree grant SFRH/BD/51951/2012. The authors are thankful to Professors Cláudia

Cavadas and Luís Almeida for valuable information (technical drawings and additional detailed information) about the building assessed in this article. We are also thankful to an anonymous reviewer for detailed comments and valuable suggestions. The contribution of David Wimhurst to the English language revision is also gratefully acknowledged. This work has been framed under the Energy for Sustainability Initiative of the University of Coimbra and is supported by the Energy and Mobility for Sustainable Regions - EMSURE - Project (CENTRO-07-0224-FEDER-002004). The support from FCT project PTDC/SEN-TRA/117251/2010 is also acknowledged.

References

[1] EPDB, "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings," *Off. J. Eur. Union*, vol. L1/65–1/71, 2002.

[2] REH and RECS, "DL 118/2013 - Regulamento de Desempenho Energético dos Edifícios de Habitação, Comércio e Serviços, Code of the energy performance of buildings (residential and commercial)," Ministry of Economy and Employment, 2013, pp. 4988–5005.

[3] EPDB (recast), "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)," *Off. J. Eur. Union*, vol. L153/13–15, 2010.

[4] X. G. Casals, "Analysis of building energy regulation and certification in Europe: Their role, limitations and differences," *Energy Build.*, vol. 38, no. 5, pp. 381–392, May 2006.

[5] A. Z.-Z. Szalay, "What is missing from the concept of the new European Building Directive?," *Build. Environ.*, vol. 42, no. 4, pp. 1761–1769, Apr. 2007.

[6] M. Bell, "Energy Efficiency in Existing Buildings : The role of Building Regulations," in *COBRA 2004 Proc. Of the RICS Foundation Construction and Building Research Conference*, 2004, no. September, pp. 7–8.

[7] A. Säynäjoki, J. Heinonen, and S. Junnila, "A scenario analysis of the life cycle greenhouse gas emissions of a new residential area," *Environ. Res. Lett.*, vol. 7, no. 3, p. 034037, Sep. 2012.

[8] European Comission, "EU Energy Roadmap 2050 (COM(2011) 885 final of 15 December 2011)," Luxembourg, 2011.

[9] K. Adalberth, "Life-cycle assessment of four multi-family buildings," *Int. J. Low Energy Sustain. Build.*, vol. 2, pp. 1–21, 2001.

[10] B. Peuportier, "Life cycle assessment applied to the comparative evaluation of single family houses in the French context," *Energy Build.*, vol. 33, no. 5, pp. 443–450, May 2001.

[11] Lollini, Barozzi, Fasano, Meroni, and Zinzi, “Optimisation of opaque components of the building envelope. Energy, economic and environmental issues,” *Build. Environ.*, vol. 41, no. 8, pp. 1001–1013, Aug. 2006.

[12] A. Sharma, A. Saxena, M. Sethi, and V. Shree, “Life cycle assessment of buildings: A review,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 871–875, Jan. 2011.

[13] B. Rossi, A.-F. Marique, and S. Reiter, “Life-cycle assessment of residential buildings in three different European locations, case study,” *Build. Environ.*, vol. 51, pp. 402–407, May 2012.

[14] A. Stephan, R. H. Crawford, and K. de Myttenaere, “Towards a comprehensive life cycle energy analysis framework for residential buildings,” *Energy Build.*, vol. 55, pp. 592–600, Dec. 2012.

[15] H. Monteiro and F. Freire, “Life-cycle assessment of a house with alternative exterior walls : comparison of three impact assessment methods,” *Energy Build.*, vol. 47, pp. 572 – 583, 2012.

[16] S. Saiz, C. Kennedy, B. Bass, and K. Pressnail, “Comparative life cycle assessment of standard and green roofs.,” *Environ. Sci. Technol.*, vol. 40, no. 13, pp. 4312–6, Jul. 2006.

[17] L. Kosareo and R. Ries, “Comparative environmental life cycle assessment of green roofs,” *Build. Environ.*, vol. 42, no. 7, pp. 2606–2613, Jul. 2007.

[18] S. Blanchard and P. Reppe, “Life Cycle Analysis of a Residential Home in Michigan,” Center for Sustainable Systems, University of Michigan, Ann Arbor, MI, 1998.

[19] I. Sartori and A. G. Hestnes, “Energy use in the life cycle of conventional and low-energy buildings: A review article,” *Energy Build.*, vol. 39, no. 3, pp. 249–257, Mar. 2007.

[20] G. A. Blengini and T. Di Carlo, “Energy-saving policies and low-energy residential buildings: An LCA case study to support decision makers in Piedmont (Italy),” *Int. J. Life Cycle Assess.*, vol. 15, no. 7, pp. 652–665, May 2010.

[21] A. Dodoo, L. Gustavsson, and R. Sathre, “Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard,” *Resour. Conserv. Recycl.*, vol. 54, no. 12, pp. 1152–1160, Oct. 2010.

[22] L. Gustavsson and A. Joelsson, “Life cycle primary energy analysis of residential buildings,” *Energy Build.*, vol. 42, no. 2, pp. 210–220, Feb. 2010.

[23] O. Ortiz, F. Castells, and G. Sonnemann, “Sustainability in the construction industry: A review of recent developments based on LCA,” *Constr. Build. Mater.*, vol. 23, no. 1, pp. 28–39, Jan. 2009.

[24] C. W. Scheuer and G. A. Keoleian, “Evaluation of LEED ^{TM} Using Life Cycle Assessment Methods,” Center for Sustainable Systems, University of Michigan, Ann Arbor, MI, 2002.

[25] G. A. Blengini and T. Di Carlo, “The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings,” *Energy Build.*, vol. 42, no. 6, pp. 869–880, Jun. 2010.

[26] A. Stephan, R. H. Crawford, and K. de Myttenaere, “A comprehensive assessment of the life cycle energy demand of passive houses,” *Appl. Energy*, vol. 112, pp. 23–34, Dec. 2013.

[27] R. Ghattas, J. Gregory, E. Olivetti, and S. Greene, “Life Cycle Assessment for Residential Buildings : A Literature Review and Gap Analysis,” Concrete Sustainability Hub, MIT, Cambridge, Massachusetts, 2013.

[28] A. Stephan, R. H. Crawford, and K. de Myttenaere, “Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia,” *Build. Environ.*, vol. 68, pp. 35–49, Oct. 2013.

