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Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions

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ABSTRACT

This paper describes the implementation of an integrated cost optimality and environmental assessment involving alternative energy efficiency retrofit packages for a building that dates from the beginning of the 20th century. A building typical of the building stock in the centre of Coimbra (located in the central region of Portugal and recently classified as a UNESCO World Heritage Site) was used to illustrate the methodology presented. The results were also analysed for the same building in two other locations. A life-cycle (LC) model was implemented to assess different energy efficiency measures for an apartment. The economic assessment complied with European Directive 2010/31/EU. The results show that the lowest life-cycle environmental impacts were obtained for insulation thicknesses between 50 and 120 mm, which are also cost-optimal. It is also shown that insulation thicknesses of more than 80 mm do not improve energy efficiency or global cost reduction. This paper shows that, even though historic buildings in Portugal do not have to comply with building energy codes, significant energy savings can be achieved for them without changing their historic character. It was also concluded that economic and environmental costs can both be minimised by choosing the most suitable energy efficiency retrofit measures.

1. Introduction

Buildings are an important source of environmental impacts, not only during the construction phase but also the due to the long term impact of energy use over their life span. The residential and commercial sectors in Portugal accounted for 18% and 12%, respectively, of the total final energy use in 2010 [1]. Moreover, it has been claimed that the use stage is the most costly for energy use and environmental impacts over a building's life-cycle [2–4]. However, as buildings become nearly zero energy (NZEBs), the balance shifts and the embodied phase become the most costly [5]. Moreover, user behaviour is not considered in most life-cycle and cost optimality studies.

Given their long life span, it is essential that buildings meet energy performance requirements in line with the local climate when major retrofit works are planned. European Directive 2010/31/EU (EPBD) [6] requires all EU state-members to establish a comparative methodological framework for the calculation of cost optimality levels for the energy performance requirements of buildings. However, buildings in World Heritage sites are not obliged to comply with these requirements since doing so may affect their architectural and historic value [7]. About 25% of the building stock in Europe was built in the middle of the 20th century. Most of those buildings have an architectural, cultural or even historic value and represent the unique character and identity of European cities; however, they are among the largest contributors to the poor energy performance of the building sector.

Various strategies can promote the fulfilment of sustainability criteria to achieve an optimum balance between return on investment, energy savings and minimisation of environmental impacts over a building's life span. In 2012, Delegated Regulation (EU) No. 244 [8] (supplementing the EPDB) laid down rules to compare energy efficiency measures using a cost optimality approach. This methodological framework is based on the primary energy performance and cost of each measure, looking at both the macroeconomic perspective (looking at the costs and benefits of energy efficiency investments for the society as a whole) or a strictly financial viewpoint (looking only at the investment itself) [9]. From the macroeconomic perspective, there are assumed to be additional costs related to greenhouse gas emissions. However, the environmental assessment aspect of our methodology is limited and does not represent a life-cycle perspective. Life-cycle assessment (LCA) addresses the potential environmental life-cycle (LC)

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Nomenclature

List of symbols and acronyms

AC	air conditioner
ADENE	Portuguese national agency for energy
CED	cumulative energy demand
CO_2	carbon dioxide
DHW	domestic hot water
EH	electric heater
EPBD	energy performance of buildings directive
EPS	expanded polystyrene
ERSE	Portuguese energy regulator
FIN	financial perspective
GB	gas boiler
GHG	greenhouse gas emissions
HDD	heating degree days
LC	life-cycle
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
MAC	macroeconomic perspective
NRPE	non-renewable primary energy
RPH	air changes per hour

impacts of products and systems (ISO 14040:2006) [10]. It can identify the critical components of the environmental performance of existing buildings and evaluate the potential benefit of different energy efficiency retrofit packages (set of measures applied to the building).

