Carla Abreu Rodrigues

LIFE-CYCLE ENVIRONMENTAL AND COST ASSESSMENT OF BUILDING RETROFITS

EVALUATING CONVENTIONAL AND STREAMLINED APPROACHES

PhD thesis in Sustainable Energy Systems, supervised by Professor Fausto Miguel Cereja Seixas Freire,
presented to the Department of Mechanical Engineering, Faculty of Sciences and Technology, University of Coimbra

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UNIVERSIDADE DE COIMBRA

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Abstract

Building retrofits can promote a significant reduction in the environmental load and operating costs of the European building stock. In Portugal, there are two million households needing refurbishment (34% of the Portuguese building stock). Most of those buildings are among the largest contributors to the poor energy performance of the building sector. However, given their long life-span, it is essential that designers and developers are encouraged to identify effective strategies that reduce the overall burden of the building in life-cycle (LC) perspective.

Life-cycle approaches have been extensively applied to analyze building environmental impacts and costs. However, they are time consuming and resource-intensive to implement, preventing a more widespread use. Additionally, they are usually performed in late design stages when significant reduction in total life-cycle impacts is costly to achieve.

The main goal of this PhD thesis is to explore both conventional and streamlined LCA and LCCA approaches to identify the most appropriate strategies to improve the LC environmental and economic sustainability of building retrofits for family households and office buildings in South European climates. An integrated cost and environmental conventional LC approach combined with thermal dynamic simulation was developed and implemented to different building retrofit projects (a single-family house, an apartment, and an office building). Final and primary energy, environmental impacts and costs are assessed and trade-offs identified. LCCA is performed using the equivalent annual cost method to calculate the net annual savings. A sensitivity analysis addressing occupancy is performed to increase the robustness of the results.

A novel approach was developed to streamline LCA and LCCA for building retrofits that both accommodates varying amounts (and quality) of information on retrofit design and provides both estimates and uncertainty in the estimate for both environmental and economic performance. A framework was developed that fully integrates a streamlined embodied LCA, statistical-based operational energy and cost models. The method comprises the application of structured under-specification, probabilistic triage, and guided sequential specification.

Drawing on the results, some recommendations can be provided to enhance the environmental performance of building retrofits in historic city centers with load-bearing stone wall systems in South European buildings from the late 1800s to the early 1900s, pointing to a roof and exterior-wall insulation thickness threshold (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off) depending on the type of house and occupancy. Highly-insulated retrofit strategies are more beneficial for high occupancy levels with higher thermal comfort conditions. Exterior-wall with 40 mm insulation presents the highest marginal savings and the lowest environmental impacts. There are no benefits in roof insulation of more than 80 mm for all types of occupancy. A sensitivity analysis performed on a set of building cases concluded that highly influential design attributes should be defined early in the design process as it may leverage further design decisions. Occupancy-related parameters have been identified as highly influential on the total LC impacts of buildings retrofit irrespective of location, type of house and wall-system.

Three retrofit strategies were assessed to compare the recommendations derived from the streamlined approach with the previous conventional LCA studies. The model identified the same preferred options as conventional LCA with only five to eight building design attributes specified. The streamlined approach allows the designers either to identify an environmentally and economically superior design or to evaluate the design choices by increasing specification efficiently until the level of resolution in the result is sufficient to make decisions. An equally important aspect is to enhance the potential of this approach for widespread use of LCA and LCCA as decision-making tools in current building design practice.

Keywords: Building retrofits, decision-making, life-cycle assessment, life-cycle cost assessment, occupancy patterns, probabilistic triage, streamlining, uncertainty

Resumo

A reabilitação de edifícios pode contribuir para potenciar uma redução significativa do impacte ambiental e económico do sector imobiliário na Europa. Em Portugal, existem dois milhões de habitações a necessitar de reabilitação (34% do parque imobiliário). Em particular, os edifícios históricos são aqueles que mais contribuem para o mau desempenho energético no sector da construção. Dada a sua longa vida útil, é essencial adotar estratégias eficazes que permitam reduzir o impacte global de ciclo de vida (CV) do edifício. As diversas abordagens de avaliação de CV (ACV) têm sido amplamente aplicadas nas análises dos impactes ambientais e dos custos de edifícios. No entanto, as abordagens convencionais requerem demasiado tempo e dados para a respetiva implementação, dificultando o seu uso generalizado pelos vários intervenientes no projeto. Além disso, estas análises são geralmente realizadas nas fases finais do projeto quando o potencial de redução significativa dos impactes totais de CV é já muito limitado.

O principal objetivo desta tese é explorar as abordagens tradicionais e simplificadas[1] de ACV e análise de custo de CV (ACCV), identificando as estratégias mais eficazes para a promoção da sustentabilidade ambiental e económica de CV aquando da reabilitação de edifícios em climas do sul da Europa. Implementou-se uma abordagem integrada de CV ambiental e económica, combinada com simulação térmica dinâmica, para diferentes soluções na reabilitação de edifícios (uma habitação unifamiliar, um apartamento, e um edifício de escritórios). Analisaram-se a energia final e primária, os impactes ambientais, e os custos, e foram identificados os potenciais compromissos ("trade-offs") entre impactes incorporados (demolição, construção e manutenção) e operacionais. Aplicou-se a ACCV usando o método de custo anual equivalente, para calcular as

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[1] O termo "abordagem simplificada" (tradução do termo inglês "streamlined") aplica-se no sentido de racionalizar ou agilizar o processo de avaliação, e também de melhorar a eficácia através da simplificação.

poupanças anuais líquidas. Foi ainda incorporada uma análise de sensibilidade considerando diferentes padrões de ocupação, a fim de aumentar a credibilidade dos resultados.

Desenvolveu-se uma nova abordagem simplificada de ACV e ACCV para a reabilitação de edifícios, considerando quantidades (e qualidade) variáveis de informação e incorporando incerteza no cálculo de resultados. Este método inclui a aplicação de uma base de dados, estruturada e hierarquizada com vários níveis de especificação, triagem probabilística e especificação sequencial guiada. O modelo desenvolvido integra uma análise de impactes incorporados, de energia operacional baseada em modelos estatísticos e de custos.

Com base nos resultados, é possível fornecer determinadas recomendações para melhorar o desempenho ambiental e económico na reabilitação de edifícios (especificamente nos sistemas de parede simples de pedra, construídos entre finais de 1800 e inícios de 1900, e localizados em centros históricos urbanos no sul da Europa). Essas recomendações apontam para níveis ótimos de espessuras de isolamento para coberturas e paredes exteriores nos quais os impactes totais de CV são minimizados, dependendo do tipo de edifício e padrão de ocupação. As soluções que utilizam maiores espessuras de isolamento são mais benéficas para níveis de ocupação elevados e condições de maior conforto térmico. Paredes exteriores com isolamento de 40 mm apresentam maiores poupanças marginais e menores impactes ambientais. O isolamento da cobertura não apresenta benefícios ambientais ou económicos para espessuras superiores a 80 mm, independentemente do tipo de ocupação. A análise de sensibilidade concluiu que os parâmetros com maior influência no desempenho ambiental e económico de CV estão relacionados com a ocupação, independentemente da localização, tipo de edifício ou sistema construtivo.

Foram analisadas três soluções para comparar as recomendações fornecidas pelo modelo simplificado e pela abordagem de ACV convencional. O modelo simplificado identificou as mesmas soluções preferenciais especificando apenas cinco a oito parâmetros do projeto. A abordagem simplificada permite que os projetistas possam identificar as melhores soluções em termos ambientais e económicos, e ainda avaliar opções através de uma especificação progressiva e eficiente, de forma a reduzir a incerteza dos resultados para tomar decisões. Esta tese demostra ainda o potencial desta abordagem na difusão do uso de ACV e ACCV como ferramenta para tomadas de decisão na prática corrente da reabilitação de edifícios.

Palavras-chave: abordagem simplificada, avaliação de ciclo de vida, avaliação de custo de ciclo de vida, incerteza, padrões de ocupação, reabilitação de edifícios, tomada de decisão, triagem probabilística.

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Acronyms

AAM: Attribute to activity model

CC: Climate change

CED: Cumulative energy demand

CI: Comparison indicator

CO_2: Carbon dioxide

EAC: Equivalent annual cost

EPBD: Energy Performance of Buildings Directive

EPS: Expanded polystyrene

EU: European Union

EW: Exterior wall

FE: Freshwater eutrophication

FU: Functional unit

GHG: Greenhouse gases

HDD: Heating degree days

HFC: Hydrofluorocarbon

HVAC: Heating, ventilation and air-conditioning

ICB: Insulation cork board

IPCC: Intergovernmental Panel on Climate Change

ISO: International Standardization Organization

LC: Life-cycle

LCA: Life-cycle assessment

LCCA: Life-cycle cost assessment

LEED: Leadership in Energy and Environmental Design

LCI: Life-cycle inventory

LCIA: Life-cycle impact assessment

ME: Marine eutrophication

NPV: Net present value

NRPE: Non-renewable primary energy

OD: Ozone depletion

PUR: Polyurethane foam

RW: Rock wool

SD: Standard deviation

TA: Terrestrial acidification

XPS: Extruded polystyrene

1 Introduction

1.1 Background and motivation

Building retrofits can play an important role not only in promoting important savings in operating costs but also in reducing the environmental load of building stock (European Comission 2012a). The European Commission established a long-term objective of decreasing the CO_2-emission levels for the building sector by 88-91%, compared to 1990 levels, to be implemented by 2050. In order to achieve this target, which is also a prerequisite for meeting other EU economic and climate goals, the EU especially needs to tackle its existing building stock and reduce its energy use in the long term (European Comission 2011).

Existing buildings, especially the older ones, are one of the biggest contributors to the high level of energy consumption in the residential sector. Almost 70% of the buildings in Portugal were built before 1990 (Statistics Portugal 2011), when the first Portuguese regulation regarding the energy performance of buildings was published. In 2010, 35% of the buildings in Portugal are in the need of major retrofit works and about 3% presented a high level of degradation (Statistics Portugal 2011). Moreover, almost 70% of buildings constructed before 1919 need retrofit works.

Many of those buildings have an architectural, cultural or even historic value and represent a unique heritage, while they are among the largest contributors to the poor energy performance of the building sector. However, buildings under historic or architectural protection are not obliged to comply with minimum energy requirements since retrofits may affect their architectural and historic value (United Nations Environment Programme (UNEP) Sustainable Buildings and Construction Initiative – SBC 2007; Mazzarella 2014). However, given their long-life span, it is essential to encourage designers and developers to identify effective strategies for all building types. To influence those decisions in a manner that reduces the overall burden of the building it is important take a life-cycle (LC) perspective. Appropriate techniques are needed to fulfill current demand for comfort and high standards of energy, as well as environmental targets.

Building standards, materials and solutions have changed in the last decades. Recent building codes or energy efficiency standards have been mainly focused in the use phase of a building in order to achieve very low or nearly zero energy buildings. In consequence, the embodied phase starts to play an important role when considering a LC perspective. A wider approach regarding different environmental issues is needed to assess the whole building performance during its life span. Life-cycle assessment (LCA) is a widely used technique to evaluate quantitatively the environmental impacts of a building to identify the hot spots and improvement opportunities for each phase of its life-cycle (Rebitzer et al. 2004).

Major building retrofits can be costly and different strategies can be used to promote the fulfillment of sustainability criteria to achieve an optimum balance between initial investments, energy cost savings and minimization of environmental impacts during the building life-cycle. In 2012, the Delegate Regulation (EU) nº 244 (European Comission 2012b) (complementary to the Energy Performance of Buildings Directive (EPBD (recast) 2010)) was published defining rules to compare energy efficiency strategies using a cost optimality approach. However, this methodological framework stills lacks a LC perspective and does not promote an integrated environmental and cost assessment. Life-cycle cost assessment (LCCA) has also been widely used to characterize the cost-effectiveness of energy-saving retrofit strategies (Nemry et al. 2010; Dylewski and Adamczyk 2012; Mata et al. 2015). It can be applied to compare different retrofit strategies by calculating the investment of a specific solution, and the associated changes in the operating costs such as reduced running costs (including operational costs and costs of energy saved).

However, one issue preventing a more widespread use of conventional LCA and LCCA is that both are time-consuming and resource-intensive to implement. Because of these challenges, LCA and LCCA are usually performed in late design stages where there is little opportunity to improve the design (Schlueter and Thesseling 2009). Therefore, LCA approaches have not been conducted in current building design practice unless needed for environmental building certification schemes, such as LEED (Leadership in Energy and Environmental Design) (U.S. Green Building Council 2016). Impacting early-stage decisions will require streamlined methods that can accommodate limited and often uncertain information. Streamlined approaches can promote robust results in an efficient and effective manner.

This thesis explores both conventional and streamlined LCA and LCCA approaches to identify most appropriate strategies to improve the life-cycle environmental and economic sustainability of building retrofits, for family households and office buildings in South European climates.

1.2 Literature review

This PhD thesis addresses different topics in the scope of LCA and LCCA of building retrofit, namely conventional and streamlined LCA and LCCA approaches. The following sections present a brief state of the art for each topic addressed. Additional literature review on each topic will be further discussed in each chapter of the thesis.

1.2.1 LCA and LCCA of buildings and building retrofits

The first LC studies of buildings focused on energy, followed by greenhouse gas (GHG) analysis. Cole and Kernan (1996) performed a life-cycle energy analysis on an office building in Canada and Adalberth (1997) on a single-family house in Sweden. Blanchard and Reppe (1998) introduced GHG emissions and costs to the LCA of a single-family house in Michigan throughout pre-use (materials production and construction), use (operational use and maintenance) and demolition phases. Later, Peuportier (2001) integrated for the first time thermal dynamic simulation with LCA. LCA was applied to the comparative evaluation of three single-family houses in France: a standard construction made of concrete blocks, a solar house made of stones and wood and a well-insulated wooden frame reference house. This study concluded that the increase of CO_2 emissions of the standard concrete-block house compared to the well-insulated wooden house represents 18% of the total emissions for the wooden house, but accounting for end-of-life processes may reduce this value. Since then many LCA studies have been performed, not only in residential buildings but also in commercial buildings. Many review papers have been published, as well (Sartori and Hestnes 2007; Bribián et al. 2009; Ortiz et al. 2009; Sharma et al. 2011).

The main focus of LCA studies has been on new buildings. The few studies that addressed the retrofit of residential buildings, primarily evaluate energy efficiency measures, such as thermal insulation of the building envelope (Lollini et al. 2006; Sharma et al. 2011). The main goal of these studies was to improve the energy performance of buildings during the use phase, often neglecting embodied impacts during production and assembly of materials or building systems (construction phase). Moreover, these studies were mainly developed for cold climates, where buildings have very different characteristics and energy requirements compared to Mediterranean or hot climates (Crawford et al. 2010; Stephan et al. 2013a). For instance, Fay et al. (Fay et al. 2000) 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). Building typologies, construction techniques, and the location of buildings largely influence their operational performance, with ceiling, roof and external-wall insulation being the most effective retrofit measures (Iyer-Raniga and Wong 2012; Liu et al. 2014). Moreover, most LCA of building retrofits have been performed on more conventional brick or concrete wall buildings (from mid-to-late 1990s). Historic buildings from the beginning of the 20th century or earlier, in Europe, have not been assessed in a life-cycle perspective.

LCA studies for buildings located in South European climates were mainly focused on new buildings (Blengini 2009; Ortiz et al. 2010; Blengini and Di Carlo 2010a; Ortiz-Rodríguez et al. 2010; Rossi et al. 2012; Asdrubali et al. 2013; Cellura et al. 2013). In the Portuguese context, Monteiro & Freire (2012; 2016) studied the influence of different exterior-wall solutions for a new single-family house. Silvestre et al. (2013) addressed the recent European standards in the LCA of different insulation materials in exterior walls. Other LCA studies were performed to compare and assess the performance of several insulation materials (Pargana et al. 2014; Silvestre et al. 2016). Addressing the whole building, Bastos et al. (2014) 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.

Use phase has been claimed as the most significant contributor to the energy consumption and associated environmental impacts of a building life-cycle. However, occupant preferences and expectations have not been considered in most life-cycle studies. The occupancy level of a building influences its operational energy use as well as the contribution of the different phases to the overall life-cycle of a building (Hernandez and Kenny 2010; Nordby 2011). De Meester et al. (2013) and Azar & Menassa (2012) emphasized the need to account properly 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 occupant preferences, not only in the operational energy use of buildings, but also in the assessment of trades-offs between embodied and operational energy (Hernandez and Kenny 2010). Several studies used thermal dynamic simulation for operational energy calculation, focusing only on the energy performance of buildings during the use phase (Peuportier 2001;

Thormark 2002; Verbeeck and Hens 2010; Rossi et al. 2012; Thiers and Peuportier 2012). However, more recently, LCA and thermal dynamic simulation have been integrated to assess building envelope components for new buildings (Anastaselos et al. 2009; Stazi et al. 2012; Peuportier et al. 2013; Gervásio et al. 2014). The influence of user behavior was also assessed by Blom et al. (2011) who concluded that the electricity used is mainly user-related, thus showing that changes in user behavior may be effective in reducing the environmental impact of electricity consumption.

Different LCCA methods have been applied in the literature to assess the LC costing of buildings. The LC costs of current housing stock in the UK were calculated by Cuéllar-Franca and Azapagic (2013) as part of sustainability assessment of the residential construction sector. Regarding the analysis of retrofit strategies, Nemry et al. (2010) assessed the environmental benefits and cost assessment of energy-saving retrofit strategies of existing buildings. The investment analysis of each strategy was based on two cost indicators: net present value (NPV) and internal rate of return (IRR). Another approach addressed in the literature (Dylewski and Adamczyk 2012) defined indicators for the economic assessment of external-wall insulation of the building, such as: NPV, profitability indicator and payback period. Recently Mata el al. (2015) investigated how the cost-effectiveness of different energy-saving strategies in buildings was dependent upon energy prices and discount rates. The methodology used in Mata el al. was based on the equivalent annual cost (EAC) method that annualizes all the costs during the building life-cycle.

A great gap in the literature still exists combining environmental and cost life-cycle assessment of building retrofits (or even new buildings). An integrated assessment can provide a more comprehensive framework to select the most cost-effective and environmentally friendly options. Combined LCA and LCCA of building retrofits have been performed for insulation materials (Anastaselos et al. 2009) or building components (e.g., exterior walls, roofs)) (Lollini et al. 2006; Nemry et al. 2010; Silvestre et al. 2013). Very few studies have analyzed the whole-building (all building envelope components) (Ibn-Mohammed et al. 2014), and rarely to historic buildings (Tadeu et al. 2015). Furthermore, LCA and LCCA can be integrated in a more comprehensive assessment by means of eco-efficiency to assess the trade-offs between cost and environmental impacts. However, very few studies have addressed eco-efficiency in the building sector and none regarding the whole building, although it has been assessed for building materials (Zabalza Bribián et al. 2011; Ibáñez-Forés et al. 2013), as well as for specific building systems, such as partition walls (Ferrández-García et al. 2016).

1.2.2 Streamlined LCA and LCCA of buildings

Although LCA and LCCA are widely recognized as very useful methodologies to analyze whole-building environmental impacts and costs, conventional LCA and LCCA are time consuming and resource-intensive. Moreover, they are usually performed in late design stages when all decisions have already been made. Late design-stage decisions have been proven to lead to significant increases in buildings LC environmental impacts (Schlueter and Thesseling 2009). A decision made in an early-design stage can promote greater potential in reducing environmental impacts and costs by evaluating which materials or components contribute the most to the total LC impacts. Additionally, the uncertainties in conventional LCAs are sufficiently great that the results often present uncertain guidance, even after performing a long and costly assessment (Weitz et al. 1996). Furthermore, LCA often requires a high level of detail in data inventory.

Many approaches have already been proposed to streamline LCA (Weitz et al. 1996; Hur et al. 2005), such as: removal of <10-30% of the upstream and/or downstream processes (Hunt et al. 1998), or use of qualitative, proxy or less accurate data. Streamlined LCA approaches have been applied to the building sector, mainly by grouping the design attributes into macro-components or clusters of building materials and systems (Pushkar et al. 2005; Zabalza Bribián et al. 2011; Gervásio et al. 2014). A parametric approach (Hollberg and Ruth 2016) and a computational-method that integrates BIM (Building Information Modeling), LCA, and energy simulation software (Basbagill et al. 2013) have also been proposed to provide early-stage decisions support by requiring a reduced number of inputs. However, this approach still requires manually creating a BIM model, which can both limit applications and also increase the complexity of integrating several software programs. Another limitation not addressed in the existing streamlined approaches is the lack of consistent information about the inputs to the model or how the bill of activities/materials is calculated. As there is no established method to calculate the bill of materials in a building LCA study, it is generally presented as an undescribed ad hoc process.

Finally, it is worth noting that the streamlined approaches described in the literature generally do not address uncertainty. Dealing with data gaps, data asymmetries, and inconsistencies in LC inventories is a general problem in LCA studies (Weitz et al. 1996). Different aspects can contribute to this uncertainty, whereas uncertainty in parameters of the LCA model and uncertainty in model structure are the most mentioned (Ciroth 2004). Uncertainty analysis can be used to increase transparency, and therefore credibility of a study (Blengini and Di Carlo 2010a). Olivetti et al. (2013) explored the impact of streamlining on the credibility of LCA results given the uncertainty. This technique incorporates a structured under-specification analysis of the bill of materials that leverages statistical analysis in the context of uncertainty and explores the impact of streamlining on the credibility of LCA results given the uncertainty.

To encourage and improve LCA as a decision support tool with more reliable results, sensitivity analyses can identify the key parameters that influence the environmental and cost of building retrofits. Those analyses may also provide an interval of results and insights that can be used in further studies, or to provide recommendations to the building design process.

In summary, several gaps were identified as follows:

i) None of studies in the literature evaluated the environmental benefits of retrofitting historic building from the late 1800s to the early 1900s in South European (mild Mediterranean) climates. These types of buildings have very specific characteristics and construction systems (such as load-bearing stone masonry walls and wood-frame roofs), which may lead to very different performances compared to conventional brick or concrete-wall buildings (from mid- or late-1990s).

ii) Historic buildings in World Heritage protected areas (with several architectural constraints) have not been assessed in terms of their environmental and cost performance.

iii) Trade-offs between embodied and operational impacts of the whole-building retrofit have not been assessed, nor the tipping point at which the LC impacts achieve a minimum value when combining different retrofit strategies (roof and exterior walls).

iv) Adaptive reuse, which has been common practice in European cities, has never been addressed from a life-cycle perspective by examining alternative occupancy patterns; particularly, existing residential historic buildings adapted to office use.

v) None of the reviewed literature relates environmental and cost impacts of building retrofits by means of an eco-efficiency assessment.

vi) Existing streamlined approaches have been developed to assess new buildings and are not geared towards retrofit. Existing building stock is much more complex than new construction, as there is a myriad of different buildings from several time periods, with different construction systems, each requiring different types of decisions, such as whether a retrofit is worth it, which components need to be retrofitted, and how. Additionally, the existing streamlined approaches have a limited scope with very few metrics assessed (usually GHG emissions and primary energy).

vii) None of the described streamlined methods implemented an integrated environmental and cost assessment, or fully integrated the embodied and operational energy assessments.

Additionally, the trade-offs between embodied impacts and operational energy are rarely addressed in the literature and never discussed in any of the streamlined approaches reviewed.

viii) Many studies have assessed several retrofit strategies but none of them have focused on identifying the key parameters that influence the environmental and cost performance of building retrofits.

This thesis seeks to address these gaps by tackling building retrofits in South European climates through environmental and cost life-cycle assessments and identifying their main drivers.

1.3 Research questions

The main goal of this PhD thesis is to explore both conventional and streamlined LCA and LCCA approaches to identify strategies and select the most effective options to improve the life-cycle environmental and economic sustainability of building retrofits, for family households and office buildings in South European climates. An integrated cost and environmental life-cycle model, combined with thermal dynamic simulation, is developed and implemented for different building retrofit projects in Coimbra, Portugal (single-family house, apartment, and office building). Final and primary energy, environmental impacts and costs are assessed and trade-offs identified. A sensitivity analysis addressing occupancy is implemented to increase the robustness of the results. Although LCA and LCCA are very useful tools for assessing the building environmental and cost performance, they are both time consuming and resource-intensive, discouraging a more widespread use. To address this challenge, a novel approach was developed to streamline LCA and LCCA for building retrofits that accommodates varying amounts (and quality) of information on retrofit design, and provides both estimates and uncertainty in the evaluation of environmental and economic performance. A framework was developed that fully integrates a streamlined embodied LCA, statistically-based operational energy and cost models. The method comprises the application of structured under-specification, probabilistic triage, and guided sequential specification.

Based on the gaps presented in section 1.2, six research questions were formulated and specific objectives were defined, as presented in Table 1.1.

Table 1.1 Research questions and specific objectives or tasks

Research question	Specific objectives / tasks	Chapter
1. What is the impact of energy-saving retrofit strategies on the energy and environmental performance of buildings?	i) Perform an environmental LCA of alternative retrofit strategies for the roof and exterior walls of three building types (single-family house, apartment and office building ii) Identify hot-spots	2
2. Are there potential trade-offs between embodied and operational energy environmental impacts?	i) Evaluate embodied and operational impact trade-offs for the three building types	2
3. Is it possible to find solutions that are at the same time environmentally friendly and cost effective?	i) Perform an integrated cost and environmental life-cycle assessment of alternative retrofit strategies for the three building types ii) Assess the potential improvements in energy efficiency and trade-offs between costs and environmental impacts (eco-efficiency)	3 and 4
4. How does type of use and occupancy pattern influence the economic and environmental performance of building retrofits?	i) Investigate how occupancy and adaptive reuse influence the environmental and cost performance of building retrofit strategies to support decision-making ii) Perform comprehensive 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	3 and 4
5. Can a streamlined approach to LCA and LCCA of building retrofits be more efficient (with the same effectiveness) than a conventional LCA?	i) Present an integrated streamlined LCA-LCCA approach of building retrofits to provide environmental impacts and cost feedback at early-design stage decisions ii) Investigate whether a streamlined approach can be more efficient (with the same effectiveness) than a conventional LCA and LCCA of building retrofits (validation) iii) Explore the potential to support early-stage decisions (case-study analyses)	5
6. What matters in environmental and cost LCA of residential building retrofits?	i) Application of the streamlined approach to assess the environmental and cost performance of various residential building retrofits ii) Perform a comprehensive sensitivity analysis to assess the influence of location, type of house, wall system and occupancy iii) Identify key drivers of environmental and cost impacts of building retrofits in South European climates	6

1.4 Potential impact

This PhD research can provide a potential impact to improve the robustness of LCA and LCCA assessments in order to encourage good environmental practice among the building sector (architects, engineers, contractors, and manufactures) and stimulate market demand through more accurate information for users. Furthermore, the outcome of this research may also contribute to the definition of thresholds for environmental impacts in the building sector and consequently in designing future policies. The streamlined LCA and LCCA model for building retrofits developed here can contribute providing more accurate and robust information in the early stages of the building design process.

The research presented in this PhD thesis can have a potential impact in:

1. Promoting better environmental practice among building sector stakeholders, particularly in the building retrofit process;

2. Streamlining LCA and LCCA of building retrofits to become more user-friendly for LCA experts and non-experts;

3. Stimulating the incorporation of LCA and LCCA techniques in current practice and building design process;

4. Supporting the building design decision process by providing insights on the key drivers that influence the environmental and cost of building retrofits;

5. Defining environmental thresholds for the building sector that can help draft future building standards and policies.

1.5 Thesis main publications

Most of this PhD thesis is based on the following core articles that are published, under review, or in final preparation for submission to ISI-indexed journals (abstracts and keywords for the articles are presented in Appendix I):

1. **Rodrigues C.**, Freire F. (2017). Environmental impact trade-offs in building envelope retrofit strategies. International Journal of Life Cycle Assessment, 22 (4), 557-570. doi:10.1007/s11367-016-1064-2

JCR® impact factor (2015): 3.324

2. **Rodrigues C.**, Freire F. (2017). Building retrofit addressing occupancy: an integrated cost and environmental life-cycle analysis. Energy and Buildings, 140, 388-398. doi: 10.1016/j.enbuild.2017.01.084

   JCR® impact factor (2015): 2.973

3. **Rodrigues C.**, Freire F. (2017). Adaptive reuse of buildings: Environmental and cost life-cycle assessment of retrofit strategies and alternative uses for an historic building (in final review in Journal of Cleaner Production)
4. **Rodrigues C.**, Kirchain R., Freire F., Gregory J. (2016). Streamlined environmental and cost life-cycle approach for building retrofits: a case of residential building in South European climates (submitted)
5. **Rodrigues C.**, Freire F., Kirchain R., Gregory J. (2016). Environmental impacts and costs of residential building retrofits – what matters? (in preparation)

This PhD research also contributed to the following articles:

6. Tadeu S., **Rodrigues C.**, Tadeu A., Freire F., Simões N. (2015). Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. Journal of Building Engineering, 4, 167–176. doi:10.1016/j.jobe.2015.09.009

7. **Rodrigues C.**, Freire, F. (2014). Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. Building and Environment, 81, 204–215. doi:10.1016/j.buildenv.2014.07.001

   JCR® impact factor (2015): 3.394

8. Tadeu S., **Rodrigues C.**, Tadeu A., Simões S., Gonçalves M. (2016). Multi-criteria analysis of occupants' perceptions on the benefits of energy retrofitting of buildings. International Journal of Housing Science and Its Applications, 40 (1)

In addition, articles related to the PhD research published in conference proceedings with scientific refereeing are presented in the full list of publications in Appendix II.

1.6 Thesis outline

This thesis consists of seven chapters and is structured as presented in Figure 1.1 following the research questions and objectives stated in this chapter (Table 1.1), as follows:

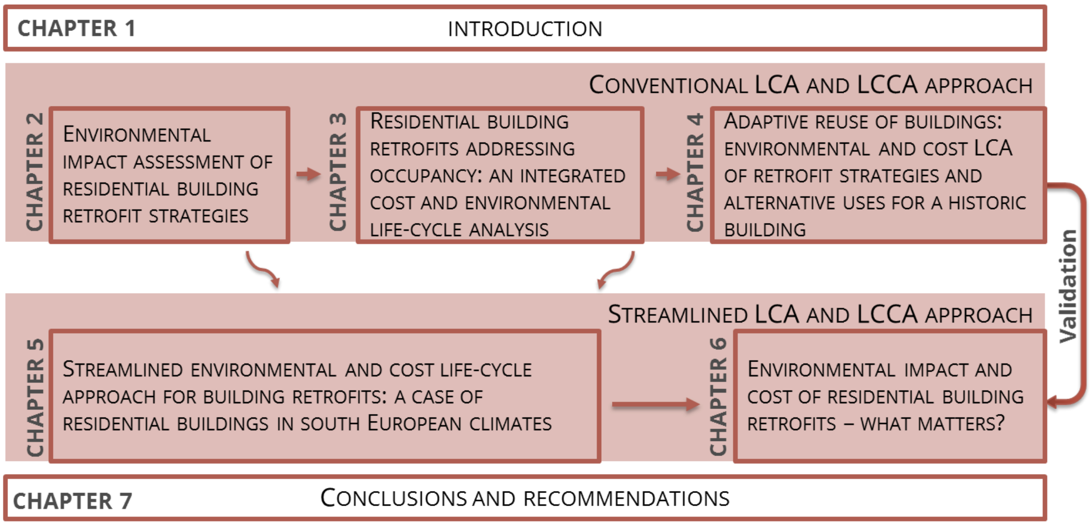

Figure 1.1 Thesis overview

Chapter 2 presents an environmental LC assessment of alternative retrofit strategies for the roof and exterior walls of a Portuguese single-family house and an apartment. Embodied and operational impact trade-offs are evaluated for both residential building types. A comprehensive analysis of alternative insulation thicknesses is performed to identify optimal thickness levels minimizing life-cycle environmental impacts.

Chapter 3 presents an integrated cost and environmental life-cycle assessment of alternative retrofit strategies for a Portuguese single-family house located in the city center of Coimbra, Portugal. A comprehensive analysis of different retrofit strategies (roof and exterior walls) combining alternative insulation levels and occupancy patterns is performed to identify opportunities to minimize life-cycle environmental and cost impacts. Moreover, the influence of occupancy in the economic and environmental performance of building retrofit strategies is assessed.

Chapter 4 investigates how occupancy and adaptive reuse influences the environmental and cost performance of building retrofit strategies supporting decision-making. A comprehensive analysis of different retrofit strategies (roof and exterior walls) combining alternative insulation levels and occupancy patterns is performed to identify opportunities to minimize life-cycle environmental and cost impacts for an historic building (currently used as an office building) from the 19th century in Coimbra, Portugal. The potential improvements in energy efficiency and trade-offs between costs and environmental impacts are assessed (eco-efficiency).

Chapter 5 firstly, presents an integrated streamlined LCA-LCCA approach of building retrofits to provide environmental impacts and cost feedback at early-design stage decisions; secondly, investigate whether a streamlined approach can be more efficient (with the same effectiveness) than a conventional LCA and LCCA of building retrofits (validation); and thirdly, explore the potential to support early-stage decisions (case-study analyses).

Chapter 6 presents a comprehensive sensitivity analysis to identify key drivers of environmental and cost impacts of building retrofits in South European climates using different types of single-family houses with different wall systems (from different time periods), and occupancy patterns in alternative climate locations.

Chapter 7 draws the conclusions together by summarizing the key findings and contributions, and providing recommendations for further research.

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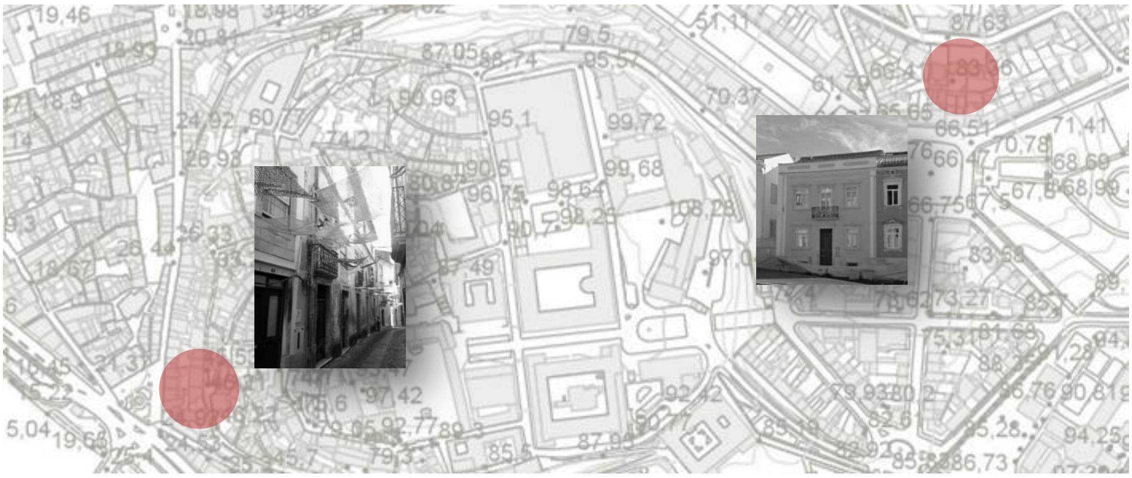
2 Environmental impact trade-offs in building envelope retrofit strategies

Based on:

Rodrigues C., Freire F. (2017) Environmental Impact trade-offs in building envelope retrofit strategies. International Journal of Life Cycle Assessment, 22 (4), 557-570. doi: 10.1007/s11367-016-1064-2

Tadeu S., Rodrigues C., Tadeu A., Freire, F., Simões, N. (2015) Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. Journal of Building Engineering, 4, 167–176. doi: 10.1016/j.jobe.2015.09.009



Abstract This chapter presents an environmental LC assessment of alternative retrofit strategies for the roof and exterior walls of a Portuguese single-family house and an apartment. Embodied and operational impact trade-offs are evaluated for both residential building types. A comprehensive analysis of alternative insulation thicknesses was performed to identify optimal thickness levels minimizing life-cycle environmental impacts.

2.1 Introduction

Building standards are mainly focused on reducing energy consumption during the use phase of a building without including the whole life-cycle perspective. It is a commonly held opinion that high levels of thermal insulation constitute one of the first steps towards reducing the energy consumption of existing buildings. However, this approach generally does not consider the embodied burdens associated with the additional insulation materials. As full impacts of materials and use patterns become better mapped, the role of the life-cycle phases may change (Thormark 2002; Blengini and Di Carlo 2010b; Blom et al. 2011).

Moreover, questions regarding the risks of over-specifying some construction elements and installations have emerged, particularly for mild climate regions. The increase of the embodied impacts due to improved building materials and technologies is not balanced by a reduction of the operating energy, and thus, the impact of the complete building life-cycle is not further reduced (Sartori and Hestnes 2007; Ramesh et al. 2010). An extra insulation level can lead to higher embodied impacts without significant reduction in the operational energy, which can in turn result in higher total life-cycle impacts for these buildings (Hernandez and Kenny 2010; Rodrigues and Freire 2014a).

According to Nemry et al. (2010), single-family houses present the major potential for energy and environmental improvement at EU-level, followed by multi-family houses. Single-family houses account for about 64% of the total environmental impacts in the EU-25 building stock and multi-family buildings for about 32% (Nemry et al. 2010). Building-retrofit LCA studies have been mainly focused on single-family houses (Verbeeck and Hens 2010; Bin and Parker 2012; Beccali et al. 2013; Rodrigues and Freire 2014a). The main finding of these studies lies in the significant reduction of the operational energy due to retrofit actions (60-80%); however, they all come to the conclusion that this reduction leads to additional embodied environmental impacts (construction, end-of-life and demolition phases). Moreover, as buildings become more energy efficient (with very low operational energy needs), the embodied impacts become higher than the operational energy impacts.

For instance, Verbeeck and Hens (2010) concluded that, in an extreme low energy scenario, embodied energy contributes to about 55% of total LC energy use. Bin and Parker (2012) showed that the embodied impacts of retrofitting a residential building in Australia account for approximately 70% while operating impacts account for just 30%, over a 50-year life span. Rodrigues and Freire (2014) revealed that using insulation thicknesses of 80 mm or more in retrofitting historic buildings in Portugal, leads to an insignificant reduction in operational energy

(5% or less), while the embodied impacts increase from 6% to 20%. For insulation thicknesses of 120 mm, the embodied impacts become higher than the operational in most impact categories namely climate change, ozone depletion, marine eutrophication and non-renewable primary energy.

Furthermore, while several studies have all assessed the environmental impacts of multi-family building retrofits from different points of view (Dodoo et al. 2010; Blom et al. 2011; Iyer-Raniga and Wong 2012; Thiers and Peuportier 2012; Liu et al. 2014) each mainly focused on the operational energy consumption of the building. For instance, Liu et al. showed that the multifamily buildings in Sweden have good potential to reduce their energy use by more than 50%, which in turn will contribute to a 43% primary energy reduction and a 48% CO_2 emissions reduction (Liu et al. 2014). Dodoo et al. (2010) explored the life-cycle primary energy implication of improving an existing conventional apartment building to the passive house standard. The primary energy use for material production can make an important contribution to the whole life-cycle primary energy impact; however, depending on the energy supply system, the material production impact can be offset by the operational energy savings (Dodoo et al. 2010). Additionally, Thiers and Peuportier (2012) showed evidence that the choice of construction materials can strongly contribute to the environmental performance of the buildings.

The comparison between retrofits for single-family houses and multi-family buildings is also addressed in the literature. Asdrubali et al. (2013) performed an assessment and comparison of the life-cycle impact of three typical Italian buildings: a detached single-family house, a multi-dwelling building and an office building. The relative importance of the various life phases of buildings was investigated comparing different scenarios, namely the original design and alternative optimized configurations. This study showed that the use of passive and active systems to improve the performance of a building need to be carefully evaluated, since an excessive use of one or both may even be counterproductive. These studies assessed different types of residential buildings without taking into account the fact that they are comparing a single use by only one family with a multiple use, by several families. However, there is no study comparing a single-family house with an apartment retrofit, which entails evaluating dwellings with the same use. Basically, while these studies assess the benefits of retrofitting a single-family or an apartment they do not compare options for the same use (one-family occupancy).