[29] R. H. Crawford, I. Czerniakowski, and R. J. Fuller, “A comprehensive framework for assessing the life-cycle energy of building construction assemblies,” *Archit. Sci. Rev.*, vol. 53, no. 3, pp. 288–296, Aug. 2010.

[30] R. Fay, G. Treloar, and U. Iyer-Raniga, “Life-cycle energy analysis of buildings: a case study,” *Build. Res. Inf.*, vol. 28, no. 1, pp. 31–41, Jan. 2000.

[31] F. Asdrubali, C. Baldassarri, and V. Fthenakis, “Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings,” *Energy Build.*, vol. 64, pp. 73–89, Sep. 2013.

[32] M. Cellura, F. Guarino, S. Longo, M. Mistretta, and A. Orioli, “The role of the building sector for reducing energy consumption and greenhouse gases: An Italian case study,” *Renew. Energy*, vol. 60, pp. 586–597, Dec. 2013.

[33] G. A. Blengini, “Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy,” *Build. Environ.*, vol. 44, no. 2, pp. 319–330, Feb. 2009.

[34] O. Ortiz-Rodríguez, F. Castells, and G. Sonnemann, “Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development.,” *Sci. Total Environ.*, vol. 408, no. 12, pp. 2435–43, May 2010.

[35] O. Ortiz, F. Castells, and G. Sonnemann, “Operational energy in the life cycle of residential dwellings: The experience of Spain and Colombia,” *Appl. Energy*, vol. 87, no. 2, pp. 673–680, Feb. 2010.

[36] J. D. Silvestre, J. de Brito, and M. D. Pinheiro, “From the new European Standards to an environmental, energy and economic assessment of building assemblies from cradle-to-cradle (3E-C2C),” *Energy Build.*, vol. 64, pp. 199–208, May 2013.

[37] J. Bastos, S. Batterman, and F. Freire, “Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon,” *Energy Build.*, vol. 69, pp. 344–353, Feb. 2014.

[38] A. S. Nordby, “Carbon reductions and building regulations : the case of Norwegian mountain cabins,” *Build. Res. Inf.*, no. December 2012, pp. 37–41, 2011.

[39] P. Hernandez and P. Kenny, “Integrating occupant preference and life cycle energy evaluation: a simplified method,” *Build. Res. Inf.*, vol. 38, no. 6, pp. 625–637, Dec. 2010.

[40] T. de Meester, A.-F. Marique, A. De Herde, and S. Reiter, “Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe,” *Energy Build.*, vol. 57, pp. 313–323, Feb. 2013.

[41] E. Azar and C. C. Menassa, “A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings,” *Energy Build.*, vol. 55, pp. 841–853, Dec. 2012.

[42] G. Verbeeck and H. Hens, “Life cycle inventory of buildings: A contribution analysis,” *Build. Environ.*, vol. 45, no. 4, pp. 964–967, Apr. 2010.

[43] C. Thormark, “A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential,” *Build. Environ.*, vol. 37, no. 4, pp. 429–435, Apr. 2002.

[44] S. Thiers and B. Peuportier, “Energy and environmental assessment of two high energy performance residential buildings,” *Build. Environ.*, vol. 51, pp. 276–284, May 2012.

[45] B. Peuportier, S. Thiers, and A. Guiavarch, “Eco-design of buildings using thermal simulation and life cycle assessment,” *J. Clean. Prod.*, vol. 39, pp. 73–78, Jan. 2013.

[46] H. Gervásio, P. Santos, R. Martins, and L. Simões da Silva, “A macro-component approach for the assessment of building sustainability in early stages of design,” *Build. Environ.*, vol. 73, pp. 256–270, Mar. 2014.

[47] D. Anastaselos, E. Giama, and A. M. Papadopoulos, “An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions,” *Energy Build.*, vol. 41, no. 11, pp. 1165–1171, Nov. 2009.

[48] F. Stazi, A. Mastrucci, and P. Munafò, “Life cycle assessment approach for the optimization of sustainable building envelopes: An application on solar wall systems,” *Build. Environ.*, vol. 58, pp. 278–288, Dec. 2012.

[49] ISO (International Organization for Standardization), “ISO 14040: Environmental Management Life Cycle Assessment Principles and Framework,” Geneva, Switzerland, 2006.

[50] K. Adalberth, “Energy use during the life cycle of single-unit dwellings: Examples,” *Build. Environ.*, vol. 32, no. 4, pp. 321–329, Jul. 1997.

[51] I. Z. Bribián, A. A. Uso, and S. Scarpellini, “Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification,” *Build. Environ.*, vol. 44, pp. 2510 – 2520, 2009.

[52] O. Ortiz, C. Bonnet, J. C. Bruno, and F. Castells, “Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain,” *Build. Environ.*, vol. 44, no. 3, pp. 584–594, Mar. 2009.

[53] R. M. Cuéllar-Franca and A. Azapagic, “Environmental impacts of the UK residential sector: Life cycle assessment of houses,” *Build. Environ.*, vol. 54, pp. 86–99, Aug. 2012.

[54] S. Suh and G. Huppes, “Missing inventory estimation tool using extended input-output analysis,” *Int. J. Life Cycle Assess.*, vol. 7, no. 3, pp. 134–140, May 2002.

[55] R. H. Crawford, “Validation of a hybrid life-cycle inventory analysis method.,” *J. Environ. Manage.*, vol. 88, no. 3, pp. 496–506, Aug. 2008.

[56] G. J. Treloar, P. E. D. Love, O. O. Faniran, and U. Iyer-Raniga, “A hybrid life cycle assessment method for construction,” *Constr. Manag. Econ.*, vol. 18, no. 1, pp. 5–9, Jan. 2000.

[57] G. Majeau-Bettez, A. H. Strømman, and E. G. Hertwich, “Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues.,” *Environ. Sci. Technol.*, vol. 45, no. 23, pp. 10170–7, Dec. 2011.

[58] B. Müller and L. Schebek, “Input-Output-based Life Cycle Inventory,” *J. Ind. Ecol.*, vol. 17, no. 4, pp. 504–516, Aug. 2013.

[59] G. J. Treloar, “Extracting Embodied Energy Paths from Input–Output Tables: Towards an Input–Output-based Hybrid Energy Analysis Method,” *Econ. Syst. Res.*, vol. 9, no. 4, pp. 375–391, Dec. 1997.