LCA methodology has been applied to assess the environmental impacts of building retrofit actions [11–16]. This approach has also been applied to redesign the concept of NZEB with the aim of reaching an electricity target of net zero energy assuming that these type of buildings can heavily be influenced by the energy carrier weighting factors chosen [17]. Moreover, extended input–output models have also been applied in environmental assessment of buildings retrofit [18,19]. For instance, Cellura et al. [19] developed an energy and environmental extended input output model, combined with life cycle assessment, to analyse the role of the building sector in the reduction of Italian energy consumption and CO_2 emissions.

The environmental and economic assessments have mainly been applied to products/services (e.g. energy systems, materials, etc. [20–22]) and recently also to buildings. Several studies have carried out an economic assessment of energy efficiency retrofit measures, but very few include an environmental assessment of existing buildings and none do so for historic buildings. Lollini et al. [23] studied the optimisation of opaque components regarding their energy, environmental and economic impacts. Anastaselos et al. [24] created a tool to perform an integrated energy, economic and environmental evaluation of thermal insulation solutions. Kim et al. [25] assessed the carbon emissions and related costs of apartment buildings, and Kneifel [26] assessed energy efficiency measures in new commercial buildings. In the Portuguese context, Silvestre et al. [27] performed an environmental, energy and economic assessment of building assemblies for new residential buildings.

Thermal dynamic simulation has been included in LCA studies to assess the potential contribution of the occupants' preferences not only to the operational energy use of buildings, but also to trade-offs between embodied and operational energy [28]. The occupancy level of a building influences the operational energy use and the contribution of the different LC stages to the overall life span of a building [28,29]. De Meester et al. [30] and Azar and Menassa [31] emphasised the need to properly take occupancy into account at the design stage, to arrive at more reliable building energy performance estimates.

This article implements an integrated cost optimality and environmental assessment by combining alternative energy retrofit packages that can also be used in historic buildings. A building that represents the building stock in the old part of Coimbra (a city in the central region of Portugal and recently classified as a UNESCO World Heritage Site) was assessed. The same building is analysed as if it was in two other places (in the north and south of Portugal) in order to encompass different climate conditions. These two places represent the mildest (south) and coldest (north) winters in Portugal.

Even though historic buildings do not have to comply with minimum energy performance requirements, we intend to show the importance of the energy retrofitting of old constructions by looking at the potential energy savings and environmental impact reduction in cost-effective terms, without affecting their historical and architectural value. This article sets out to identify cost-optimal solutions based on an occupancy pattern and to assess whether these solutions also ensure low LC environmental impacts. Thermal dynamic simulation results were compared to seasonal steady-state method based on the Portuguese regulation on the thermal performance of buildings [32]. This comparison allows a coefficient of reduction to be applied to the seasonal method results for a specific occupancy pattern (in the thermal dynamic simulation calculations). A sensitivity analysis was also performed on the insulation cost, energy price trends and discount rate (for the financial perspective), to assess the influence on heating energy needs.

Section 2 describes the methodology. The building's characteristics, the retrofit packages, and the economic and environmental inventories are described in Section 3. Section 4 presents the cost and environmental results, as well as the sensitivity analyses. Finally, Section 5 sets out the conclusions.

2. Methodology

The methodology includes the selection of the main energy efficiency retrofit packages. The energy retrofit packages combine thermal insulation options for the roof (7), exterior walls (7) and floor (7), solutions for windows (including an option of reinforcement with second window frames) (2) and the use of alternative heating (3) and domestic hot water (DHW) systems (2). The parametric assessment resulted in 4116 energy retrofit packages calculated for each location (12,348 in total). Each package was calculated for three different locations, HDD (Heating Degree Days) 987, 1304 and 1924. In conjunction with the average U-value, HDD provides a simple metric for roughly quantifying the amount of energy required to heat this historic building over a year, in these three locations.

A life-cycle model was developed to assess nine packages selected for each location (within the cost-optimal range) and alternative insulation materials, aiming to identify optimum thickness levels in terms of non-renewable primary energy (NRPE) and greenhouse gas emissions (GHG). A life span of 30 years was assumed. Subsections 2.1–2.3 describe the methodology for energy, cost optimality and environmental impact assessments.