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

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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 was 1 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 60–70% 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.

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

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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 Fig. 1.

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. Refs. [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