[60] M. Lenzen, “Errors in Conventional and Input-Output—based Life—Cycle Inventories,” *J. Ind. Ecol.*, vol. 4, no. 4, pp. 127–148, Sep. 2000.

[61] U.S. Department of Energy, “EnergyPlus v.8.0,” 2013. [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/.

[62] C. Pina dos Santos and L. Matias, “ITE 50 - Coeficientes de Transmissão Térmica da Envolvente dos Edifícios (Portuguese Reference Heat Transfer Coefficients for the Building Envelope).” Civil Engineering National Laboratory, Lisbon, 2006.

[63] D. Kellenberger, H. Althaus, T. Künniger, M. Lehmann, and N. Jungbluth, “Life Cycle Inventories of Building Products,” *Ecoinvent Rep. n.^{o}7*, no. 7, 2007.

[64] M. Spielmann, C. Bauer, R. Dones, and M. Tuchschmin, “Life Cycle Inventories of Transport Services,” *Ecoinvent Rep. n.^{o}14, v2.0*, no. 14, 2007.

[65] H.-J. Althaus, C. Bauer, G. Doka, R. Frischknecht, N. Jungbluth, T. Nemecek, A. Simons, M. Stucki, J. Sutter, and M. Tuchschmin, “Documentation of changes implemented in ecoinvent Data v2.1 and v2.2,” *Ecoinvent Rep. n.^{o}16*, no. July, 2010.

[66] R. Hischier, B. W. Editors, H. Althaus, C. Bauer, G. Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni, and T. Nemecek, “Implementation of Life Cycle Impact Assessment Methods,” *Ecoinvent Rep. n.^{o}3, v2.2*, no. 3, 2010.

[67] M. C. Peel, B. L. Finlayson, and T. A. Mcmahon, “Updated world map of the Köppen-Geiger climate classification,” pp. 1633–1644, 2007.

[68] A. M. Rodrigues, A. C. Piedade, and A. M. Braga, *Thermal Behavior of Buildings (in Portuguese)*. Edições Orion, 2009, pp. 1–673.

[69] U.S. Department of Energy, “Input Output Reference - The Encyclopedic Reference to EnergyPlus Input and Output,” 2013.

[70] M. Goedkoop and M. Huijbregts, “ReCiPe 2008, A life cycle assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,” 2012.

[71] F. Nemry, A. Uihlein, C. M. Colodel, B. Wittstock, A. Braune, C. Wetzel, I. Hasan, S. Niemeier, Y. Frech, J. Kreißig, and N. Gallon, “Environmental Improvement Potentials of Residential Buildings (IMPRO-Building),” 2008.

List of Figure captions

Fig. 1. Front façade, section and plans of the single-family house

Fig.2. Main processes of the model and system boundaries

Fig. 3. Life-Cycle Impact Assessment for three frame materials: wood frame (W), light steel frame (LS) and lightweight concrete slab (LWC) (per functional unit: 1 square meter of living area over a period of 50 years)

Fig. 4. Environmental and primary energy assessment of the main construction processes and materials: Three frame materials (per functional unit: 1 square meter of living area over a period of 50 years)

Fig. 5. Life-cycle environmental and primary energy assessment of the insulation options: rock wool (RW), extruded polystyrene (XPS) and polyurethane foam (PUR) (0, 40, 80 and 120 mm); per functional unit: 1 square meter of living area over a period of 50 years)

Fig. 6. Life-Cycle Impact Assessment of the insulation materials: rock wool (RW), extruded polystyrene (XPS) and polyurethane foam (PUR) (80 mm); per functional unit: 1 square meter of living area over a period of 50 years)

Table 1

Roof retrofit scenarios

Retrofit Options		**Number of scenarios**
Frame material	Wood (W); Light Steel (LS); Lightweight Concrete (LWC)	3
Thermal Insulation material	Rock wool (RW); Extruded Polystyrene (XPS); Polyurethane Foam (PUR)	3
Insulation level (mm)	40; 80; 120	3
Total number of retrofit scenarios		27 (3 x 3 x 3)

Table 2

Building materials inventory

a) Frame material options

					by Roof Area		by Functional Unit	
	Roof Layers	Material	Units	Thickness (mm)	Total Weight (kg)	Total Volume (m^3)	Weight (kg/m^2)	Volume (m^3/m^2)
Original Roof	Exterior Coating	- ceramic tiles	840		2940	-	35	-
	Existing Wood Frame	- secondary structure[1]	48+26+50	80*40/40*40	949	1.4	11.3	0.016
		- rafters	12	80*160	630	0.9	7.5	0.011
		- trusses	3	160*160	553	0.8	6.6	0.009
	Interior Coating	- wood panels	-	20	176	0.7	2.1	0.008
Wood (W)	Wood Frame	- secondary structure[1]	48+26+50	80*40/40*40	1138	1.6	13.6	0.019
		- rafters	12	80*160	756	1.1	9.0	0.013
		- trusses	3	160*160	664	0.9	7.9	0.011
	Thermal Insulation			(see table b)				
		- vapor control layer	-	2	15	-	0.2	-
	Interior Coating	- gypsum plaster board	-	25	2117	4.4	12	0.05
Light Steel (LS)	Light Steel Frame	- steel battens	32	0.6	108	-	1.3	-
		- main structure	20	2	999	-	11.9	-
		- OSB	-	15	794	1.3	9.5	0.02
	Thermal Insulation			(see table b)				
		- vapor control layer	-	2	15	-	1.2	-
	Interior Coating	- gypsum plaster board	-	25	2117	4.4	12	0.05
Lightweight Concrete (LWC)	Lightweight Concrete Slab	- pre-stressed beams	30	-	2336	0.8	27.8	0.01
		- formwork concrete[3]	538	-	4515	-	53.8	-
		- complementary concrete	-	-	8568	5.4	102	0.06
		- reinforcement steel	-	-	556.4	-	6.6	-
	Thermal Insulation			(see table b)				
		- vapor control layer	-	2	15	-	1.2	-
	Interior Coating	- stucco	-	20	4234	3.4	50	0.04