LC impacts of buildings combine both operational and embodied components. However, the literature has been focused on reducing the operational impacts, without accounting for the associated embodied impacts (Dodoo et al. 2010; Thiers and Peuportier 2012; Stephan et al. 2013b).

Exceptions are reviewed, as follows: Hacker et al. addressed the balance between embodied and operational CO_2 impacts to assess the influence of thermal mass and climate change, as well as the potential optimum weight of construction where the initial embodied CO_2 offsets the operational impacts (Hacker et al. 2008). Lützkendorf et al. (2014) provided practical guidance to designers to take into account the importance of incorporating embodied impacts in the assessment of net-zero buildings. Ibn-Mohammed et al. (2013) critically reviewed the relationship between embodied and operational emissions over the life-cycle of buildings. Previous studies have assessed the trade-offs between embodied and operational energy for specific building retrofit scenarios, for instance, Rodrigues & Freire (2014a) developed a life-cycle model to assess 27 alternative retrofit scenarios for the roof retrofit of a single-family house combining different types of insulation material and levels, as well as types of frame material. Tadeu et al. (2015) performed an environmental assessment for 33 cost-optimal energy retrofit strategies for an apartment.

However, none of these studies evaluated the environmental benefits of a single-family house and an apartment retrofit in mild Mediterranean climates from the beginning of the 20th century. The trade-offs have not also been assessed between embodied and operational impacts of the whole-building retrofit, or the tipping point identified at which the LC impacts achieve a minimum value when combining different retrofit strategies (roof and exterior walls). These types of buildings have very specific characteristics and construction systems (like massive stone walls and wooden-frame roofs) which lead to very different performances comparing to conventional brick or concrete walls buildings (from the mid- or late-1990s). Moreover, historic buildings in World Heritage protected areas (with several architectural constraints) have not been assessed in terms of their environmental performance.

To tackle the gaps previously identified, this chapter presents an environmental LC assessment of alternative retrofit strategies for the roof and exterior walls of a Portuguese single-family house and an apartment. Embodied and operational impact trade-offs are evaluated for both residential building types. A comprehensive analysis of alternative insulation thicknesses was performed to identify optimal thickness levels minimizing life-cycle environmental impacts.

2.2 Materials and methods

An integrated life-cycle approach combining LCA and thermal dynamic simulation was implemented to assess the energy and environmental performance of selected energy efficient retrofit measures. An LC model was developed for a single-family house and a single-family apartment from the beginning of the 20th century (early 1900s) located in the historic city center of Coimbra, Portugal. The single-family house is a semi-detached house organized on four floors, with a finished attic on the upper floor (Rodrigues and Freire 2014a). The apartment is located on the upper floor of a multi-family building organized on three floors, with the ground floor being used for commercial purposes, and has an unfinished attic (Tadeu et al. 2015).

Both houses are located in 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 their historic and cultural value. The main features of both buildings are massive stone walls (average thickness 50 cm), single-glazed wooden windows and a conventional wood-frame roof. Figures 2.1 and 2.2 present the technical drawings (main façade, sections and plans) of the single-family house and the apartment, respectively. Table 2.1 presents the main characteristics and dimensions (number of floors, floor area, exterior walls area, roof area, windows area and average floor height) of the two dwellings.

The roof retrofit process incorporates the replacement of frame material, interior and exterior coverings, as well as the incorporation of a thermal insulation layer. As can be seen in the technical drawings (Figure 2.1 and Figure 2.2) the structure of the roofs is different and for each one a different retrofit option was considered. The single-family house roof structure retained the same wooden roof (almost the exact reproduction of the existing one). The apartment roof, besides being more complex, was adapted to better fit the modifications made in the interior of the apartment. Furthermore, for stability reasons, some steel elements were added to the apartment roof. The single-family-house roof is above a heated area while the apartment exterior roof is above a non-heated area. These retrofits were made in real buildings, so all the quantities were provided either by the owner or the technical team.

The exterior wall retrofit incorporates a layer of thermal insulation on the interior surface, as well as a new interior covering (gypsum plasterboard). All scenarios assumed the replacement of the existing single-glazed windows by double-glazed windows.

Figure 2.1 Technical drawings (main façade, section and plans) of the single-family house

Twenty-four retrofit strategies (12 for each dwelling) combining roof and exterior-wall thermal insulation were assessed. Four insulation levels (0, 40, 80 and 120 mm) for the roof and three (0, 40 and 80 mm) for the exterior walls were compared. The thermal insulation material considered was expanded polystyrene (EPS). EPS has been proved to have better environmental and cost performance than most of the insulation materials used in the Portuguese context (Tadeu et al. 2013; Rodrigues and Freire 2014b; Rodrigues and Freire 2014c; Tadeu et al. 2015). Moreover, EPS is one of the most used insulation material in the Portuguese construction sector. Since manufacturers use standardized thicknesses, in actual applications the choice of insulation material is based on market availability. Technical data from scientific literature (Kellenberger et al. 2007; Althaus et al. 2010; Moreno Ruiz et al. 2014), producers and contractors were gathered to calculate the quantities of materials required for each retrofit strategy (foreground data). The main inventory data regarding material processing (background data) was obtained from Kellenberger et al. (2007). Table 2.2 presents the main thermal characteristics of the 24 scenarios analyzed.

Figure 2.2 Technical drawings (main façade, section and plans) of the multi-family building (the apartment in study is identified with a transparency)

Table 2.1 Single-family house and apartment main characteristics

	Single-family house	**Apartment**
Number of floors	4	2
Floor area (m^2)	280	119
Exterior wall area (m^2)	250	71
Roof area (m^2)	84	52
Window area (m^2)	27.7	18
Average floor height (m)	3.00	2.85
Window-to-wall ratio	0.11	0.25
Wall-to-floor ratio	0.9	0.55

The functional unit selected for this study was one square meter of living area over a period of 50 years. The service life of a building is defined by the design of the building, construction methods and solutions, user behavior and maintenance strategy. Some of those factors are difficult to predict, so this research follows many other studies that have also assumed a 50-year lifespan for buildings. [e.g. Refs. (Sartori and Hestnes 2007; Gustavsson and Joelsson 2010; Monteiro and Freire 2012; Cuéllar-Franca and Azapagic 2012; Dodoo et al. 2014)] Fifty years is also commonly the average time between major retrofits during the service life of the building.

Life-cycle impacts from buildings incorporate two components: embodied and operational impacts. Embodied impacts are those associated with the extraction of raw materials, manufacture, production, transport and assembly of building materials and systems (Ibn-Mohammed et al. 2013). Operational impacts are related to the energy used for heating and cooling; and, when applied, lighting, appliances and ventilation (Ramesh et al. 2010). Figure 2.3 presents the LC model, which includes the following main processes: removal of the original components (roof and exterior-wall finishes); construction and use phase (heating, cooling and maintenance). Since the scope of this research is to access retrofit strategies, the initial construction and previous uses of the building were not considered. Nor was the end-of-life stage of the new components considered (dismantling scenarios and waste treatment after service life) because this cannot be accurately predicted due to the long life of buildings and is considered of minor importance for the residential sector, where it accounts for less than 5% of total LC impacts and not so different between alternatives (Nemry et al. 2008; Ortiz et al. 2010). However, this assessment included a demolition stage that represents the end-of-life of some existing components that will be replaced. Moreover, the end-of life may also depend on the maintenance strategy defined. This study implemented a process-based LC inventory to compare alternative scenarios. The model and life-cycle inventory were implemented using SimaPro 8 software (www.pre.nl).

Table 2.2 Building envelope (roof, exterior walls, floor and windows) characterization – Insulation thickness in [mm], insulation thermal resistance R-value in [m^2K/W] and heat transfer coefficient U-value in [$W/(m^2K)$]

		Roof	Exterior walls	Floor
Thickness	$R_{insulation}$[1]	U_{roof}	U_{walls}	U_{floor}
0	0	1.92(SFH[3])/1.53(A[4])	3.27/1.74	-
40	1.01	0.55/0.60	0.62/0.53	-
80	2.16	0.35/0.36	0.38/0.33	0.48
120	3.24	0.25/0.26	-	-

Windows	
SHGC[2]	$U_{windows}$
0.85	5.10
0.75	2.00

[1] R-value for one square meter of insulation material

[2] Solar Heat Gain Coefficient

[3] Single-family house U-values

[4] Apartment U-values

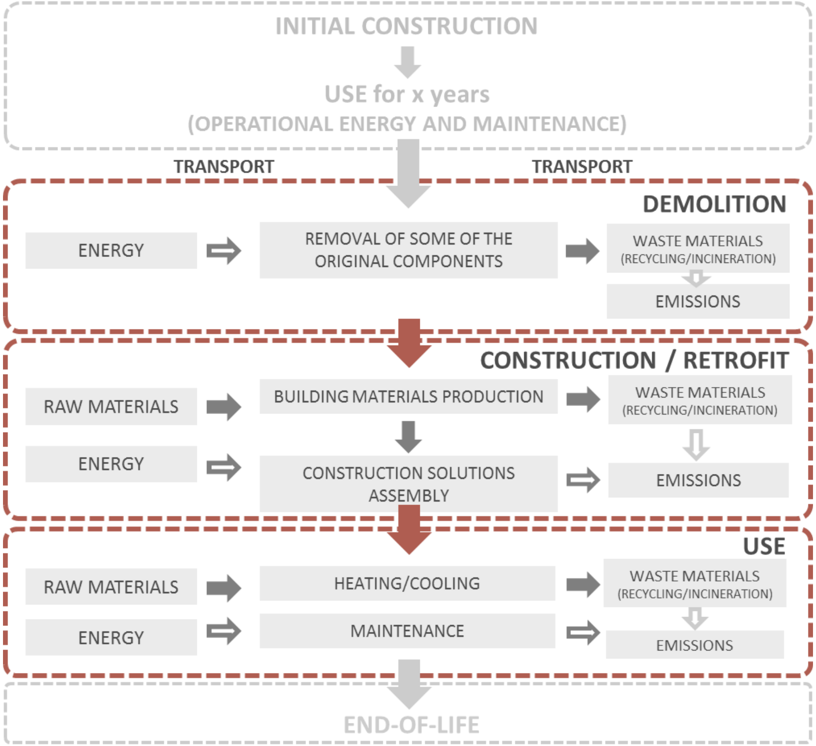


Figure 2.3 Main processes of the model and system boundaries

2.2.1 Demolition phase

The removal of the original components included dismantling and transport for recycling or incineration. The original wood frame roof was considered to have been completely removed and replaced by a new roof. Transportation distances, from the building site to the recovery (recycling, incineration) sites were calculated based on the locations of the local end-of-life facilities nearest to the building site.

2.2.2 Construction phase

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 wooden structure, insulation, tile placement (roof) and interior finish (gypsum plaster board both for roof and exterior walls). The delivery of construction materials to the building site assumed truck (3.5-16t) and lightweight (<3.5t) transportation, with European-fleet average characteristics. Transportation distances from the production site to the building site were calculated based on the locations of the nearest local material producers and contractors to the building site. Table 2.3 presents the inventory (construction material weights and transportation) for the alternative retrofit scenarios, per total living area and per square meter.

2.2.3 Use phase

The use phase included heating, cooling and maintenance requirements. The energy needs were calculated on an annual basis for the defined functional unit. The operational energy modelling was carried out using the dynamic thermal modelling program Energy Plus (U.S. Department of Energy 2015). The Portuguese climate is classified as maritime temperate with Mediterranean influence under the Köppen-Geiger classification system (Csa/Csb; C: hot temperate climate; s:dry summer; a,b: hot, mild summer) (Peel et al. 2007).

Thermal dynamic simulation allows for modeling the building conforming to its specific uses and characteristics. In a dynamic approach, the internal heat gains are computed using the estimated number of persons and their metabolic activity, as well as the schedules defined for people, lighting and appliances. For both houses, 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. The heating system was only partially activated during occupied hours. The heating set-point was fixed at 20ºC (with a drop in temperature to 18ºC during the night) and a natural ventilation rate of 0.4 air changes per hour was considered, in keeping with Portuguese building thermal regulations (REH and RECS 2013).

Table 2.4 presents the energy requirements for the various insulation materials and thicknesses. The differences in heating and cooling between the two buildings are mainly due to geometry, size and building orientation. The wall-to-floor ratio is considerably higher in the single-family house (0.9) than in the apartment (0.55); on the other hand, the window-to-wall ratio is considerably lower in the single-family house (0.11) than in the apartment (0.25). The window heat gains are much higher in the single-family house (12957 kWh) than in the apartment (6589 kWh); on the other hand, the window heat losses are much higher in the apartment (6635 kWh) than in the single-family house (1352 kWh). The maintenance activities include conservation of the interior and exterior finishes of the building throughout the 50-year life span.

Table 2.3 Building materials inventory

		Single-family house				Apartment			
		Weight		Losses	Transport	Weight		Losses	Transport
	Material	by living area (kg)	by FU (kg/m²)	kg	tkm[1]	by living area (kg)	by FU (kg/m²)	kg	tkm[1]
Original Roof Demolition									
Exterior Covering	- ceramic roof tiles	2940	11	-	412	1498	13	-	214
Wood Frame	- primary and secondary structure[2]	2132	8	-	51	1523	13	-	36
Auxiliary materials	- ceramic bricks	-	-	-	-	3645	31	-	512
Interior Coating	- wood panels	176	0.6	-	4	-	-	-	-
Roof retrofit									
Exterior Covering	- ceramic roof tiles	2940	11	147	294	1498	13	113	155
Wood Frame	- primary and secondary structure[2]	2558	9	379	460	579	5	102	142
	- oriented strand board (OSB)	-	-	-	-	1065	9	77	192
	- steel	-	-	-	-	1114	9	49	250
	- concrete (normal)	-	-	-	-	7	0.1	479	214
Thermal Insulation	- expanded polystyrene 40 mm	53	0.2	3	7	44	0.4	2	6
	- expanded polystyrene 80 mm	106	0.4	6	14	87	0.7	4	12
	- expanded polystyrene 120 mm	159	0.6	8	21	131	1	7	14
	- vapor barrier	18	0.1	0.9	6	-	-	-	-
Interior Coating	- gypsum plaster board	2117	8	106	255	737	6	32	72

[1] tonne-kilometer [2] Primary structure: rafter and trusses; Secondary structure: lath and counter-lath strips

Table 2.3 Building materials inventory (con’t)

Material		Single-family house Weight by living area (kg)	Single-family house Weight by FU (kg/m²)	Single-family house Losses kg	Single-family house Transport tkm[1]	Apartment Weight by living area (kg)	Apartment Weight by FU (kg/m²)	Apartment Losses kg	Apartment Transport tkm[1]
Exterior-wall retrofit									
Thermal Insulation	- expanded polystyrene 40 mm	158	0.6	7.88	20	57	0.5	1	2
	- expanded polystyrene 80 mm	315	1	15.8	41	115	1	2	3
Interior Covering	- Steel	-	-	-	-	392	3	5	24
	- gypsum plaster board	6300	26	315.0	731	1481	12	43	100
Floor retrofit									
Thermal insulation	- rock wool 80 mm	764	3	38	222	-	-	-	-
Floor covering	- wood floor	1260	5	63	368	2993	25	528	475
	- steel	-	-	-	-	1942	16	86	394
	- wood	202	0.7	10	59	1995	17	352	317
Window replacement									
	- PVC	2628	9	0	604	-	-	-	-
	- wood	-	-	-	-	1372	12	-	278

[1] tonne-kilometer [2] Primary structure: rafter and trusses; Secondary structure: sticks, battens & counter battens

Table 2.4 Heating and cooling requirements in kWh (per total living area and per square meter) over one year by exterior wall and roof insulation thicknesses [mm]. EW=Exterior wall

Insulation thickness		Single-family house				Apartment			
Roof	EW	Heating (kWh /m^2.year)	Total Heating (kWh/year)	Cooling (kWh /m^2.year)	Total Cooling (kWh/year)	Heating (kWh /m^2.year)	Total Heating (kWh/year)	Cooling (kWh/ m^2.year)	Total Cooling (kWh/year)
0	0	46.6	13048	3.3	924	72.1	8580	1.5	178.5
	40	38.5	10780	3.8	1064	58.6	6973	3.1	368.9
	80	29.4	8232	4.4	1232	58.1	6914	3.0	357
40	0	35.7	9996	3.5	980	71.9	8556	0.8	95.2
	40	27.0	7560	3.5	980	58.3	6938	1.5	178.5
	80	25.5	7140	3.5	980	55.2	6569	1.8	214.2
80	0	35.0	9800	3.3	924	72	8568	0.6	71.4
	40	26.3	7364	3.3	924	57.9	6890	1.4	166.6
	80	24.7	6916	3.3	924	57.4	6831	1.3	154.7
120	0	34.7	9716	3.2	896	72	8568	0.6	71.4
	40	25.9	7252	3.3	924	57.8	6878	1.3	154.7
	80	24.3	6804	3.3	924	57.3	6819	1.2	142.8

Two complementary LC impact assessment (LCIA) methods were applied: Cumulative Energy Demand 1.08 (CED) to quantify the non-renewable primary energy (NRPE), in order to address energy resource depletion, and ReCiPe 1.11 at midpoint level (H) (Goedkoop et al. 2013) to assess climate change (greenhouse gas emissions (GHG) following IPCC 2013 for a time horizon of 100 years), ozone layer depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE) and marine eutrophication (ME). The GHG intensity of electricity was 387 g CO_2 eq/kWh (calculated based on the average from 2009-2013) (Marques et al. 2015). The final and primary energy conversion factors used were 1.40 kWh/kWh for electricity (calculated based on the average 2009-2013) (Marques et al. 2015).

2.3 Results and discussion

Twelve alternative scenarios for each house were assessed combining exterior wall and roof retrofit strategies. The results show the influence of using different insulation thickness (40, 80 and 120 mm) on the total life-cycle impacts. Firstly, total LC impacts for the various scenarios are analyzed, in order to identify a tipping point for which total LC impacts are minimized. Secondly, LCIA results are presented for understanding the contribution of the various LC phases.

2.3.1 Embodied vs operational energy results

Figure 2.4 presents total LC impacts, as well as the impacts from both operational and embodied impacts. A trend line (polynomial, order 2) was applied for total LC impacts (correlation of about 95-99%) to assess the life-cycle tipping points of selected retrofit strategies. LCIA results showed that an optimal insulation thicknesses for life-cycle tipping point range from 30 to 40 mm for the roof and from 40 to 60 mm for the exterior walls of the apartment.

The life-cycle tipping point for the single-family house is achieved combining 80-100 mm of roof insulation with 60-80 mm of exterior walls insulation. As the roof in the apartment is above a non-heated area (as mentioned in Section 2.2), its influence in the operational energy performance is lower than in the single-family house (where the roof is above a heated area), leading to lower optimal insulation levels. Moreover, the environmental benefits, measured in the reduction of total LC impacts, remain very low (< 3%) for thicknesses of more than 80 mm for both roof and exterior walls. The apartment embodied impacts account for about 6 (ME) to 50% (NRPE) of total LC impacts (varying between categories) and the operational impacts account for 50(NRPE) to 94% (ME). The contribution of operational emissions is significantly higher than embodied emissions for ozone depletion (about 70-75% of the total LC impacts), terrestrial acidification (about 62-68%) and marine eutrophication (about 89-94%). The combination of both exterior and interior roof insulation in the apartment did not result in significant energy savings (< 2%) when compared to insulating the exterior roof alone. Furthermore, the apartment embodied impacts offset the operational impacts for insulation thicknesses of 80 mm or more.

The single-family house embodied impacts account for about 26% (ME) to 57% (NRPE) of total LC impacts and the operational impacts account for 43% (NRPE) to 74% (ME). The contribution of operational emissions is significantly higher than embodied emissions for terrestrial acidification (about 60-70% of the total LC impacts), freshwater eutrophication (about 52-63%) and marine eutrophication (about 64-74%). The single-family house embodied impacts offset the operational impacts for insulation thicknesses of 40 mm or more.

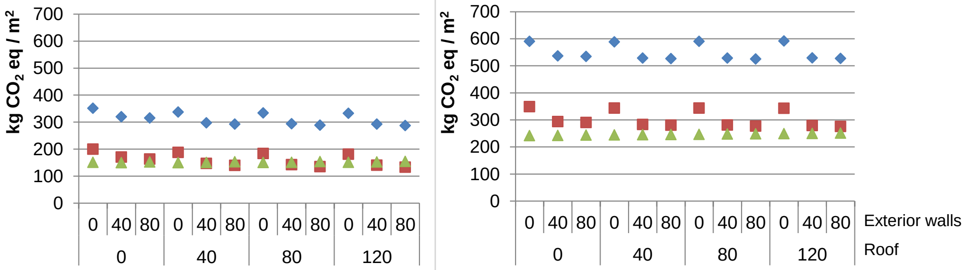
2.3.2 Construction phase results

Figure 2.6 and Figure 2.7 demonstrates that the construction phase (floor, roof and exterior walls retrofits) accounts for 13-27% of the total LC impacts of the single-family house and 4-39% for the apartment. The demolition phase accounts for about 1-3% (for both single-family house and apartment). LCIA results show the construction phase of all building envelope components (windows, floor, roof and exterior walls) retrofit contributes about 10% each to the total LC impacts. Exterior wall retrofit has the highest impacts (8-17% of total LC impacts) for the single-family house. Conversely, the roof contributes the most (2-18%) to the apartment total LC impacts. The roof retrofit has the greatest influence in the upper floor energy needs of buildings.

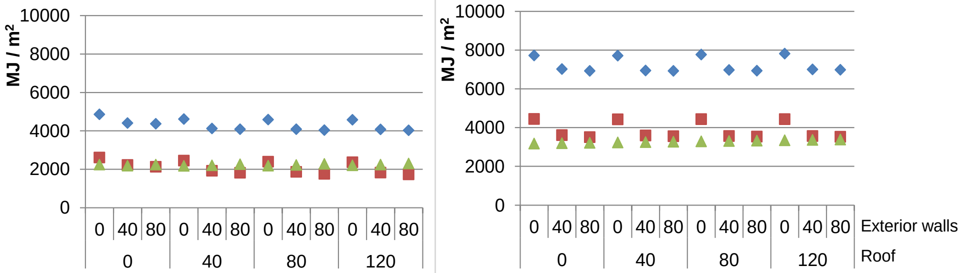
Single-family house

Apartment

Climate Change



Non-renewable Primary Energy



Ozone Depletion

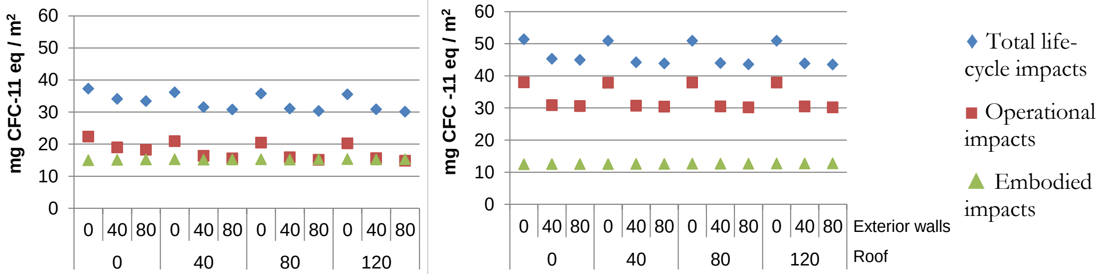


Figure 2.4 Climate change, non-renewable primary energy and ozone depletion life-cycle impact assessment of alternative exterior-wall (0, 40 and 80 mm) and roof (0, 40, 80, 120 mm) thermal insulation retrofit strategies (per one square meter of living area over a period of 50 years.

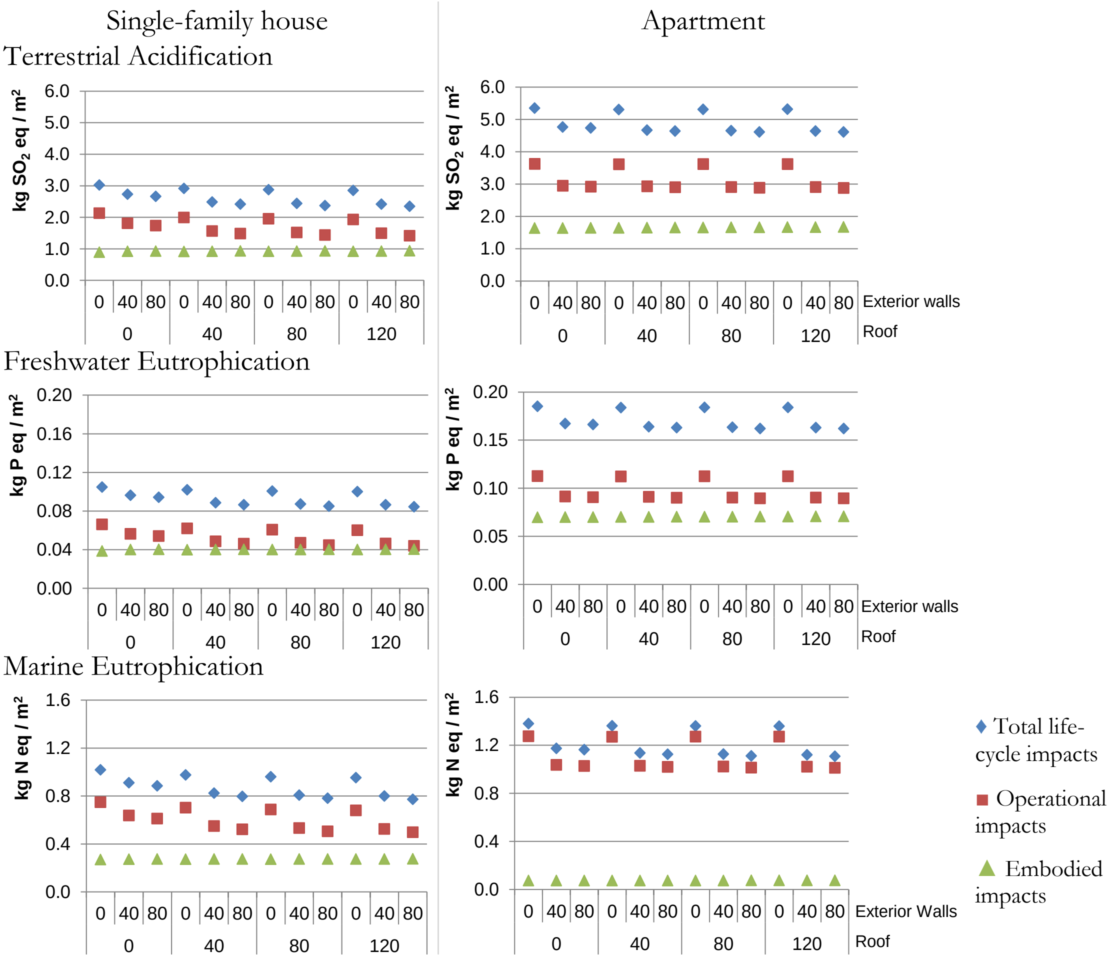


Figure 2.5 Terrestrial acidification, freshwater eutrophication and marine eutrophication life-cycle impact assessment of alternative exterior-wall (0, 40 and 80 mm) and roof (0, 40, 80, 120 mm) thermal insulation retrofit strategies (per one square meter of living area over a period of 50 years.

Exterior wall and roof retrofits have larger contributions for climate change, non-renewable primary energy and ozone depletion (comparing to the other categories assessed). Although floor retrofit and windows replacement were fixed variables in this study their contribution to the total LC impacts is acknowledged. Window replacement accounts for 1-8% of total LC impacts of the apartment and 3-14% of the single-family house. Floor retrofit accounts for about 1-2% of LC impacts of the single-family house and 2-18% of the apartment.

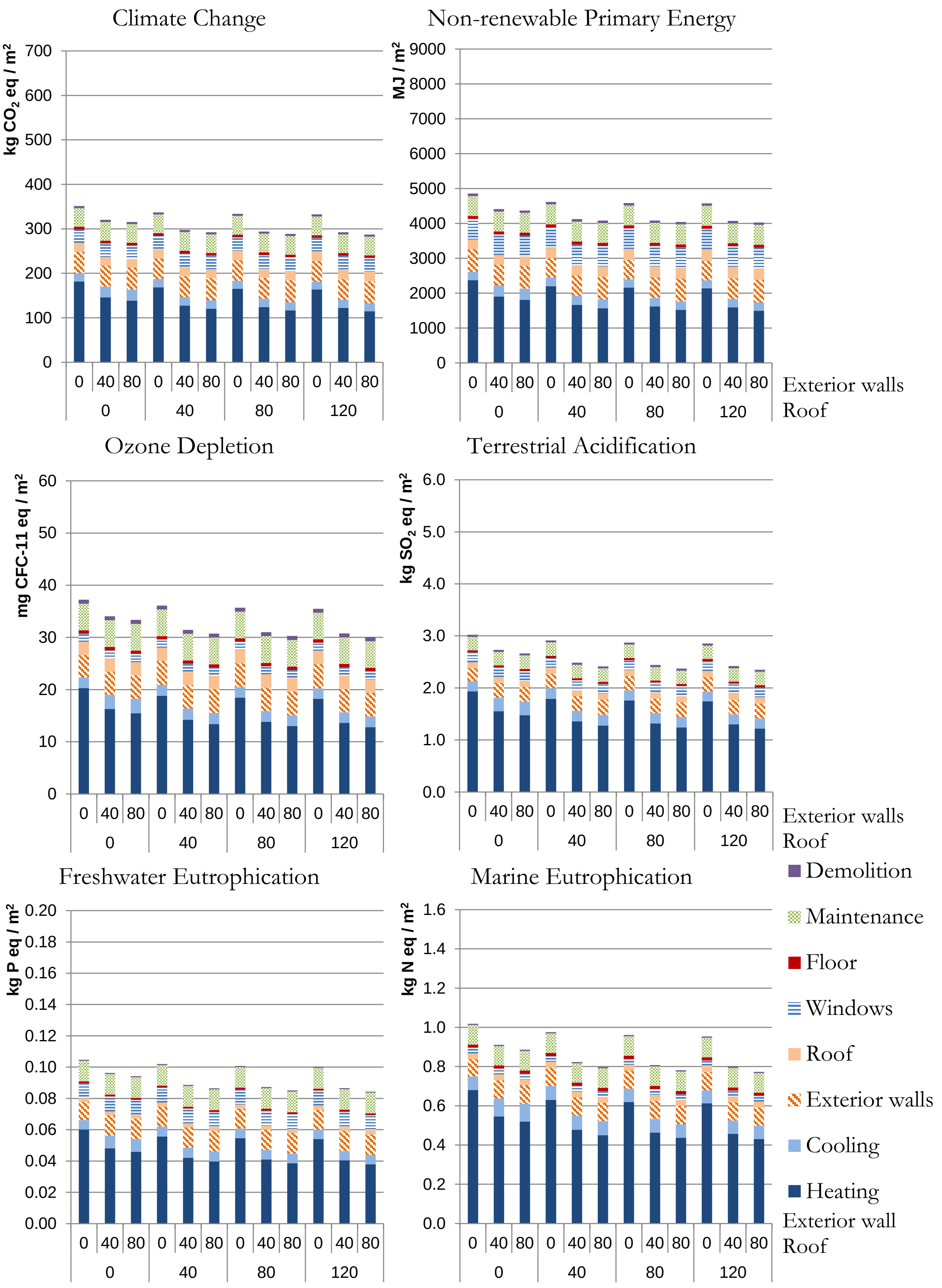


Figure 2.6 Environmental and non-renewable primary energy LCIA of the exterior wall (0, 40 and 80 mm) and roof insulation (0, 40, 80, 120 mm) thermal insulation retrofit strategies (per LC phases) for the single-family house (per one square of living area)

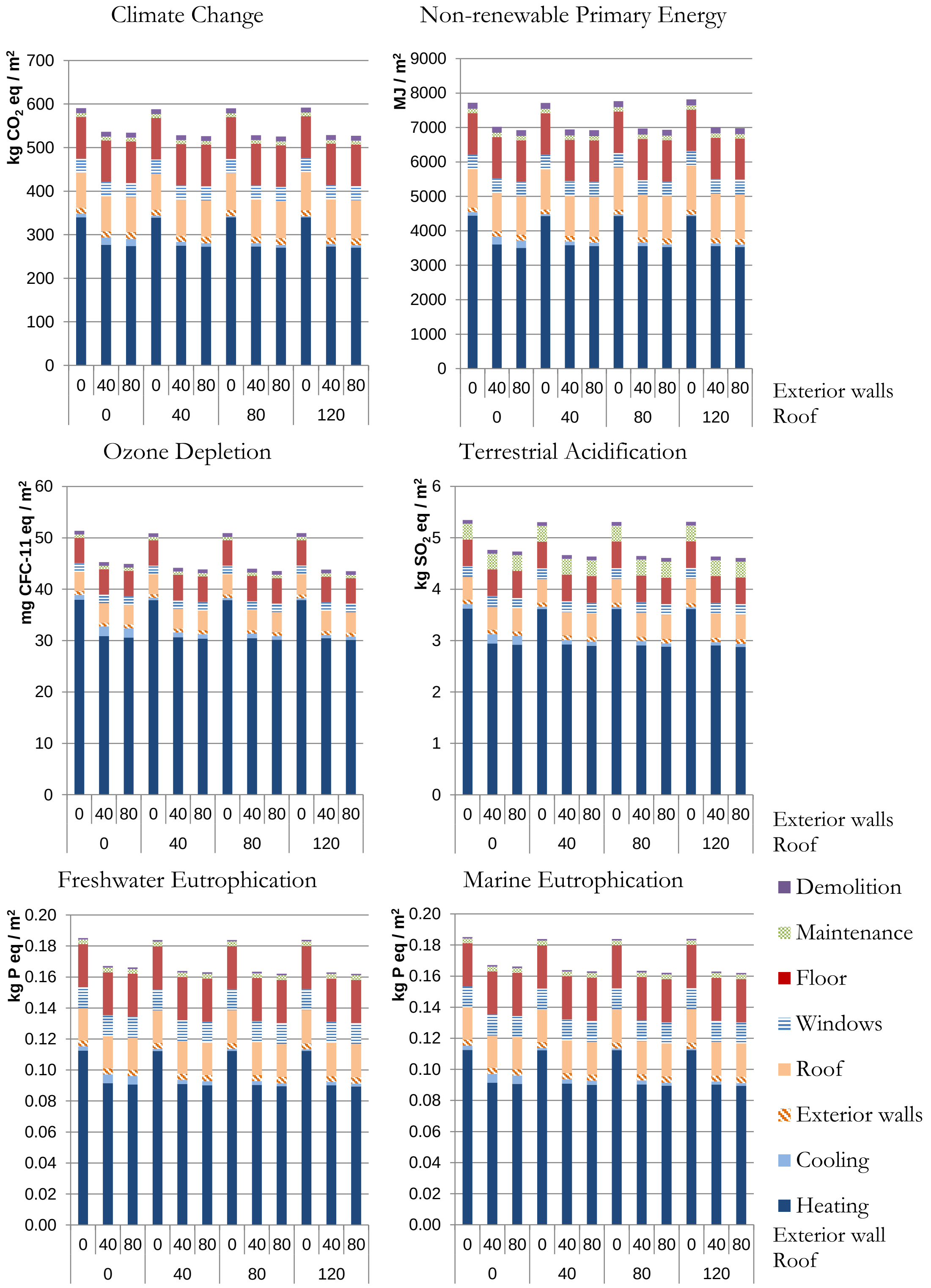


Figure 2.7 Environmental and non-renewable primary energy LCIA of the exterior wall (0, 40 and 80 mm) and roof insulation (0, 40, 80, 120 mm) thermal insulation retrofit strategies (per LC phases) for the apartment (per one square meter of living area)

2.3.3 Use phase results

The use phase results include operational energy (heating and cooling) and maintenance requirements. Operational impacts account for 43-54% (single-family house) and 50-94% (apartment). Maintenance accounts for about 9-16% for the single-family house and 1-7% for the apartment. For both single-family house and apartment, the benefit of adding 40 mm of insulation to the exterior walls represents a reduction in the total LC impacts of about 10% (both dwelling types), with a reduction in operational emissions of about 20%, while adding an extra 40 mm (for a total of 80 mm of insulation) only leads to a decrease of further 1-2% of total LC impacts and 3-5% of operational emissions.

The benefit of insulating the roof with 40 mm is higher in the single-family house (reduction of about 5% in the total LC impacts and 10% in the operational emissions) than in the apartment (about 1-3%). As for the roof insulation, an extra 40 mm of insulation (with a total of 80 mm of insulation) leads to a further reduction of less than 1% in the total LC impacts and about 1-3% in the operational emissions. The environmental benefits (reduction in total LC impacts) are very low (reduction of about 5%) for thicknesses greater than 80 mm (for both roof and exterior walls).

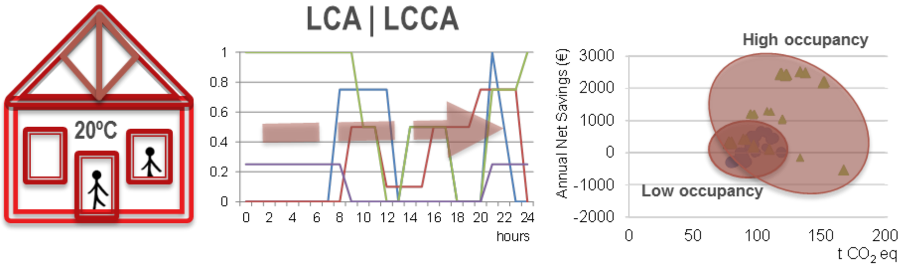
2.4 Concluding remarks

This chapter presented an environmental and energy life-cycle assessment of alternative retrofit strategies on the roof and exterior walls of a Portuguese single-family house and an apartment, combining four insulation levels for the roof (0, 40, 80 and 120 mm) and three for the exterior walls (0, 40, 80 and 120 mm). These buildings are both representative of the Portuguese building stock in old city centers dating from the beginning of the 20th century and are also located in a World Heritage protected site. Such sites have several imposed constraints on the building stock, such as volume, façade height, materials and design. Moreover, buildings under historic or architectural protection are not obliged to comply with minimum energy requirements, as retrofits could affect their architectural and historic value. The main features of both buildings are very specific from their construction period, with massive stone walls (50 cm thick on average), single-glazed wooden windows and a conventional wood-frame roof. Five environmental categories – climate change (greenhouse gas emissions), ozone depletion, terrestrial acidification, freshwater eutrophication and marine eutrophication – and non-renewable primary energy were evaluated to identify hot spots and optimal insulation thicknesses. This assessment showed that additional insulation levels in temperate climates could lead to higher embodied impacts, without significant reduction in operational emissions, and greater total life-cycle impacts. Furthermore, a tipping point can be found where total life-cycle impacts are minimized and an insulation level threshold is revealed (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off).

Drawing on the results, some recommendations can be provided to enhance the environmental performance of building retrofits in historic city centers with characteristics of the beginning of the 20th century (50-cm massive stone walls) and low occupancy in Mediterranean climates, pointing to the use of about 40 mm (apartment) and 80 mm (single-family house) of insulation as a threshold for the roof retrofit and about 60-80 mm (for both apartment and single-family house) in exterior-wall retrofits.

3 Residential building retrofits addressing occupancy: an integrated cost and environmental life-cycle analysis

Based on:
Rodrigues C., Freire F. (2017). Building retrofit addressing occupancy: an integrated cost and environmental life-cycle analysis. Energy and Buildings, 140, 388-398. doi: 10.1016/j.enbuild.2017.01.084



ABSTRACT The main goal of this chapter 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 chapter builds on the environmental LCA presented on the previous chapter. This chapter 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 LC environmental and cost impacts. Moreover, it investigates how occupancy influences the economic and environmental performance of building retrofit strategies and supports decision-making.

