Energy and Buildings 140 (2017) 388–398

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis

Carla Rodrigues*, Fausto Freire

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

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form
30 December 2016
Accepted 28 January 2017
Available online 1 February 2017

Keywords:
Building retrofit
Environmental impacts
Life-cycle assessment (LCA)
Life-cycle costing (LCC)
Occupancy patterns

ABSTRACT

Building retrofit can lead to important savings in operating cost and environmental impacts; however, the actual savings depend on future house occupancy, which is generally not taken into account. The goal of this article is to carry out an integrated (cost, environmental and energy) life-cycle (LC) assessment of alternative roof and exterior-wall insulation retrofit strategies for a single-family house addressing occupancy. Alternative scenarios were defined by type of use (residential and office) and occupancy level (low and high), set-points and family size. LC impacts were calculated for five environmental categories and non-renewable primary energy showing that an insulation level threshold (where total LC impacts are minimized) can be identified for exterior-wall retrofit (60–70 mm for all scenarios) and roof retrofit (90–100 mm for low residential occupancy; 80–90 mm for high residential occupancy and office use). Recommendations can be provided to enhance the retrofit performance of historic buildings in Southern Europe, depending on their use and occupancy level. Highly-insulated retrofit is more beneficial for high occupancy levels with higher thermal comfort conditions. No benefit is derived from incorporating insulation for lower comfort conditions. Interior insulation on exterior walls presents higher savings than exterior insulation.

1. Introduction

The need for retrofitting existing buildings has increased in European city centers. The building stock is getting old and several neighborhoods have been abandoned over the years. Both financial and technical efforts are being made by the European Union to gentrify those old and abandoned neighborhoods. Existing buildings in historic European city centers need to be retrofitted for contemporary uses whilst retaining their historic value. Major retrofits are costly and require important quantities of material and products, but different strategies can be adopted to achieve an optimum balance between initial investment, energy savings and minimization of environmental impacts during the building life-cycle (LC). Building retrofits can lead to important savings in operating cost and environmental impacts; however, the actual savings depend on future house occupancy, which has not generally been assessed or taken into account.

The occupancy level of a building influences the operational energy use and the contribution of the different phases to the overall LC of a building [1–3]. De Meester et al. [4] and Azar and Menassa [5] emphasized the need to account accurately for occupancy during the design phase in order to provide more reliable building energy performance estimates. Monteiro et al. [6] addressed the occupant's habits in an LC perspective aimed at framing resident occupancy and heating/cooling habits compared to current standards that assume a permanent occupancy. However, occupancy has not been addressed in the LCA literature of building retrofits. Additionally, the use of thermal dynamic simulation to assess the influence of occupancy has rarely been used in life-cycle assessment (LCA). The integration of thermal dynamic simulation in LCA studies addresses the potential contribution of occupancy not only in the operational energy of buildings, but also in the assessment of trades-offs between embodied and operational energy [2,3,11]. Buildings located in Southern European climate have seldom been addressed in LCA studies, and particularly in the Portuguese context, except for a few LC studies that were mainly focused on new construction [6–10]. Rodrigues and Freire [3] concluded that for the roof retrofit of a single family house in Portugal, the reduction in operational energy due to an additional thermal insulation can be low relative to the increase in the embodied impacts. None of these studies have included costs in the overall assessment of retrofit strategies.

The economic feasibility of retrofit strategies is typically calculated for the investment in a specific solution, seeking reduced

---

* Corresponding author.
E-mail address: carla.rodrigues@dem.uc.pt (C. Rodrigues).

http://dx.doi.org/10.1016/j.enbuild.2017.01.084
0378-7788/

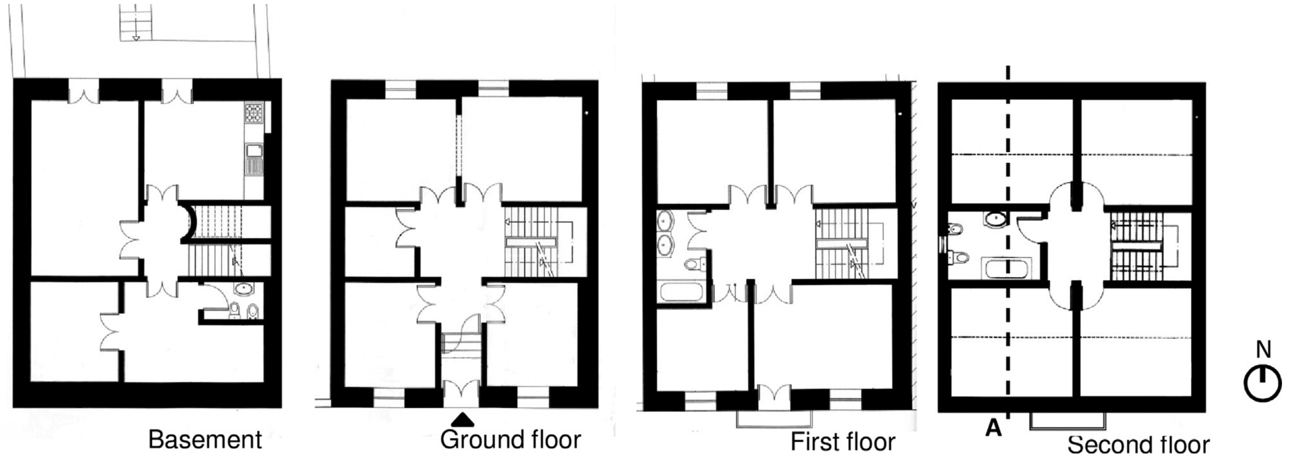

Fig. 1. Single-family house plans.