[1] Secondary Structure: Sticks, Battens & Counter Battens

[2] Extruded Polystyrene

[3] Hollow Concrete

b) Insulation material and thickness options

				by Roof Area		by Functional Unit	
Insulation material	Thickness (mm)	Thermal conductivity (W/(m.K))	Density (kg/m^3)	Total Weight (kg)	Total Volume (m^3)	Weight (kg/m^2)	Volume (m^3/m^2)
Rock wool	40	0.042	130	459	3.5	5.5	0.04
	80			917	7.1	10.9	0.08
	120			1376	10.6	16.4	0.13
Extruded Polystyrene	40	0.037	35	123	3.5	1.5	0.04
	80			247	7.1	2.9	0.08
	120			370	10.6	4.4	0.13

Polyurethane foam	40	0.026	35	123	3.5	1.5	0.04
	80			247	7.1	2.9	0.08
	120			370	10.6	4.4	0.13

Table 3

Building materials: weight and transportation distances

Construction Materials		**Mass** (ton)	**Distance** (km)
Frame material			
Wood		0.9	90
Steel	light steel	1.1	115
	other	0.6	10
Concrete	reinforced	6.9	10
	not reinforced	8.6	10
Other components			
Roof Tile		2.9	50
Rock wool	40 mm	0.5	145
	80 mm	0.9	145
	120 mm	1.4	145
Extruded polystyrene	40 mm	0.1	78
	80 mm	0.3	78
	120 mm	0.4	78
Polyurethane foam	40 mm	0.1	110
	80 mm	0.3	110
	120 mm	0.4	110
Vapor Control Layer		0.01	120
Oriented Strand Board		0.8	90
Gypsum Plaster Board		2.1	58
Stucco		4.2	90

Table 4

Energy requirements for the single-family house (SFH, 279 m^2) and for the 2nd floor (70 m^2) per insulation level and material in kWh/(m^2.year)

	No insulation		Rock Wool (RW)						Extruded Polystyrene (XPS)						Polyurethane foam (PUR)					
Thickness	0		40		80		120		40		80		120		40		80		120	
Zone	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**	SFH	**2nd**
Heating	47.3	**12.6**	44.0	**9.6**	42.8	**8.6**	42.3	**8.1**	43.8	**9.4**	42.6	**8.5**	42.1	**8.0**	43.5	**9.4**	42.5	**8.2**	42.0	**7.8**
Cooling	1.61	**1.03**	1.46	**0.91**	1.41	**0.87**	1.39	**0.86**	1.46	**0.91**	1.41	**0.88**	1.38	**0.86**	1.43	**0.91**	1.39	**0.87**	1.36	**0.85**

Table 5

Inventory of Maintenance

	Activity	Density (kg/L)	Area (m^2)	Volume (L)	Mass including coats (kg)	Material service life (years)	Number of replacements
Roof	plaster board	-	71	-	852	20	2
	interior paint	1.0	71	10	21	20	2
	interior varnish	1.5	64	6	28	10	4

Table 6

Description of the environmental impact categories referred to the ReCiPe method, at midpoint level. [54]

Environmental Impact Category	**Description**	**Unit**
Climate Change (CC)	Climate change is the global warming potential.	kg CO_2 eq
Ozone Depletion (OD)	Ozone depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances.	kg CFC -11 eq
Terrestrial Acidification (TA)	Terrestrial acidification represents the environmental persistence (fate) of acidifying substances causing changes in acid deposition of the soil.	kg SO_2 eq
Freshwater Eutrophication (FE)	Freshwater eutrophication represents the environmental persistence of the emission of nutrients containing P.	kg P eq
Marine Eutrophication (ME)	Marine eutrophication represents the environmental persistence of the emission of nutrients containing N.	kg N eq

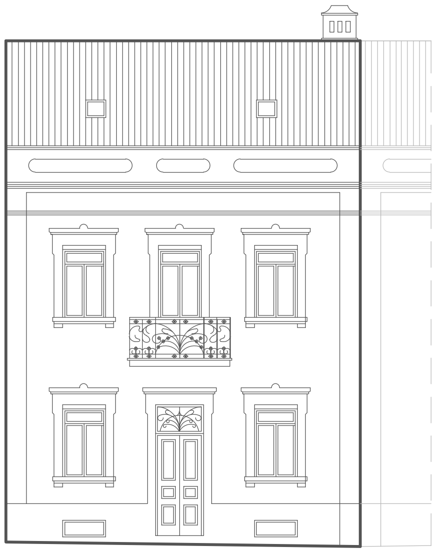
Table 7

Life-Cycle Impact Assessment of three rock wool insulation thicknesses: 40, 80 and 120 mm (per functional unit: 1 m^2 of living area over a period of 50 years)

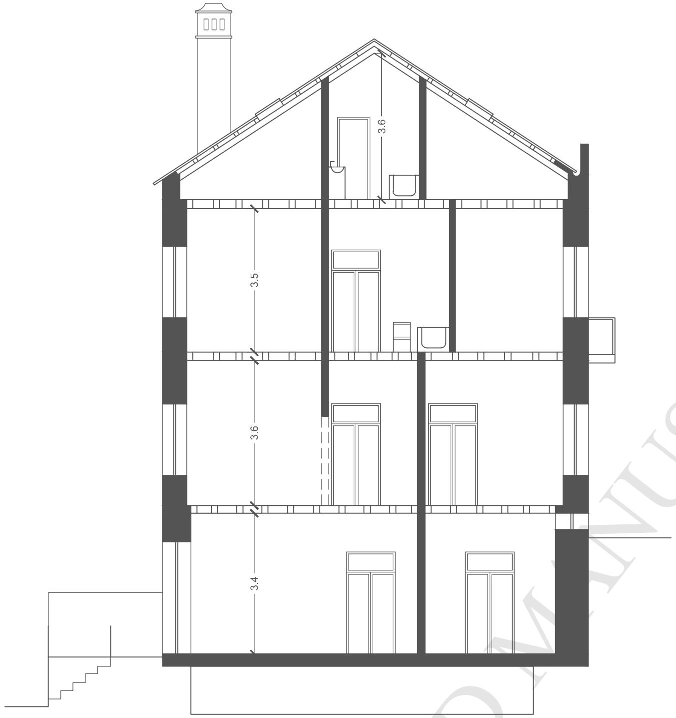
	Climate change (kg CO$_2$ eq)				**Primary energy (MJ)**			
	No insulation	RW40	RW80	RW120	No insulation	RW40	RW80	RW120
Removal	4.3 (2%)	4.3 (2%)	4.3 (2%)	4.3 (2%)	33 (1%)	33 (1%)	33 (1%)	33 (1%)
Construction	50 (21%)	59 (28%)	69 (32%)	78 (36%)	846 (24%)	1035 (32%)	1201 (37%)	1357 (41%)
Operational Energy	160 (69%)	130 (61%)	120 (57%)	115 (53%)	2277 (65%)	1843 (57%)	1705 (52%)	1626 (49%)
Maintenance	19 (8%)	19 (9%)	19 (9%)	19 (9%)	324 (9%)	324 (10%)	324 (10%)	324 (10%)
Total	233	212	211	215	3479	3235	3263	3340