3.1 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. 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 considered.

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 (Hernandez and Kenny 2010; Nordby 2011; Rodrigues and Freire 2014a). De Meester et al. (2013) and Azar & Menassa (2012) 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. (2016) addressed occupant behavior in an LC perspective aimed at framing resident occupancy and heating/cooling habits compared to current standards that assume a permanent occupancy. The Southern European climate (mild Mediterranean) has 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 (Monteiro and Freire 2012; Silvestre et al. 2013; Bastos et al. 2014; Bastos et al. 2015; Monteiro et al. 2016).

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 (Hernandez and Kenny 2010; Rodrigues and Freire 2014a; Rodrigues and Freire 2017). Moreover, occupancy has not been addressed in the LCA literature of building retrofits. Rodrigues and Freire (2014a) concluded that for the roof retrofit of a single family house in Portugal, the reduction in operational energy due to additional thermal insulation can be low relative to the increase in the embodied impacts.

The economic feasibility of retrofit strategies is typically calculated for the investment in a specific solution, seeking reduced 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. (2010) 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). Dylewski and Adamczyk (2012) defined indicators for the economic assessment of external-wall insulation of the building, such as: NPV, profitability indicator and payback period. Recently Mata et al. (2015) 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 (Tadeu et al. 2015). Lollini et al. (2006) studied the optimization of opaque components regarding energy, environmental and economic impacts. Anastaselos et al. (2009) created a tool to perform an integrated energy, economic and environmental evaluation of thermal insulation solutions. To manage the reduction of LC environmental impacts effectively, Ibn-Mohammed et al. (2014) linked costs with both operational and embodied emissions to produce optimal decisions in the selection of retrofit strategies. Tadeu et al. (2015) 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 integration of cost and environmental impact assessments of a whole-building retrofit has rarely been presented in the literature and has never taken into consideration the preferences and behavior of the occupants.

3.2 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 the semi-detached house presented in Chapter 2. The main features of the house are load-bearing stone masonry walls (average thickness 50 cm), single-glazed wood windows and a conventional 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 3.1. The base-case occupancy scenario was defined by a four-person family with low occupancy, and set-points fixed at 20ºC (heating) and 25ºC (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 (External Thermal Insulation Composite System - ETICS), as well as new interior and exterior finishes (base plaster and gypsum plaster board). The thermal insulation material was expanded polystyrene (EPS), one of the most common insulation materials in the Southern Europe construction sector. All scenarios assumed the replacement of the existing single-glazed windows by double-glazed windows and the existing roof by a new wooden roof and the incorporation of a HVAC (heating, ventilation and air conditioning) system.

Table 3.1 Occupancy scenarios and retrofit insulation levels

Occupancy scenarios			**Insulation thickness (mm)**	
Type of use	Family size / Number of workers	Occupancy level[1]	Roof	Exterior wall
Residential	4-person	Low (LO)	0; 40; 80; 120	Inside: 0, 40, 80 Outside: 40
		High (HO)		
Office	20 people	Office[2]		

[1] Number of occupied hours (number of people*hours)

[2] HVAC activated during working hours (9am-6pm)

3.2.1 Life-cycle model and inventory

The LC model developed includes the following main processes: removal of the original components, construction (roof and exterior-wall retrofit) and use (heating, cooling and maintenance). A process-based LC inventory was implemented to compare the alternative scenarios. As the scope is to access retrofit, the initial construction and previous use of the building were not considered. Nor were the end-of-life stage of the new components considered (dismantling scenarios and waste treatment after service life) because this cannot be accurately predicted due to the long life of buildings and is considered of minor importance for the residential sector, accounting for less than 5% of total LC impacts (Nemry et al. 2008; Ortiz et al. 2010). The demolition phase which represents the end-of-life of the existing components replaced during retrofit. A corrective maintenance strategy was assumed which includes the conservation of the interior and exterior finishes of the building throughout the 50-year life span. The components are only replaced in case of deterioration: interior painting of walls, varnishing of wood surfaces and plaster board replacement (every 20 years). Technical data from scientific literature (Kellenberger et al. 2007; Althaus et al. 2010; Moreno Ruiz et al. 2014), producers and contractors were gathered to calculate the quantities of materials required for each retrofit strategy (foreground data). The main inventory data regarding material processing (background data) was obtained from Kellenberger et al. (2007). The functional unit selected is one square meter of living area over a period of 50 years.

3.2.1.1 Demolition phase

The removal of the original components included dismantling and transport for an end-of-life facility (recycling or incineration). The original wood frame roof was completely removed and replaced by a new roof. Exterior-wall finishes were also partially removed (both inside and outside) depending on the level of degradation. Transportation distances, from the building site to the recovery (recycling or incineration) sites, were calculated based on average distances to the nearest local end-of-life facilities.

3.2.1.2 Construction phase

The construction phase included the production of materials and transport to the site, as well as on-site processes: carpentry/joinery, assembly of the wood structure, insulation, tile placement (roof), roof's interior finish (gypsum plaster board) and exterior-wall interior and exterior finishes. The delivery of construction materials to the building site assumed lightweight (<3.5t) transportation or truck (3.5-16t) with European-fleet average characteristics. Transportation distances from the production site to the building site were calculated based on average distances from local material producers and contractors. Table 3.2 presents the main inventory for the roof and exterior-wall retrofits.

Table 3.2 Building retrofits inventory

	Material	Total Weight (kg)	Transport (tkm)
Roof retrofit			
Exterior Covering	- ceramic tiles	2940	294
Wood Frame	- primary and secondary structure[1]	2558	459.9
Interior Finish	- gypsum plaster board	2117	254.8
Thermal Insulation (three alternative levels)	- expanded polystyrene 40 mm	52.9	6.9
	- expanded polystyrene 80 mm	105.8	13.8
	- expanded polystyrene 120 mm	158.8	20.6
	- vapor barrier	18	5.6
Exterior-wall retrofit			
Inside insulation scenarios			
Exterior Finish	- base plaster	4410	7.1
Interior Finish	- gypsum plaster board	6300	731
Thermal Insulation (two alternative levels)	- expanded polystyrene 40 mm	158	20
	- expanded polystyrene 80 mm	315	41
Outside insulation scenarios			
ETICS[2]	- base plaster	4410	7.1
	- glass fiber	35.28	0.1
	- adhesive mortar	987	1.6
Interior Finish	- gypsum plaster board	6300	731
Thermal Insulation	- expanded polystyrene 40 mm	158	20

[1] Primary structure: rafter and trusses; Secondary structure: lath and counter-lath strips

[2] External thermal insulation composite system

3.2.1.3 Use phase

The use phase includes heating and cooling, and maintenance. A thermal dynamic simulation model was implemented to calculate the energy needs of the whole building. Each room (kitchen, dining room, living room and bedrooms) was modeled as a thermal zone with a specific thermal behavior and occupancy pattern (internal heat gains and occupancy schedules). Details on the energy model are described in Rodrigues and Freire 2014a and in section 2.2.2 of Chapter 2. Two residential levels of occupancy were assessed combining low and high occupancy levels (LO and HO) with low and high HVAC operation hours. Each occupancy level was characterized by occupied hours: low (14h) or high (20h)) and the HVAC operation hours (low (8h) or high (24h)). Figure 3.1 shows the occupancy and HVAC operation hourly rates over 24h for weekdays and weekends. An office-use pattern (five working days in a small office building with permanent occupancy of 20 people) was also assessed assuming eight hours of permanent occupancy with HVAC activated. The number of people varied according to the occupancy schedule.

A sensitivity analysis on the set-point temperatures was performed assuming alternative heating and cooling set-points: 18ºC, 20ºC and 22ºC for heating combined with 23ºC, 25ºC and 27ºC for cooling. The set-points fixed at 20ºC (heating) and 25ºC (cooling) defined as the base-case assume standard thermal comfort conditions. The scenario with set-points fixed at 18ºC (heating) and 27ºC (cooling) represents less demanding thermal comfort conditions (higher discomfort) and the scenario with set-points fixed at 22ºC (heating) and 23ºC (cooling) represents more demanding thermal comfort conditions (lower discomfort). A sensitivity analysis on the family size was also performed assuming a two-, three-, four-, five-, and six-person family.

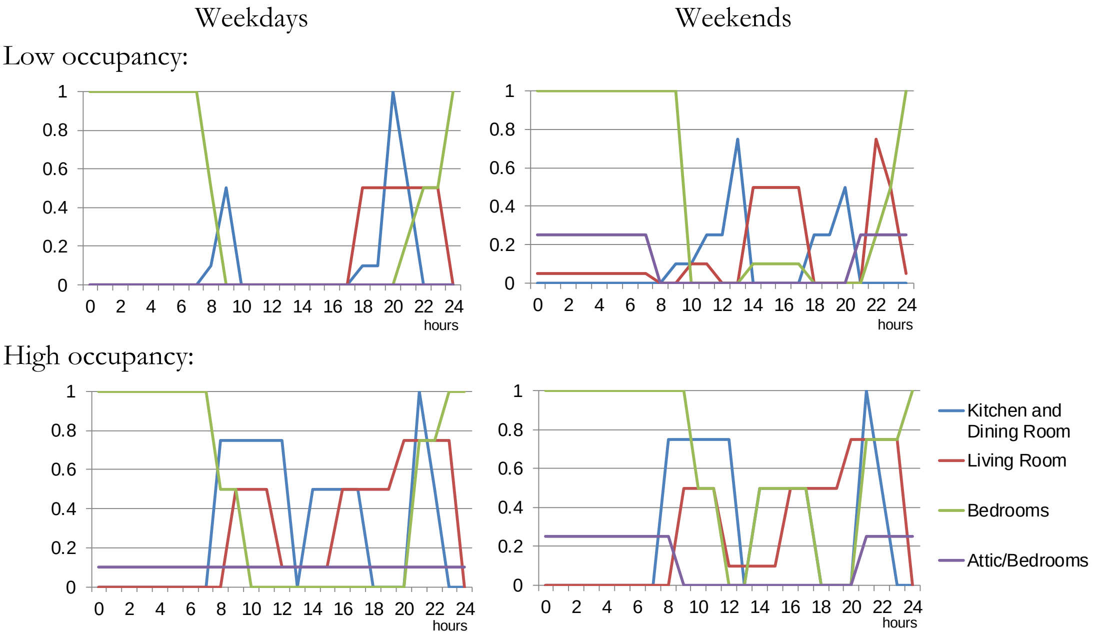


Figure 3.1 Residential occupancy schedules (operation rates per hour)

Table 3.3 presents the operational energy needs (heating and cooling) for low and high residential occupancy and office use per exterior-wall and roof-insulation levels. Results show that higher occupancy leads to 58-144% higher cooling needs and 28-57% higher heating needs. Office use leads to 16-30% lower heating needs and 24-89% higher cooling needs. Outside insulation leads to higher heating needs and lower cooling needs than inside insulation. Moreover, inside insulation presents larger differences in heating needs, from high to low occupancy, indicating that the occupancy level has greater influence over energy use in an internally insulated space.

Table 3.3 Operational energy needs (heating and cooling) for low and high residential occupancy (four-person family), and office use, and relative differences (in percentage) to the low residential occupancy per exterior-wall and roof insulation levels in kWh/(m^{2}year)

Insulation thickness (mm)		Residential (low occupancy)		Residential (high occupancy)				Office use			
Roof	Exterior wall	Heating	Cooling	Heating		Cooling		Heating		Cooling	
no retrofit		46.6	3.3	62.6	34%	8.0	144%	32.8	-30%	5.2	59%
0	0	38.5	3.8	60.4	57%	7.5	96%	32.4	-16%	5.0	31%
	40	30.9	4.4	42.9	39%	8.2	86%	24.5	-21%	5.5	24%
	80	29.4	4.4	40.1	37%	8.4	88%	23.3	-21%	5.5	25%
	40 out	32.4	3.7	43.4	34%	7.9	111%	25.2	22%	5.3	43%
40	0	35.7	3.5	53.1	49%	5.5	58%	29.7	-17%	4.5	30%
	40	27.0	3.5	35.6	32%	6.2	77%	21.4	-21%	5.0	43%
	80	25.5	3.5	32.8	29%	6.3	81%	20.1	-21%	5.1	45%
	40 out	28.3	2.8	36.1	28%	5.8	110%	21.9	-22%	4.8	75%
80	0	35.0	3.3	52.9	51%	5.3	60%	29.2	-17%	4.5	35%
	40	26.3	3.3	35.3	34%	6.0	80%	20.8	-21%	5.0	49%
	80	24.7	3.3	32.5	32%	6.1	83%	19.5	-21%	5.0	50%
	40 out	27.5	2.6	35.8	30%	5.6	117%	21.3	-22%	4.8	84%
120	0	34.7	3.2	52.7	52%	5.2	61%	28.9	-17%	4.4	38%
	40	25.9	3.3	35.1	36%	5.9	81%	20.5	-21%	4.9	52%
	80	24.3	3.3	32.4	33%	6.0	84%	19.3	-21%	5.0	53%
	40 out	27.1	2.5	35.7	32%	5.5	120%	21.0	-22%	4.8	89%

3.2.1.4 LCIA methods

Two complementary methods were applied. Cumulative Energy Demand (CED) (Hischier et al. 2010) to measure the non-renewable primary energy (NRPE) to address energy resource depletion, and ReCiPe (Goedkoop et al. 2013), to calculate five environmental impact categories: Climate Change (CC, following IPCC 2013 for a time horizon of 100 years), Ozone Depletion (OD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE) and Marine Eutrophication (ME). Environmental impacts are presented at midpoint level (problem-oriented) to avoid the high uncertainty associated with impacts at endpoint level (damage-oriented).

3.2.2 Life-cycle cost model and inventory

Life-cycle cost assessment (LCCA) was performed using the Equivalent Annual Cost (EAC) method to compare different retrofit strategies addressing the relevant costs: construction site preparation and preliminary works, construction (retrofit), maintenance, repair and replacement costs, and operational energy costs. Calculating EAC is useful to compare alternative retrofit strategies since it converts the different costs to an equivalent annual amount, using a discount rate in a similar way to other investment evaluation methods, such as the NPV. A 2% discount rate is assumed reflecting the current interest rates for a long-term current-market-value mortgage. The implementation framework of the cost-optimal methodology established by the European Commission (Buildings Performance Institute Europe (BPIE) 2013) to determine a cost-optimal level of minimum energy performance of buildings suggests a 1-3% discount rate taking into account the current economic perspective. The annual net savings of each retrofit strategy were calculated by comparing the EAC of retrofit with the EAC of no-retrofit, as follows:

Annual net savings of retrofit strategy (i) = – [*EAC retrofit strategy (i) – EAC no-retrofit*] = (Eq. 3.1)
=*EAC no-retrofit – EAC retrofit strategy (i)*

The no-retrofit scenario assumes the single-family house before retrofit, with single-glazed windows, building envelope without insulation, an electrical heating system (Joule effect, i.e. coefficient of performance of one) and without cooling. There is no initial investment so the only costs considered are maintenance and heating. Table 3.4 presents the retrofit costs, including the common costs to all scenarios and the insulation cost of each option. Roof retrofit incorporating insulation has an additional cost of 72-90% compared to roof retrofit without insulation. The no-insulation option includes the ceramic tiles, battens, vapor control layer, and labor costs while the other insulation options (40, 80 and 120 mm) include these common costs, plus the insulation material cost. The roof insulation material cost represents an increase of 5%. The same occurs with exterior-wall insulation alternatives. Exterior-wall retrofit with insulation is 1.5 to 5 times more expensive than exterior-wall without insulation (just repairing and replacing finishes). From no insulation to 40 mm insulation, the additional costs include gypsum plasterboard or OSB (needed to accommodate the insulation layer), as well as labor costs, while the other insulation options include these common costs plus the insulation material cost. The exterior-wall insulation material cost represents an increase of 12%.

Table 3.4 Retrofit costs and relative difference (in percentage) of alternative insulation options to the no-insulation option

	Surface (m^2)	Initial Investment		Maintenance costs per year[1]
Construction site preparation and preliminary works		5 650 €		-
Decommissioning / Demolition				
Roof decommissioning including transport to final disposal	84	1 900 €		-
Windows removal	27	150 €		-
Exterior walls plaster repairing and conservation	210	5 700 €		-
Windows stonework restoration, repairing and cleaning		1 100 €		-
Waste management		200 €		-
Construction / Retrofit				
Roof	84			
Structure		2 400 €		36 €
Alternative roof insulation options[2]:				
No insulation[3]		5 600 €		200 €
40 mm expanded polystyrene		9 650 €	(72%)	280 €
80 mm expanded polystyrene		10 100 €	(81%)	280 €
120 mm expanded polystyrene		10 608 €	(90%)	280 €
Exterior walls	210			
Exterior painting		2 250 €		200 €
Alternative exterior-wall insulation options[2]:				
No insulation[4]		2 100 €		5 €
40 mm expanded polystyrene placed inside		5 350 €	(158%)	10 €
80 mm expanded polystyrene placed inside		6 000 €	(188%)	10 €
40 mm expanded polystyrene placed outside (ETICS)		12 500 €	(500%)	60 €
Interior painting		2 100 €		210 €
Windows	28	12 150 €		150 €
Floor	70	1 300 €		-
HVAC Systems				
Air Conditioner		4 000 €		100 €

[1] 10-year running cost annualized

[2] The percentage inside brackets represents the relative difference of alternative insulation options to the no-insulation option.

[3] The no-insulation roof option includes: ceramic tiles, battens, vapor control layer, and labor costs.

[4] The no-insulation exterior-wall option includes: repairing existing plasters and finishes, new base plaster layer, and labor costs.

Table 3.5 presents the total retrofit costs for each retrofit strategy, which include common costs associated with site preparation, demolition, window replacement, floor retrofit and HVAC systems. The energy cost of cooling was not considered in this analysis since there is no cooling system in the original house (the no-retrofit option). The costs of investment (for all retrofit options presented in Table 3.4) and maintenance (after retrofit) were gathered from manufactures and contractors' information as well as from a database (www.cype.com) with current market costs for the Portuguese context. The electricity costs were obtained from the Portuguese Regulator for Energy Services (ERSE) (Entidade Reguladora dos Serviços Energéticos 2009).

Table 3.5 Breakdown of costs for the alternative insulation retrofit strategies and the no-retrofit option

Insulation thickness (mm)		**Initial Investment**	**Maintenance costs per year**	**Energy costs per year [€]**		
				Occupancy scenarios		
Roof	Exterior wall	[€]	[€]	Residential Low occupancy	Residential High occupancy	Office
no retrofit		-	409	698	938	491
0	0	46 423	1 102	577	904	485
	40	49 700	1 107	462	642	367
	80	50 335	1 107	440	601	349
	40 (out)	51 209	1 159	484	650	377
40	0	50 459	1 188	534	795	444
	40	53 736	1 193	404	532	320
	80	54 371	1 193	381	491	301
	40 (out)	55 245	1 159	423	541	328
80	0	50 942	1 188	524	791	437
	40	54 219	1 193	393	528	312
	80	54 854	1 193	370	487	293
	40 (out)	55 728	1 245	412	536	319
120	0	52 192	1 188	519	789	433
	40	55 469	1 193	388	526	307
	80	56 104	1 245	364	485	288
	40 (out)	56 978	1 102	406	534	315

Some retrofit benefits were not considered in this analysis because they are subjective and common in all the retrofit strategies, namely strategies that can promote greater thermal comfort and property value, which are important benefits that could result in additional cash-flows, for example if the house were rented or sold. As these are subjective and beyond the scope of the study they are not accounted for in this analysis, but discussed in Section 3.2 together with the results.

The marginal benefit of adding 40 mm insulation was also calculated, expressed as:

$$\textit{Marginal benefit of additional 40 mm of insulation} = -\left[EAC\ (x+40\ mm) - EAC\ (x)\right] = EAC\ (x) - EAC\ (x+40\ mm) \tag{Eq. 3.2}$$

where x can vary between 0 (no insulation) and 80 mm for the roof and 0 to 40 mm for the exterior walls.

It should be noted that the marginal benefit of adding an extra 40 mm of insulation is not linear since adding 40 mm to a non-insulated wall increases the investment cost by about 70%, but leads to a reduction of 15-30% (depending on occupancy pattern) in the energy needs. On the other hand, adding 40 mm to a wall with 40 mm of insulation (making 80 mm in total) results in about 10% higher investment but leads to an energy needs reduction of 6-7%.

3.3 Results and discussion

This section presents the main results for the retrofit strategies and occupancy scenarios assessed. Section 3.3.1 presents the environmental LC impact assessment and Sections 3.3.2 the LCCA and marginal savings. Sensitivity analyses for the set-point and family size are discussed in Section 3.3.3.

3.3.1 Environmental life-cycle impact assessment

Environmental LC impacts for the various retrofit scenarios are presented in Figure 3.2, showing that high residential occupancy has greater environmental impacts than low residential occupancy or office use due to higher heating and cooling needs. Moreover, additional insulation levels lead to considerably higher benefits (10-45% of impact reduction) for high occupancy than low occupancy (5-24%). For example, the incorporation of 40 mm exterior-wall insulation leads to an LC impact reduction from 20% (CC, NRPE and OD) to 61% (ME) in high occupancy, but from 3% (OD) to 32% (ME) in low occupancy and office use.

Additional roof insulation results in a reduction of 15% to 19% of total LC impacts in high occupancy, but only 1-3% in low occupancy and office use. The LC impact reduction of additional 40 mm of exterior-wall or roof insulation (80 mm in total) is only 1-5% (in all occupancy scenarios). The shape of the results for the six impact categories presented in Figure 3.2 is similar.

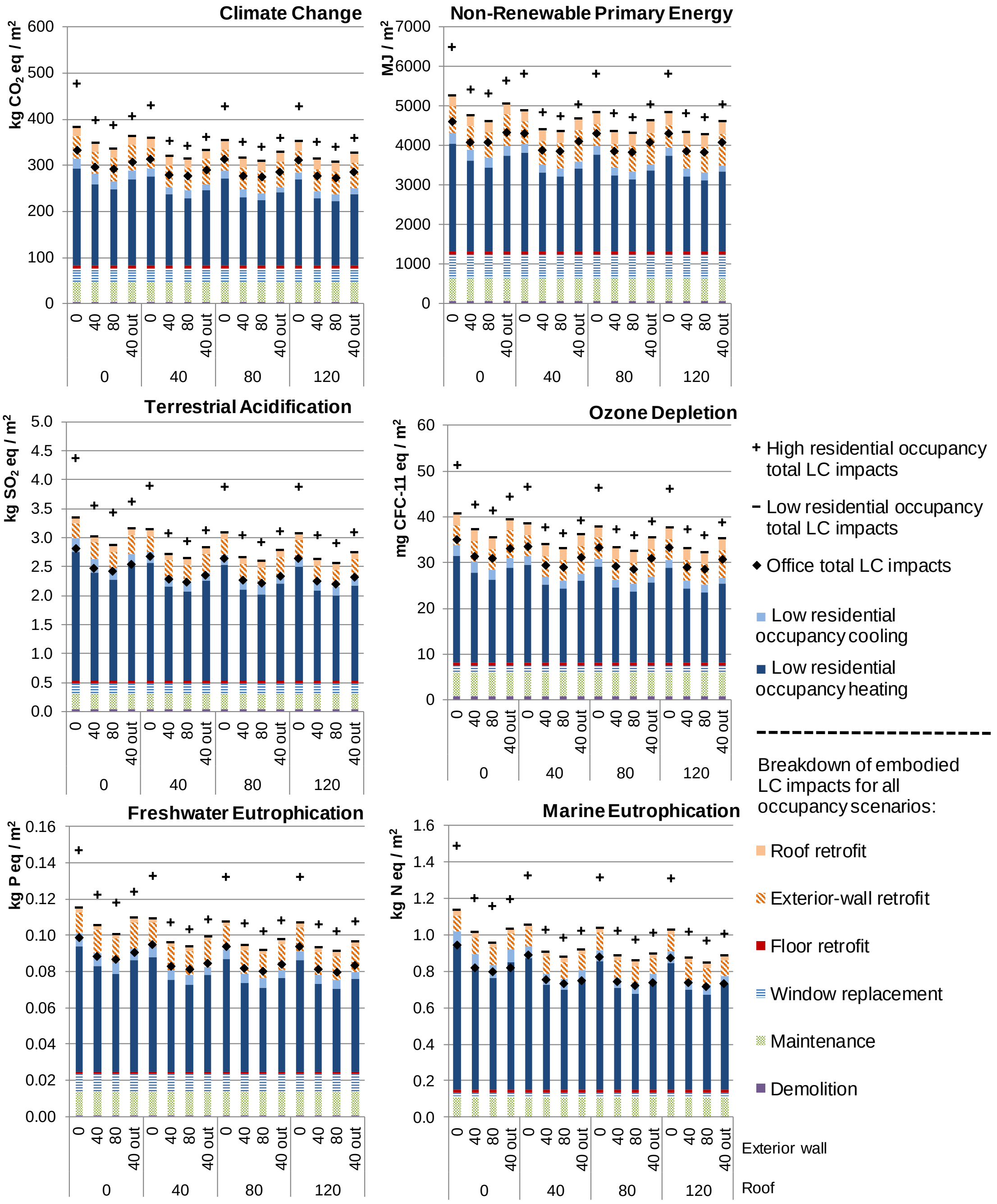


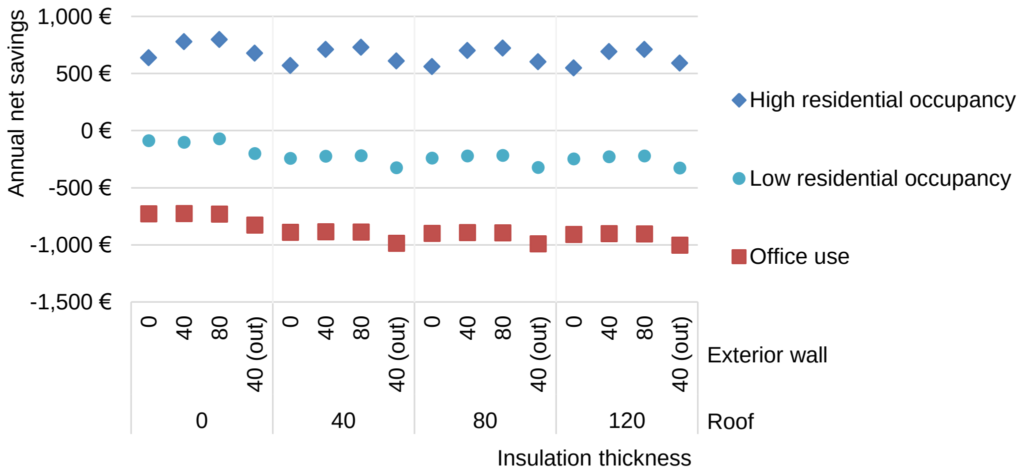
Figure 3.2 Life-cycle impact assessment of exterior-wall and roof retrofit insulation strategies for three occupancy levels: low residential, high residential and office use (per one square meter of living area over a period of 50 years)

Office use presents lower heating and cooling impacts than low residential occupancy and consequently lower total LC impacts in all impact categories. The lower operational energy impact in office use results from the fact that the building is mainly occupied during the day when outside temperatures are higher, leading to lower heating needs during the winter. Higher outside temperatures during the day in the summer do not result in significant cooling needs (as shown in Table 3 in Section 2.1) as the overheating period in this building is very short (high heat gain coefficient). The breakdown of total LC impacts includes the removal of the original components (demolition), construction of each retrofit strategy, maintenance (material replacement) and operational energy (heating and cooling). Embodied impacts contribute to 26-57% of total LC impacts in low occupancy and 18-52% in high occupancy. In office use, embodied impacts offset the operational energy impacts in all insulated scenarios for CC, NRPE, OD and FE and contribute to 30-63% of total LC impacts.

3.3.2 Life-cycle costing

This section presents the LCCA results, including a discussion of the marginal benefit of additional insulation levels. LCCA was performed to compare the various retrofit strategies to a no-retrofit option. Figure 3.3 shows that high residential occupancy presents higher net annual savings (up to about 800€). In low residential occupancy and office use, none of the retrofit strategies present positive savings. For all types of occupancy, inside insulation presents higher savings than outside insulation. For low residential occupancy and office use, 40 mm of outside exterior-wall insulation is worse than no exterior-wall insulation.

Roof insulated retrofit strategies present lower net annual savings than the option without roof insulation. As mentioned in section 3.2.2, the LCCA only addresses the retrofit benefits associated with the reduction of heating energy costs. However, if other more subjective retrofit benefits would have been accounted for (e.g. indoor environmental quality and property value increase), the annual net savings for low residential occupancy and office use would become positive, if just the property value were to represent a positive cash flow of at least 100€/month.



● Low residential occupancy ♦ High residential occupancy ■ Office

Figure 3.3 Annual net savings of exterior-wall and roof retrofit insulation strategies (relative to no-retrofit) assuming alternative occupancy scenarios: residential low and high occupancy, and office use

Insulation marginal analysis

Figure 3.4 shows the marginal benefit of additional 40 mm insulation, disregarding the common retrofit measures (window replacement, floor retrofit and HVAC incorporation). The results show that exterior-wall and roof retrofit strategies have a different behavior when additional insulation levels are considered. Additional insulation in exterior-wall retrofit is always beneficial, but the marginal benefit is very different depending on the type of occupancy and use. High residential occupancy has a positive marginal benefit when including the first 40 mm of insulation but almost zero for the second 40 mm layer, while low residential occupancy and office use always present zero marginal benefits.

An unexpected behavior of the marginal benefit is observed for the roof when insulation levels increase. The marginal benefit for the first 40 mm of insulation is negative, while for the second and third layer of 40 mm it is about zero. The energy savings does not offset the additional material costs. The nearly-zero marginal benefit of roof insulation in this particular house can be justified by the fact that it is a four-story house and the top floor is used intermittently, mainly for storage or occasional visitors. In houses with one or two floors, the roof insulation would have a much more prominent influence.

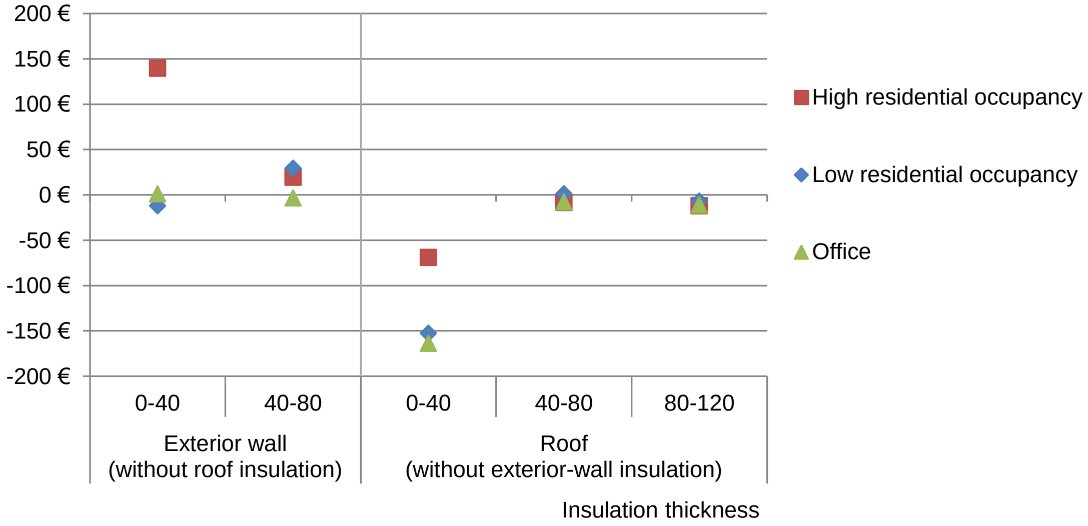


Figure 3.4 Marginal benefit of additional 40 mm insulation for the exterior-wall and roof retrofit (discount rate of 2% and base-case occupancy scenario)

3.3.3 Sensitivity analysis

3.3.3.1 Set-point

Alternative set-points for low and high residential occupancy and office use were assessed in terms of environmental and cost impacts. The scenario with set-points fixed at 18ºC (heating) and 27ºC (cooling) represents lower thermal comfort conditions (higher discomfort), while the scenario with set-points fixed at 22ºC (heating) and 23ºC (cooling) represents higher thermal comfort conditions (lower discomfort). The set-points fixed at 20ºC (heating) and 25ºC (cooling) are defined as the base case, assuming standard thermal comfort conditions.

Figure 3.5 shows that higher thermal comfort lead to higher LC impact differences relatively to the base case than lower thermal comfort (in all occupancy levels). Lower thermal comfort leads to an LC impact reduction of 7% (low residential occupancy) to 29% (high residential occupancy) and higher thermal comfort leads to an increase of 5% (low residential occupancy) to 27% (office) when compared to the base case (standard comfort conditions). Differences within impact categories range between 1-5%. In office use, a reduction of 21-45% in total LC impacts was calculated for the lower thermal comfort, and an increase of 17-28% for the higher thermal comfort, when compare to the base case.

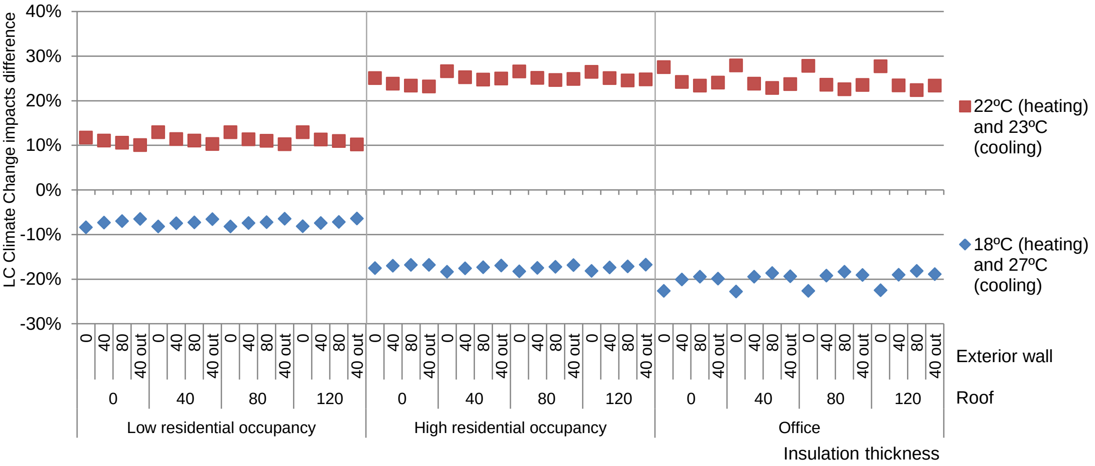


Figure 3.5 Variation (%) of LC climate change impacts of alternative set-point scenarios relative to base case set-points (20ºC for heating and 25ºC for cooling) for roof and exterior-wall insulation retrofit strategies for alternative occupancy levels (low and high residential occupancy, and office use)

Figure 3.6 shows that high residential occupancy combined with higher thermal comfort presents the higher savings due to additional insulation (annual net savings of about 2500€). In lower thermal comfort scenario, there is no benefit in incorporating insulation as it always leads to lower net annual savings than the base case (negative in the case of low residential occupancy and office). In this case, the window replacement and the incorporation of an HVAC system (common in all retrofit strategies) presents higher savings than additional insulation (annual net savings of about 355€ to 595€).

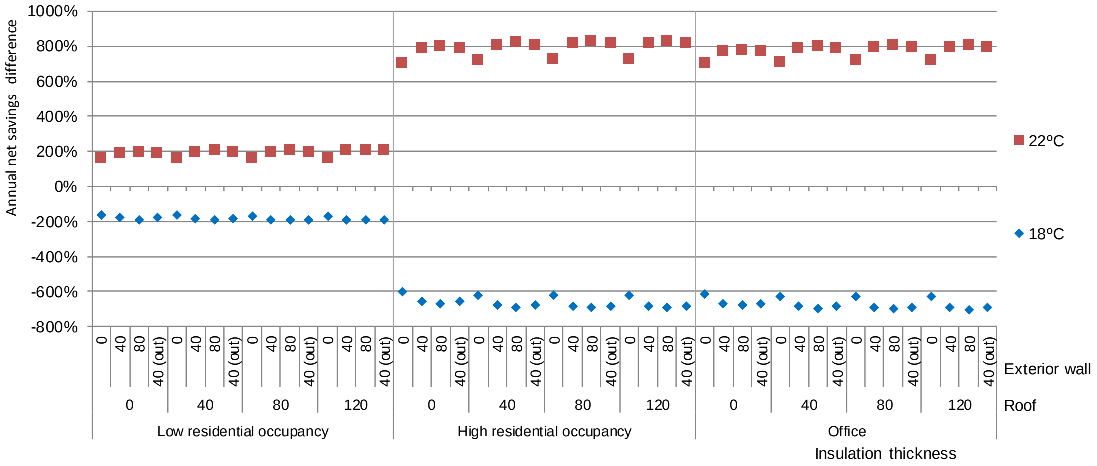


Figure 3.6 Variation (%) of annual net savings of alternative heating set-point scenarios (18ºC and 22ºC) relative to base-case set-point (20ºC) for roof and exterior-wall insulation retrofit strategies for alternative occupancy levels (low and high residential occupancy, and office use)

3.3.3.2 Family size

Alternative family sizes (two-, three-, five- and six-person family) with low and high occupancy were compared to a four-person family assuming standard thermal comfort conditions. LCIA results were calculated for one square meter of living area over a period of 50 years showing that two- and three-person families lead to an LC impact increase of about 100% and 35%, respectively. Five- and six-person families lead to LC impact decrease of 20% and 35%, respectively. There is an increase of 11-34% from low to high occupancy for all types of families. The marginal benefit of additional insulation varies from 1% (low residential occupancy) to 10% (high residential occupancy). All impact categories present the same relative differences to the base case.

Figure 3.7 shows that smaller family types (two- and three-person families) lead to higher savings than bigger families. Smaller families (lower internal loads) lead to higher energy needs that consequently promote higher savings. Low residential occupancy presents negative savings in all family scenarios. The highest annual net savings are presented in two- and three-person families in high residential occupancy (400€ to 950€). The relative differences to the base case (four-person family) are higher in low residential occupancy than in high residential occupancy in all family types, meaning that family size has higher influence in low occupancy levels.

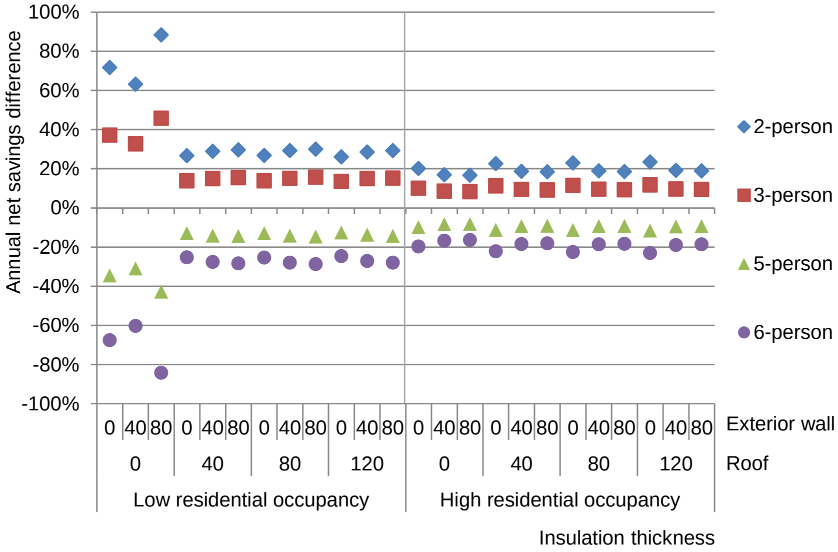


Figure 3.7 Variation (%) of annual net savings of alternative family-size scenarios relative to base-case family size (four-person family) for roof and exterior-wall insulation retrofit strategies, and alternative occupancy levels (low and high residential occupancy)

3.4 Concluding remarks

An integrated approach combining environmental LCA, LCCA and thermal dynamic simulation was implemented to assess the performance of retrofit strategies for historic buildings in Southern European climates assuming different occupancy scenarios. An LC model was implemented for a single-family house constructed at the beginning of the 20th century in the city center of Coimbra, Portugal. Three occupancy scenarios (defined by type of use and occupancy level) were created combining alternative roof and exterior-wall insulation levels.