Source: Adapted from Rodrigues and Freire [3,11].

running costs (e.g., operational and energy savings costs). Different methods have been applied in the literature to assess LC costing of building retrofits. Nemry et al. [12] has assessed the environmental benefits and costs of the energy efficiency options of existing buildings. The quantification of the overall costs of each improvement option was calculated using net present value (NPV) and internal rate of return (IRR). Another approach addressed in the literature [13] defined indicators for the economic assessment of external-wall insulation of the building, such as: net present value, profitability indicator and payback period (DPP). Recently Mata et al. [14] investigated how the cost-effectiveness of different energy-saving strategies in buildings was dependent upon energy prices and discount rates, using the equivalent annual cost (EAC) method that annualizes all costs during the building life-cycle.

Few studies have incorporated an environmental and cost assessment of energy efficiency retrofit strategies and fewer still regarding existing or historic buildings [15]. Lollini et al. [16] studied the optimization of opaque components regarding energy, environmental and economic impacts. Anastaselos et al. [17] created a tool to perform an integrated energy, economic and environmental evaluation of thermal insulation solutions. To effectively manage the reduction of LC environmental impacts, Ibn-Mohammed et al. [18] linked costs with both operational and embodied emissions to produce optimal decisions in the selection of retrofit strategies. Tadeu et al. [15] discussed the implementation of an integrated cost optimality and environmental assessment for the retrofit of an early 20th century multi-family building, and concluded that the lowest LC impacts were obtained for insulation thicknesses between 50 and 120 mm, which are also cost-optimal.

In summary, the following gaps were identified. No studies in the literature evaluated the environmental impacts and costs of retrofitting historic buildings from the late 1800s to the early 1900s. Additionally, alternative occupancy patterns have not been examined for residential historic buildings adapted to alternative uses in South European climates. These types of buildings have very specific characteristics and construction systems (such as load-bearing stone masonry walls and wood-frame roofs), which lead to very different performances compared to conventional brick or concrete-wall buildings (from mid- or late-1990s). The main goal of this article is to present an integrated cost and environmental LCA of alternative retrofit strategies for a single-family house from the early 1900s located in the city center of Coimbra, Portugal, as representative of typical retrofit strategies for South European climate buildings. This article builds on a previous environmental LCA [3,11] focused on identifying optimal insulation thickness levels minimizing impacts for low residential occupancy levels. This article presents a comprehensive complementary analysis of different retrofit strategies (roof and exterior walls) combining alternative insulation levels and occupancy patterns to identify opportunities to minimize life-cycle environmental and cost impacts. Moreover, this article investigates how occupancy influences the economic and environmental performance of building retrofit strategies and supports decision-making. The main innovation of the approach implemented in this article lies on the integration of occupancy variables in the environmental and cost LC assessment of building retrofits.

2. Integrated cost and environmental life-cycle analysis

An integrated environmental, energy and cost LC analysis was implemented to assess alternative retrofit strategies. A LC model was implemented for the roof and exterior-wall retrofit of a single-family house from the beginning of the 20th century (early 1900s) assuming different occupancy patterns. The single-family home is a semi-detached house organized on four floors, with a finished attic on the upper floor [3]. The plans of the house are presented in Fig. 1. The main features of both buildings are load-bearing stone masonry walls (average thickness 50 cm), single-glazed wood windows and a traditional wooden-frame roof. The house is located close by a World Heritage protected site, which means there are several imposed constraints on the building stock, such as volume, façade height, materials and design, in order to preserve its historic and cultural value.

Three occupancy scenarios were defined combining alternative roof and exterior-wall insulation levels and occupancy patterns (uses and occupancy schedules). The occupancy scenarios are defined by type of use (residential and office) and residential level of occupancy (low and high). Details of each scenario and the various insulation levels assessed are presented in Table 1. The base-case occupancy scenario was defined by a four-person family with low occupancy, and set-points fixed at 20 °C (heating) and 25 °C (cooling). A sensitivity analysis was also performed to assess the influence of heating and cooling set-points, and family size, on the environmental impacts and costs of alternative retrofit strategies.

The exterior-wall retrofit incorporates an additional thermal insulation layer on the interior or exterior surface (ETICS) of the wall, as well as new interior and exterior finishes (stucco and