	Terrestrial acidification (kg SO$_2$ eq)				**Ozone depletion (mg CFC-11 eq)**			
	No insulation	RW40	RW80	RW120	No insulation	RW40	RW80	RW120
Removal	0.02 (1%)	0.02 (1%)	0.02 (1%)	0.02 (1%)	0.3 (2%)	0.3 (2%)	0.3 (2%)	0.3 (2%)
Construction	0.23 (14%)	0.28 (20%)	0.34 (24%)	0.39 (28%)	4.9 (27%)	5.7 (34%)	6.4 (38%)	7.1 (41%)
Operational Energy	1.29 (79%)	1.04 (73%)	0.96 (68%)	0.92 (65%)	10.4 (58%)	8.4 (50%)	7.8 (46%)	7.5 (43%)
Maintenance	0.09 (6%)	0.09 (7%)	0.09 (7%)	0.09 (7%)	2.4 (13%)	2.4 (14%)	2.4 (14%)	2.4 (14%)
Total	1.6	1.44	1.41	1.42	18.1	16.8	16.9	17.3

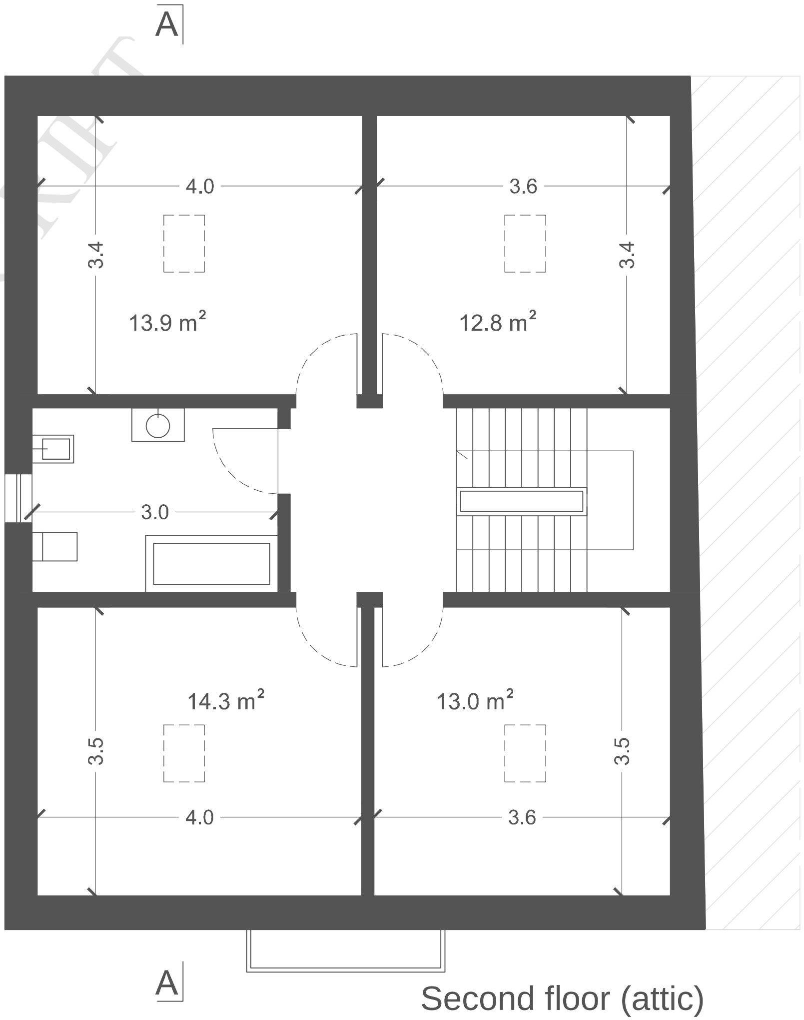
	Freshwater eutrophication (kg P eq)				**Marine eutrophication (kg N eq)**			
	No insulation	RW40	RW80	RW120	No insulation	RW40	RW80	RW120
Removal	0.0004 (0.4%)	0.0004 (0.5%)	0.0004 (1%)	0.0004 (0.5%)	0.001 (3%)	0.001 (3%)	0.001 (3%)	0.001 (3%)
Construction	0.014 (16%)	0.016 (22%)	0.019 (26%)	0.022 (30%)	0.012 (23%)	0.014 (29%)	0.017 (33%)	0.019 (37%)
Operational Energy	0.066 (77%)	0.053 (71%)	0.049 (66%)	0.047 (63%)	0.033 (62%)	0.027 (54%)	0.025 (50%)	0.024 (47%)
Maintenance	0.005 (6%)	0.005 (7%)	0.005 (7%)	0.005 (7%)	0.007 (12%)	0.007 (14%)	0.007 (14%)	0.007 (13%)
Total	0.085	0.075	0.074	0.075	0.054	0.049	0.05	0.05