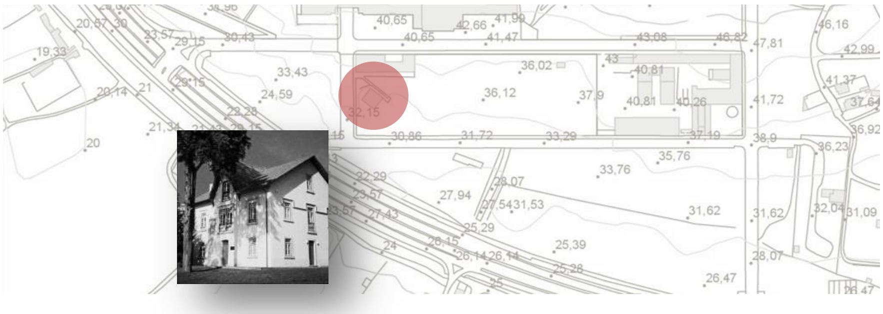
LC impacts were calculated for five environmental categories and non-renewable primary energy showing that the reduction of impacts due to retrofit is larger for high occupancy than for low occupancy. Additionally, increasing the comfort conditions in office use leads to higher LC impact, compared to residential uses. Insulation level thresholds (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off) were identified for exterior-wall retrofit (60-70 mm for all occupancy patterns) and roof retrofit (90-100 mm for low occupancy, plus 80-90 mm for high occupancy and office use).

The EAC method was employed to calculate annual net savings for the alternative retrofit scenarios showing that high residential occupancy presents higher net annual savings (up to about 800€). For all types of occupancy, inside insulation presents greater savings than outside insulation. However, higher exterior-wall insulation levels present greater savings where the marginal benefit of additional insulation levels depends on occupancy level and use. There is no marginal benefit in additional roof insulation levels as the energy savings do not offset the additional material costs. This can be justified by the fact that in the four-story house, the top floor is used intermittently for storage or occasional visitors. In houses with one or two floors, the roof insulation would have a much more prominent influence.

Drawing on the results, some recommendations can be provided to enhance the retrofit environmental and cost performance of historic buildings from the beginning of the 20th century (e.g. 50-cm massive masonry stone walls) in Southern European climates. The retrofit strategies that maximize LC benefits depend on the type of use and occupancy level. Highly-insulated retrofit is more beneficial for high occupancy levels with higher thermal comfort conditions. Residential use with higher thermal comfort presents higher environmental and cost performances. In lower comfort conditions, there is no benefit from incorporating insulation. Inside insulation presents lower environmental impacts and higher savings than outside insulation. Exterior-wall with 40-mm insulation presents the highest marginal savings and the lowest environmental impacts. Even though roof insulation does not present relevant savings, it leads to lower environmental impacts; however, there is no advantage in roof insulation of more than 80 mm for all types of occupancy.

4 Adaptive reuse of buildings: eco-efficiency assessment of retrofit strategies for alternative uses of an historic building

Based on:
Rodrigues C., Freire F. (2017) Adaptive reuse of buildings: eco-efficiency assessment of retrofit strategies for alternative uses of an historic building. (in final review in Journal of Cleaner Production)



ABSTRACT This chapter investigates how occupancy and adaptive reuse influences the eco-efficiency performance of building retrofit strategies. An eco-efficiency assessment (integrating cost and environmental impacts) of alternative retrofit strategies is carried out for an office building. This type of historic building can be representative of South European climate buildings from the late 1800s to the early 1900s. A comprehensive analysis of retrofit strategies (roof and exterior walls) combining alternative insulation levels and occupancy patterns is performed to identify opportunities to minimize life-cycle environmental and cost impacts. The potential improvements in energy efficiency and trade-offs between costs and environmental impacts are assessed to support the decision-making process.

4.1 Introduction

Adaptive reuse is a process of retrofitting old buildings for new uses. Historic buildings in European cities are often being retrofitted to be adapted as office buildings whilst keeping their historical value. The main challenge of adaptive reuse is to reconcile historic preservation and sustainable design. Historic buildings encompass various construction techniques and materials, depending on the construction period and/or geographical zone. Major building retrofits are costly and require important quantities of material, but different strategies can be adopted to achieve an optimum balance between initial investments, energy cost savings and minimization of environmental impacts during the building life-cycle.

Environmental LCA and LCCA methodologies have been widely used to assess the LC impacts and cost of buildings; however, they have been mainly focused on residential buildings. In one of the first studies published on LCA of buildings, Cole and Kernan (1996) assessed the LC energy of a three-story generic office building for alternative wood, steel and concrete structural systems. After that, a number of LCA studies were published on new commercial buildings but mainly focused on large buildings (> 500 m^2) (Cole and Kernan 1996; Yohanis and Norton 2002; Van Ooteghem and Xu 2012; Azari 2014). Azari (2014) carried out an integrated energy and environmental LCA of office building envelopes by conducting a comparative assessment of several envelope scenarios (insulation material, window-to-wall ratio, window-frame material, and double-glazing cavity gas) revealing that scenarios with low-to-medium window-to-wall ratio and fiberglass window frame result in the lowest impacts. LC carbon and cost analysis of energy efficiency measures in new commercial buildings (Kneifel 2010a) was performed to estimate energy savings, carbon emission reduction, and cost-effectiveness of energy efficiency measures using an integrated design approach, and estimate the implications from of carbon emission costs. Kneifel (2010a) concluded that energy-efficiency measures not only present cost and energy savings, but also reduce the carbon footprint of a building by 16%, on average.

Very few studies have addressed commercial building retrofits. Scheuer et al. (2003) implemented an LC model to a university building in Michigan, USA, in order to evaluate the primary energy intensity during its life span. Recently, Van Ooteghem and Xu (2012) concluded that the roof alone accounts for around 50% of the total embodied energy and global warming potential in single-story retail buildings in Canada. An energy retrofit of a commercial building was performed by Aste and Del Pero (2012) and highlighted that a reduction in primary energy use by 40 % can be achieved by passive strategies alone on the building envelope, without HVAC, lights, or other technical systems. From an economic perspective, Chidiac et al. (2011) proposed a screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings. The selection of an optimal set of energy retrofit measures is influenced by climate, occupancy, heating and cooling systems, envelope properties and building geometry. An historic public building was addressed by Ascione et al. (2015) in an energy and cost perspective.

None of the reviewed articles relates environmental and cost impacts by means of an eco-efficiency analysis. Within the field of sustainable construction, eco-efficiency analyses can be used to facilitate the identification of environmentally and economically optimal construction systems/materials. However, very few studies have addressed eco-efficiency in the building sector and none regarding the whole building. Some, though, have focused on building materials (Zabalza Bribián et al. 2011; Ibáñez-Forés et al. 2013), as well as on specific building systems, such as partition walls (Ferrández-García et al. 2016).

Adaptive reuse, which is a common practice in South European cities, has not been addressed in an integrated environmental and cost life-cycle perspective by examining alternative occupancy patterns, and particularly existing residential historic buildings adapted to commercial uses. Moreover, no eco-efficiency analysis has been performed on historic building retrofits to assess the most eco-efficient strategies based on the type of use and occupancy.

4.2 Materials and methods

An eco-efficiency assessment (integrating environmental impacts and costs) was performed for an historic building to assess alternative retrofit strategies and uses. LCA was applied to calculate the environmental impacts and LCCA to assess the annual net savings of each alternative (section 4.2.2). The eco-efficiency assessment examines the best alternatives in terms of environmental impacts and savings calculated using LCA and LCCA. A LC model was implemented for a single-family detached house from the beginning of the 20th century retrofitted to an office building. This building is located in Polo II, the new campus of the University of Coimbra (UC), and serves as the headquarters of the Institute for Interdisciplinary Research (IIIUC). According to EPBD, buildings are considered historic when they are officially protected as part of a designated environment or because of their special architectural or historical merit. This building belongs to the architectural heritage of the UC and it is under protection meaning that its character cannot be altered. The building is organized on three floors, with a finished attic on the upper floor. Even though the building is currently being used as office space, the analysis considers that the original building could have been retrofitted to be used as either a residential or an office building. Following that, two scenarios for the layout design of the building were considered, one for residential use and another for office use. As an office building, the ground floor includes offices, restrooms, a storage room and a living area, the first floor includes offices and a workshop/conference room, and the second floor includes a workshop/conference room, offices and a storage area. As a single-family house, the ground floor includes a kitchen, living room and two small offices, the second floor includes four bedrooms, and the third floor includes a living area and storage area.

The original main features of the building are load-bearing stone masonry walls (average thickness 50 cm), single-glazed wood windows and a conventional wooden frame roof. Figure 4.1 shows pictures of the southeast, southwest and northeast façades, as well as the plans of the building. Table 4.1 presents the building's main characteristics and dimensions (number of floors, floor area, exterior walls area, roof area, windows area, and average floor height).

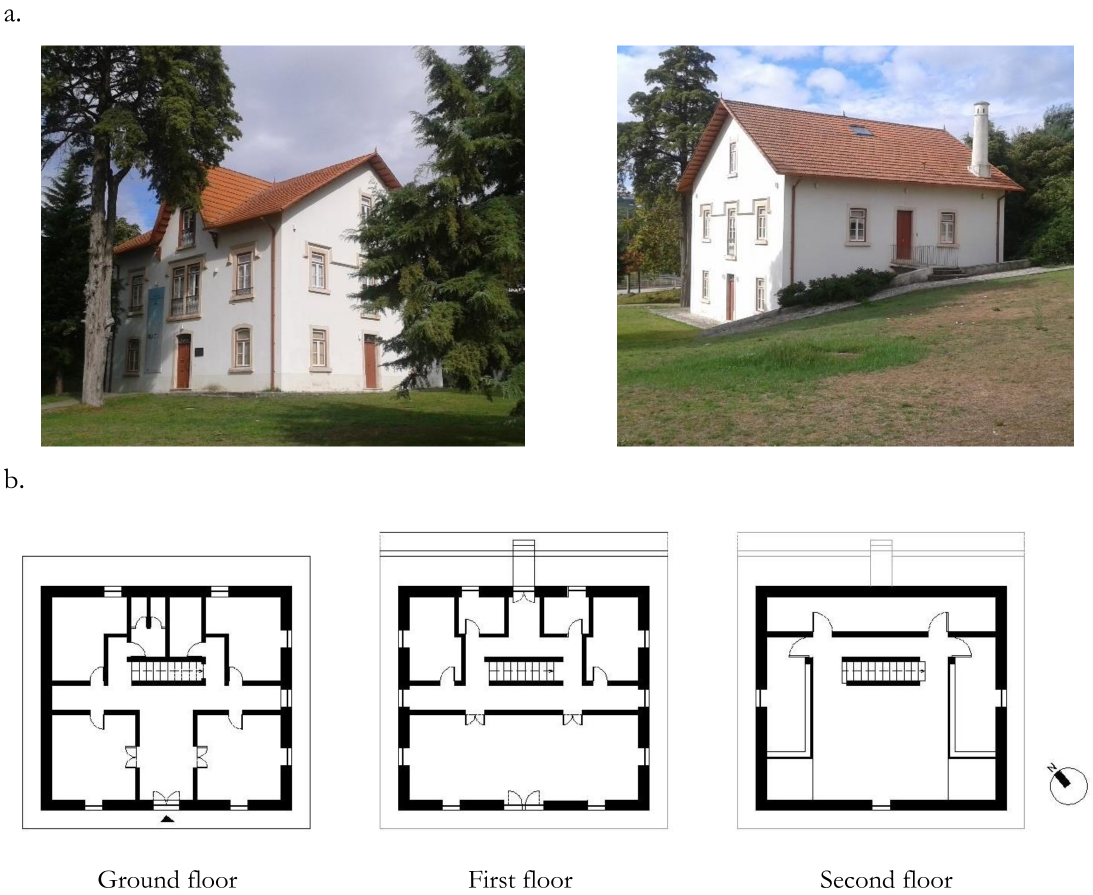


Figure 4.1 a) Southeast, southwest and northeast façades and b) plans of the current use as an office building (ground floor, first floor and second floor)

Table 4.1 Office building main characteristics

Number of floors	3
Floor area (m^2)	438
Exterior wall area (m^2)	412
Roof area (m^2)	177
Window area (m^2)	36
Average floor height (m)	3
Window-to-wall ratio	0.08
Wall-to-floor ratio	0.94

The roof retrofit incorporates the replacement of the existing roof frame material, interior and exterior finishes, as well as an additional thermal insulation layer. The exterior-wall retrofit incorporates an additional layer of thermal insulation on the interior surface, as well as new interior and exterior finishes (base plaster and gypsum plaster board). For both roof and exterior wall, the insulation material considered was expanded polystyrene (EPS), as one of the most common insulation materials used in Southern Europe construction. All scenarios assumed the replacement of the existing single-glazed windows by double-glazed windows and the incorporation of air conditioning.

Nine occupancy scenarios were defined to evaluate alternative retrofit strategies assuming various insulation levels. The insulation levels comprise alternative roof insulation levels (0, 40, 80 and 120 mm) and exterior-wall inside insulation levels (0, 40 and 80 mm). The occupancy scenarios are defined by level of residence (office use, and low and high residential occupancy) and set-points (18ºC, 20ºC and 22ºC for heating combined with 23ºC, 25ºC and 27ºC for cooling). Details of the occupancy scenarios are presented in Table 4.2. The current use of the building is defined by an office-use pattern (five working days assuming eight hours of permanent occupancy with HVAC activated), with set-points fixed at 20ºC (heating) and 25ºC (cooling).

Table 4.2 Retrofit occupancy scenarios with alternative insulation levels

Occupancy scenarios					**Insulation thickness (mm)**	
Type of use	Occupancy level[1]	Family size / Number of workers	Set-point		Roof	Exterior wall
			Heating	Cooling		
Residential use	Low (LO)	4-person	18ºC 20ºC 22ºC	27ºC 25ºC 23ºC	0, 40, 80, 120	0, 40, 80
	High (HO)					
Office use	Office[2]	20 people				

[1] Number of occupied hours (number of people*hours)

[2] HVAC activated during working hours (9am-6pm)

4.2.1 Life-cycle model and inventory

The LC model developed includes the removal of the original components, construction (roof and exterior-wall retrofit) and use phase (heating, cooling and maintenance). The previous uses of the building and its initial construction were not considered as the scope is to access retrofit. The end-of-life of the building was kept out of the scope because it cannot be accurately predicted due to the long life of buildings and is expected to have a small LC magnitude; for instance, it represented around 1–3.5% of total LC impacts in South European buildings (Nemry et al. 2008; Ortiz et al. 2010). However, this model included a demolition phase, which represents the end-of-life of the existing components replaced during retrofit. A process-based LC inventory was implemented to compare the alternative retrofit strategies. Technical data from scientific literature (Kellenberger et al. 2007; Althaus et al. 2010; Moreno Ruiz et al. 2014), producers and contractors were gathered to calculate the quantities of materials required for each retrofit strategy (foreground data). The main inventory data regarding material processing (background data) was obtained from Kellenberger et al. (2007). The functional unit selected is one square meter of living area over a period of 50 years, as also considered in the previous chapters.

4.2.1.1 Embodied inventory

The embodied inventory includes demolition, construction, and maintenance phases. The demolition phase comprises the dismantling of the original components, and transport to an end-of-life facility (recycling or incineration). The original roof was completely removed and replaced by a new wood-frame roof. Exterior-wall finishes were also removed (both inside and outside). Transportation distances, from the building site to the recovery (recycling or incineration) sites, were calculated based on local end-of-life facility location.

The construction phase includes the production and transportation of materials, as well as on-site processes: carpentry/joinery, assembly of the wooden roof structure, exterior-wall and roof insulation placement, roof tile placement, and roof and exterior-wall interior and exterior finishes. An additional 5% of materials were considered lost on site due to cutting and fitting processes. Lightweight (<3.5t) transportation or truck (3.5-16t) was assumed with European fleet average characteristics (Spielmann et al. 2007). Table 4.3 presents the bill of materials and transportation distances for the all the retrofit phases and building components, per total living area and per square meter. Transportation distances from production to the building site were calculated based on the nearest local material producer and contractor locations to the building site.

Table 4.3 Building materials inventory

	Material	by living area	by functional unit	Transport (tkm)
		Total Weight (kg)	Weight (kg/m^2)	
Original Roof Demolition				
Exterior Covering	- ceramic roof tiles	6195	14.1	867
Wood Frame	- primary and secondary structure[1]	2132	4.9	51
Interior Coating	- wood panels	372	0.8	9
Roof retrofit (R)				
Exterior Covering	- ceramic tiles	6195	14.1	663
Wood Frame	- primary and secondary structure[1]	2558	5.8	473
	- oriented strand board (OSB)	1673	3.8	303
Thermal Insulation (three alternative insulation levels)				
	- 40 mm expanded polystyrene	83	0.2	11
	- 80 mm expanded polystyrene	166	0.4	22
	- 120 mm expanded polystyrene	248	0.6	32
	- vapor barrier	37	0.1	9
Interior Coating	- gypsum plaster board	4460	10.2	522
Exterior-wall retrofit (EW)				
Thermal Insulation (two alternative insulation levels)				
	- 40 mm expanded polystyrene	213	0.5	28
	- 80 mm expanded polystyrene	426	1.0	56
Interior Covering	- gypsum plaster board	8518	19.4	997
No Insulation	- base plaster	8652	19.8	1618
Coating	- interior paint	-	-	-
Floor retrofit				
Thermal insulation	- 80 mm rock wool	1196	2.7	347
Floor covering	- wood floor	2628	6.0	770
	- wood battens	202	0.5	92
Coating	- varnish	-	-	-
Window replacement				
	- PVC	3420	7.8	787

[1] Primary Structure: rafter and trusses; Secondary Structure: lath and counter-lath strips

The main maintenance activities considered are associated with the conservation of the interior and exterior finishes of the building during its 50-year life span. A corrective maintenance strategy was assumed where the components are replaced after their defined service life. The maintenance activity schedule (service life of each component) was established based on data from Kellenberger et al. (2007) and material producers. Table 4.4 presents the main assumptions for the inventory of maintenance activities, including interior painting of walls, varnishing of wood surfaces and plasterboard replacement.

Table 4.4 Maintenance activities

Component	Activity	Density (kg/l)	Area (m^2)	Volume (l)	Mass including coats (kg)	Material service life	Number of replacements
Exterior wall	exterior paint	1.71	412	103.0	528.4	20	2
	interior paint	1.46	338	48.3	141.0	20	2
Ceilings	interior ceiling paint	1.46	469	67	174.4	20	2
	plaster board	-	177	-	2124	20	2
Floors	varnish	1.04	438	43.8	155.052	10	4

4.2.1.2 Operational energy inventory

Commercial buildings are assumed to be large energy users; however, the building assessed in this chapter is a small office building that was adapted from a residential building presenting a very specific thermal behavior. A thermal dynamic simulation model was implemented to calculate the energy needs of the whole building. Each room of the building was modelled as a thermal zone with a specific thermal behavior and occupancy pattern (internal loads and occupancy schedules). An air conditioner with a coefficient of performance (COP) of 4.2 for heating and 3.5 for cooling was assumed. A natural ventilation rate of 0.6 air changes per hour was considered in all scenarios, in keeping with Energy Performance of Buildings Directive (EPBD (recast) 2010). Each residential occupancy level was characterized by occupied hours: low (14h) or high (20h)), and HVAC operation hours (low (8h) or high (24h)). The office use is defined by five working days assuming eight hours of permanent occupancy with HVAC activated. The detailed occupancy schedule and HVAC operation hourly rates is presented in Figure 3.1. For the residential scenarios, a four-person family was assumed, and for the office use scenario, 20 people were distributed around the different rooms and floors with permanent occupancy during working hours.

Table 4.5 presents the operational energy needs (heating and cooling) for the office use (the current use of the building) and for low and high residential occupancy. Residential occupancy scenarios present higher heating needs than office use as the occupancy is mainly during the night (when outside temperatures are lower). Regarding the energy needs for the different occupancy scenarios, results shows that, for office use, a set-point increase of 2ºC leads to an increase of 40-50% of heating needs and 30-45% of cooling needs. A set-point decrease of 2ºC results in a decrease of 120-200% of heating needs and 20-30% of cooling needs. Compared to the office use, low residential occupancy leads to higher heating needs (40-70%) and lower cooling needs (40-200%, except for retrofit strategies without exterior-wall insulation which results in an increase of up to 10%). High residential occupancy leads to higher heating (60-83%) and cooling needs (12-55%, expect with set-point fixed at 27ºC which results in a decrease of 12-40%) when compared to the office use.

Table 4.5 Operational energy needs (heating and cooling) for low and high residential occupancy and office use and percentage differences for office use per exterior-wall and roof insulation levels, in kWh/(m^2.year)

Retrofit strategy code	Insulation thickness (mm)		Office use (current use)		Residential - low occupancy				Residential - high occupancy			
	Roof	EW	Heating	Cooling	Heating		Cooling		Heating		Cooling	
	no retrofit		11.9	11.4	22.2	46%	8.2	-39%	38.6	69%	16.7	32%
R0EW0	0	0	12.0	11.1	22.4	46%	7.8	-42%	38.7	69%	15.9	30%
R0EW40		40	7.6	10.1	17.9	57%	7.2	-40%	28.4	73%	13.5	25%
R0EW80		80	7.1	9.9	17.1	59%	7.1	-41%	26.6	73%	13.1	24%
R40EW0	40	0	9.6	10.6	19.1	50%	6.7	-57%	31.9	70%	13.9	24%
R40EW40		40	5.2	9.6	14.1	63%	5.9	-62%	21.2	75%	11.4	16%
R40EW80		80	4.7	9.4	13.2	65%	5.8	-63%	19.3	76%	11.0	15%
R80EW0	80	0	9.1	10.5	18.3	50%	6.5	-61%	30.5	70%	13.6	23%
R80EW40		40	4.8	9.5	13.2	64%	5.7	-67%	19.7	76%	11.0	14%
R80EW80		80	4.2	9.3	12.2	65%	5.5	-69%	17.8	76%	10.6	12%
R120EW0	120	0	8.9	10.5	18.0	51%	6.4	-63%	29.7	70%	13.5	22%
R120EW40		40	4.6	9.4	12.7	64%	5.6	-70%	19.0	76%	10.9	13%
R120EW80		80	4.0	9.3	11.7	65%	5.4	-72%	17.1	76%	10.4	11%

EW=Exterior wall

4.2.2 LCIA methods

Cumulative Energy Demand (CED) was applied to measure the non-renewable primary energy (NRPE) to address energy resource depletion, while ReCiPe (Goedkoop et al. 2013) assessed climate change (CC, following IPCC (2013) for a time horizon of 100 years), ozone depletion (OD), 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).

4.2.3 Life-cycle costs and methods

Life-cycle cost assessment (LCCA) was performed following the approach described in Chapter 3 (Sub-section 3.3.2) that uses the Equivalent Annual Cost (EAC) method to compare different retrofit strategies. A 2% discount rate is assumed reflecting the current interest rates for a long-term mortgage at current market values and suggested by the European Commission (Buildings Performance Institute Europe (BPIE) 2013) taking into account the current economic perspective. The annual net savings of each retrofit strategy were calculated by comparing the EAC of retrofit with the EAC of no-retrofit option following (Eq. 3.1 presented in Chapter 3.

Table 4.6 presents the retrofit costs (initial investment), including the common costs to all scenarios, and the insulation cost of each option. The no-retrofit scenario considers the building features before retrofit, such as single-glazed windows, building envelope without insulation, an electrical heating system (Joule effect, i.e. coefficient of performance of one), and no cooling system. In a no-retrofit scenario there is no initial investment, so the only costs considered are maintenance and heating. The roof retrofit includes a no-insulation strategy and three alternative insulation options (40, 80 and 120 mm). The no-insulation option includes the roof tiles, battens, vapor control layer, and labor costs, while the other insulation options include these common costs, plus the insulation material cost. The roof insulated options have an additional cost of 72-100% compared to the no-insulation option. The exterior-wall retrofit includes a no-insulation strategy and two alternative insulation options (40, 80 mm). In this case, exterior-wall retrofit with insulation is up to three times more expensive than exterior-wall without insulation (just repairing and replacing finishes), as it comprises some additional materials, such as gypsum plaster board.

Table 4.7 presents the total retrofit costs for each retrofit strategy, which include common costs associated with site preparation, demolition, window replacement, floor retrofit and HVAC systems. The energy cost of cooling was not considered in this analysis since there is no cooling system in the original building (the no-retrofit option).

Table 4.6 Retrofit costs

	Surface (m^2)	Initial Investment	Maintenance costs per year[1]
Construction site preparation and preliminary works		5 650 €	-
Decommissioning / Demolition			
Roof decommissioning including transport to final disposal	177	2 700 €	-
Windows removal	36	350 €	-
Exterior walls plaster repairing and conservation	412	4 700 €	-
Windows stonework restoration, repairing and cleaning		2 200 €	-
Waste management		200 €	-
Construction / Retrofit			
Roof	177		
Structure		3 100 €	45 €
Alternative insulation options (including finishes)			
No insulation		11 800 €	235 €
40 mm expanded polystyrene		20 300 €	235 €
80 mm expanded polystyrene		21 300 €	235 €
120 mm expanded polystyrene		24 000 €	235 €
Exterior walls	338		
Exterior painting		4 400 €	400 €
Alternative insulation options			
No insulation		2 850 €	285 €
40 mm expanded polystyrene		2 100 €	5 €
80 mm expanded polystyrene		8 300 €	10 €
Interior painting		24 473 €	120 €
Windows	36	21 304 €	100 €
Floor	146	1 304 €	20 €
HVAC Systems			
Air Conditioner		10 000 €	300 €

[1] 10-year running cost annualized

The costs of investment and maintenance (after retrofit) were gathered from manufacture and contractor information, as well as from a database (www.cype.com) with current market costs for the Portuguese context. The electricity prices were obtained from the Portuguese Regulator for Energy Services (ERSE) (Entidade Reguladora dos Serviços Energéticos 2009). Some retrofit benefits were not considered in this analysis because they are subjective and common in all the retrofit strategies, namely strategies that can promote higher thermal comfort and property value increase, which are important benefits that could result in additional cash-flows, for example if the house were rented or sold. As these issues are subjective and beyond the scope of the study, they are not accounted for in this analysis.

Table 4.7 Breakdown of costs for the alternative insulation retrofit strategies and the no-retrofit option

Retrofit strategy code	Initial Investment [€]	Maintenance per year [€]	Energy costs per year [€]		
			Occupancy scenarios		
			Office	Residential low occupancy	Residential high occupancy
no retrofit	-	645	1146	2137	3721
R0EW0	66 162	1 189	1157	2159	3729
R0EW40	71 323	1 187	736	1726	2739
R0EW80	72 182	1 192	681	1647	2564
R40EW0	74 667	1 189	924	1842	3075
R40EW40	79 828	1 187	504	1359	2044
R40EW80	80 687	1 192	448	1268	1864
R80EW0	75 684	1 189	879	1767	2934
R80EW40	80 846	1 187	462	1270	1900
R80EW80	81 704	1 192	409	1175	1719
R120EW0	78 318	1 189	856	1730	2865
R120EW40	83 480	1 187	444	1224	1829
R120EW80	84 338	1 192	390	1128	1647

4.2.4 Eco-efficiency analysis metric

LCA and LCCA can be integrated towards a more comprehensive assessment by means of eco-efficiency to evaluate the trade-offs between cost and environmental impacts. The economic impact of each retrofit strategy was compared with the environmental impact throughout its whole life-cycle (Bidwell and Verfaillie 2000). Eco-efficiency has been defined as a general goal of creating value while decreasing environmental impact (Huppes and Ishikawa 2007), in this chapter, the goal is to maximize the annual net savings while minimizing environmental impacts.

The eco-efficiency approach employed for the building retrofit strategies integrates the environmental and cost assessments and assumes the minimum and maximum results of each set of retrofit strategies to define four eco-efficiency areas. Figure 4.2 shows the eco-efficiency method plot in which the x-axis of the eco-efficiency plots presents the total environmental LC impact and the y-axis presents the annual net savings (€) for each retrofit strategy. To identify the eco-efficient alternatives, the plots are divided into four equal areas limited by the maximum and minimum values on both axes (Ferrández-García et al., 2016; Ibáñez-Forés et al., 2013). The midpoints divide the results into higher and lower environmental impacts and higher and lower savings. Each area represents a different level of eco-efficiency. For the purpose of this analysis, the upper left area represents the area of maximum eco-efficiency (better options): retrofit strategies with the lowest environmental impact and the maximum annual net savings. This approach allows selecting the strategies with better results, i.e. in the range of minimum environmental impacts and maximum savings.

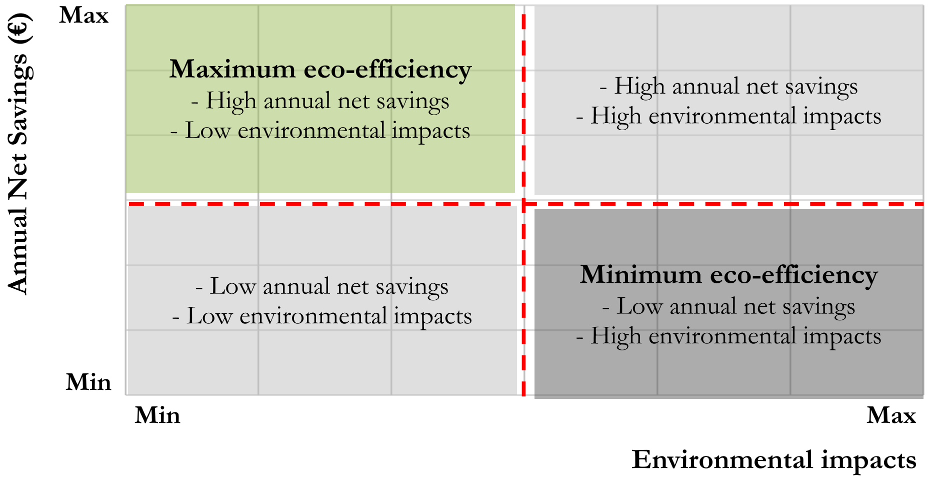


Figure 4.2 Eco-efficiency analysis (based on (Ibáñez-Forés et al. 2013; Ferrández-García et al. 2016))

4.3 Results and discussion

This section presents the main results for the retrofit strategies and occupancy scenarios assessed. Section 4.3.1 presents the environmental LC impact and section 4.3.2 the life-cycle costing. The eco-efficiency analysis results are discussed in section 4.3.3.

4.3.1 Environmental life-cycle impact assessment

Environmental LC impacts for the various retrofit strategies and occupancy scenarios are presented in Figure 4.3, showing that office use presents lower total LC impacts followed by low residential occupancy and high residential occupancy. LCIA results shows that heating, cooling and roof retrofit are the main contributors to the total LC impacts in all categories. Cooling is the greatest contributor in the office use, while heating has the highest impacts in residential uses. Roof retrofit is the second greatest contributor in office and low residential use.

In office use, cooling has the highest contribution to total LC impacts (27% (NRPE) to 40% (ME)), followed by roof retrofit (from 14% (FE) to 40% (CC)) and heating (from 11% (CC) to 26% (ME)). In a residential low occupancy, heating has the highest contribution to total LC impacts (28% (CC) to 49% (TA)) followed by roof retrofit (from 12% (FE) to 38% (CC)) and cooling (from 14% (OD) to 22% (ME)). In a residential high occupancy, heating has the highest contribution to total LC impacts (31% (NRPE) to 58% (ME)) followed by cooling (from 12% (FE) to 38% (CC)) and roof retrofit (from 9% (FE) to 31% (NRPE)).

Low and high residential occupancy present an increase of about 20% to 80% of the total LC impacts, when compared with the office use. In high residential occupancy, less insulated retrofit strategies lead to higher differences (about 80%) compared to office use than more insulated retrofit strategies (about 40%).

A reduction of 8-32% in total LC impacts due to the incorporation of insulation was calculated for residential high occupancy, 7-19% for residential low occupancy and 5-15% for office use. The incorporation of roof insulation leads to a higher decrease of total LC impacts when considering high residential occupancy (about 10-17%), while it represents about 7-14% in low residential occupancy, and only 5-8% in office use. The incorporation of exterior-wall insulation represents a decrease of about 16-25% in high residential occupancy and only 9-17% of total LC impacts in low residential occupancy and office use. More than 40 mm of exterior-wall or roof insulation represents a decrease of 1-5% of total LC impacts in all occupancy patterns. In office use, roof retrofit presents the highest contribution (from 14% (FE) to 39% (CC)), followed by cooling (22% (NRPE) to 36% (ME)).

An insulation level threshold (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off, for both exterior walls and roof) was identified for exterior walls (60-70 mm for all occupancy patterns) and roof retrofit (80-90 mm for low occupancy, 90-100 mm for high occupancy and 60-80 mm for office use).

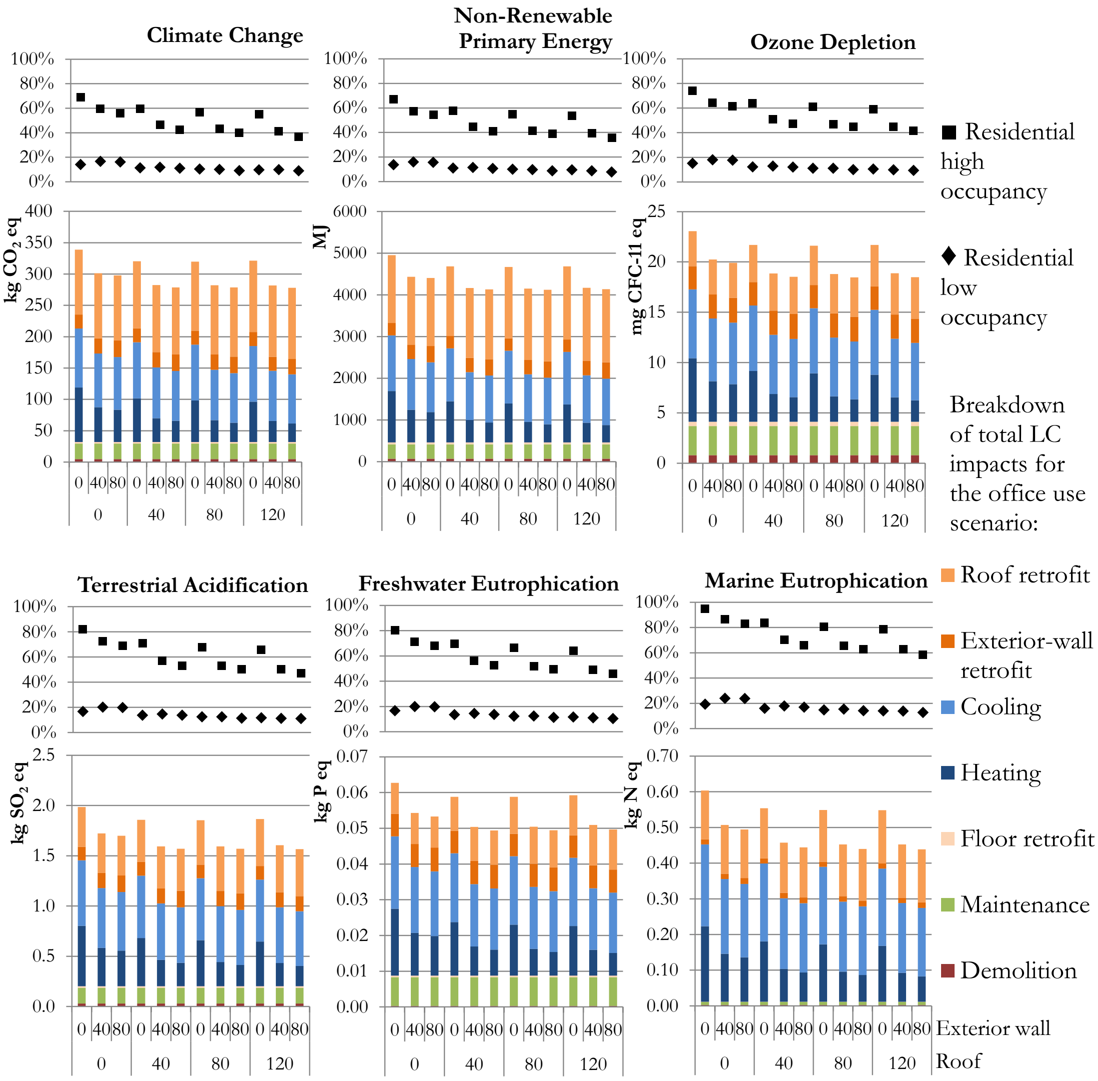


Figure 4.3 LCIA of exterior-wall and roof retrofit insulation strategies for office use per one square meter of living area over a period of 50 years, and percentage difference of total LC impacts of alternative occupancy scenarios (low and high residential occupancy) to the office use

A sensitivity analysis was performed to assess alternative set-points for all the occupancy scenarios. The scenario with set-points fixed at 18°C (heating) and 20°C (cooling) represents lower thermal comfort conditions (higher discomfort), and the scenario with set-points fixed at 22°C (heating) and 23°C (cooling) represents higher thermal comfort conditions (lower discomfort). The set-points fixed at 20°C (heating) and 25°C (cooling) are defined as the base case, assuming standard comfort conditions. Figure 4.4 presents the variation (%) of climate change impacts showing that higher comfort leads to higher impact differences relative to the base case than lower thermal comfort (in all occupancy levels). Lower thermal comfort leads to an LC impact reduction of from 5% (office use) to 20% (high residential occupancy) and higher thermal comfort leads to an increase from 5% (low residential occupancy) to 30% (office use) when compared to the base case (standard thermal comfort conditions). Differences within impact categories range between 1-5%. In low residential occupancy, it is possible to provide better comfort conditions without significant increase in the total LC impacts.

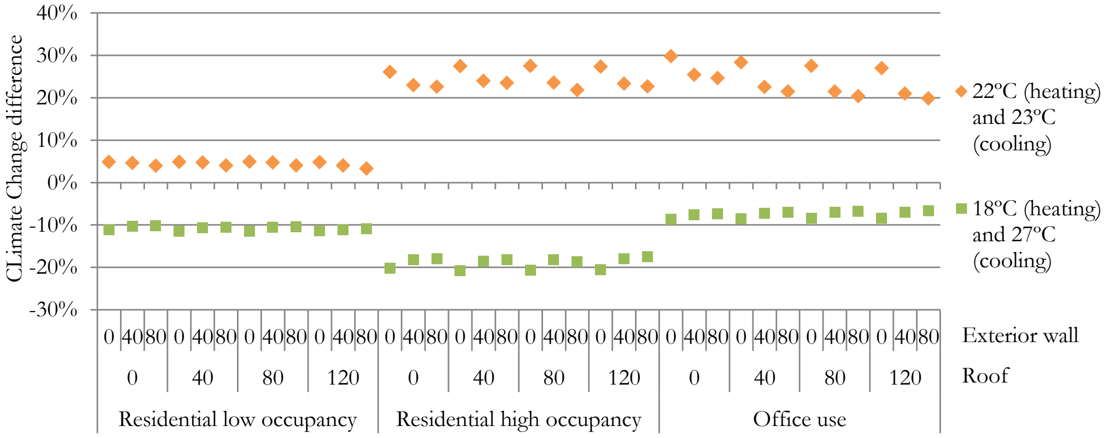


Figure 4.4 Variation (%) of climate change of alternative set-point scenarios relative to a base case set-point (20°C for heating and 25°C for cooling) for roof and exterior-wall insulation retrofit strategies with alternative occupancy levels (low and high residential occupancy, and office use)

4.3.2 Life-cycle costing

LCCA was performed to compare the various retrofit strategies to a no-retrofit option. Figure 4.5 shows that high residential occupancy present higher annual net savings (up to 500€). Residential low occupancy and office use scenarios lead to negative net savings in all retrofit strategies. In high residential occupancy, an increase in the exterior-wall insulation level leads to an increase in the annual net savings. Conversely, in low residential occupancy and office use, an increase in the exterior-wall insulation leads to lower net annual savings (energy cost reduction does not offset the additional material costs).

Figure 4.6 shows that high residential occupancy combined with higher thermal comfort presents the higher savings (annual net savings of about 1000€). Alternative heating set-points (18°C and 22°C) in low residential occupancy and office use result in a difference of about 30% to 40%, compared to the base case (20°C). Even though higher comfort conditions result in an increase in savings, undertaking retrofits that assume residential low occupancy or office use provides no benefit. In high residential occupancy, higher comfort conditions lead to a savings increase of 200-600% in all retrofit strategies, while lower comfort conditions result in a decrease of 200-400%.

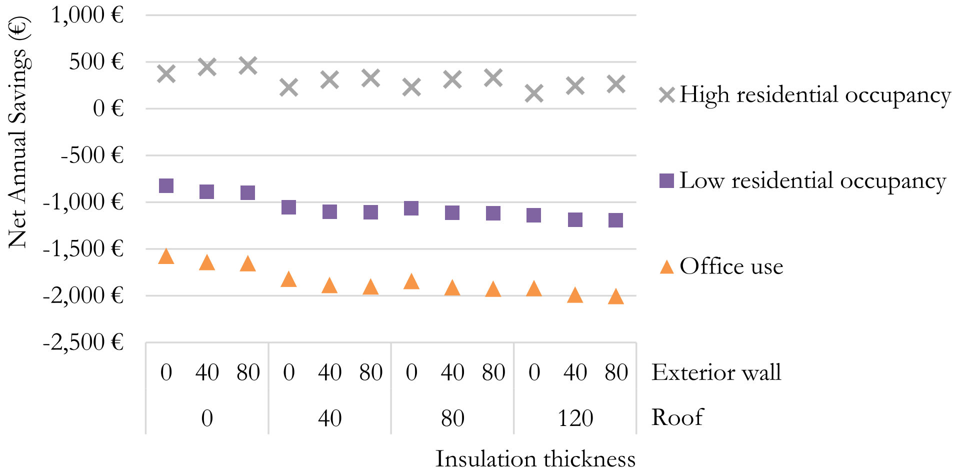


Figure 4.5 Annual net savings of exterior-wall and roof retrofit insulation strategies (relative to no retrofit option) assuming alternative occupancy scenarios: residential low and high occupancy, and office use

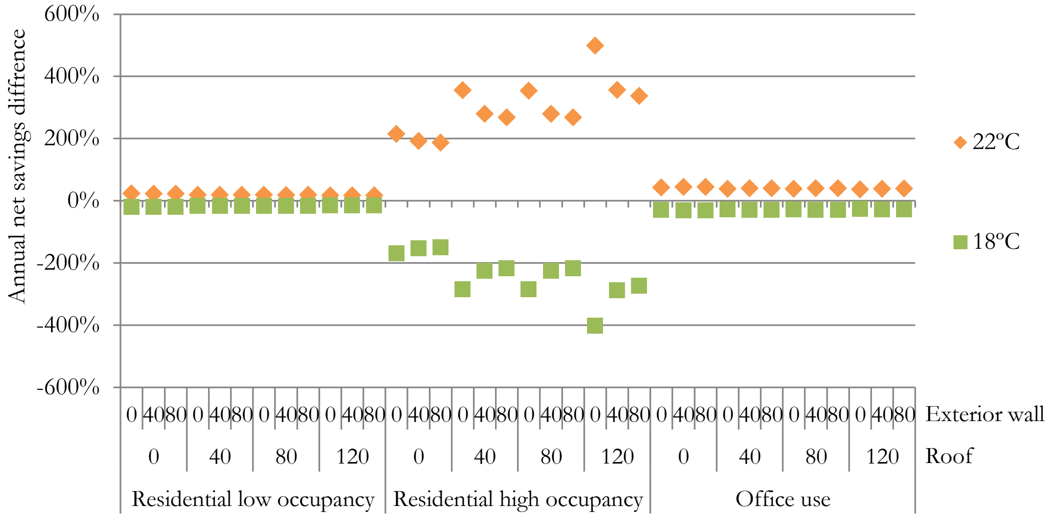


Figure 4.6 Variation (%) of annual net savings of alternative heating set-points scenarios (18ºC and 22ºC) relative to the base case set-point (20ºC) for roof and exterior-wall insulation retrofit strategies for alternative occupancy levels (low and high residential occupancy, and office use)

4.3.3 Eco-efficiency assessment

This section presents an eco-efficiency analysis based on the environmental and economic LC results presented in the previous sections. Figure 4.7 presents the eco-efficient results for the retrofit strategies in all occupancy scenarios. The upper left area (shaded) represents the area of maximum eco-efficiency (better options), where the retrofit strategies have the lowest total LC climate change with the maximum annual net savings. Results show that higher comfort conditions lead to better eco-efficient results for all types of occupancy. Even though standard and higher comfort conditions in residential high occupancy are the only occupancy scenarios that present positive annual net savings, eco-efficient retrofit strategies can be found in other occupancy scenarios within the options available. Exterior-wall insulation with 80 mm and roof without insulation (R0EW80) is the most eco-efficiency retrofit strategy, followed by exterior-wall insulation with 40 mm and roof without insulation (R0EW40). In low residential occupancy, R0EW80 in higher thermal comfort conditions was the only retrofit strategy found to be eco-efficient. In high residential occupancy with higher thermal comfort, the options that combine exterior-wall insulation of 40 to 80 mm with roof insulation of 40 to 80 mm (R40EW40, R40EW80, R80EW40 and R80EW80) are the most eco-efficient retrofit strategies. The strategies with more than 80 mm of roof insulation are not eco-efficient in any occupancy pattern.

Additional results for the other environmental categories are documented in Figures A1-A5 in Appendix III. Residential high occupancy has slight differences within categories, namely the retrofit strategy R120EW40, which is found to be eco-efficient in all categories except climate change. Office use presents the same results in all categories. In residential low occupancy, all categories present similar results, except marine eutrophication, freshwater eutrophication and terrestrial acidification, where the retrofit strategy R0EW80 is found to be eco-efficient in some categories when assuming standard comfort conditions.

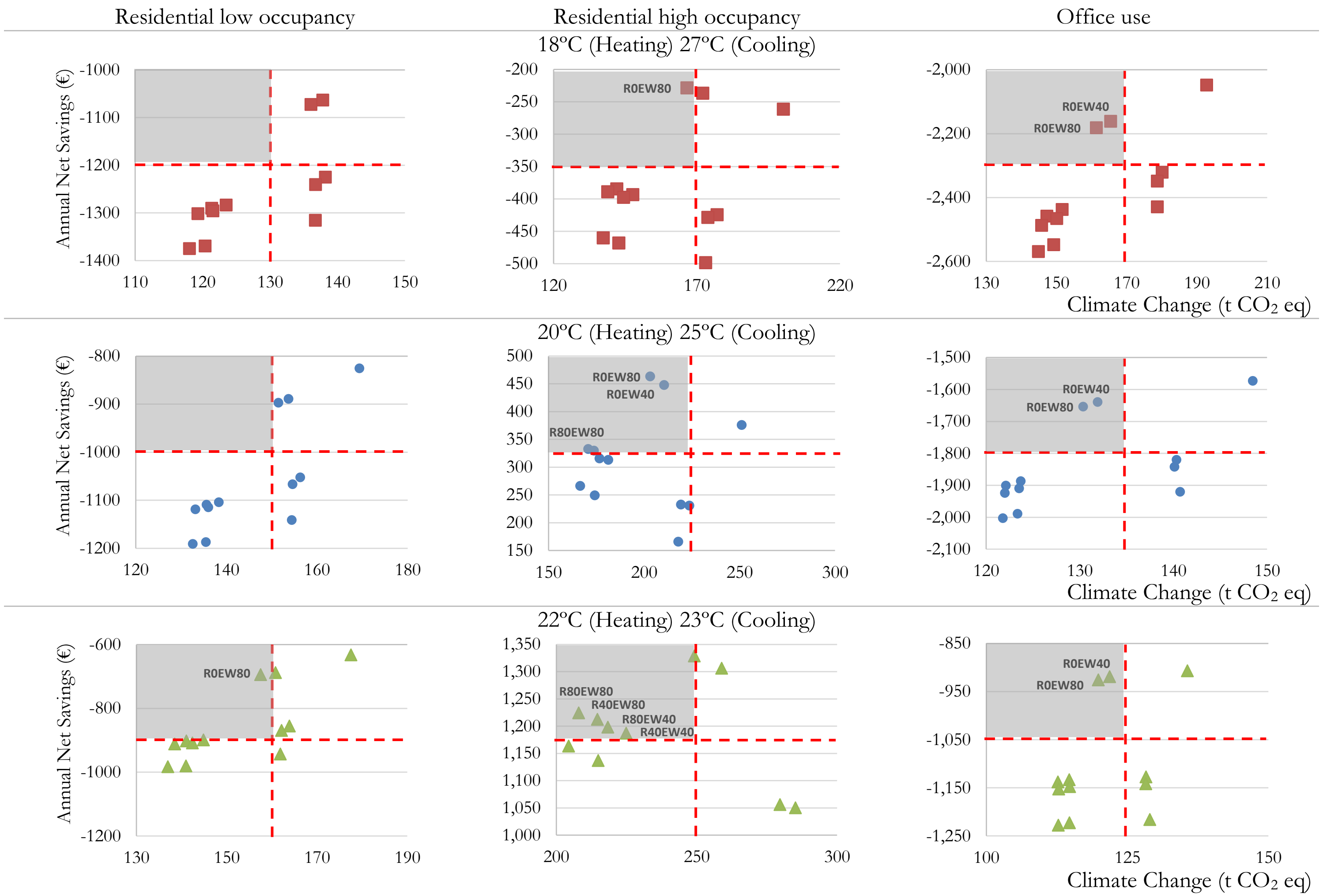


Figure 4.7 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-points for low and high residential occupancy, and office use (annual net savings in the y-axis and climate change in the x-axis) Retrofit strategy code: R(roof)0-120(insulation thickness in mm)EW(exterior wall)40-80(insulation thickness in mm)

4.4 Concluding remarks

The main goal of this chapter was to investigate how occupancy and adaptive reuse influences the eco-efficiency performance of building retrofit strategies supporting decision-making. An eco-efficiency assessment (integrating environmental impacts and costs) of alternative retrofit strategies was performed for an historic building in Coimbra, Portugal, as representative of South European climate buildings from the 19th century. A scenario analysis was performed combining alternative insulation levels and occupancy patterns. The insulation levels comprise alternative roof insulation levels (0, 40, 80 and 120 mm) and exterior-wall inside insulation levels (0, 40 and 80 mm). The occupancy patterns are defined by level of occupancy (office use, and low and high residential occupancy) and set-points (18ºC, 20ºC and 22ºC for heating combined with 23ºC, 25ºC and 27ºC for cooling).

Life-cycle impact assessment results show that office use presents lower total LC impacts, followed by low residential occupancy and high residential occupancy. A reduction of 8-32% in total LC impacts due to the incorporation of insulation was calculated for high residential occupancy, 7-19% for residential low occupancy, and 5-15% for office use. Thermal comfort conditions have higher influence to the total LC impacts in higher occupancy levels. An insulation level threshold (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off, for both exterior walls and roof) was identified for exterior walls (60-70 mm for all occupancy patterns) and roof retrofit (80-90 mm for low residential occupancy, 90-100 mm for high residential occupancy and 60-80 mm for office use).

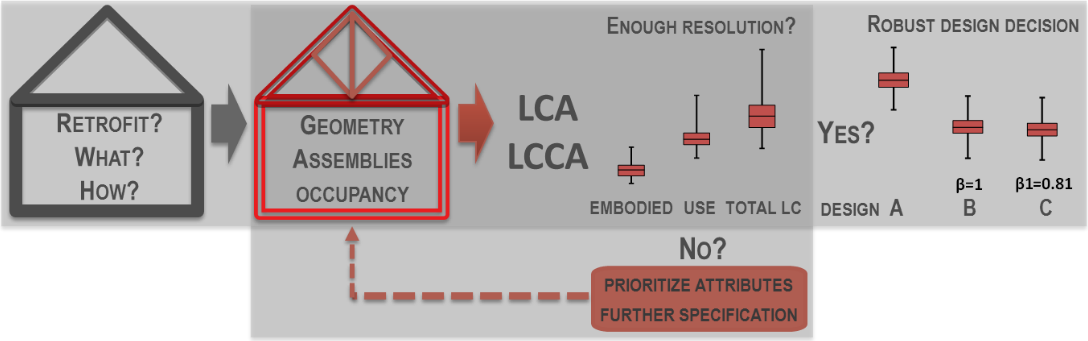
The EAC method was employed to calculate the annual net savings of the alternative retrofit scenarios, showing that only residential high occupancy levels present significant savings due to retrofit. Eco-efficiency assessment results show that higher comfort conditions result in better eco-efficient results in all types of occupancy. Retrofit strategies with more than 80 mm of roof insulation are not eco-efficient.

In summary, different retrofit strategies should be adopted to maximize savings and minimize environmental impacts depending on the type of use and occupancy level. It is crucial to consider both the economic and environmental perspective in support of a comprehensive retrofit decision process. This chapter showed that an eco-efficiency analysis can be a useful approach for assessing the performance of building retrofits.

5 Streamlined environmental and cost life-cycle approach for building retrofits: a case of residential buildings in South European climates

Based on:

Rodrigues, C., Kirchain, R., Freire, F., Gregory, J. (2016) Streamlined environmental and cost life-cycle approach for buildings retrofits: a case for South European climates (submitted)



Abstract This chapter, firstly, presents an integrated streamlined LCA-LCCA approach of building retrofits to provide environmental impacts and cost feedback for early-design stage decisions, including the uncertainty in that feedback; secondly, investigates whether a streamlined approach can be more efficient (with the same effectiveness) than a conventional LCA and LCCA of building retrofits (validation), and thirdly, explores the potential to support early-stage decisions (case-study analyses).

5.1 Introduction

One issue preventing more widespread use of LCA and LCCA is that both are time consuming and resource-intensive to implement. This onus is further exacerbated because these analyses are usually performed in separate tools. Because of these challenges, LCA and LCCA are often evaluated in late-design stages when there is little opportunity to improve the design (Schlueter and Thesseling 2009). Impacting early-stage decisions will require methods that can accommodate limited and often uncertain information. To foster confidence in these results such analyses must also provide an honest estimate of the uncertainty.

This chapter describes a novel approach to streamline LCA and LCCA for building retrofits that both accommodates varying amounts (and quality) of information on retrofit design and provides estimates and associated uncertainty for environmental and economic performance. The method comprises the application of structured under-specification, probabilistic triage, and guided sequential specification. It is applied to the case study of a single-family house built at the beginning of the 20th century located in Portugal as representative of a Mediterranean-climate building type. The results suggest that the specification of fewer than 10 attributes in the early stages of a building design can produce robust estimates of building environmental impacts. The case-study analyses assessed also suggest that the model is both effective (results were statistically consistent with conventional LCA results) and efficient (results were consistent with only limited information about most material, assembly, and cost attributes). The streamlined approach provides feedback to the designer identifying the main drivers of the impact of the building. This allows the designer to either identify an environmentally and economically superior design or to efficiently evaluate the design choices that he/she makes.

Many approaches have already been proposed to streamline LCA (Weitz et al. 1996; Hur et al. 2005), such as: removal of upstream and/or downstream processes (<10-30%) (Hunt et al. 1998), use of qualitative information, and use of proxy data.

Streamlined LCA approaches have been applied to the building sector, mainly by grouping the design attributes into macro-components or clusters of building materials and systems (Pushkar et al. 2005; Zabalza Bribián et al. 2011; Gervásio et al. 2014). Moreover, several authors have addressed this challenge by leveraging CAD (computer-aided design) tools and, in particular, parametric variants of those tools (such as BIM (Building Information Modeling) tools) to translate technical drawings into a bill of materials. Applications of this approach include analyzing both single-family and multi-family residential buildings (Basbagill et al. 2013; Basbagill et al. 2014; Gervásio et al. 2014; Hollberg and Ruth 2016), as well as office buildings (Wang et al. 2005; Flager et al. 2012), including a selection of refurbishment strategies for a multi-story office building (Seo et al. 2005).

These approaches have been developed to assess new buildings and are not geared towards retrofit. The existing building stock confronts different types of decisions, such as whether it is worth it to retrofit, or which components need to be retrofitted and how.

None of the described streamlined methods has developed an integrated environmental and cost assessment, or a fully integrated embodied and operational energy assessment. Additionally, the existing streamlined approaches report on a limited set of metrics (usually greenhouse gas emissions and primary energy). Finally, it is worth noting that the streamlined approaches described in the literature generally do not address uncertainty. Dealing with data gaps, asymmetries, and inconsistencies in LC inventories is a general problem in LCA studies (Weitz et al. 1996). Uncertainty analysis can be used to increase transparency, and therefore the credibility of a study (Blengini and Di Carlo 2010a). A notable exception to this is the work of Basbagill et al. (2013), who present a novel search dependent method to estimate building impact based on variable amounts of information.

5.2 Methodology

This section describes the streamlined approach concepts and analytical process (sub-section 5.2.1), and the application of the streamlined approach to building retrofits, including the description of the structured under-specification database and attribute to activity model (sub-sections 5.2.2 to 5.2.4). The metrics used to generate the results are also presented, which include both model validation and a demonstration of an early-design decision process analysis (sub-sections 5.2.5 and 5.2.6).

5.2.1 Streamlined approach concepts and analytical process

An integrated streamlined LCA, LCCA, and statistically-based operational energy model was developed to create an automated process that provides environmental and cost feedback on building-retrofit early-stage design decisions, based on the Building Attribute to Impact Algorithm (BAIA) approach developed by Hester et al. (2016b). BAIA is a streamlined LCA method that incorporates uncertainty and probabilistic triage to calculate impact predictions and to identify influential attributes for the whole building life-cycle. Embodied, energy, and cost impacts are calculated in the same parametric model from the same set of inputs, thereby avoiding the difficulties of correcting independent models. The general steps of the proposed building-retrofit LCA-LCCA streamlined approach are presented in Figure 5.1. The iterative process begins by introducing a limited description of the building (physical characteristics, assembly, energy, and cost attributes) (Step 1). For each attribute, different levels of specification can be defined according to the level of information available (from unspecified to full specification). In a second step, an attribute to activity model (AAM) is used to estimate the bill of materials and activities and other life-cycle characteristics (Step 2). Using this information, LCA and LCCA are performed, and the model estimates operational energy (heating and cooling) and impacts, embodied energy and impacts, and the total costs of the design alternative (Step 3). The model estimates the distribution of outcomes by using Monte Carlo simulation.

Based on the results, two alternative paths can be pursued. If there is sufficient resolution (low standard deviation (SD)), a decision can be made about a single design or alternative designs using a comparison indicator. If there is insufficient resolution, a probabilistic triage is performed to rank the building attributes (Step 4) by influence (specifically according to their contribution to variance), and data can be refined (following the available information and the rank of attributes in the sensitivity analysis) (Step 5 and 6). The process is repeated until a sufficiently reduced level of uncertainty is achieved and a decision can be made.

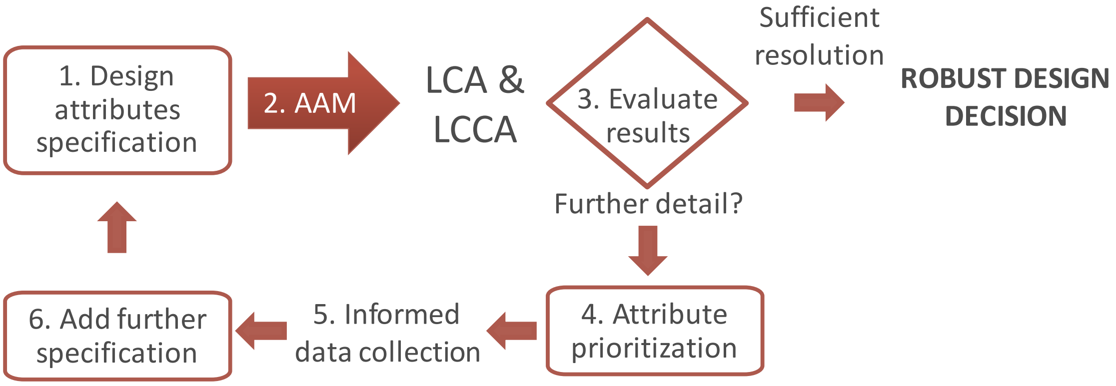


Figure 5.1 Building-retrofit LCA-LCCA streamlined approach.

5.2.2 Application of approach for residential building retrofits

5.2.2.1 Scope definition

This approach was developed to support decision-making for residential building retrofits in the European context. The LC phases, main processes and system boundaries defined for building retrofits are presented in Figure 5.2. The LC model includes the demolition (e.g., existing roof, windows), construction (retrofit), and use phases. As the scope of this streamlined model is to assess retrofit strategies, the initial construction and previous uses of the building are not considered. The end-of-life phase of the building after retrofit is not included because these are considered of minor importance for the residential sector (Nemry et al. 2008). The functional unit is the living area over a period between 30 and 100 years.

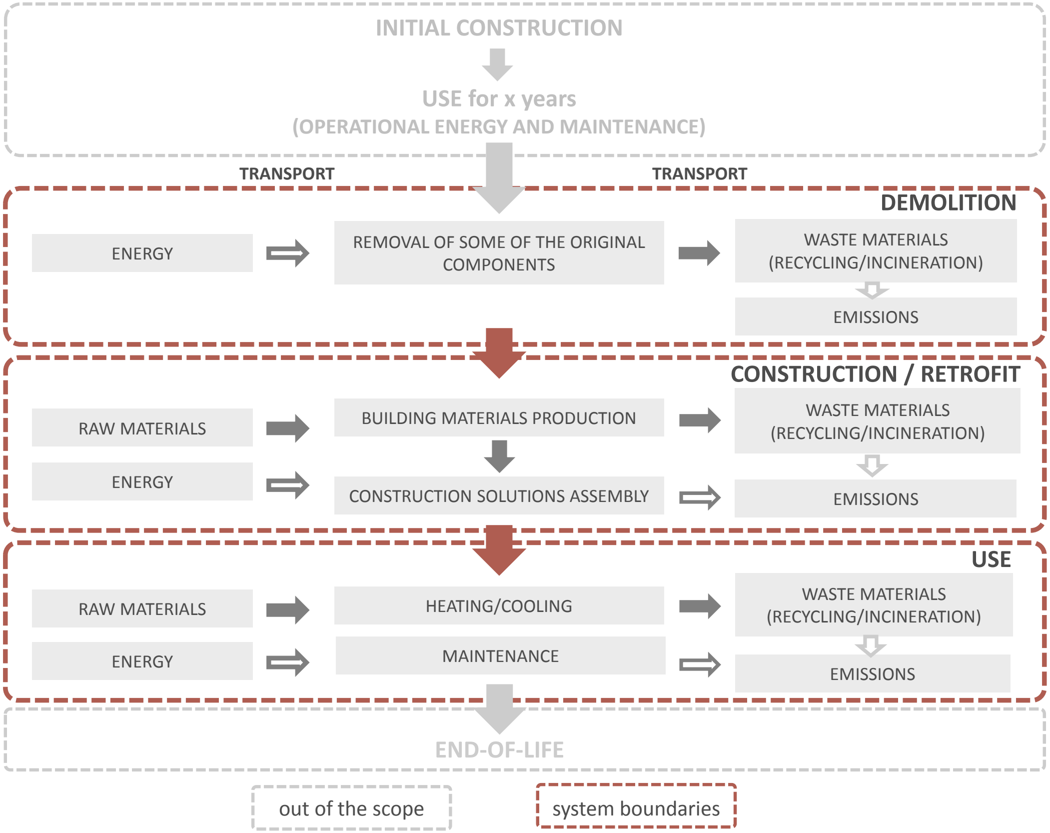


Figure 5.2 Building life-cycle phases, main processes and system boundaries of the life-cycle model

5.2.2.2 Retrofit process decisions and design attributes

The main building-retrofit decisions in the European context are related to improving the thermal performance of the building envelope, namely exterior walls, roofs and windows. The roof retrofit process includes the replacement of the frame material, interior and exterior finishes, as well as the incorporation of thermal insulation. The exterior-wall retrofit incorporates thermal insulation either on the interior or exterior surface of the wall, as well as interior and exterior finishes. The window retrofit consists of replacing the existing window by one with higher thermal performance.

The design attributes included in the model were selected to be representative of Mediterranean-climate building systems (as they may differ depending on the region) and occupancy. They are related to building geometry parameters, envelope components (existing and after retrofit), thermal properties and occupancy. The geometry parameters were selected as the variables necessary to determine the bill of materials. Additionally, they have been acknowledged in other studies to be critical (Lollini et al. 2006; Beccali et al. 2013; Rodrigues and Freire 2014a; Rodrigues and Freire 2017).

Table 5.1 describes the 33 residential building design attributes defined for the streamlined approach, as follows. Fourteen related to the existing building characteristics (building attributes), nine related to the retrofit strategies (assembly attributes: roof, exterior walls and windows), eight related to the operational energy performance and user behavior (energy attributes), the discount rate related to costs (cost attributes), and service life of the building after retrofit. Additional detailed information on the building design attributes is documented in Appendix IV, section A4.1.

Table 5.1 Attributes for the building retrofits streamlined model

Building attributes	Assemblies attributes	Energy attributes	Cost attributes
Location	Exterior walls – retrofit type	Number of occupants	Discount rate
Region	Exterior walls – insulation material	Heating set-point (day)	
Time period	Exterior walls – insulation thickness	Heating set-point (night)	
Existing exterior-wall type	Roof – retrofit type	Cooling set-point (day)	
Existing roof frame	Roof – insulation material	Cooling set-point (night)	
House type	Roof – insulation thickness	Heating COP	
Floor area	Windows – frame and glazing	Cooling EER	
Number of stories		Operational energy fuel	
Orientation			
Floor aspect ratio			
Window-to-wall ratio			
Windows distribution			
Roof type			
Roof pitch			
Floor height			
Building service life			

5.2.2.3 Under-specification

To accommodate the limited and variable amount of information available at the early design stage we have applied a streamlining method referred to as structured under-specification that was developed by Olivetti et al. (2013). and first described in Patanavanich (2011).

Specifically, a range of possible values or options was defined for each attribute at various levels of specification (L1 to L5 if applicable). Each set of attributes (building, assembly, energy and cost) have their own hierarchical categorization scheme. The levels of specification for each attribute are defined as BL for the building attributes, AL for the assembly attributes, EL for the energy attributes, and CL for the cost attribute. Examples of the hierarchical categorization scheme of each set of attributes are presented in Figure 5.3, Figure 5.4 and Figure 5.5.

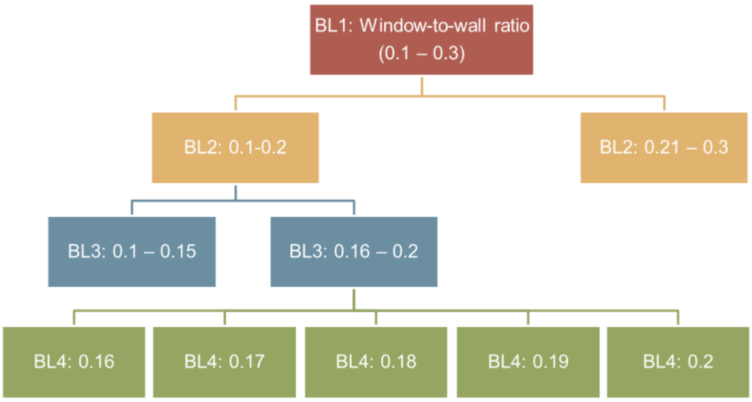


Figure 5.3 Window-to-wall ratio structure under-specification scheme (building attribute)

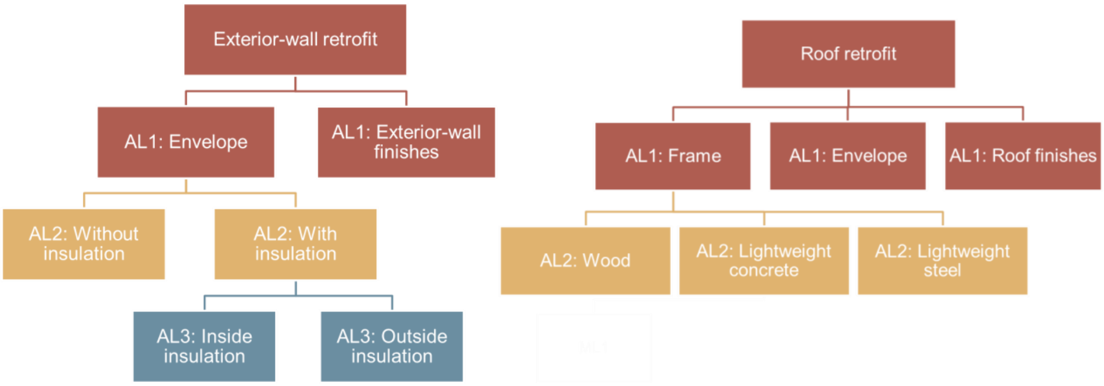


Figure 5.4 Exterior-wall and roof retrofit structured under-specification scheme (assembly attribute)

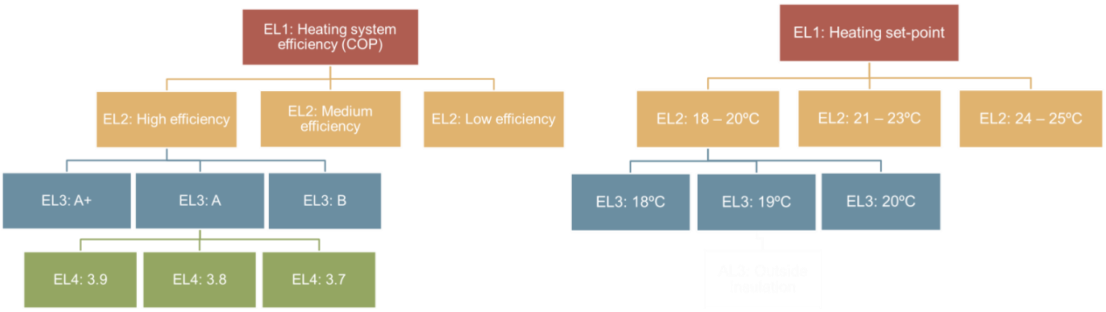


Figure 5.5 Heating system efficiency (COP) and heating set-point structured under-specification scheme (energy attribute)

Structured under-specification database

The materials and activities (e.g., transportation) LC inventory database was also classified into a hierarchical categorization scheme (under-specification). Each entry in these databases contains estimates of impact, relevant physical properties, and uncertainty in those estimates (Tecchio et al. 2016). The data structure allows each activity to be identified precisely (e.g., Rockwool insulation, Type A) or ambiguously (e.g., thermal insulation). This approach both accommodates whatever level of information is available at the time of evaluation and estimates the uncertainty due to a lack of accurate information.

The materials were categorized into four hierarchical levels of specificity: Level 1 (ML1) to Level 4 (ML4), with ML1 being the most general or underspecified and ML4 the most specified. The ML4 consists of individual entries from LC databases. The uncertainty at ML4 is based on either empirical data or is estimated using a pedigree approach (Tecchio et al. 2016). Uncertainty for any other level is estimated based on the uncertainty in the members that it comprises.

Table 5.2 presents an example of a hierarchical structure of specification for insulation materials. ML1 can be any insulation material (randomly chosen between all the insulation materials). In ML2 the materials are divided into three groups (blanket, blown, and board types), and in ML3 these are divided into a specific material type (rock wool, expanded polystyrene, etc.). At ML4 each type is subdivided into specific processes (e.g., expanded polystyrene 45% recycled).

Table 5.2 Example of a hierarchic level of specification for the insulation material

ML1	ML2	ML3	ML4 (specific process data)
THERMAL INSULATION	Ins-board	Foam glass	Foam glass
			Foam glass (AT)
			Foam glass (CH)
		Insulation cork board	ICB
		EPS	Polystyrene foam slab (EPS)
			Polystyrene foam slab (EPS), 100% recycled
			Polystyrene foam slab (EPS), 45% recycled
			Polystyrene foam slab with graphite
			Polystyrene foam slab, 10% recycled
		XPS	Polystyrene, extruded (XPS)
			Polystyrene, extruded (XPS) CO_2 blown
			Polystyrene, extruded HFC-134a (XPS)
			Polystyrene, extruded HFC-152a (XPS)
		PUR	Polyurethane flexible foam
			Polyurethane rigid foam
		Rock wool	Rock wool, packed
		Urea formaldehyde foam board	Urea formaldehyde foam slab, hard
	Ins-blanket	Glass wool	Glass wool mat
			Glass wool, fleece
		Rock wool blanket	Rock wool
			Rock wool, fleece
	Ins-blown	Urea formaldehyde foam	Urea formaldehyde foam, in situ foaming
		Cellulose	Cellulose fiber

5.2.2.4 Attribute to Activity Modeling

An AAM is an algorithm that maps design attributes to the material or activity inputs associated with realizing that design (Hester et al. 2016b). The following sub-sections describe the embodied, operational energy, and cost attribute to activity models.

AAM - Embodied

The embodied inventory includes demolition, construction and maintenance processes. Demolition includes dismantling and transport to an end-of-life facility of the original components. The construction phase of the retrofit process includes material production and transport to the site, as well as on-site assembly processes. The maintenance strategy adopted is mainly corrective, i.e., the materials are only replaced or repaired in case of deterioration (e.g., finishes and auxiliary materials). None of the core materials are defined to be replaced during the building service life. The maintenance activity schedule (service life of each component) was established based on data from the literature (Kellenberger et al. 2007; Hoxha et al. 2014; Grant et al. 2014) and material producers. All materials are characterized by functional unit, density, specific heat, service life (number of replacements), distance to manufacturers, costs (material, labor, maintenance and other), and impact factors. A probability distribution function was defined for each material/activity property according to the level of information collected (density: uniform; service life: triangular; distance to manufactures: triangular; costs: uniform; and impact factor: lognormal).

As opposed to most existing LCA approaches, this streamlined method has a pre-established and consistent estimation of the bill of activities/materials based on very few attributes (defined as early-design parameters). The BAIA approach used in this methodology avoids the use of external software, like BIM or any other undescribed method, to create the bill of materials (BOM). The building attributes are automatically converted into a bill of activities/materials by the model simplifying the amount of information that is usually needed to perform a robust LCA. The calculation of assembly areas was performed using geometric formulas based on the building geometry parameters. These areas are then used to calculate the quantity of materials for each assembly.

The quantities of materials are uncertain due to losses during transportation, cutting process or assemblage. Data uncertainties are associated with the level of specification of building attributes, materials properties, transportation modes and distances, and end-of-life activities. Firstly, the lack of reliable information about properties of materials and data regarding characteristics such as density, service life, thermal conductivity, thermal resistance or heat capacity leads to high uncertainty. Secondly, the quantity of materials quantity can vary according to potential losses due to cutting and fitting processes on site. Thirdly, transport distances from manufacturer to construction site can be very uncertain due to the lack of information about manufacturers/distributors particularly in early design stages. Finally, the uncertainties associated with end-of-life activities are mainly waste materials, end-of-life disposal (final disposal, sorting plant or recycling) as well as end-of-life facility location. A probability distribution function (uniform) was defined for the distance from the construction site to the end-of-life facility for each material according to the accuracy and robustness of the information collected. A value for each attribute, material or activity is then randomly selected. Once a statistical distribution is characterized for each input parameter, the Monte Carlo simulation is performed to propagate the uncertainty into a range of values.

Scientific literature (Pina dos Santos and Matias 2006) and technical data were gathered from producers and contractors in order to calculate the quantities (or thicknesses) of materials. Material production was modeled based on Kellenberger et al. (2007), which presents average European LCI data. The main inventory data regarding material processing for the construction was obtained from Kellenberger; Spielmann; and Althaus (Kellenberger et al. 2007; Spielmann et al. 2007; Althaus et al. 2010; Hischier et al. 2010; Moreno Ruiz et al. 2014). 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 based on the locations of material producers and contractors, assuming an average distance depending on the building location.

AAM - Energy

The AAM for operational energy is a metamodel that results from the combination of two sub-metamodels, one for heating energy and one for cooling energy. The method used to develop the metamodels was a stepwise linear regression analysis (Hester et al. 2016a) using the statistical software JMP (SAS Institute Inc. 2015). The stepwise regression analysis was first used to select which predictors seem to provide a good fit. The selected variables were then introduced into a standard linear regression model. The data used to develop the metamodel was obtained from a thermal dynamic simulation software, EnergyPlus (U.S. Department of Energy 2015). Thirty-thousand simulations were carried out randomly across all the design alternatives presented in

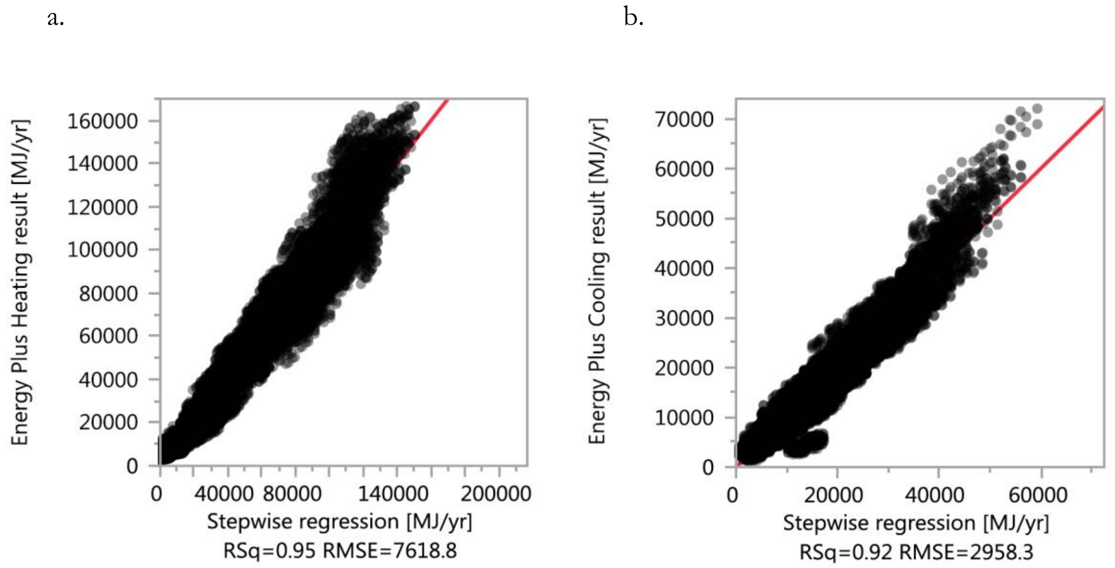
Table 5.3. Once the energy metamodel is incorporated into the streamlined embodied LCA-LCCA model, heating and cooling energy requirements can be calculated by defining 14 building attributes. Details on the form of the model are documented in Figure 5.6 and Section A4.2 of the Appendix IV.

The occupancy pattern defined for the simulations considered people, lighting and appliances schedules. The number of people can vary between two and six assuming a low occupancy during the day and full occupancy at night. Lights and appliances were defined to be activated during occupied hours and were assumed as fixed variables. Natural ventilation rate was also defined as a fixed variable (0.6 air changes per hour was retained, in keeping with Portuguese building thermal regulations (REH and RECS 2013)). Hot-water energy use was not considered since it does not affect the thermal comfort of the house.