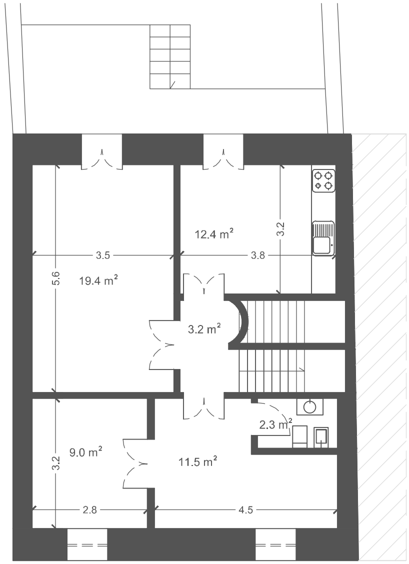
Front façade



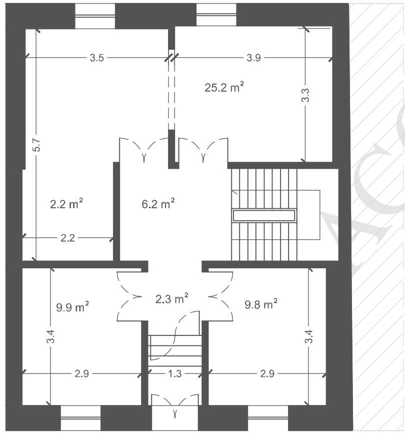
Section A



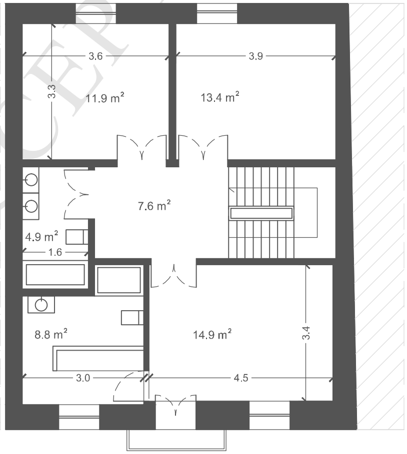
Second floor (attic)