The variables were screened done to determine those to be used in the regression model, following the design parameters needed to input in the streamlined model (hypothesis). The selected variables are presented in Table 5.3. The categorical variables selected were transformed into numerical variables either by converting into a tailored numerical value (location into HDD) or by creating dummy variables (type of house). JMP converts each categorical variable into a collection of numerical variables that represent its information. These dummy variables use only the numbers +1, 0, and –1. A categorical variable with k categories requires (k-1) of these special numerical variables. Thus, the building type categorical variable with four categories added three numerical variables to the model.

Table 5.3 Summary of building parameters and their initial ranges

Parameter	**Comments**	**Unit**	**Min**	**Max**
Type of house	Semi-detached (SD) left; semi-detached (SD) right; row; detached (categorical variable)	-	-	-
Heating degree days (HDD)	Climate	ºC/day	987	2015
Orientation	Degrees from south of the front façade	º	0	180
Bedrooms	As measure of occupancy level	-	3	5
Exterior wall (EW) R-value	Exterior wall thermal resistance	m^2K/W	0.7	4.3
Exterior wall (EW) Q	Exterior wall heat capacity	J/m^2K	210484	989315
Roof (R) R-value	Roof thermal resistance	m^2K/W	0.84	4.2
Window area	Percentage of windows area over total exterior wall area	%	0.1	0.18
Window distribution	Percentage of window area in the front façade	%	0.2	0.5
Window type	Window U-value	W/m^2K	2.8	4.3
Heating set point day	During unoccupied hours	ºC	17	24
Heating set point night	During occupied hours	ºC	17	24
Cooling set point day	During unoccupied hours	ºC	21	30
Cooling set point night	During occupied hours	ºC	22	27



*Root-mean-square error

Figure 5.6 Test-set performance of heating (a) and cooling (b) stepwise regression metamodel

AAM - Cost

The cost model is defined by a set of algorithms (based on LCCA methods) that converts all costs (construction, maintenance and energy) into cost metrics. The form of the cost model is defined by the base-case scenario costs (the existing building without retrofit is used as baseline to assess the benefits of the retrofits (Kneifel 2010b), and includes standard maintenance and energy costs), total retrofit costs (initial investment (retrofit costs), maintenance (repair and replacement) and energy costs), discount rate, and service life of the building. Details on the LCCA methods are provided in Section A4.3 of Appendix IV.

The embodied bill of materials is automatically converted into initial investment and maintenance costs. All materials have an associated cost per unit which is defined once a specific material is selected, and then the cost per unit is multiplied by the quantity of material. The initial investment and maintenance costs are calculated by summing the exterior-wall and roof retrofit, and window replacement costs. The energy costs are calculated by multiplying the energy model output (in kWh/year) by energy price (in kWh/€).

5.2.2.5 LCIA and LCCA methods

Six environmental and energy metrics are used to illustrate the performance of this approach using two complementary impact assessment methods: Cumulative Energy Demand (CED) calculates non-renewable primary energy, and ReCiPe mid-point (H) (Goedkoop et al. 2013) for climate change, ozone depletion, terrestrial acidification, marine eutrophication and freshwater eutrophication. These impact categories have been broadly used in LCA studies and have been recommended by several building LCA guides (Bayer et al. 2010), standards (CEN 2011) and environmental certification systems (e.g., LEED). A statistical distribution is characterized for each impact factor using a pedigree matrix approach (Ciroth et al. 2013). LCCA is performed using both net present value (NPV) and equivalent annual cost (EAC) methods. EAC annualizes the initial investment cost and compares it with future annual operating costs (Mata et al. 2015). NPV calculates future running cost savings and actualizes to the present value so that it can be compared with the initial investment. For both methods a discount rate is defined, either as a single value or randomly selected between 1% and 8%, according to the level of specification.

5.2.2.6 Analysis metrics

The approach can generate several results to support the decision-making process. The metrics calculated by the streamlined model include: single alternative, contribution to variance, and comparative analysis using a comparison indicator. A scenario analysis can be used to assess a single design alternative. If the level of resolution is low, a contribution to variance analysis (probabilistic triage), calculated using the normalized Spearman rank correlation coefficient, can enable the identification of key parameters that can reduce uncertainty. Additionally, to increase the robustness of the decision, the use of a comparison indicator (CI) (Huijbregts et al. 2003; Noshadravan et al. 2013; Gregory et al. 2016) can statistically characterize the difference in each environmental and cost metric of two alternative designs taking into account the correlation in the input parameters. Some results showing the benefit of these support-decision analyses are presented in Section 5.3.

5.3 Results and discussion

To explore the effectiveness and efficiency of the model and framework described here, it was applied to support the decision-making around retrofits of historic buildings in a South European context, specifically several locations within Portugal. The results of the streamlined approach were compared to those of detailed LCA and LCCAs (Chapters 2 and 3). Sub-section 5.3.1 explores the overall effectiveness of the streamlined approach through comparison between the conventional LCA and LCCA results and the streamlined approach results. Sub-section 5.3.2 refines this assessment of effectiveness by comparing the recommendations derived from the tool with those of previous studies and evaluates efficiency by mapping out what (limited) information is needed to reach a statistically defensible conclusion. Finally, sub-section 5.3.3 demonstrates a hypothetical but realistic application of the model using directed sequential specification to identify an environmentally preferred solution.

5.3.1 Comparison with a conventional LCA and LCCA approach – validation of overall model effectiveness

The objective of a streamlined method is to produce similar results to those reached through conventional LCAs, with less effort. While some inconsistencies are acceptable, they should be minimized. However, many streamlined methods are not validated with conventional LCA results (Hunt et al. 1998).

For the purpose of validation, results derived using the streamlined approach were compared with a conventional LCA study. Because of the data requirements for conventional LCA, cases were selected for which this level of detail was available (Chapters 2 and 3).

Model validation was carried out using a case study of a single-family house built at the beginning of the 20th century located in Portugal, referred in chapters 2 and 3 (Rodrigues and Freire 2014a; Rodrigues and Freire 2017). This is a semi-detached house organized on four floors, with a finished basement and a finished attic. The main features of the house are massive stonewalls (average thickness of 50 cm), single-glazed wood windows and a wooden frame roof (Rodrigues and Freire 2014a; Rodrigues and Freire 2017). The functional unit selected was the total living area over a period of 50 years. For the operational energy calculation, a four-person family was considered, with loads mainly at night. The heating and cooling set-points were fixed at 20ºC (18ºC during the day) and 25ºC (30ºC during the day), respectively. An electric heat-pump was considered for heating (COP 4.1) and cooling (EER 3.5). Operational energy requirements were calculated using EnergyPlus for the conventional LCA (Rodrigues and Freire 2014a). The conventional LCA methods and results for this case study are presented in Chapters 2 and 3 (Rodrigues and Freire 2014a; Rodrigues and Freire 2017).

Three scenarios were evaluated involving a single combined retrofit strategy and three distinct building locations. The specific retrofit strategy explored includes a combination of exterior-wall retrofit (inside insulation with 40 mm of EPS), roof retrofit (wood-frame roof with 80 mm of EPS), and window replacement (double-glazed PVC windows). Three alternative climate zones were considered (Portuguese cities of Faro (HDD 987), Coimbra (HDD 1304), and Bragança (HDD 2015)).

In the streamlined model, the attributes were defined as permitted by the accuracy of the information usually available. Assembly attributes are specified at AL3 (fully specified), and materials attributes are specified at ML2 (ML4 being the most specified). Energy attributes are specified at EL2 for set-points and number of occupants (EL3 being the most specified) and EL4 for heating and cooling systems efficiencies (EL4 being the most specified). A discount rate was chosen at CL2 (CL3 being the most specified). The main goal of this validation was to determine whether the conventional LCA results lie within those of the streamlined method, given that decreasing input specification would just provide a wider range of results.

Figure 5.7 shows that conventional LCA results (red markers) are within the range of the streamlined model results for all the metrics evaluated here. Five environmental metrics, non-renewable primary energy, operational energy needs, and net present value are presented to illustrate the validation assessment.

5.3.2 Evaluation of the streamlined approach in a comparative assessment

In many cases, LCAs are undertaken to select among alternatives. This requires comparing the performance of those alternatives. In the context of a comparison, an effective model leads to the same conclusion as conventional LCA results. Here three selection decisions that were previously discussed in Rodrigues and Freire (2014) and in the previous chapters are examine: exterior-wall wall insulation thickness (40 mm vs 60 mm), insulation materials (rock wool vs EPS), and a combined exterior-wall and roof insulation retrofit (80 mm exterior-wall insulation with 80 mm roof insulation vs 80mm exterior-wall insulation with 100 mm roof insulation). These cases were used to explore three aspects of the streamlined approach: 1) is the streamlined model effective? (i.e. does its result agree with a conventional LCA); 2) is the streamlined approach efficient? (i.e. can it provide a useful result with less information and, therefore effort, than a conventional LCA); and 3) how can the streamlined model and sequential directed feedback be used to support a decision while minimizing information requirements?

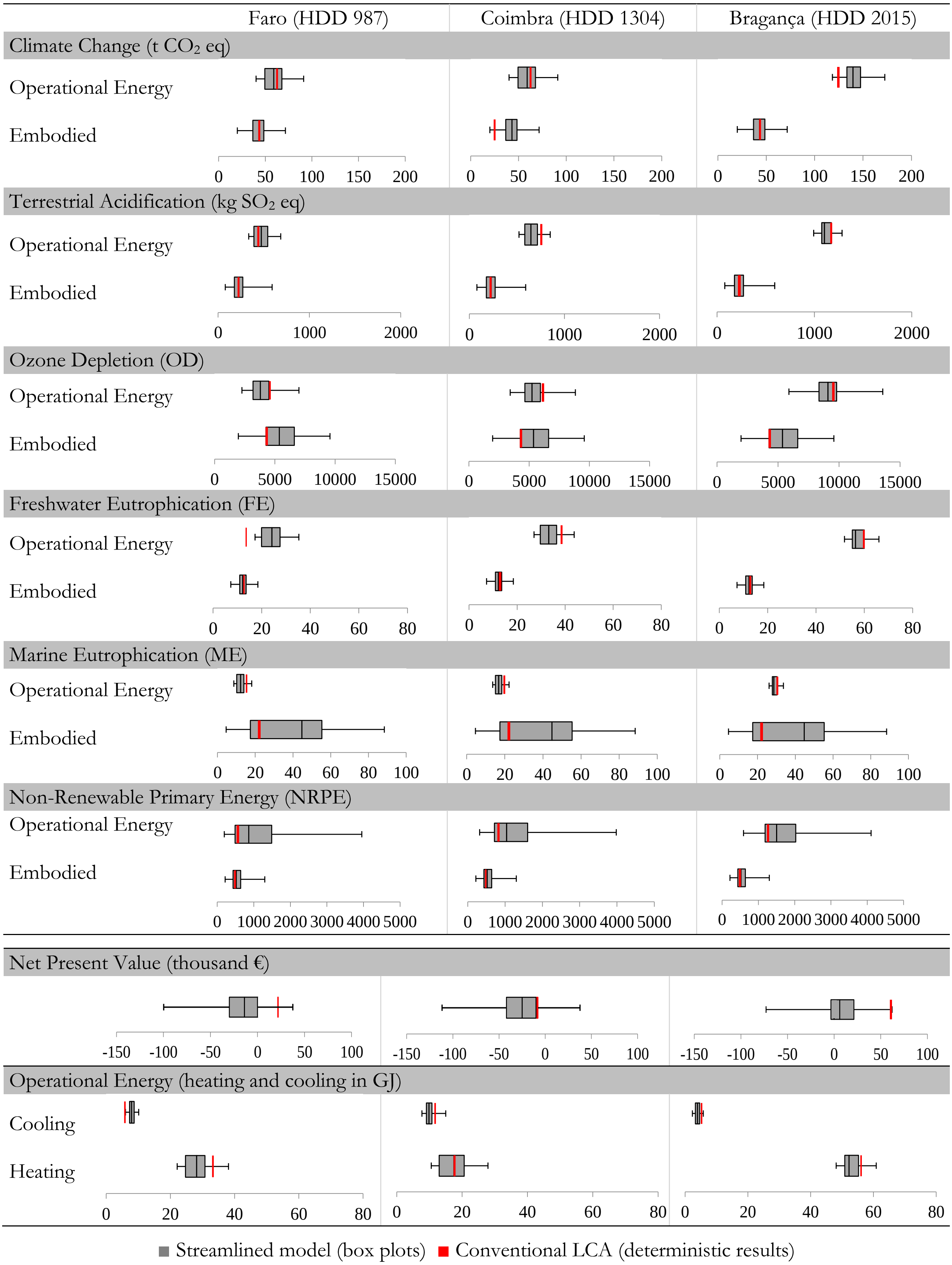


Figure 5.7 Streamlined and conventional LCA results for three scenarios: embodied and operational energy for climate change, terrestrial acidification, net present value and operational energy (heating and cooling). The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval.

The statistical characteristics of a comparison indicator (CI) (Huijbregts et al. 2003; Noshadravan et al. 2013; Gregory et al. 2016) were evaluated to compare the relative performance of the alternatives. The use of a CI is a statistically-based method that characterizes the difference in the environmental impacts of two alternative designs taking into account both uncertainty and, when present, correlation among the results being compared. The CI can inform the level of confidence that one design is better than the other. Here the CI is defined as the ratio between the environmental impacts (EI) of two alternative designs. Specifically, it is the frequency with which the CI falls below some critical value (here set to 1). This frequency is referred to as β and is defined as:

$$\beta = P(CI < 1) = P\left(\frac{EI_A}{EI_B} < 1\right) \qquad \text{(Eq. 5.1)}$$

A comparison is assumed to be statistically significant when β>=0.85 (level of confidence that A is better than B, i.e., A is better than B 85% of the times). CI characterizes the likelihood that design A has lower impact than design B (alternatively, 1-β characterizes the likelihood that design B has lower impact than design A).

For this purpose, the effectiveness is simply evaluated based on congruence with the conclusion from the conventional LCA. That is the result is deemed effective if it identifies, with some established significance, the same alternative to be of lower impact than the conventional LCA. The efficiency is evaluated based on the number (count) of pieces of information that must be provided to the model to reach the effective result.

For each analysis, the building attributes were defined at the BL4 level of specification (fully specified), while all assembly, energy, cost, and materials attributes were defined at AL1, EL1, CL1, and ML1, respectively (fully unspecified). Once the inputs are defined, the BAIA approach calculates the bill of materials, activities and costs, and the energy model calculates the energy needs. In these analyses, attributes are sequentially resolved based on the rank in the sensitivity analysis. Specifically, the highest ranking (most influential) attribute is resolved to one third of the range it had in the previous analysis. Using that refined value the simulation and sensitivity analysis is repeated. As an example, results are presented for CC and NPV.

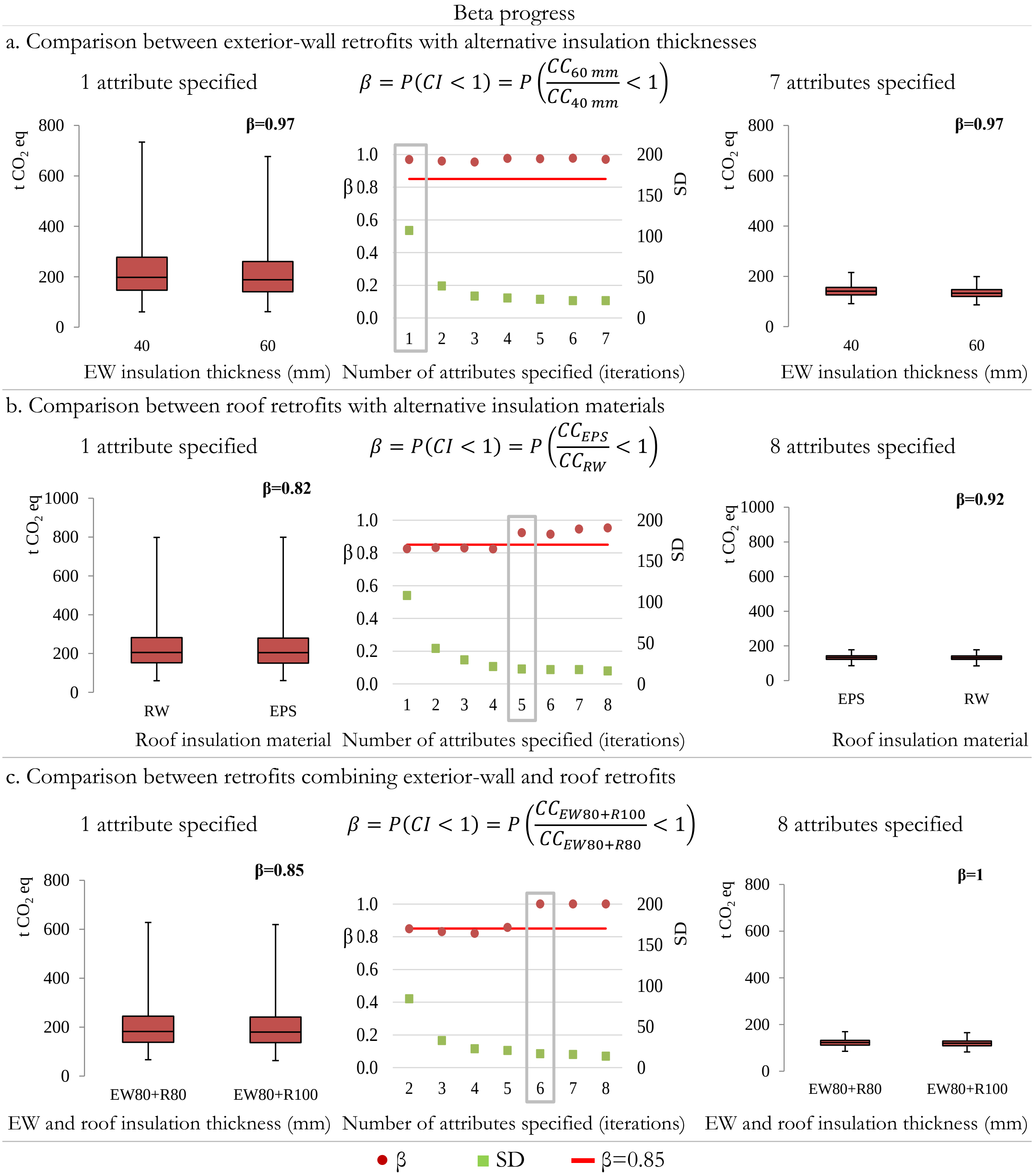
Figure 5.8a represents the CC result for both alternatives (40mm and 60mm exterior-wall insulation) when only the assembly attribute is specified (left) and when six additional attributes (heating set-point night, heating system efficiency, exterior-wall finishes, roof framing, window type and number of occupants) are specified (right). Additionally, Figure 5.8a plots the progression of both result SD (middle plot, green dots) and the β as the analysis progresses from one resolved attribute to seven or eight. Comparing the left and right plot shows that the result with seven resolved attributes is much more precise (SD for one resolved attribute is approximately 100, while it falls to about 20 for eight resolved.). However, Figure 5.8a also shows that the level of precision is not necessary to support this decision. In fact, for this analysis the streamlined approach is particularly efficient in that it is only necessary to specify one attribute (plus fully specified BL attributes) to achieve a sufficient beta to be able to make a robust decision. For this case, the model effectively identifies the same lower impact alternative (60mm) as in Chapter 2.

Another example is presented in Figure 5.8b, showing that to assess the roof insulation material we have to specify at least five attributes to replicate the conventional LCA result and achieve the beta threshold. Finally, an example comparing alternative exterior-wall and roof retrofits is presented in Figure 5.8c. For this case, the streamlined model supports the same conclusions as Chapter 2 (Rodrigues and Freire 2017), with only six attributes specified. These results suggest that the streamlined model and framework can efficiently deliver an effective result even with very few attributes specified.

For the NPV assessment, we define the comparison indicator (CI) as the ratio between the NPV of two alternative designs. Specifically, we are interested in the frequency with which the CI falls below some critical value (here set to 1). We refer to this frequency as β and define it as:

$$\beta = P(CI < 1) = P(\frac{NPV_A}{NPV_B} < 1) \qquad \text{(Eq. 5.2)}$$

A comparison is assumed to be statistically significant when β>=0.85 (level of confidence that B is better than A, i.e., B is better than A 85% of the times). Conversely to environmental impacts, here the CI characterizes the likelihood that design B has higher NPV (higher profit) than design A (alternatively, 1-β characterizes the likelihood that design A has higher NPV than design B). Repeating the climate change example, the following comparisons were explored: two alternatives for exterior-wall wall insulation thickness (60 mm vs 80 mm), two alternatives for insulation materials (rock wool vs EPS), and two alternatives for a combined exterior-wall and roof insulation retrofit (60-mm exterior-wall insulation with 80-mm roof insulation vs 60-mm exterior-wall insulation with 100-mm roof insulation).



The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval. EW80+R80 = 80 mm of exterior-wall insulation combined with 80 mm of roof insulation; EW80+R100 = 80 mm of exterior-wall insulation combined with 100 mm of roof insulation

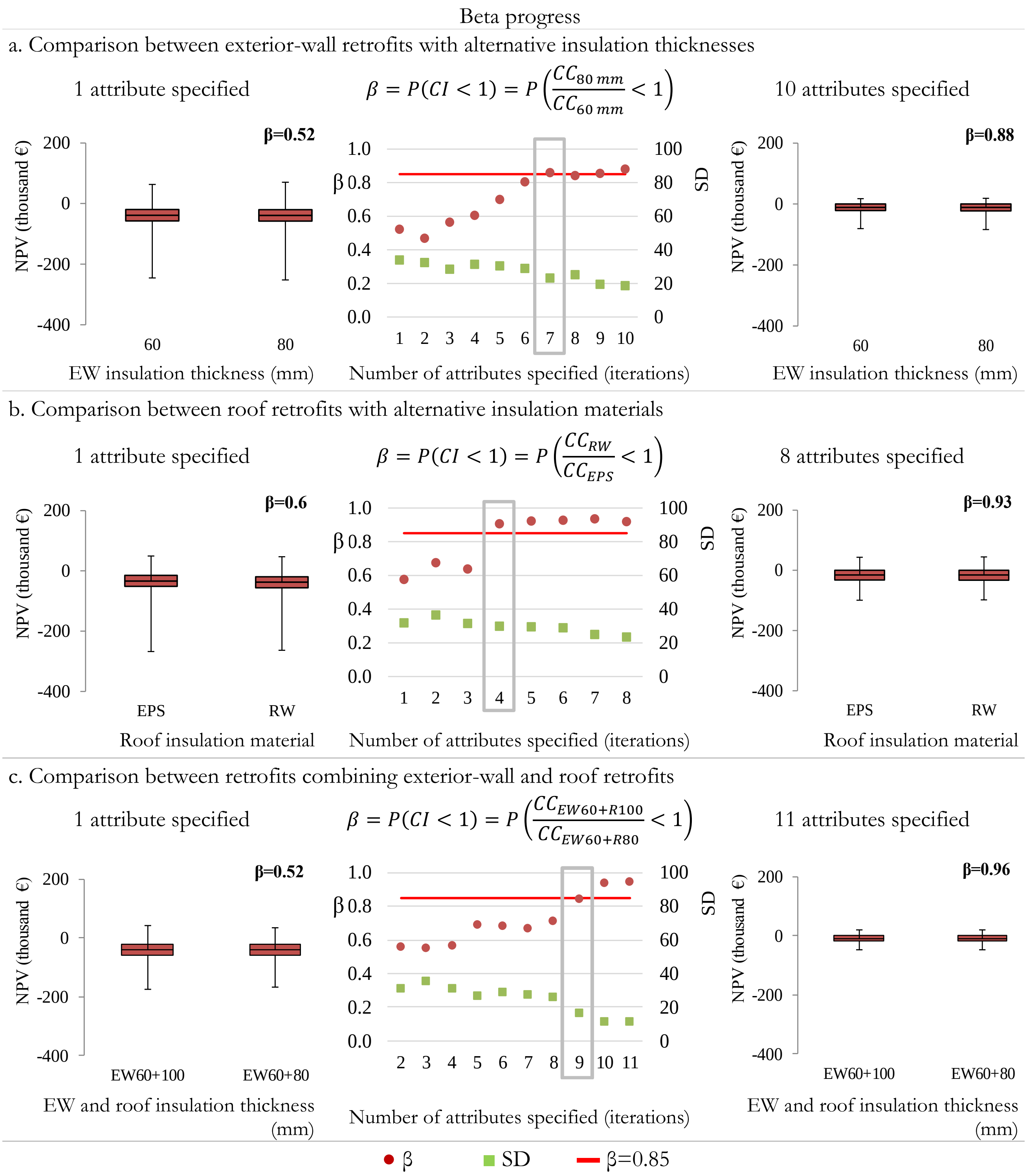
Figure 5.8 Total climate change (CC) life-cycle impacts for: a) alternative exterior-wall insulation thickness (40 and 60 mm), b) alternative roof insulation material (rock wool (RW) and expanded polystyrene (EPS)) and c) alternative retrofits combining exterior-wall and roof retrofits

Figure 5.9b shows that a high level of precision is not necessary to support this decision about the roof insulation material. Another example is presented in Figure 5.9a, showing that to assess the exterior-wall thickness material at least seven attributes must be specified to achieve the beta threshold. Finally, an example comparing alternative exterior-wall and roof retrofits is presented in Figure 5.9c, showing that combining 60-mm exterior-wall insulation with 80 mm roof insulation is better than combining 80-mm exterior-wall insulation with 100-mm roof insulation (with just nine attributes specified). Depending on the design decision, the comparison indicator can show whether one option is better than the other, even when the level of resolution is very low (with very few attributes specified).

5.3.3 Demonstration of an early-design decision process

This section demonstrates an example of an early-design process following the analytical approach presented in Section 5.2.1 (Figure 5.1) for evaluating a retrofit strategy. Following the examples used for validation in the previous sub-sections, the application of the streamlined approach is explored to assess the combined exterior-wall, roof and window retrofits of the single-family house located in Coimbra described previously. Here the early-design stage is defined to be when most of the attributes are unspecified. As such, it is assumed that the designer comes to the tool with knowledge only of the site (location) and a high-level sense of the buildings attributes. The streamlined approach described here then provides feedback to the designer identifying the main drivers of the impact of the building. This allows the designer to either identify an environmentally and economically superior design or to evaluate the design choices that he/she makes increasing specification efficiently until the level of resolution in the result is sufficient to make decisions.

By using the model to guide decisions about retrofits, the designer would have information about an already existing building, with the building attributes (Step 1 from Figure 5.1) at BL4 (fully specified). Assembly, energy, cost, and materials attributes were defined at AL1, EL1, CL1, and ML1, respectively (fully unspecified). Once the inputs are defined, the BAIA model, including the Monte Carlo simulation, is executed (Step 2).



The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval. EW60+R80 = 60 mm of exterior-wall insulation combined with 80 mm of roof insulation; EW60+R100 = 60 mm of exterior-wall insulation combined with 100 mm of roof insulation

Figure 5.9 NPV results for: a) alternative exterior-wall insulation thickness (40 mm and 60 mm), b) alternative roof insulation material (rock wool (RW) and expanded polystyrene (EPS)) and c) alternative retrofits combining exterior-wall and roof retrofits

Figure 5.10 shows that results based on fully unspecified assembly, energy, cost and materials attributes have high uncertainty (SD of about 100). Assuming that this level of resolution is not robust enough to make a decision (Step 3), probabilistic triage (statistical analysis) is conducted to identify the most influential attributes (with the highest contribution to variance) (Step 4). Specifically, we identify the attributes that contribute the most to the LC impact variance, using the normalized Spearman rank correlation coefficient. Each building-attribute contribution to variance is assessed for six environmental metrics, net present value, and equivalent annual cost. The attributes will be further specified according to their contribution to variance (Steps 5 and 6).

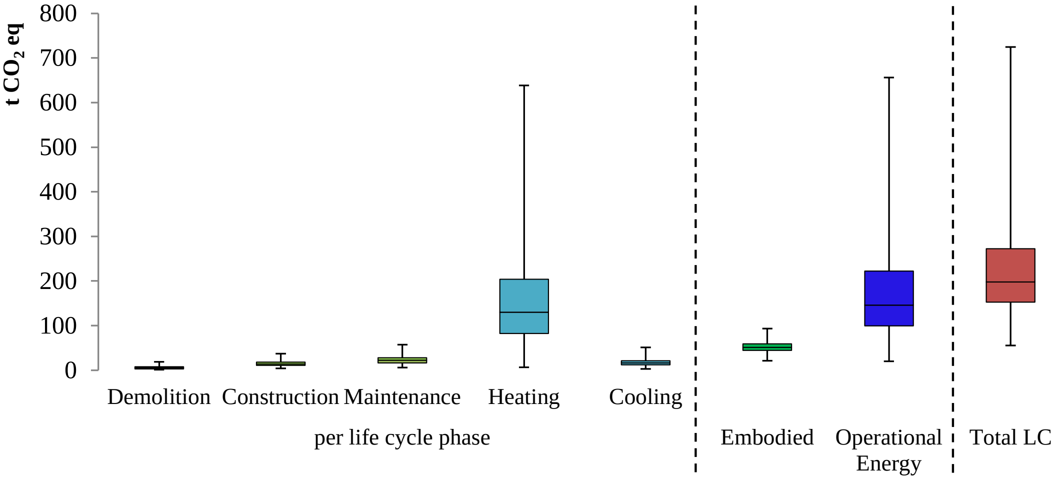


Figure 5.10 Breakdown of climate change total life-cycle results (demolition, construction, maintenance, heating, cooling, embodied and operational energy) with fully unspecified attributes. The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval.

Figure 5.11 presents the attributes with the highest contribution (>10%) to the total LC; embodied, heating, and cooling impacts are also presented. The attributes with the higher contribution to variance can differ depending on the metric, as well as on the LC phase, as shown in Figure 5.11. Nevertheless, there are five attributes that are most common across all the metrics. The overall most influential of these include the heating set points (day and night), heating system efficiency, exterior-wall type retrofit, and exterior-wall insulation thickness. Based on this information, the expected heating set point range was evaluated and the model was rerun with a more refined (i.e., narrower) specification of this influential characteristics.

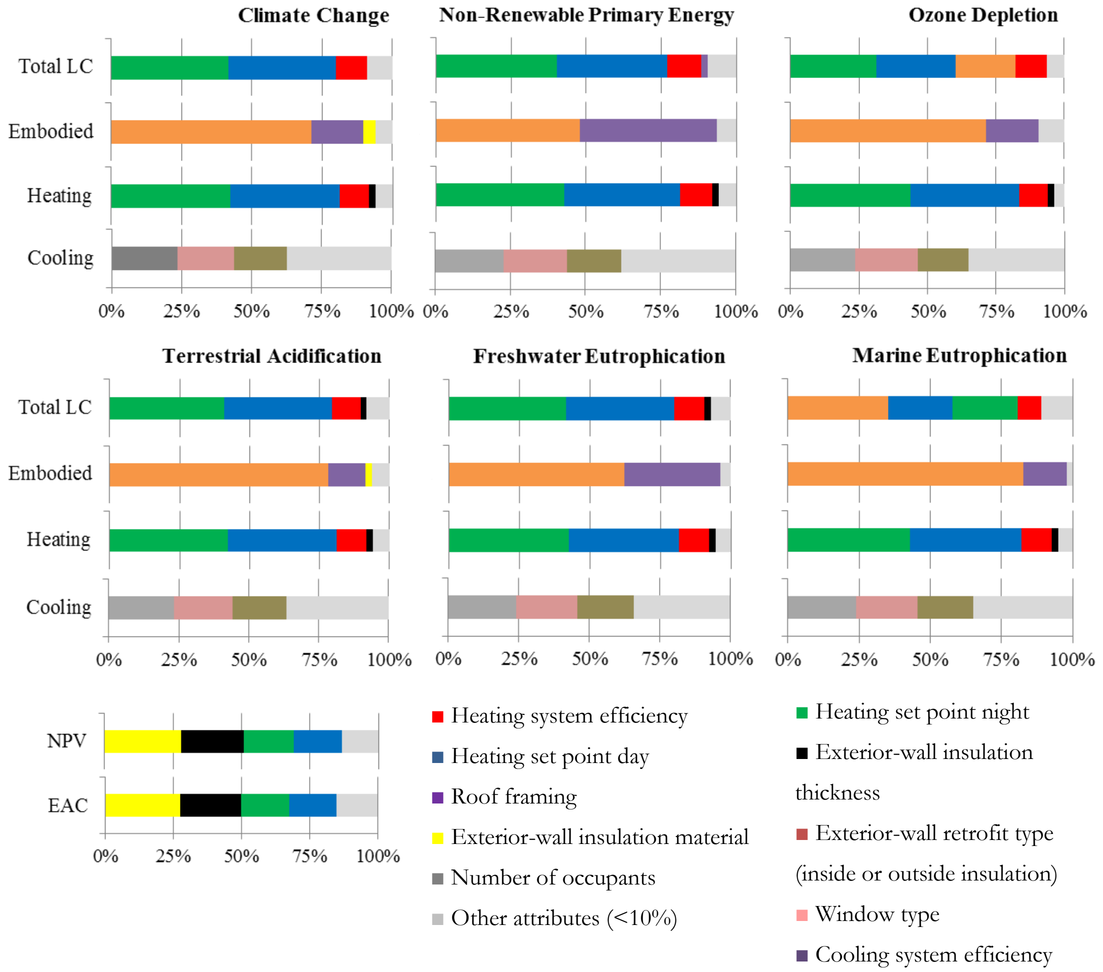


Figure 5.11 Attributes with the highest contribution (>10%) to embodied, heating, cooling or total life-cycle (LC) impacts variance for five environmental impact categories, non-renewable primary energy, net present value (NPV) and equivalent annual cost (EAC) (calculated using the normalized Spearman's rank correlation coefficient)

Following a directed iterative process, the analysis can be repeated (Steps 2-6) until a significant level of resolution is achieved (evaluated at Step 3). Figure 5.12 shows the path-dependent analysis for this case where attributes were further specified until the SD in the results decreased to 10. The selected attributes were resolved at L2 and then at L3 resolution of specificity, as required. The results suggest that the specification of fewer than 10 attributes in the early stages of a building design can produce robust results in the estimation of building environmental impacts. This represents a significant reduction in data collection efforts.

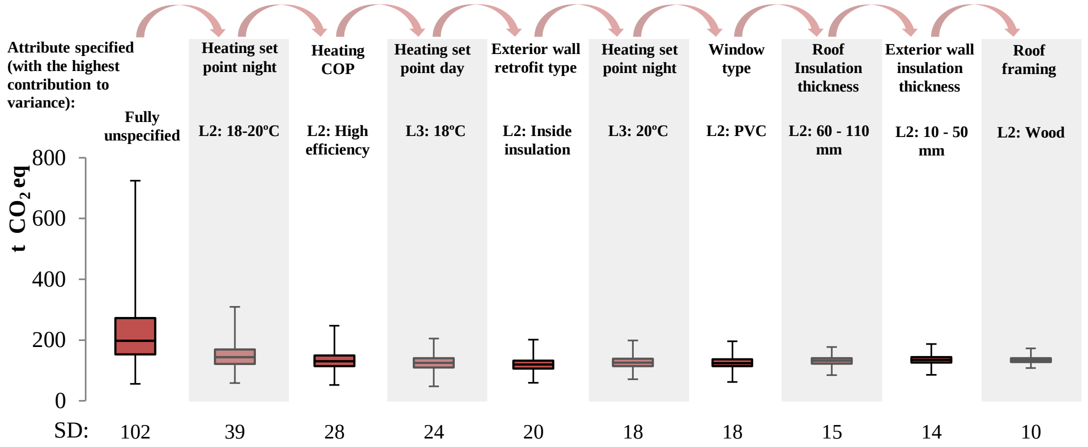


Figure 5.12 Climate change total life-cycle impact results for 10 levels of specificity: All assembly, materials and energy attributes unspecified and one to eight attributes specified. Standard deviation (SD) results for each level. The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval.

Figure 5.13 presents a sequential specification analysis for NPV. As was shown for climate change, the results suggest that the specification of fewer than 10 attributes in the early stages of a building design can produce robust results in the estimation of building costs. After the first run (fully unspecified attributes), the most influential attributes are the exterior-wall insulation material and thickness, and the heating set-point (night and day). Even though there is a significant decrease in the SD after nine attributes specified, the NPV results still retain some uncertainty. At this stage, the most influential attributes are the cooling set-point (night and day) and the roof insulation material.

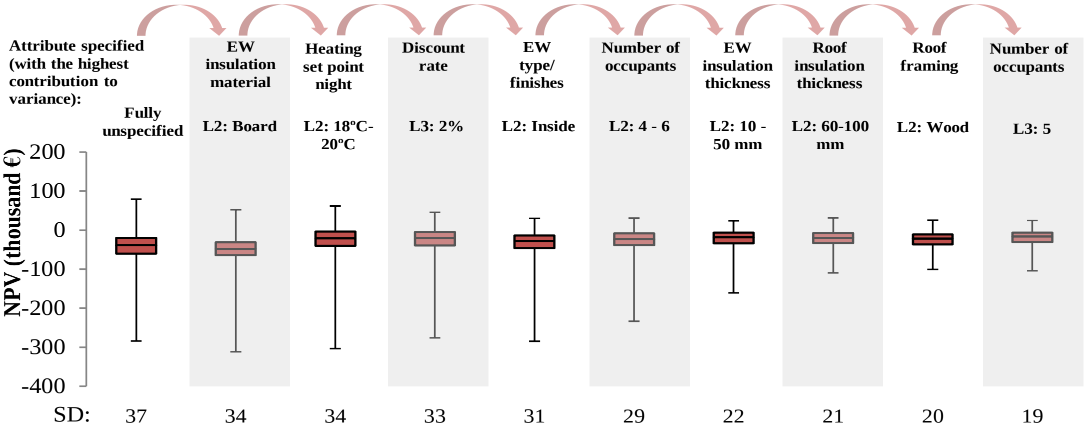


Figure 5.13 Net present value (NPV) results for 10 levels of specificity: All assembly, materials and energy attributes unspecified and one to nine attributes specified. Standard deviation (SD) results for each level. The box plots represent the 25th (lower line), the 50th (median), and the 75th percentile (upper line). The whiskers represent the lower and upper bounds with a 95% confidence interval. EW= Exterior wall

The decrease in the SD in the climate change example is much higher than in the NPV example due to the fact that there is much more uncertainty associated with the variables underlying the environmental impact assessment, for instance, the uncertainty associated with the impact factors.

5.4 Concluding remarks

This chapter described a model and modeling approach that 1) provides consistency by using a structured method to estimate the bill of materials/activities for a building or project, 2) can accommodate limited and uncertain information both in terms of quantities and types of activities (the latter is accomplished through the use of under-specification and an appropriately structured database), 3) evaluates the uncertainty in the estimate for several metrics, and 4) provides feedback on the most influential attributes and data elements. The integrated (embodied, operational energy and cost) streamlined approach presented here neither discards information, nor limits the scope of the analysis, and computes and communicates uncertainty to address the lack of information inherent within early stage evaluations.

The case-study analyses described here suggest that the model is both effective (results were statistically consistent with conventional LCA results – see Figure 5.7, Figure 5.8 and Figure 5.9) and efficient (results were consistent with only limited information about most material, assembly, and cost attributes). Altogether, these results suggest that a streamlined model like the one described here could be an effective tool in informing design decisions for building retrofits, even for historic structures. Given this outcome, it would not be necessary to perform a conventional LCA to assess, for instance, what is the most appropriate insulation thickness or material for the retrofit of a house. This should allow designers to more rapidly evaluate the many options available to improve the economic and environmental performance of buildings.

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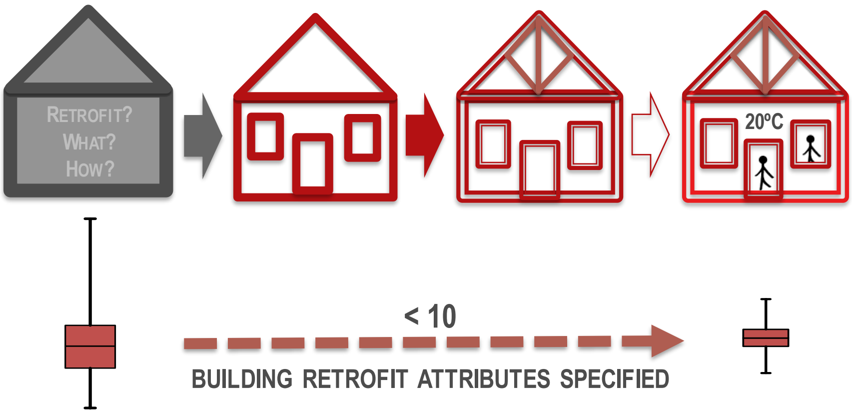
6 Environmental impact and cost of residential building retrofits – what matters?



ABSTRACT To increase the scope of this thesis to cover a larger set of building scenarios and provide recommendations, this chapter presents a comprehensive sensitivity analysis to identify key drivers of the environmental and cost impacts of building retrofits in South European climates. Different types of single-family houses with varied wall systems (from distinct time periods) and occupancy patterns in alternative locations were assessed. The identification of the main influential attributes can efficiently provide environmental and cost feedback to streamline the decision-making process of building retrofits.

6.1 Introduction

Environmental and cost life-cycle assessments face several challenges when applied to buildings. Buildings are complex systems with many different components, materials and quantities which result in data-intensive processes. Additionally, buildings have very long and uncertain life-spans that can include several changes in their use over time.

The building design process includes several stages that can be defined as shown in Figure 6.1. The data gathered come from several different sources at each stage of the design process, which increases the level of uncertainty. Moreover, each stage requires different levels of information detail. The lack of environmental data also usually places a limitation on building material and activity inventories. Finally, architects and designers still lack the knowledge of life-cycle assessment (LCA) and do not incorporate environmental impact issues in the decision-making process.

Decisions taken in early design stages have greater influence in the total LC environmental impact and cost of buildings even though the information available tends to be scarce and uncertain. A comprehensive bill of materials and quantities, as well as product-specific information needed for a conventional LCA are only available at later stages (technical design). By then, any change in the design can be very costly and results become less useful. Moreover, LCA are not usually conducted in current building-design practice, unless needed for environmental building certification schemes, such as LEED.

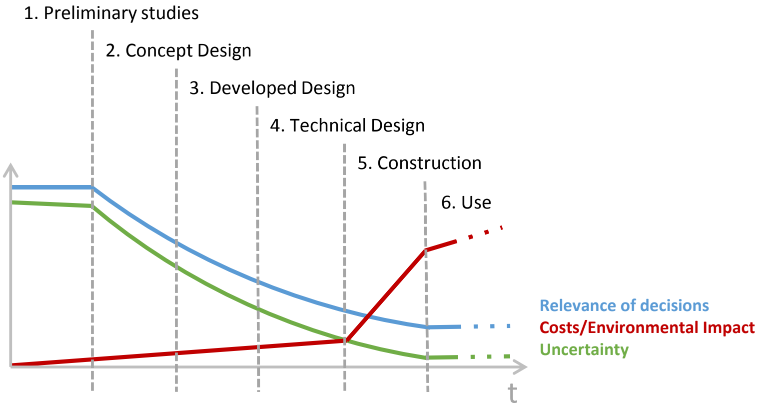


Figure 6.1 Six stages in the architectural design process (Hollberg and Ruth 2016)

To accommodate the limited and variable amount of information available to perform at early-design stage, it is important to define the most influential attributes to streamline the LCA and LCCA of building retrofits and efficiently assess the performance of various building-retrofit cases in early-design stages.

6.1.1 Incorporation of sensitivity analysis in LCA and LCCA of buildings

Sensitivity analysis in LCA and LCCA studies of buildings has been mainly performed to compare various predefined options without previously assessing what actually drives the results. Operational energy has been claimed to be the highest contributor to the total LC impacts of buildings. However, the key parameters that influence the energy performance of buildings have not been identified in a life-cycle perspective, particularly in building retrofits where the improvement of energy efficiency is usually the main objective. Many studies have compared retrofit strategies but none of them focused on identifying what really influences the environmental and cost performance of building retrofits.

Sensitivity analyses have been performed on both embodied- and operation-related parameters. Blengini (2009) carried out an extensive sensitivity analysis of an LCA study on a multi-family residential building considering different data sources for the two most important materials: steel and concrete. Moreover, Hoxha et al. (2014) proposes a simplified statistical method based on a Taylor-series expansion to address uncertainty and contribution analyses in the LCA models of buildings and building materials. Zhang et al. (2014) conducted a sensitivity analysis to investigate the impact associated with the choice of building materials. Verbeeck and Hens (2010) presented the results of a contribution analysis of the LC inventory (LCI) of four typical Belgian residential buildings. The LCI was analyzed and interpreted by means of a contribution analysis, a perturbation analysis and an uncertainty analysis based on Monte Carlo simulations.

Operational energy performance is closely related to the variability in user behavior, which is rarely included in building environmental and cost assessments. Blom et al. (2011) compared energy consumption scenarios by performing a sensitivity analysis of energy supply scenarios (electricity mixes), while Iyer-Raniga and Wong (2012) addressed the variation of building life span and heating equipment efficiencies. The attributes related to occupancy are usually not considered in the decision process or they are only defined in the end of the design process to comply with standards. Different types of occupancy can significantly influence the design decisions. Furthermore, the location of buildings, their typologies and construction techniques can also influence the environmental and cost performance, with window replacement, and roof and external-wall insulation being the most effective building interventions (Iyer-Raniga and Wong 2012; Liu et al. 2014). However, none of the reviewed literature investigated the role and sensitivity of the building attributes and occupancy or their influence on the environmental impact and cost of building retrofits.

6.2 Materials and methods: streamlined LCA-LCCA modeling

The streamlined LCA and LCCA approach to building retrofits described in Chapter 5 was used to perform a complementary sensitivity analysis to different building-retrofit cases and to identify the key drivers to environmental and cost performance for buildings located in Southern Europe. This approach fully integrates a streamlined embodied LCA, statistically-based operational energy and cost models, and incorporates uncertainty to address the lack of information by using structured under-specification combined with probabilistic triage. An automated process enables several scenarios to be assessed and compared as a means of better informing designers of the relative environmental impact of materials and dimensioning choices. By selecting very few attributes, robust retrofit decisions can be made in early-design stages, thereby promoting a reduction in environmental impacts and costs.

A sequential set of analysis is performed by refining the most influential attributes. The general steps of the analysis are presented in Figure 6.2. The iterative process begins by selecting the set scenarios that comprises the definition of building-retrofit cases. The number of scenarios is defined according to both the number of variable building attributes and to the options available. For each scenario, all the other design attributes (not defined as design options) are randomly selected and defined at L1 of specification (the most underspecified). The streamlined model estimates the distribution of outcomes by computationally sampling the possible design-attribute values using Monte Carlo (each iteration runs a set of a 1000 samples). Each iteration combines a set of scenarios refined sequentially. In these analyses, attributes are sequentially resolved based on the rank in the sensitivity analysis, thus creating a set of scenarios with different design options.

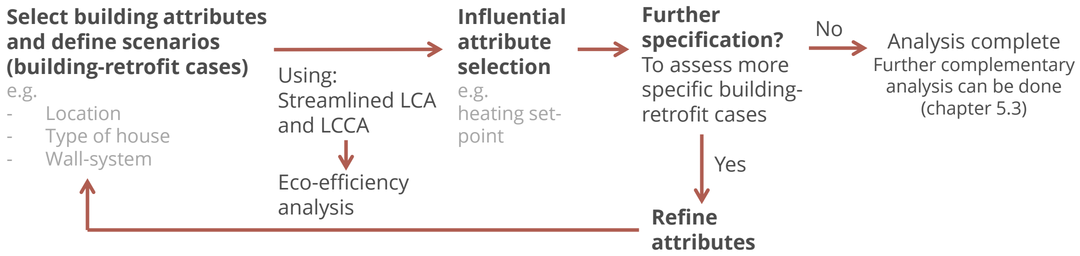


Figure 6.2 Sequential analysis to assess the most influential attributes for a set of residential building-retrofit cases

6.2.1 Scope definition and scenarios

LCA and LCCA were performed for the single-family house presented in Chapter 2 and 3. The LC model implemented includes the following main processes: demolition (e.g., existing roof, windows), construction (retrofit) and use phase (detailed information is presented in Chapters 2 and 3). For the purpose of this analysis, the functional unit is the living area over a period of 50 years. A sequential sensitivity analysis is performed to assess the most influential attributes depending on location, type of house, wall system, heating set-point, and family size. Location includes three alternative cities in Portugal, defined by heating degree days (HDD): Coimbra (1304 HDD), Faro (987 HDD) and Bragança (2015 HDD). Type of house includes three alternatives: semi-detached, detached, and row. Wall-system includes three alternatives: single-leaf stone wall, single- and double-leaf brick. These wall systems represent three different time-periods in building stock development. Single-leaf stone walls without insulation are representative of buildings from early 1900s. Single-leaf brick walls without insulation are representative of the mid-1900s to the late 1900s. Double-leaf brick walls are representative of the period from late 1900s to the early 2000s. Heating set-point analysis includes three temperatures: 18°C, 20°C and 22°C. Finally, family size analysis includes three sizes: two-person, four-person and six-person families.

A sequential set of analyses was performed where the most influential design attributes are further refined. Firstly, a sensitivity analysis was performed to assess the influence of location, type of house and wall systems (Table 6.1a). The first preliminary analysis demonstrated that the heating set-point appears as one of the most influential attributes, independent from type of house or wall system. Based on this analysis, a second set of scenarios (Table 6.1b) assessed the influence of the heating set-point, revealing that family size becomes more influential in lower heating set-points which was then explored in a third set of scenarios (Table 6.1c). This analysis allows us to identify the key drivers of environmental and cost performance in building retrofits dependent on climate, type of house, wall-system and occupancy pattern. For the purpose of this study, three iterations were performed.

Table 6.1 Sequential set of scenarios with refined attributes for three locations (all other attributes are unspecified). HDD = Heating Degree Days

(a) First set of scenarios (iteration 1): type of house and wall-system analysis (27 scenarios)

Location (HDD)	Type of house	Wall system
Faro (987)	Semi-detached	Single-leaf stone
Coimbra (1304)	Detached	Single-leaf brick
Bragança (2015)	Row	Double-leaf brick

(b) Second set of scenarios (iteration 2): heating set-point analysis (nine scenarios)

Location (HDD)	Type of house	Wall system	Heating set-point
Faro (987)	Any type of house (randomly selected)	Any wall system (randomly selected)	18ºC
Coimbra (1304)			20ºC
Bragança (2015)			22ºC

(c) Third set of scenarios (iteration 3): family size analysis (nine scenarios)

Location (HDD)	Type of house	Wall system	Heating set-point	Family size
Faro (987)	Any type of house (randomly selected)	Any wall system (randomly selected)	18ºC	2-person
Coimbra (1304)				4-person
Bragança (2015)				6-person

6.2.2 Structured under-specification and probabilistic triage

A structured under-specification database is used to quantify materials and activities, expected impact, and uncertainty using a hierarchical categorization scheme. Probabilistic triage uses simulation results to assess the contribution of each attribute to the variance of each metric result.

A limited number of inputs (building, assembly, energy, and cost attributes) are introduced in the streamlined model to define the building design. Each set of attributes (building, assembly, energy and cost) have a hierarchical categorization scheme. The attributes are categorized into four hierarchical levels of specificity: Level 1 (L1) to Level 4 (L4), with L1 being the most general or underspecified and L4 the most specified. L1 represents the attribute within a broader class (e.g., any floor aspect ratio, any type of exterior-wall retrofit, any heating set-point), while L4 consists of a specific entry (e.g., floor aspect ratio of 1:3, exterior-wall retrofit with interior insulation, heating set-point of 18ºC). Each entry at L4 implicitly includes a reference to all preceding levels. The levels of specification for each attribute are defined as BL for the building attributes, AL for the assembly attributes, EL for the energy attributes, and CL for the cost attribute. Examples of the hierarchical categorization scheme of each set of attributes are presented in section 5.2.3 of Chapter 5. Once the attributes are defined, they are translated into operational energy needs, material requirements and costs, as well as environmental impact and associated costs.

For the first sensitivity analysis (location, type of house and wall systems), all assembly, energy and costs were specified at AL1, EL1 and CL1, respectively. For the heating set-point analysis, all attributes were specified at L1, with the exception of day and night heating set-points, which were specified at EL4 (18ºC, 20ºC and 22ºC). For the family-size analysis, all attributes were specified at L1, except for the heating set-point (18ºC) and the number of people (two-, four-, and six-person families), which were specified at EL4. All building attributes were specified at BL4, except for location, and type of house and wall system in the first analysis.

6.2.3 Attribute to activity model – embodied, energy and cost inventory

As described in Chapter 5, the Attribute to Activity Model (AAM) is an algorithm that maps the design attributes to material or activity inputs and converts them into a bill of materials/activities, which includes materials, energy, and costs, thereby reducing dependence on complex simulations.

The embodied inventory includes demolition, construction and maintenance processes. Additional details are presented in section 5.2 of Chapter 5. All materials are characterized by density, specific heat, service life (number of replacements), distance to manufacturers, cost (material, labor, maintenance and other), and impact factors. LC inventories can incorporate numerous sources of uncertainties. Firstly, the lack of reliable information about material properties and characteristics, such as density, service life, thermal conductivity, thermal resistance, or heat capacity, leads to high uncertainty. Secondly, material quantities can vary according to potential losses due to cutting and fitting processes on site. Thirdly, transport distances from manufacturer to construction site can be highly uncertain due to the lack of information about manufacturers/distributors, particularly in early design stages. Finally, uncertainties associated with end-of-life activities mainly comprise the amount of waste materials, end-of-life disposal mechanism (final disposal, sorting plant or recycling), as well as end-of-life facilities location. The quantities of materials are uncertain owing to losses during transportation, cutting processes or assemblage. A probability distribution function (triangular) was defined for the percentage loss of each material according to the level of information collected. Once a statistical distribution is characterized for each input parameter, the Monte Carlo simulation is performed to propagate the uncertainty into a range of values.

The AAM for operational energy is a statistically-based metamodel that results from the combination of two sub-metamodels, one for heating energy and one for cooling energy. The form of the model is documented in section 5.2.4.2 of Chapter 5 and Appendix IV. The cost model is defined by a set of algorithms (based on LCCA methods) that converts all costs (construction, maintenance and energy) into cost metrics, as documented in section 5.2.4.3 of Chapter 5 and Appendix IV.

6.2.4 LCIA, LCCA and eco-efficiency analysis methods

The streamlined LCA model calculates five environmental metrics plus non-renewable primary energy. An analysis performed in the previous chapter (Chapter 5.3, Figure 5.6) showed that most environmental metrics have the same top influential attributes. Climate change was then selected for the purpose of this analysis. The streamlined cost model uses both NPV and EAC. The NPV is used to address the relevant costs: construction (retrofit), maintenance (repair and replacement), and energy costs. The LCCA is performed by comparing the costs from a base-case scenario (existing building without retrofit) to each retrofit strategy (Kneifel 2010b). A discount rate is randomly selected between 1% and 8%.

LCA and LCCA can be integrated in a more comprehensive assessment by means of eco-efficiency to assess the trade-offs between cost and environmental impacts. Eco-efficiency has been defined as a general goal of creating value while decreasing environmental impact (Huppes and Ishikawa 2007). The eco-efficiency analysis provides a method to relate both environmental and cost aspects. Although it can be defined in different ways, for this study, the eco-efficiency analysis considers the ratio between the economic value (NPV) and the environmental impacts (EI) of the life-cycle (WBCSD 2000) to maximize the NPV while minimizing environmental impacts. This ratio is then translated into an eco-efficiency indicator. After assessing the most influential attributes for the environmental and cost performance of retrofits throughout the building life-cycle, an eco-efficiency analysis was performed to compare the economic and environmental impact of each retrofit strategy.

6.2.5 Sensitivity analysis metric

The sensitivity analysis is performed by calculating the Spearman rank correlation coefficient (not normalized) to enable the identification of the key parameters that influence the environmental and cost performance of building retrofits. The contribution to each metric variance is calculated for each design attribute. A greater number indicates a stronger relationship between the parameter and the LCIA or LCCA result. Positive correlation coefficients indicate that an increase of a parameter will cause an increase in the respective LCIA or LCCA result, and negative correlation coefficients will cause a reduction of LCIA (beneficial effect) or LCCA result. Negative correlation has a beneficial effect on LCIA results (reduced environmental impact) and positive correlation has a beneficial effect on LCCA and eco-efficient results (increased NPV and eco-efficiency indicator).

6.3 Results and discussion

The Spearman rank correlation coefficient results for the sequential set of analyses are presented in this section. Section 6.3.1 shows the results for the first set of scenarios (iteration one) where the most influential attributes are assessed depending on the type of house and wall-system in three locations. Section 6.3.2 presents the second set of scenario (iteration two) results, after the heating set-point is selected as the most influential attribute. Section 6.3.3 shows the results for the third set of scenarios (iteration three) where the occupancy parameters were further refined and family size was selected as the most influential attribute for occupancies with a low heating-set point. The design attributes, defined at the most underspecified level, are analyzed in terms of their level of influence on climate change, NPV and eco-efficiency results and they are divided into high-, medium- and low-influence attributes.

6.3.1 Influence of type of house and wall-system for three locations

Type of house and wall-system were the building attributes defined for the first set of analysis, for three locations. The combination of the three attributes results in nine scenarios analyzed for each location (27 in total). Three alternative locations in Portugal were defined by HDD: Coimbra (1304 HDD), Faro (987 HDD) and Bragança (2015 HDD). Type of house options include: semi-detached, detached, and row. Wall-system options include: single-leaf stone wall, single- and double-leaf brick.

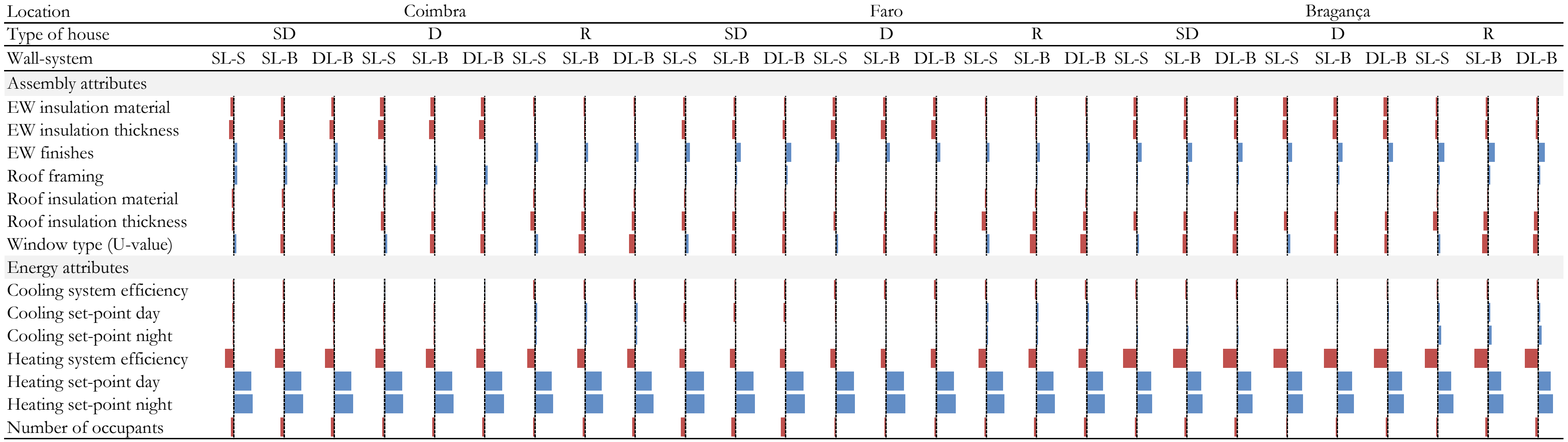
LCIA results

Figure 6.3 presents the Spearman rank correlation coefficients results (not normalized) characterizing the relative contribution of each attribute in the variance of total LC climate change impacts for the 27 scenarios defined. The three most influential attributes (high influence) are the same in the three cities and related to occupancy and operational energy performance (heating set-point night and day, and heating system efficiency). The second most influential attributes (medium influence) are exterior-wall insulation thickness, material, and finishes for semi-detached and detached houses. Roof insulation thickness, window type and exterior-wall finishes have medium influence for row houses. Heating system efficiency and exterior-wall insulation thickness are the top attributes with negative correlation, meaning that an increase in efficiency and insulation thickness leads to lower environmental impacts.

Sensitivity analysis on wall-systems shows that the three most influential attributes are the same in all wall-system options. Window type and exterior-wall insulation thickness have medium influence for single-leaf walls. Number of occupants has medium influence for double-leaf brick walls and all the other attributes have low influence. Window type has more influence in brick walls (single- and double-leaf) than single-leaf stone walls. Heating system efficiency has higher influence in colder climates (Bragança). Number of occupants has higher influence in hotter climates (Coimbra and Faro), with a negative correlation, meaning that a larger number of people leads to lower environmental impacts.

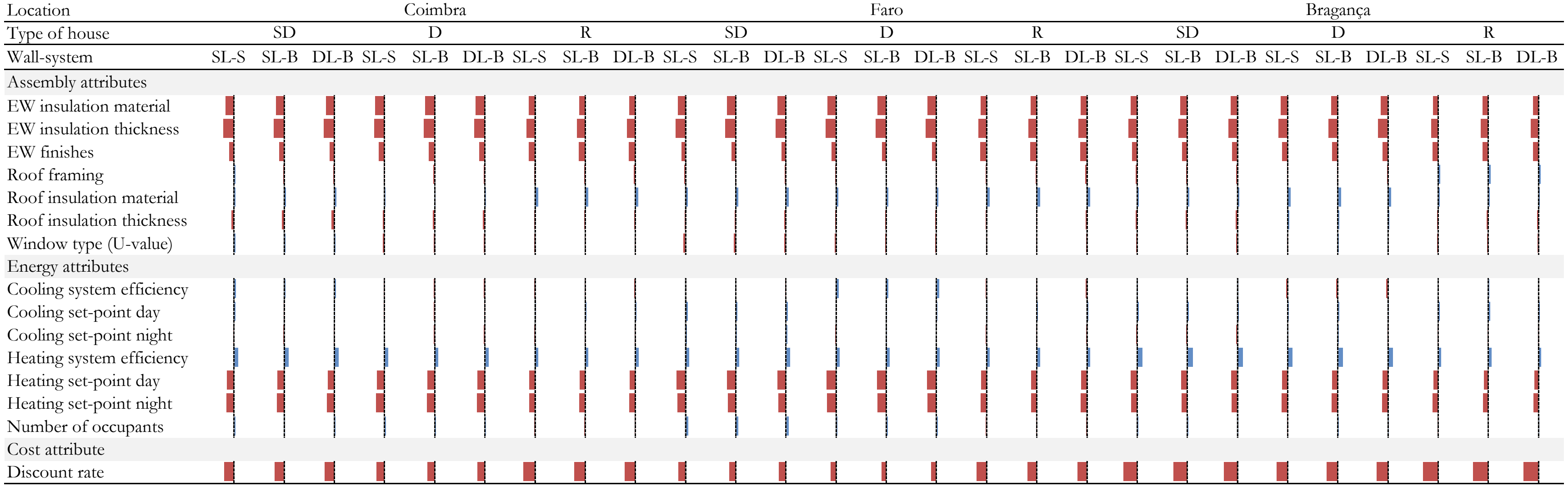
LCCA results

Figure 6.4 presents the Spearman rank correlation coefficient results characterizing the contribution to NPV variance for alternative house types and wall systems in each location (Coimbra, Faro and Bragança). Exterior-wall thickness and material, heating set-points (day and night), and discount rate are the most influential attributes. Heating system efficiency has the highest positive correlation in all scenarios, meaning that higher efficiencies lead to higher NPVs. Discount rate is the attribute with the highest negative correlation in Bragança and Coimbra, meaning that higher discount rates lead to lower NPVs. Exterior-wall insulation thickness has the highest negative correlation in Faro.



EW=Exterior-wall; SL-S= Single-leaf stone; SL-B= Single-leaf brick; DL-B=Double-leaf brick; SD=Semi-detached; D=Detached; R=Row

Figure 6.3 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of total LC climate change impacts for alternative types of house and wall systems in Coimbra (all assembly and energy attributes are unspecified). Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.



EW=Exterior-wall; SL-S= Single-leaf stone; SL-B= Single-leaf brick; DL-B=Double-leaf brick; SD=Semi-detached; D=Detached; R=Row

Figure 6.4 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of NPV for alternative types of house and wall systems in Coimbra (all assembly and energy attributes are unspecified). Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.

Eco-efficiency results

Spearman rank correlation coefficient results characterizing the contribution to eco-efficiency variance shows that exterior-wall insulation thickness and material, and discount rate have the strongest negative correlation to eco-efficiency, in all scenarios. The attributes with positive correlations are the heating set-points (day and night) and roof insulation material, meaning that even though they have low influence, they are the only attributes that have a beneficial effect on eco-efficiency results. There are no significant changes in the top-ranked attributes within all scenarios. Among the top-ranked attributes, discount rate has higher influence in Bragança and lower influence in Faro. Eco-efficiency results are presented in Figure A - 7 in Appendix V.

6.3.2 Influence of occupancy for three locations

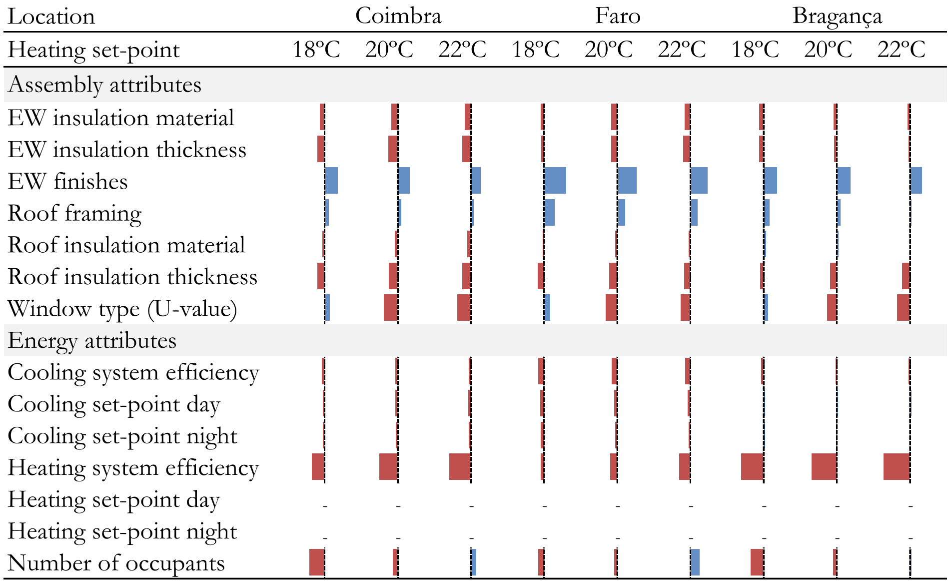
6.3.2.1 Heating set-point analysis

LCIA results

Figure 6.5 shows that the most influential attributes vary within set-points and locations. Heating system efficiency, exterior-wall finishes, and the number of occupants are the most influential attributes for lower set-points (18ºC) in Coimbra and Bragança. Window type has higher influence in higher set-points. In Faro, exterior-wall finish is the most influential attribute, followed by roof framing, roof and exterior-wall insulation (material and thickness). The influence of heating system efficiency increases with higher heating set-points. Window type has positive correlation in lower set-points and negative correlation in higher set-points. Roof and exterior-wall insulation thickness are the second most influential attributes (medium influence) for all heating set-points.

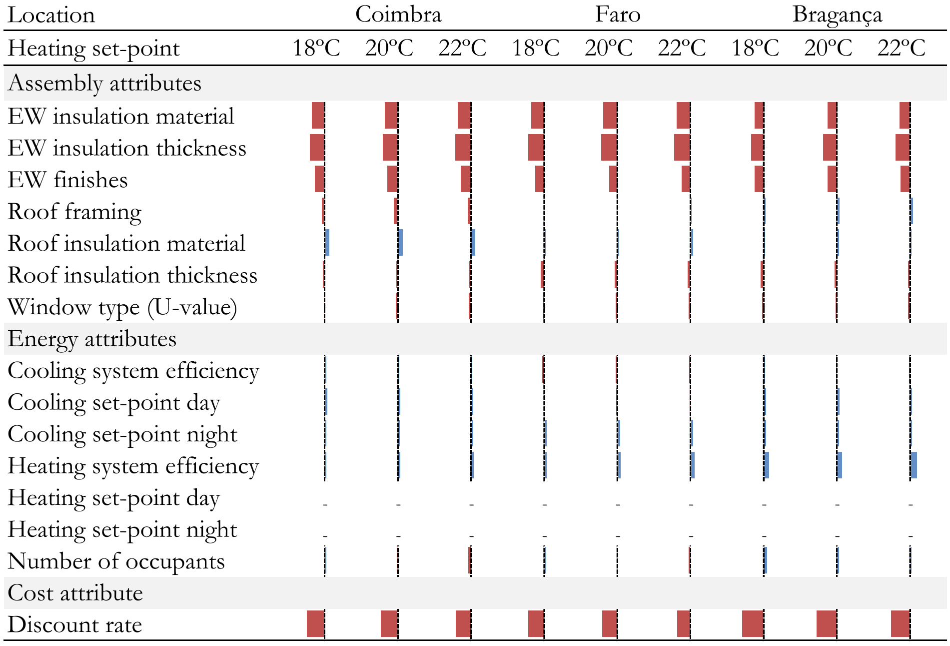
LCCA results

Figure 6.6 shows that all scenarios present similar trends. Exterior-wall related attributes and discount rate are the most influential on NPV in all scenarios. Regarding the attributes with positive correlation (beneficial effect on NPV), heating systems efficiencies become more influential with higher set-points in colder climates (higher energy needs). All other attributes have very low influence on the variance of NPV results.



EW=Exterior-wall

Figure 6.5 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of total life-cycle climate change impacts for alternative set-point scenarios for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.



EW=Exterior-wall

Figure 6.6 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of NPV for alternative set-point scenarios for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.

Eco-efficiency results

The Spearman rank correlation coefficients results (not normalized) characterizing the relative contribution of each attribute in the variance of eco-efficiency results for the alternative set-points are presented in Figure 6.7. Mirroring NPV, the discount rate, along with exterior-wall insulation material and thickness, are the most influential attributes, followed by exterior-wall finishes in all scenarios. All other attributes have very low influence on the variance of eco-efficiency results.

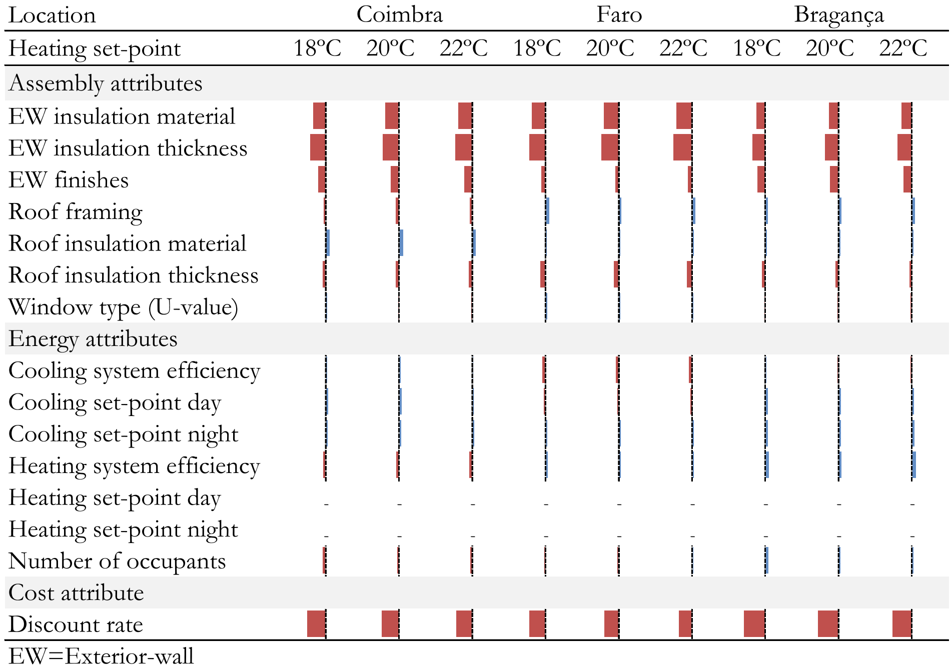
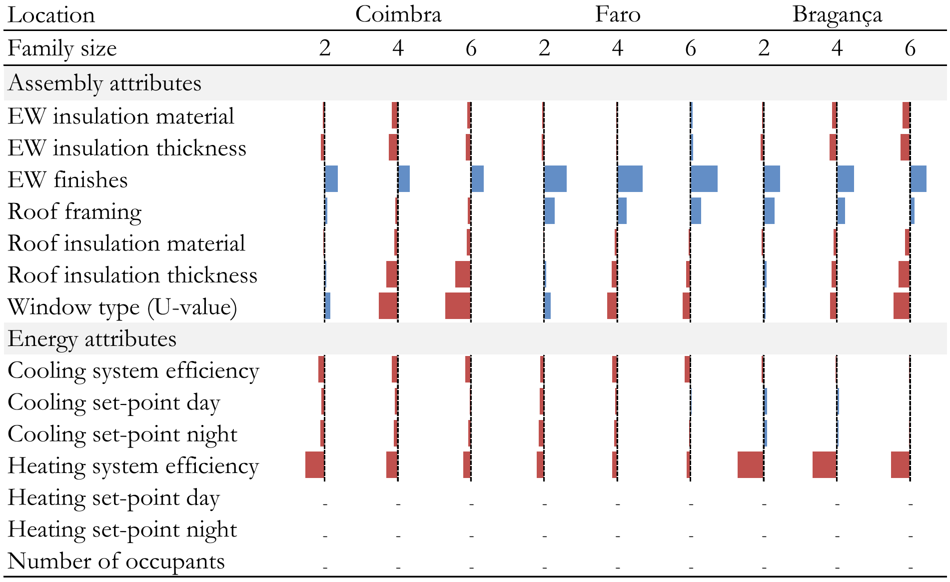


Figure 6.7 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of eco-efficiency results for alternative set-point scenarios for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.

6.3.2.2 Family size analysis

LCIA results

The most influential attributes vary within set-points and locations as shown in Figure 6.8. Heating system efficiency and exterior-wall finishes have high influence on the variance of total LC climate change impacts in Coimbra and Bragança. In Faro, exterior-wall finishes and roof framing are the most influential attributes. The influence of roof-insulation thickness and window type are higher for larger family sizes. Heating system efficiency is less influential in bigger families.

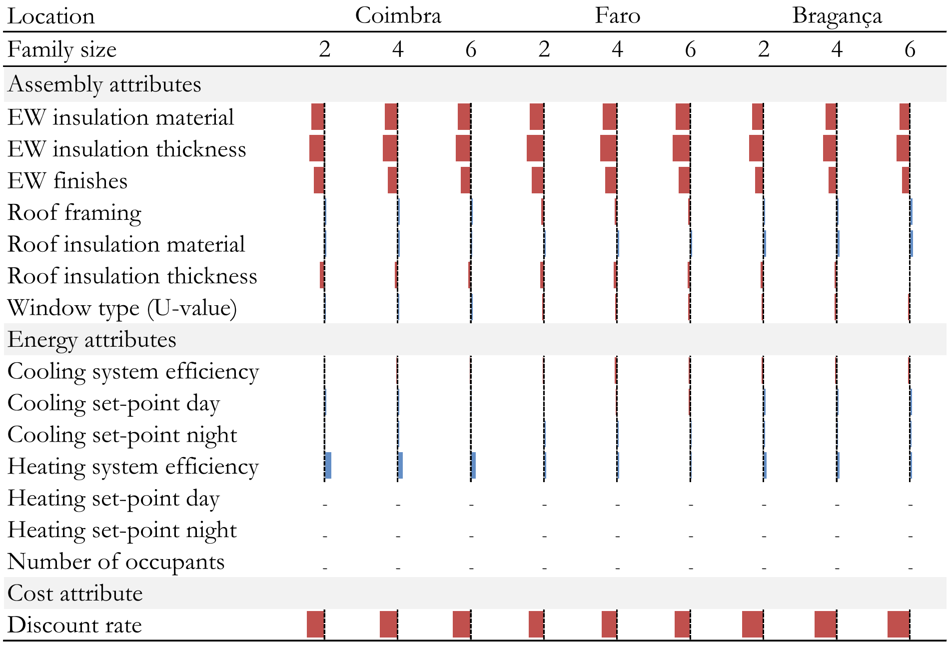


EW=Exterior-wall

Figure 6.8 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of total LC climate change impacts for alternative family-size scenarios assuming a heating set-point fixed at 18ºC, for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. EW=Exterior-wall

LCCA results

Following the trends from the previous NPV analysis, Figure 6.9 shows that the most influential attributes are exterior-wall thickness and discount rate in all scenarios, followed by exterior-wall material and finishes. The attribute with the strongest positive correlation (beneficial effect) is heating system efficiency. All other attributes have very low influence on the variance of NPV results.

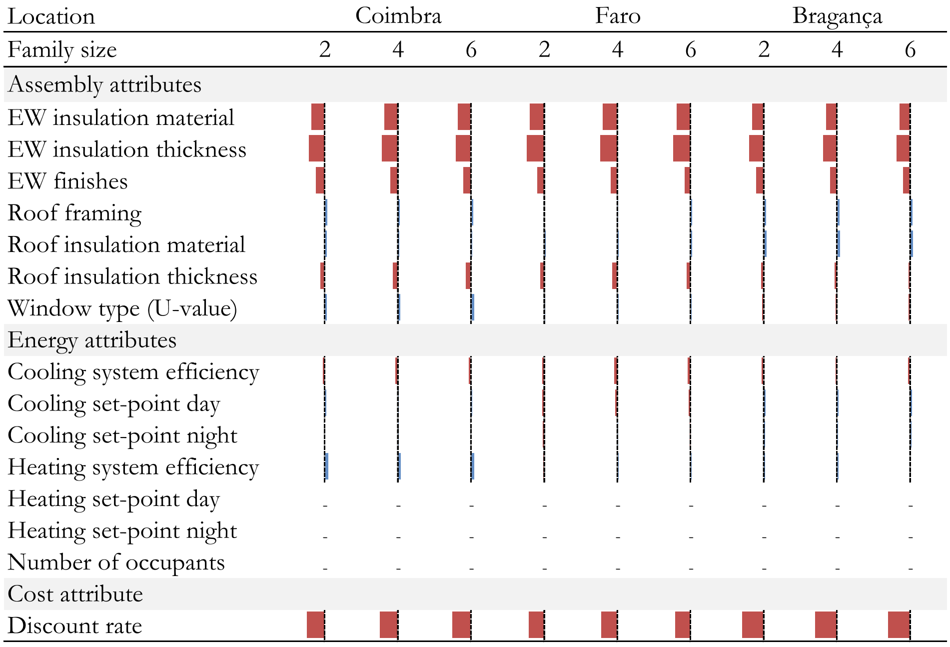


EW=Exterior-wall

Figure 6.9 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of NPV for alternative family-size scenarios assuming a heating set-point fixed at 18ºC, for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. EW=Exterior-wall

Eco-efficiency results

Figure 6.10 shows that the most influential attributes are exterior-wall thickness and discount rate in all scenarios, followed by exterior-wall material and finishes in all scenarios. The attribute with the strongest positive correlation (beneficial effect) is heating system efficiency. All other attributes have very low influence on the variance of eco-efficiency results.