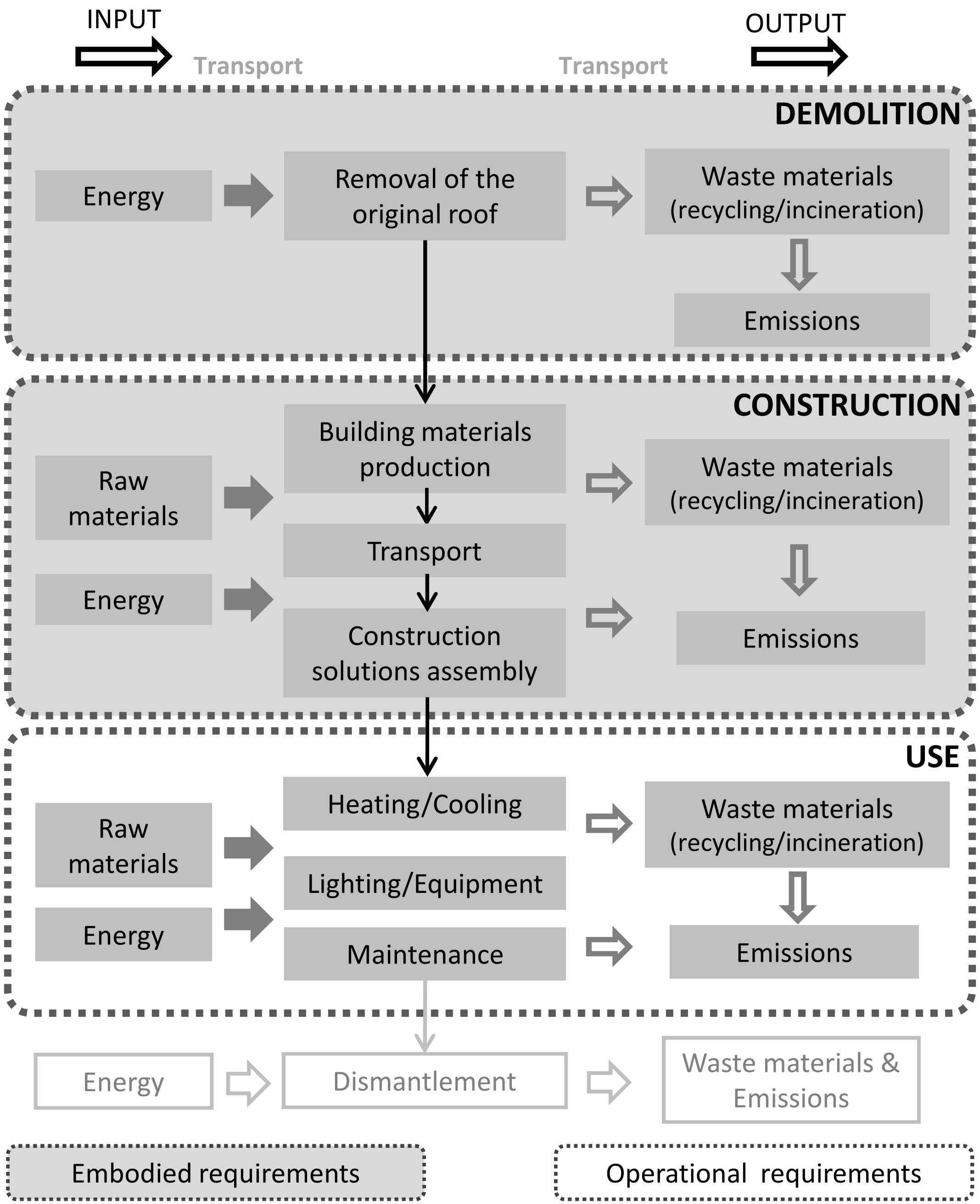
Basement

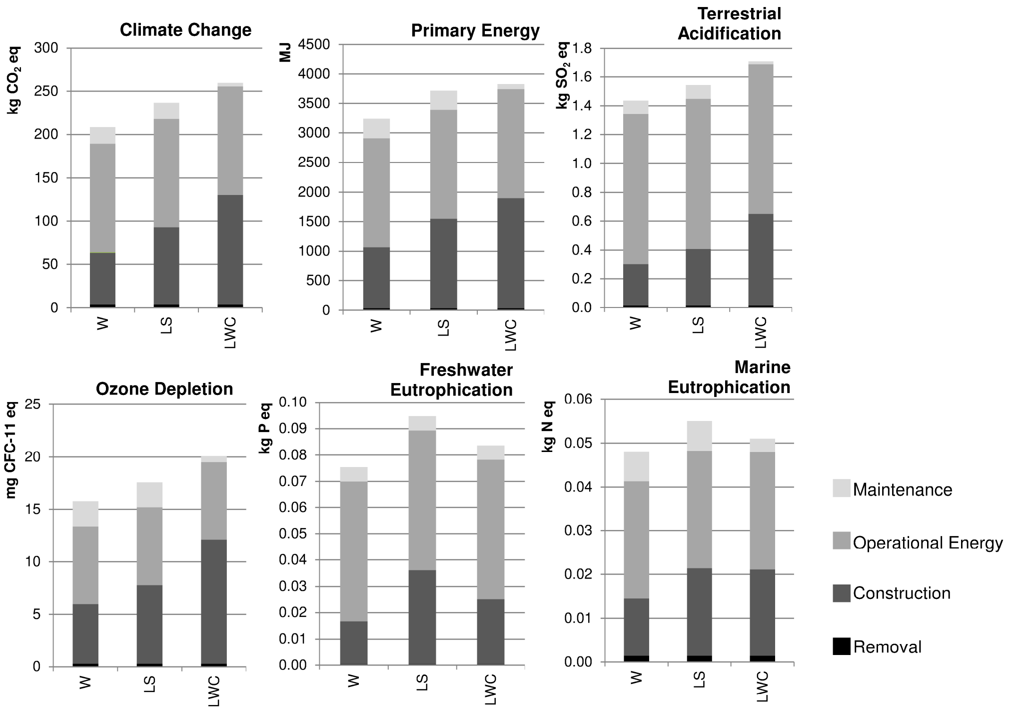


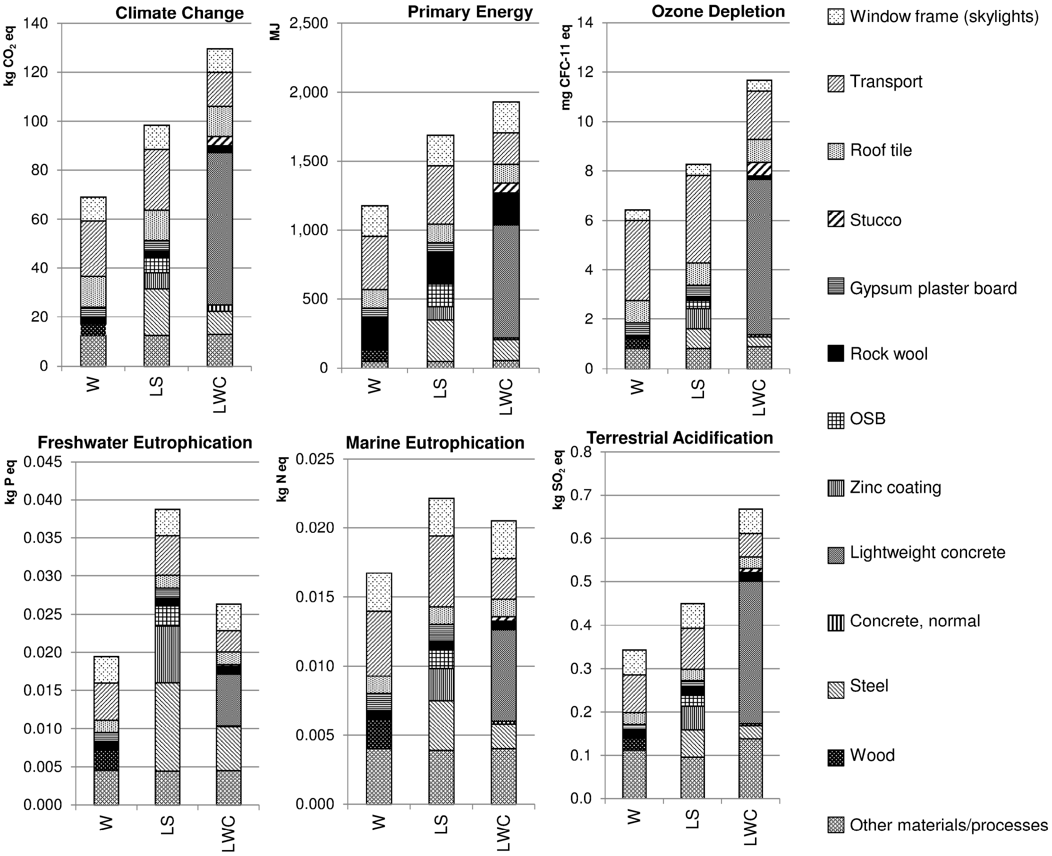
Ground floor

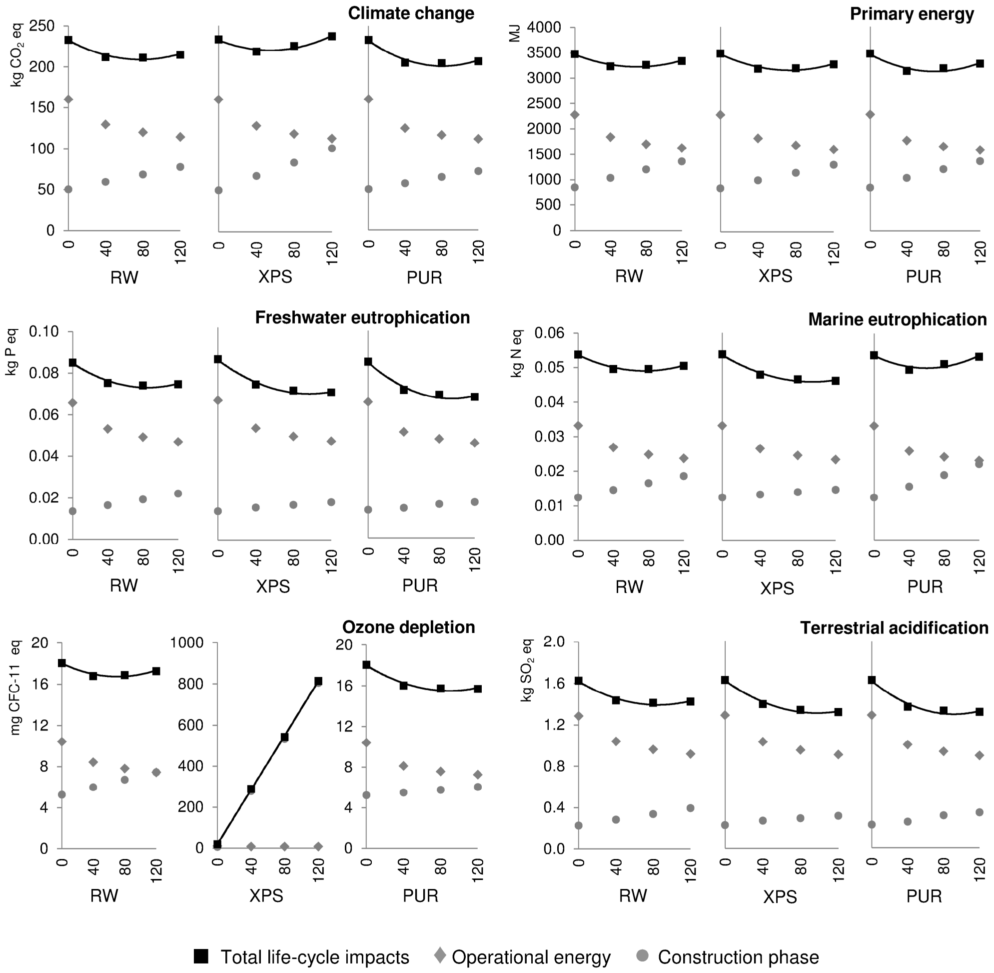


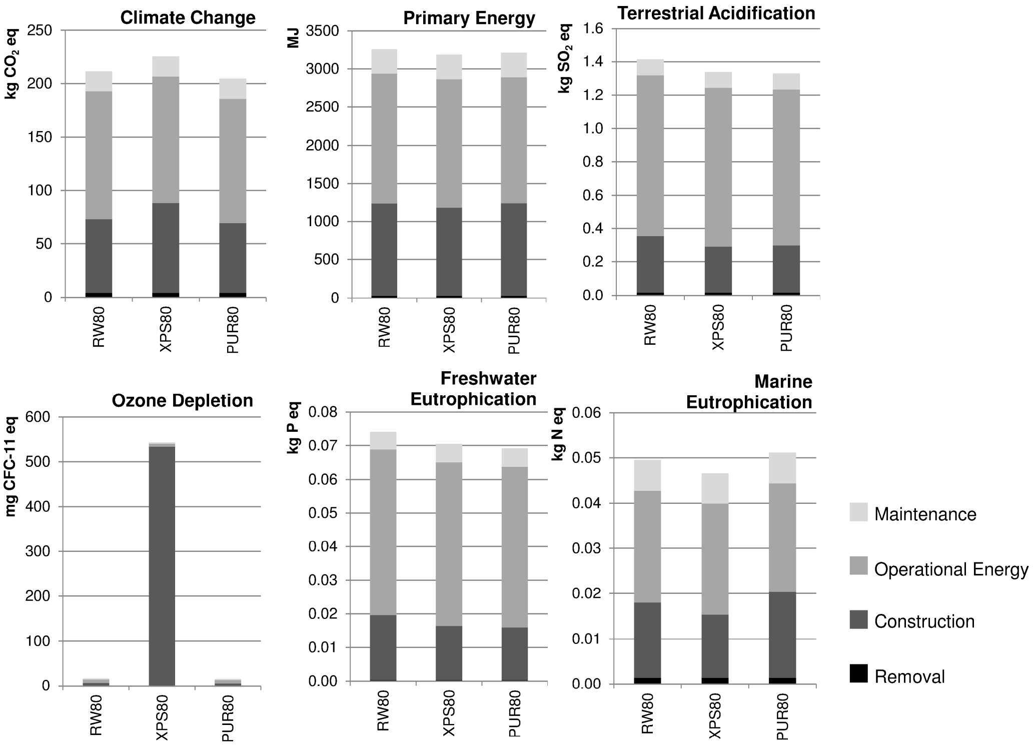
First floor


INPUT
Transport
Transport
OUTPUT
DEMOLITION
Energy
Removal of the original roof
Waste materials (recycling/incineration)
Emissions
CONSTRUCTION
Raw materials
Building materials production
Transport
Energy
Construction solutions assembly
Waste materials (recycling/incineration)
Emissions
USE
Raw materials
Heating/Cooling
Lighting/Equipment
Energy
Maintenance
Waste materials (recycling/incineration)
Emissions
Energy
Dismantlement
Waste materials & Emissions
Embodied requirements
Operational requirements


Climate Change
kg CO₂ eq
300
250
200
150
100
50
0
W
LS
LWC
Primary Energy
MJ
4500
4000
3500
3000
2500
2000
1500
1000
500
0
W
LS
LWC
Terrestrial Acidification
kg SO₂ eq
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
W
LS
LWC
Ozone Depletion
mg CFC-11 eq
25
20
15
10
5
0
W
LS
LWC
Freshwater Eutrophication
kg P eq
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
W
LS
LWC
Marine Eutrophication
kg N eq
0.06
0.05
0.04
0.03
0.02
0.01
0.00
W
LS
LWC
Maintenance
Operational Energy
Construction
Removal


Climate Change
kg CO_2 eq
0
20
40
60
80
100
120
140
Primary Energy
MJ
0
500
1,000
1,500
2,000
2,500
Ozone Depletion
mg CFC-11 eq
0
2
4
6
8
10
12
14
Freshwater Eutrophication
kg P eq
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Marine Eutrophication
kg N eq
0.000
0.005
0.010
0.015
0.020
0.025
Terrestrial Acidification
kg SO_2 eq
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
W
LS
LWC
Window frame (skylights)
Transport
Roof tile
Stucco
Gypsum plaster board
Rock wool
OSB
Zinc coating
Lightweight concrete
Concrete, normal
Steel
Wood
Other materials/processes


Climate change
kg CO$_2$ eq
0
50
100
150
200
250
Primary energy
MJ
0
500
1000
1500
2000
2500
3000
3500
4000
Freshwater eutrophication
kg P eq
0.00
0.02
0.04
0.06
0.08
0.10
Marine eutrophication
kg N eq
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Ozone depletion
mg CFC-11 eq
0
4
8
12
16
20
0
200
400
600
800
1000
Terrestrial acidification
kg SO$_2$ eq
0.0
0.4
0.8
1.2
1.6
2.0
0
40
80
120
RW
XPS
PUR
■ Total life-cycle impacts
♦ Operational energy
● Construction phase


Climate Change
kg CO_2 eq
0
50
100
150
200
250
Primary Energy
MJ
0
500
1000
1500
2000
2500
3000
3500
Terrestrial Acidification
kg SO_2 eq
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Ozone Depletion
mg CFC-11 eq
0
100
200
300
400
500
600
Freshwater Eutrophication
kg P eq
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Marine Eutrophication
kg N eq
0.00
0.01
0.02
0.03
0.04
0.05
0.06
RW80
XPS80
PUR80
Maintenance
Operational Energy
Construction
Removal

Highlights

Integrated Life-Cycle Assessment and thermal dynamic simulation

Thermal insulation optimal thickness minimizing LC environmental impacts

Tipping point for LC impacts: 40-80 mm of insulation in Mediterranean climate

There is no marginal LC benefit gained beyond 80 mm of insulation