EW=Exterior-wall

Figure 6.10 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of eco-efficiency results for alternative family-size scenarios assuming a heating set-point fixed at 18ºC, for any type of house and any wall-system (randomly selected). All assembly attributes and all the other energy attributes are unspecified. Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. EW=Exterior-wall

6.4 Concluding remarks

The streamlined environmental and cost life-cycle approach for building retrofits was applied to perform a complementary sensitivity analysis to different retrofit cases. A sequential sensitivity analysis was performed to assess the most influential attributes on total life-cycle (LC) climate change impacts, net-present value (NPV), and eco-efficiency, depending on location, type of house, wall system, heating set-point, and family size. The sequential set of analyses was performed by refining the most influential attributes. The sensitivity analysis is implemented by calculating the Spearman rank correlation coefficient (not normalized) to enable the identification of key parameters that influence the environmental and cost performance of building retrofits.

The most influential attributes on total LC climate change are: heating set-point night and day and heating system efficiency, irrespective of location, type of house and wall-system; however, they differ depending on occupancy conditions. The attributes with the strongest correlation to NPV are discount rate, heating set-point, and exterior-wall insulation material and thickness. For eco-efficiency, the most influential attributes are discount rate and exterior-wall insulation material and thickness for all scenarios assessed.

Besides the occupancy attributes identified as the most influential, other design attributes were identified with medium influence. For instance, exterior-wall-related attributes have greater influence in detached and semi-detached house. Roof insulation thickness and window type have higher influence in row houses. Window type and exterior-wall insulation thickness have more influence in houses with single-leaf walls. The number of occupants has higher influence in houses with double-leaf walls.

The most influential attributes can change depending on family size or heating set-point. It is worth noting that the number of occupants has greater influence in lower heating set-points, while heating system efficiency and window type have higher influence in higher set-points. Heating system efficiency has higher influence in colder climates. Roof insulation thickness and window type have higher influence in houses occupied by bigger families. In conclusion, highly influential attributes should be defined early in the design process as they may leverage further design decisions.

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7 Conclusions and recommendations

7.1 Key findings and contributions

This thesis explored both conventional and streamlined LCA and LCCA approaches to identify the most appropriate strategies to improve the LC environmental and economic sustainability of building retrofits for family households and office buildings in South European climates. A conventional integrated cost and environmental LC approach combined with thermal dynamic simulation was developed and implemented for different building retrofit projects in South European climates (a single-family house, an apartment, and an office building).

A comprehensive analysis of different retrofit strategies (roof and exterior walls) combining alternative insulation levels and occupancy patterns was performed to identify opportunities to minimize life-cycle environmental and cost impacts. Final and non-renewable primary energy, environmental impacts and net annual savings were assessed and trade-offs were identified. Embodied and operational impact trade-offs and potential improvements in energy efficiency were also evaluated for all building types. An eco-efficiency assessment (integrating environmental impacts and costs) was performed for the alternative retrofit strategies and uses. Moreover, the influence of occupancy and adaptive reuse in the economic and environmental performance of building retrofit strategies was assessed.

Although LCA and LCCA are very useful tools to assess the environmental and cost performance of the building, they are time consuming and resource-intensive to implement, discouraging a more widespread use, by architects, contractors, engineers or other construction-related experts. This thesis developed a novel approach to streamline LCA and LCCA for building retrofits that both accommodates varying amounts (and quality) of information on retrofit design and provides estimates and its associated uncertainty for environmental and economic performance. This approach fully integrates a streamlined embodied LCA, statistical-based operational energy and cost models. The streamlined method used to develop this framework (Hester et al. 2016b) comprises the application of structured under-specification, probabilistic triage and guided sequential specification. It is applied to a case analysis of the single-family house previously assessed in the conventional LCA approach.

The streamlined approach provides feedback to the designers by identifying the main drivers of the impact of the building. This allows the designers either to identify an environmentally and economically superior design or to evaluate the design choices that he/she makes, increasing specification efficiently until the level of resolution in the result is sufficient to make decisions.

In summary, this thesis contributes to the study of LCA and LCCA of building retrofits in four ways. Firstly, it engages in analysis of several real buildings by assessing the environmental and cost performance and by providing insights and recommendations for future practice. Secondly, it examines the extent to which occupancy influences the environmental and cost performance of building retrofits, as well as the decision-making process. Thirdly, it discusses the limitations of existing LCA and LCCA approaches and their applications in building design and current construction practices. Finally, it advances methodological frameworks by developing novel streamlined LCA and LCCA approaches for building retrofits in South European climates and providing recommendations for early-design decisions.

The main responses and related findings deriving from the six research questions formulated in Chapter 1 (Table 1.1) are discussed below.

Building retrofits are mainly focused on improving the energy efficiency of buildings.

1. WHAT IS THE IMPACT OF ENERGY-SAVING RETROFIT STRATEGIES ON THE ENERGY AND ENVIRONMENTAL LIFE-CYCLE PERFORMANCE OF BUILDINGS?

An integrated life-cycle approach combining LCA and thermal dynamic simulation was implemented to assess energy and environmental performances of alternative retrofit strategies for the roof and exterior walls retrofit of both a single-family house and an apartment. The incorporation of additional insulation levels has been widely used as an important energy-saving retrofit strategy. A comprehensive analysis of alternative insulation thicknesses was performed.

The results quantified the influence of incorporating thermal insulation as a retrofit measure in existing buildings, showing that operational energy impacts (heating and cooling) are relatively higher for the apartment (50–94%) than for the single-family house (43–54%). For both single-family house and apartment, the benefit of adding 40 mm of insulation to the exterior walls represents a reduction in the total LC impacts of about 10% (both dwelling types), with a reduction in operational emissions of about 20%; adding an extra 40 mm (for a total of 80 mm of insulation) only leads to a decrease of about 1–2% of total LC impacts and 3–5 % of operational emissions.

There was a significant benefit associated with the improvement of the thermal envelope just by adding 40 mm of insulation in both the roof (reduction of about 3% for the apartment to 5% for the single-family house in the total LC impacts) and exterior walls (a reduction of about 10% for both dwellings) in the total LC impacts. For insulation thicknesses of 80 mm or more (both roof and exterior walls), the reduction in the total LC impacts is not significant (less than 1%). The single-family house exterior walls retrofit makes a greater contribution to the total LC impacts (about 10%) than the roof retrofit (about 5%); however, the exterior wall retrofit leads to lower total LC impacts (reduction of about 10%). Conversely, the apartment exterior-wall retrofit makes a smaller contribution to the total LC impacts (about 2%) than the roof retrofit (about 14%) and also leads to lower total LC impacts (reduction of about 15%).

Energy-saving retrofit measures promote a significant reduction in the operational energy needs but the embodied impacts of these measures are often neglected.

2. ARE THERE POTENTIAL TRADE-OFFS BETWEEN EMBODIED AND OPERATIONAL ENERGY ENVIRONMENTAL IMPACTS IN BUILDING RETROFITS?

Building standards are mainly focused on reducing energy consumption during the use phase of a building without taking into account the whole life-cycle perspective. It is a commonly held opinion that high levels of thermal insulation constitute one of the first steps towards reducing the energy consumption of existing buildings. However, this approach generally does not consider the embodied burdens associated with the additional insulation materials. Moreover, questions regarding the risks of over-specifying some construction elements and installations have emerged, particularly for mild climate regions. The increase of the embodied impacts due to improved building materials and technologies is not balanced by a reduction of the operating energy, and thus, the impact of the building whole life-cycle is not further reduced (Sartori and Hestnes 2007; Ramesh et al. 2010). An extra insulation level can lead to higher embodied impacts without significant reduction in the operational energy, which can in turn result in higher total life-cycle impacts for these buildings (Hernandez and Kenny 2010; Rodrigues and Freire 2014a).

An environmental LCA was conducted to evaluate the trade-offs between embodied and operational energy impacts of alternative retrofit strategies for the roof and exterior walls retrofit of a single-family house and an apartment, and a comprehensive analysis of alternative insulation thicknesses was performed. The results show that a tipping point can be found where total life-cycle impacts are minimized and an insulation level threshold is revealed (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off). The insulation thresholds calculated for each house type are presented in the next section (7.2 Recommendations).

Major building retrofits are costly and require important quantities of material and products, but different strategies can be adopted to achieve an optimum balance between initial investments, energy cost savings and minimization of environmental impacts during the building LC.

3. IS IT POSSIBLE TO FIND SOLUTIONS THAT ARE AT THE SAME TIME ENVIRONMENTALLY FRIENDLY AND COST-EFFECTIVE?

An environmental and cost assessment was implemented to assess the roof and exterior-wall retrofit of a single-family house from the early 1900s with load-bearing stone masonry walls in Portugal (to be representative of South European climate buildings). LCA and LCCA can be integrated in a more comprehensive assessment by means of eco-efficiency, to evaluate the trade-offs between cost and environmental impacts. This research highlights the importance of addressing the entire life-cycle of building retrofit to reduce environmental impacts and costs by quantifying the marginal LC benefit of different strategies and additional insulation levels for building retrofits in South European climates.

For the single-family house, eco-efficiency results show that exterior wall insulation leads to better performances in both low and high residential occupancy. Roof insulation is more beneficial for high occupancy levels. Assuming an office-use pattern, the incorporation of insulation is not significant showing that the highest benefits are related to the replacement of windows and the incorporation of HVAC systems. Additionally, higher thermal comfort conditions lead to higher benefits of incorporating additional insulation. For the office building, results show that higher comfort conditions lead to better eco-efficient results in all types of occupancy.

In low residential occupancy, the better eco-efficient results are all roof and exterior-wall insulation strategies with standard or higher comfort conditions. In high residential occupancy, the roof insulation strategies present the better results. In office use, all retrofit strategies with higher comfort conditions are eco-efficient, as well as the retrofit strategies without roof insulation in standard comfort conditions. However, in low residential occupancy and office use, none of the retrofit strategies in any comfort conditions presents savings.

Building retrofit 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.

4. HOW DOES TYPE OF USE AND OCCUPANCY PATTERN INFLUENCE THE ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF BUILDING RETROFITS?

To address this research question, an integrated approach combining environmental LCA, LCCA, and thermal dynamic simulation was implemented to assess the performance of retrofit strategies for historic buildings in Southern European climates assuming different occupancy scenarios.

Depending on the type of use and occupancy, different retrofit strategies can be adopted to maximize life-cycle environmental and cost benefits. LC impacts were calculated for five environmental categories and non-renewable primary energy, showing that the reduction of impacts due to retrofit is larger in high occupancy than in low occupancy. Office use presents lower total LC impacts, followed by low residential occupancy and high residential occupancy. LCIA results shows that heating, cooling, exterior-wall and roof retrofit are the main contributors to the total LC impacts in all categories. The contribution of exterior-wall or roof retrofit to the total LC impacts depends on the type of building. For instance, in the semi-detached house, the exterior-wall retrofit has a greater contribution than the roof retrofit, while the roof retrofit has a greater contribution than exterior-wall retrofit for the detached building. Cooling is the greatest contributor in office use, while heating has the highest impacts in residential uses. Additionally, increasing the comfort conditions in office use leads to higher LC impacts, compared to residential uses.

The EAC method was employed to calculate annual net savings for the alternative retrofit scenarios, showing that high residential occupancy presents higher net annual savings (up to about 800€). For all types of occupancy, inside insulation presents greater savings than outside insulation. Higher exterior-wall insulation levels present greater savings but the marginal benefit of additional insulation levels depends on occupancy level and use. There is no marginal benefit in additional roof insulation levels, as the energy savings do not offset the additional material costs. This can be justified by the fact that in the four-story house, the top floor is used intermittently for storage or occasional visitors. In houses with one or two floors, the roof insulation would have a much more prominent influence.

The retrofit strategies that maximize LC benefits depend on the type of use and occupancy level. Highly-insulated retrofit is more beneficial for high occupancy levels with higher thermal comfort conditions. Residential use with higher thermal comfort presents higher environmental and cost performances. In lower comfort conditions, there is no benefit from incorporating insulation. Inside insulation presents lower environmental impacts and higher savings than outside insulation. Exterior-wall with 40-mm insulation presents the highest marginal savings and the lowest environmental impacts. Even though roof insulation does not present relevant cost savings, it leads to lower environmental impacts. However, there is no benefit in incorporating more than 80 mm of roof insulation for any type of occupancy.

One issue preventing a more widespread use of LCA and LCCA is that both are time-consuming and resource-intensive to implement.

5. CAN A STREAMLINED APPROACH TO LCA AND LCCA OF BUILDING RETROFITS BE MORE EFFICIENT (WITH THE SAME EFFECTIVENESS) THAN A CONVENTIONAL LCA?

To answer this research question, a novel approach was developed to streamline LCA and LCCA for building retrofits that both accommodates varying amounts (and quality) of information on retrofit design and provides estimates and the associated uncertainty of environmental and economic performance. This approach includes the application of structured under-specification, probabilistic triage, and guided sequential specification. It is applied to the case analysis of a single-family house built at the beginning of the 20th century, evaluated using a conventional LCA approach.

The results suggest that the specification of fewer than 10 attributes in the early stages of a building design can produce robust results in the estimation of environmental impacts. The streamlined approach provides feedback to the designer identifying the main drivers of the impact of the building. This allows the designer either to identify an environmentally and economically superior design or to evaluate the design choices that he/she makes to increase specification efficiently until the level of resolution in the result is sufficient to make decisions.

The integrated (embodied, operational energy and cost) streamlined approach presented here neither discards information, nor limits the scope of the analysis, while computing and communicating uncertainty to address the lack of information inherent within early stage evaluations. An automated process allows for several scenarios to be assessed and compared as a means of better informing designers of the relative environmental impact of materials and dimensioning choices, leading to the conclusion that different design decisions can be made at different levels of resolution. On the one hand, decisions related to the most influential attributes can be made with just one attribute fully specified (e.g., exterior-wall insulation thickness), while on the other hand, decisions related to less influential attributes can be made with fewer than 10 attributes specified (e.g., roof insulation material). Altogether, these results suggest that a streamlined model like the one described here could be an effective tool in informing design decisions for building retrofits, even for historic buildings. Given this outcome, it would not be necessary to perform a conventional LCA to assess, for instance, what is the most appropriate insulation thickness or material for the retrofit of a house. This should allow designers to more rapidly evaluate the many options available to improve the economic and environmental performance of buildings. By selecting the most influential attributes and then comparing several options, robust decisions can be made in early design phases, promoting a reduction in environmental impacts and costs.

To accommodate the limited and variable amount of information available at early-design stage, it is important to define the most influential attributes to streamline the LCA and LCCA of building retrofits and efficiently assess the performance of various building-retrofit cases.

6. WHAT MATTERS IN ENVIRONMENTAL AND COST LCA OF BUILDING RETROFITS?

To assess what matters in environmental and cost LCA of building retrofits, the key drivers of environmental and cost performance of building retrofits were identified. The design attributes were assessed by means of their contribution to environmental impact and cost variance using the Spearman rank correlation coefficient. A comprehensive sensitivity analysis was performed to assess a set of building-retrofit cases combining different types of single-family houses with various wall systems, and occupancy patterns, in alternative South

European locations. The scenarios were assessed using the streamlined LCA and LCCA approach for building retrofits developed in this thesis.

This thesis demonstrates that the most influential attributes can change depending on family size or heating set-point, meaning that an early definition of these attributes can influence those decisions that are the most important at an early design stage. The attributes bearing the most influence on total LC climate change are: heating set-point night and day and heating system efficiency, irrespective of location, type of house and wall-system; however, they differ depending on the occupancy conditions. Other influential attributes were identified for each house type and wall system. Exterior-wall-related attributes have higher influence in detached and semi-detached house. Roof insulation thickness and window type have higher influence in row houses. Window type and exterior-wall insulation thickness have higher influence in houses with single-leaf walls. Number of occupants has higher influence in houses with double-leaf walls. It is worth noting that the number of occupants has higher influence in lower heating set-points, while heating system efficiency and window type have higher influence in higher set-points. Heating system efficiency has higher influence in colder climates. Roof insulation thickness and window type have higher influence in houses occupied by bigger families.

The attributes with the strongest correlation to NPV are discount rate, heating set-point, and exterior-wall insulation material and thickness. For eco-efficiency, the most influential attributes are discount rate, exterior-wall insulation material and thickness for all scenarios assessed.

7.2 Recommendations

The outcome of this thesis can be useful for real-life applications by helping building designers, stakeholders (e.g., owners, operators), or policy makers to reduce energy, environmental impacts, and costs associated with building retrofits in South European climates.

Drawing on the results, some recommendations can be provided to enhance the environmental performance of building retrofits in historic city centers with load-bearing stone wall systems, typical construction systems in South European buildings from the late 1800s to the early 1900s), pointing to the use of about 40 mm (apartment) and 80 mm (single-family house) of insulation as a threshold for the roof retrofit and about 60-80 mm (for both apartment and single-family house) in exterior-wall retrofits. For the office building (detached), an insulation level threshold was identified for exterior walls (60-70 mm for all occupancy patterns) and roof retrofit (80-90 mm for low occupancy, 90-100 mm for high occupancy and 60-80 mm for commercial use).

Different retrofit strategies can be identified that maximize LC benefits, depending on the type of use and occupancy level. Highly-insulated retrofit is more beneficial for high occupancy levels with higher thermal comfort conditions. In lower comfort conditions, there is no benefit from incorporating insulation. Inside insulation has better environmental and cost performance. Exterior-wall with 40-mm insulation presents the highest marginal savings and the lowest environmental impacts. Even though roof insulation does not present relevant savings, it leads to lower environmental impacts. However, there is no advantage in roof insulation of more than 80 mm for all types of occupancy.

Following an eco-efficiency perspective, some recommendations can also be provided showing that, in low residential occupancy, retrofit is more beneficial with higher comfort conditions, the most eco-efficient being the retrofit strategy without roof insulation, combined with 80 mm of exterior-wall insulation. In high residential occupancy, roof with 80 mm of insulation, combined with 80 mm of exterior-wall insulation, is ranked the most eco-efficient retrofit strategy in standard and higher thermal comfort conditions. Roof without insulation combined with exterior wall with 40 to 80 mm of insulation are the most eco-efficient retrofit strategies in office use. Even though in lower occupancy levels (low residential occupancy and office use) all retrofit strategies lead to negative savings, there is a significant reduction in environmental impacts through the building life-cycle.

The use of a streamlined approach can be very effective for efficiently assessing different scenarios and making comparisons. The streamlined approach provides feedback to the designer by identifying the main drivers of the impact of the building. This allows the designers either to identify an environmentally and economically superior design or to evaluate the design choices. It promotes better informed decisions in early design stages and consequently a notable potential to reduce the environmental burden of the existing building stock in a cost-effective way. An equally important aspect is to enhance the potential of this approach for widespread use of LCA and LCCA as decision-making tools in the building design process.

Highly influential attributes should be defined early in the design process as these may leverage further design decisions. Occupancy parameters have been identified as highly influential on the total LC impacts of buildings retrofit. Heating set-point night and day, and heating system efficiency were identified as the most influential attributes on total LC climate change impacts irrespective of location, type of house and wall-system; however, they differ depending on the occupancy conditions.

Besides the occupancy attributes identified as the most influential, other medium-influence design attributes were identified for different house types with different wall systems. For detached and semi-detached houses, exterior-wall-related attributes should be defined in early-design stages, and for row houses, roof insulation thickness and window type have higher influence. For houses with single-leaf wall systems, window type and exterior-wall insulation thickness have higher influence, and for houses with double-leaf wall systems, number of occupants should be defined early. When the house is occupied with bigger families, roof insulation thickness and window type should be defined early as these can significantly leverage the LC performance of the building.

7.3 Limitations and further research

The work developed in this thesis presents some limitations from which several can be developed in future research:

The results of this thesis are primarily valid for South European climates, meaning that the construction techniques implemented in the model are mainly based on South European buildings. Future work of conventional LCA of building retrofits can follow the approach hereby presented to assess other buildings with different construction systems (buildings from different periods using different materials that lead to different performance along their life-cycle), as well as additional climate regions. Some of the assumptions may have to be reconsidered when assessing other regions, namely the range of values considered for transportation distances. The results are mainly focused on building retrofit decisions that influence the energy performance in a life-cycle perspective disregarding other retrofit strategies. Moreover, this study demonstrated that window replacement might have an important contribution to the total LC impacts; thus, a comparative study of different window options could also be the subject to further research.

The choice of an occupancy scenario entails other important attributes that were not included in the scope of this analysis, although it remains an important topic for further research. Building retrofits significantly improve the indoor environmental quality (living conditions), which is not accounted by the LCA methodology. Some indoor quality parameters, such as ventilation rate, were not considered in the scope of this analysis and may be considered in further research, as well as using the adaptive thermal comfort method to define occupancy and thermal comfort scenarios.

Further developments on the streamlined approach can be identified, such as extending the model to other types of buildings (multi-family or commercial buildings). Additional roof and exterior-wall systems can also be included. Specifically, for the energy model, a wider range of climate and additional indoor environment quality attributes could be incorporated. Data assumptions can also be refined by a progressive update of the structured database, as well as the pedigree matrix to estimate uncertainty factors. Additional analysis metrics can be included, such as the integration of eco-efficiency methodologies. The comparison indicator method can also be further explored. By being efficient and effective, the streamlined approach can be further developed to provide recommendations on a myriad of buildings types and design decisions, as well as topics for further research.

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Appendix I Core articles for PhD thesis (Abstracts)

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ENVIRONMENTAL IMPACT TRADE-OFFS IN BUILDING ENVELOPE RETROFIT STRATEGIES[a]

Carla Rodrigues, Fausto Freire

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Purpose The use of high levels of thermal insulation is a common practice towards reducing the energy consumption of the existing building stock; however, the embodied burdens associated with the additional insulation material are usually not taken into account and questions regarding the risks of over-specifying the insulation levels have been emerging, particularly for mild climate regions. This article addresses the issue presenting an integrated approach that combines Life Cycle Assessment and thermal dynamic simulation to assess alternative retrofit strategies for the roof and exterior walls of two dwellings (from the beginning of the 20th century), in the historic city center of Coimbra, Portugal. A comprehensive analysis of alternative insulation thicknesses (no insulation, 40, 80 and 120 mm of expanded polystyrene) was made to identify optimal thickness levels minimizing life-cycle (LC) environmental impacts for a single-family house and an apartment.

Methods Embodied and operational impact trade-offs were calculated for six impact categories: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication and non-renewable primary energy. The operational energy was calculated using a dynamic thermal modelling software (Energy Plus). The functional unit selected for this study was one square meter of living area over a period of 50 years.

Results and Discussion The single-family-house embodied impacts account for 26-57% of total LC impacts. For insulation thicknesses larger than 80 mm, the embodied impacts are greater than operational impacts. For the apartment, embodied impacts account for 25-49% of total LC impacts. The environmental benefits of additional insulation are very low (< 3%) for thicknesses of more than 80 mm for both roof and exterior walls. For thicknesses above the tipping point (where total LC impacts are minimized), the marginal impacts of additional insulation are higher than the benefits. The results for the apartment show that optimal insulation thicknesses (LC tipping point) range from 30 to 40 mm for the roof and from 60 to 80 mm for the exterior walls.

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[a] Rodrigues C, Freire F, (2017) Environmental Impact Trade-offs in Building Envelope Retrofit Strategies. International Journal of Life Cycle Assessment, 22 (4), 557-570. doi:10.1007/s11367-016-1064-2

The LC tipping point for the single-family house is achieved by combining 80-100 mm of roof insulation with 60-80 mm of exterior wall insulation.

Conclusions Extra insulation levels in temperate climates can lead to higher embodied impacts, without significant reduction in operational impacts, which can result in higher total LC impacts. The results show that a tipping point can be identified and recommendations are provided for the roof and exterior wall retrofits of buildings from the beginning of the 20th century.

Keywords: Apartment, Building retrofits, Embodied impacts, Temperate climates, Thermal insulation, Trade-offs, Single-family house

BUILDING RETROFIT ADDRESSING OCCUPANCY: AN INTEGRATED COST AND ENVIRONMENTAL LIFE-CYCLE ANALYSIS[a]

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Building retrofit can lead to important savings in operating cost and environmental impacts; however, the actual savings depend of future house occupancy, which is generally not assessed or taking into account. This article aims to carry out an integrated (cost, environmental and energy) life-cycle assessment of alternative retrofit strategies for a Portuguese single-family house addressing alternative user's occupation patterns. A comprehensive analysis of alternative exterior walls retrofit was performed for two types of insulation material [rock wool and expanded polystyrene] placed inside (40 and 80 mm) or outside (40 mm). A sensitivity analysis was performed to assess the influence of five occupancy patterns (four residential and one commercial) in the whole life-cycle impacts. Life-cycle costing was performed using the Equivalent Annual Costs, Net Present Value and Discounted Payback Period methods. Discount rate has more influence in outside insulation than inside insulation annual savings. Inside insulation has lower DPP (about 10 years) for all materials and thicknesses assessed. LC impact assessment results were calculated for five environmental impact categories and non-renewable primary energy showing that EPS presents the best environmental and cost performance. It was also found that inside insulation was superior to outside insulation. For both insulation materials, a reduction between 15-25% of the environmental impacts was calculated from low to high occupancy. Optimal retrofit strategies that maximize life-cycle environmental and cost benefits should address occupancy.

Keywords: Building Retrofit; Environmental Impacts; Life-Cycle Assessment (LCA); Life-Cycle Costing (LCC); Occupancy patterns

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[a] Rodrigues C, Freire F, (2017) Building retrofit addressing occupancy: an integrated cost and environmental life-cycle analysis. Energy and Buildings, 140, 388-398. doi: 10.1016/j.enbuild.2017.01.084

ADAPTIVE REUSE OF BUILDINGS: ENVIRONMENTAL AND COST LIFE-CYCLE ASSESSMENT OF RETROFIT STRATEGIES AND ALTERNATIVE USES FOR AN HISTORIC BUILDING[a]

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Adaptive reuse is a process of retrofitting old buildings for new uses. Existing residential buildings in European cities are often being retrofitted to be adapted as office buildings whilst keeping its historical value. The main goal of this paper is to investigate how occupancy influences the economic and environmental performance of building retrofit measures supporting decision-making. A life-cycle (LC) model was implemented to a single-family house from the beginning of the 20th century retrofitted as an office building. Twelve alternative retrofit scenarios were assessed for three occupancy patterns: two (low and high) occupancy patterns for residential use and a commercial use pattern (five working days assuming eight hours of permanent occupancy with HVAC activated) were assessed. Four roof insulation thicknesses (0, 40, 80 and 120 mm) combining three exterior wall insulation thicknesses (0, 40 and 80 mm). The functional unit selected was one square meter of living area over a period of 50 years. The results show that the reduction of impacts due to retrofit are higher for residential uses (low or high occupancy) than commercial. A reduction of 7-19% in total LC impacts was calculated to low occupancy, 8-32% to high occupancy and 5-15% to a commercial pattern. An insulation level threshold (when the marginal reduction in the operational energy impacts tends to even out the marginal increase in the embodied impacts, as the total LC impacts tend to level off, for both exterior walls and roof) was identified for exterior walls (60-70 mm for all occupancy patterns) and roof retrofit (80-90 mm for low occupancy, 90-100 mm for high occupancy and 70-80 mm for commercial use). Depending on the type of occupancy, different strategies should be adopted to maximize life-cycle environmental benefits from retrofit.

Keywords: Building Retrofit, Environmental impacts, Thermal Insulation, Occupancy pattern

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[a] Rodrigues C, Freire F, (2017) Adaptive Reuse of Buildings: Environmental and cost life-cycle assessment of retrofit strategies and alternative uses for an historic building *(in final review in Journal of Cleaner Production)*

STREAMLINED ENVIRONMENTAL AND COST LIFE-CYCLE APPROACH FOR BUILDINGS RETROFITS: A CASE OF RESIDENTIAL BUILDINGS IN SOUTH EUROPEAN CLIMATES[a]

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Building retrofits are often motivated by improving the energy efficiency of a building. However, burdens associated with additional materials used to accomplish energy efficiency are not usually taken into account. Life-cycle assessment (LCA) and life-cycle cost assessment (LCCA) approaches have been extensively applied to analyze building environmental impacts and costs. However, LCA and LCCA are time-consuming and resource-intensive and are usually performed in late design stages when significant reduction in total life-cycle impacts is costly to achieve. The aim of this article is to present an integrated, streamlined LCA-LCCA approach of building retrofits to provide feedback on environmental impacts and costs at early-design stage decisions. We propose a framework that fully integrates a streamlined embodied LCA, statistical-based operational energy, and cost models. This approach incorporates uncertainty to address the lack of information in early design stages by using the building attribute to impact algorithm approach, which includes structured under-specification and probabilistic triage. An automated process enables several scenarios to be assessed and compared as a means of better informing designers of the relative environmental impact of materials and dimensioning choices. It is demonstrated that by selecting very few attributes and then comparing several options, robust retrofit decisions can be made in early-design stages, thereby promoting a reduction in environmental impacts and costs.

Keywords: Buildings retrofit, Decision-making, Life-cycle assessment, Uncertainty, Probabilistic triage

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[a] Rodrigues C, Freire F, Kirchain R, Gregory J, (2016) Streamlined environmental and cost life-cycle approach for buildings retrofits: a case of residential buildings in South European climates *(submitted)*

ENVIRONMENTAL IMPACT AND COST OF RESIDENTIAL BUILDING RETROFITS – WHAT MATTERS?[a]

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Environmental and cost life-cycle assessments face several challenges when applied to buildings. Buildings are complex systems with many different components, materials and quantities that result in data-intensive processes. For this matter, it is important to define the most influential attributes to efficiently provide environmental and cost feedback and streamline the decision-making process of building retrofits. The main objectives of this article are: (1) application of the streamline approach to assess the environmental and cost performance of building retrofits in different types of single-family houses with different wall systems, and occupancy patterns, in alternative South European climate locations, (2) identify key drivers of environmental and cost impacts of building retrofits in South European climates, and (3) perform a comprehensive sensitivity analysis. The sensitivity analysis was performed by calculating the Spearman's rank correlation coefficient (not normalized) to enable the identification of key parameters that influence the environmental and cost performance of building retrofits. Climate change, net-present value (NPV) and eco-efficiency were the metrics selected for this analysis. The most influential attributes (heating set-point night and day and heating system efficiency) to total LC climate change impacts are the same irrespective to location, type of house and wall-system; however, they differ depending on the occupancy conditions. The attributes with the strongest correlation to NPV and eco-efficiency are discount rate, and exterior-wall insulation material and thickness. As shown in this analysis, the most influential attributes can change depending on family size or heating set-point meaning that an early definition of these attributes can change which decisions are the most important in an early design stage.

Keywords: Building design; Climate Change; Eco-efficiency; Net present value; Occupancy; Sensitivity Analysis

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[a] Rodrigues C, Freire F, Kirchain R., Gregory J., (2016) Environmental impacts and costs of building retrofits – what matters? *(in preparation)*

Appendix II Full list of publications

Articles in international journals with scientific refereeing

Published

1. **Rodrigues C.**, Freire F., (2017) Building retrofit addressing occupancy: an integrated cost and environmental life-cycle analysis. Energy and Buildings, 140, 388-398. doi: 10.1016/j.enbuild.2017.01.084

   JCR® impact factor (2015): 2.973

2. **Rodrigues C.**, Freire F., (2017) Environmental Impact Trade-offs in Building Envelope Retrofit Strategies. International Journal of Life Cycle Assessment, 22 (4), 557-570. doi: 10.1007/s11367-016-1064-2

   JCR® impact factor (2015): 3.324

3. Tadeu S., **Rodrigues C.**, Tadeu A., Freire F., (2015) Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. Journal of Building Engineering, 4, 167–176. doi: 10.1016/j.jobe.2015.09.009

4. **Rodrigues C.**, Freire F., (2014) Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. Building and Environment, 81, 204–215. doi: 10.1016/j.buildenv.2014.07.001

   JCR® impact factor (2015): 3.394

Submitted, under review or in final preparation for submission to ISI-indexed journals

5. **Rodrigues C.**, Freire F., (2017) Adaptive reuse of buildings: Environmental and cost life-cycle Assessment of retrofit strategies and alternative uses for an historic building (in final review in Journal of Cleaner Production)

6. **Rodrigues C.**, Freire F., Kirchain R., Gregory J., (2016) Streamlined environmental and cost life-cycle approach for buildings retrofits: a case of residential buildings in South European climates (submitted)

7. **Rodrigues C.**, Freire F., Kirchain R., Gregory J., (2016) Environmental impacts and costs of residential building retrofits – what matters? (in preparation)

Papers in proceedings of international conferences with scientific refereeing

8. **Rodrigues C.**, Freire F. (2015). Environmental Impact Trade-offs in Building Envelope Retrofit Strategies. In: Proceedings of CILCA 2015, July 2015, Lima, Peru.

9. **Rodrigues C.**, Freire F. (2014). Cost and greenhouse gas life-cycle analysis of building retrofit. In: Proceedings of the 40th IAHS Conference, Sustainable Housing Construction, December 2014, Funchal, Portugal.

10. **Rodrigues C.**, Freire F. (2014). Does type of use and occupancy influence the performance of building retrofit strategies? In: Proceedings of the 40th IAHS Conference, Sustainable Housing Construction, December 2014, Funchal, Portugal.

11. Tadeu S., **Rodrigues C.**, Tadeu A., et al (2014). Energy Retrofit of an Historic Building in a UNESCO World Heritage Site : an integrated Cost Optimality and Environmental Assessment. In: Proceedings of the International Conference in Energy Efficiency in Historic Buildings, September 2014, Madrid, Spain, pp 450–463.

12. Tadeu S., **Rodrigues C.**, Tadeu A., et al (2014). Multicriteria analysis of occupants perceptions' of the benefits of energy retrofitting of buildings. In: Proceedings of the 40th IAHS Conference, Sustainable Housing Construction, December 2014, Funchal, Portugal.

13. **Rodrigues C.**, Freire F. (2013). Addressing occupancy in the energy and greenhouse gas assessment of building retrofit. In: Proceedings of the Energy for Sustainability Multidisciplinary Conference 2013, September, 2013, Coimbra, Portugal.

14. **Rodrigues C.**, Freire F. (2013). Life-cycle assessment of roof retrofit scenarios for a single-family house. In: Proceedings of CISBAT 2013, September 2013, Lausanne, Switzerland, pp 229–233.

15. **Rodrigues C.**, Luiz I., Tadeu S., Freire F. (2012). Environmental Assessment of Alternative Options for the Roof Retrofit of an Historic Building. In: Proceedings of the Congress of Innovation on Sustainable Construction – CINCOS'12, September 2012, Aveiro, Portugal.

Oral communications (without full paper)

16. **Rodrigues C.**, Freire F. (2017). Environmental and cost life-cycle assessment of building retrofits: a streamlined approach. In: Proceedings of the Energy for Sustainability Conference 2017, Februrary 2017, Funchal, Portugal.

17. Gregory J., Miller T.R., Hester J., **Rodrigues C.**, Kirchain R. (2015). Streamlining residential building LCA via probabilistic under-specification. LCA XV Conference, October 2015, Vancouver, Canada.

18. **Rodrigues C.**, Hester J., Miller T.R., Tecchio P., Gregory J., Kirchain R. (2015). Streamlined LCA of Residential Buildings using Probabilistic Under-specification. International Symposium on Sustainable Systems and Technology (ISSST), May 2015, Dearborn MI, USA.

19. Hester J., **Rodrigues C.**, Miller T.R., Tecchio P., Gregory J., Kirchain R. (2015). Streamlined Energy Model for Residential Construction. International Symposium on Sustainable Systems and Technology (ISSST), May 2015, Dearborn MI, USA.

20. **Rodrigues C.**, Freire F. (2014). Integrated LCA and thermal dynamic simulation of building envelope retrofit. In: Book of Abstracts of the Discussion Forum on Industrial Ecology and Life-Cycle Management. April 2015. Coimbra. Portugal.

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Appendix III Adaptive reuse of buildings: eco-efficiency assessment of retrofit strategies for alternative uses of an historic building – Supplementary Information

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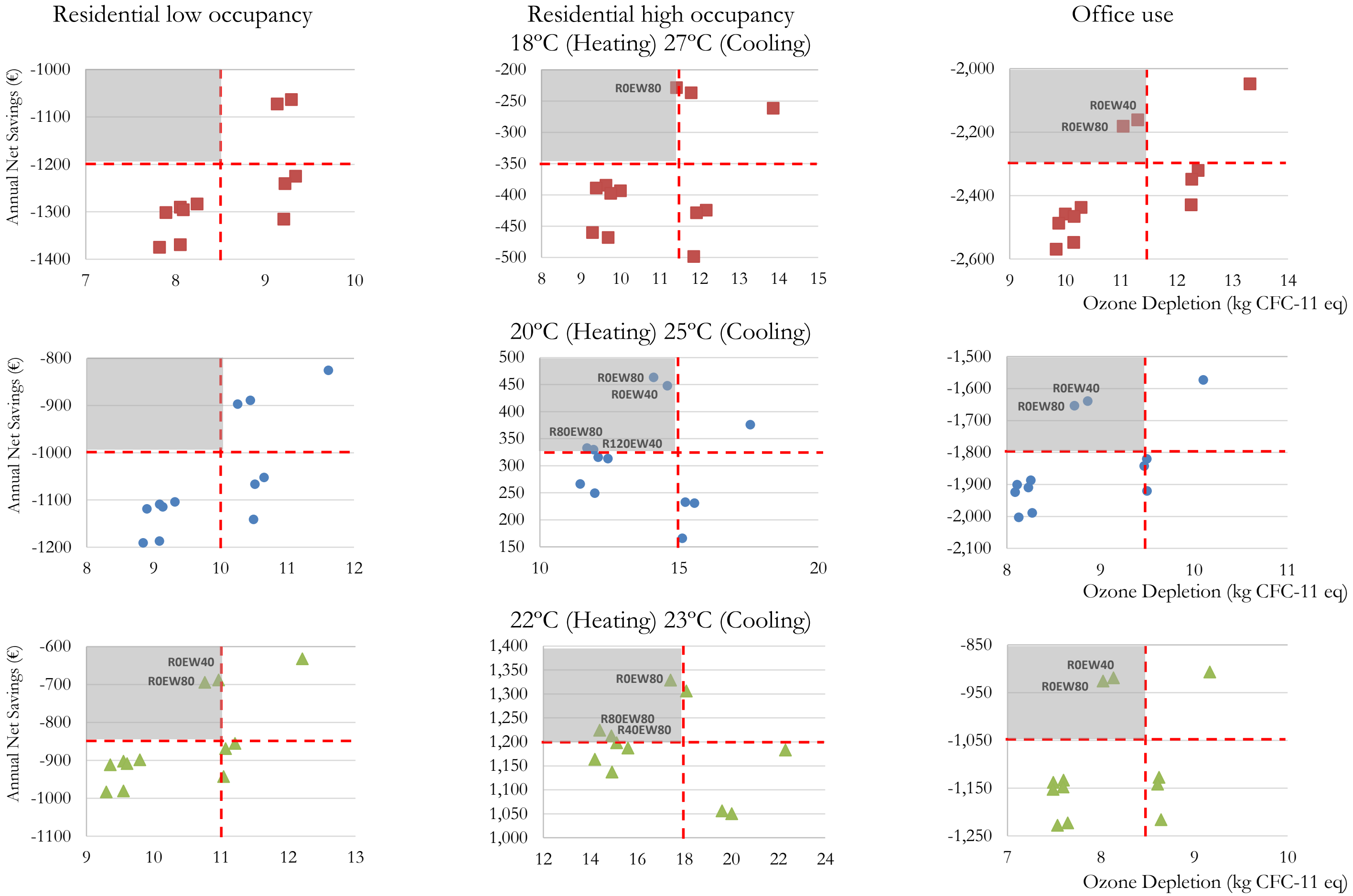

Figure A - 1 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-point scenarios for low and high residential occupancy, and office use (annual net savings in the y-axis and ozone depletion in the x-axis) R(roof) 0-120 EW(exterior wall) 40-80 (insulation thickness in mm)

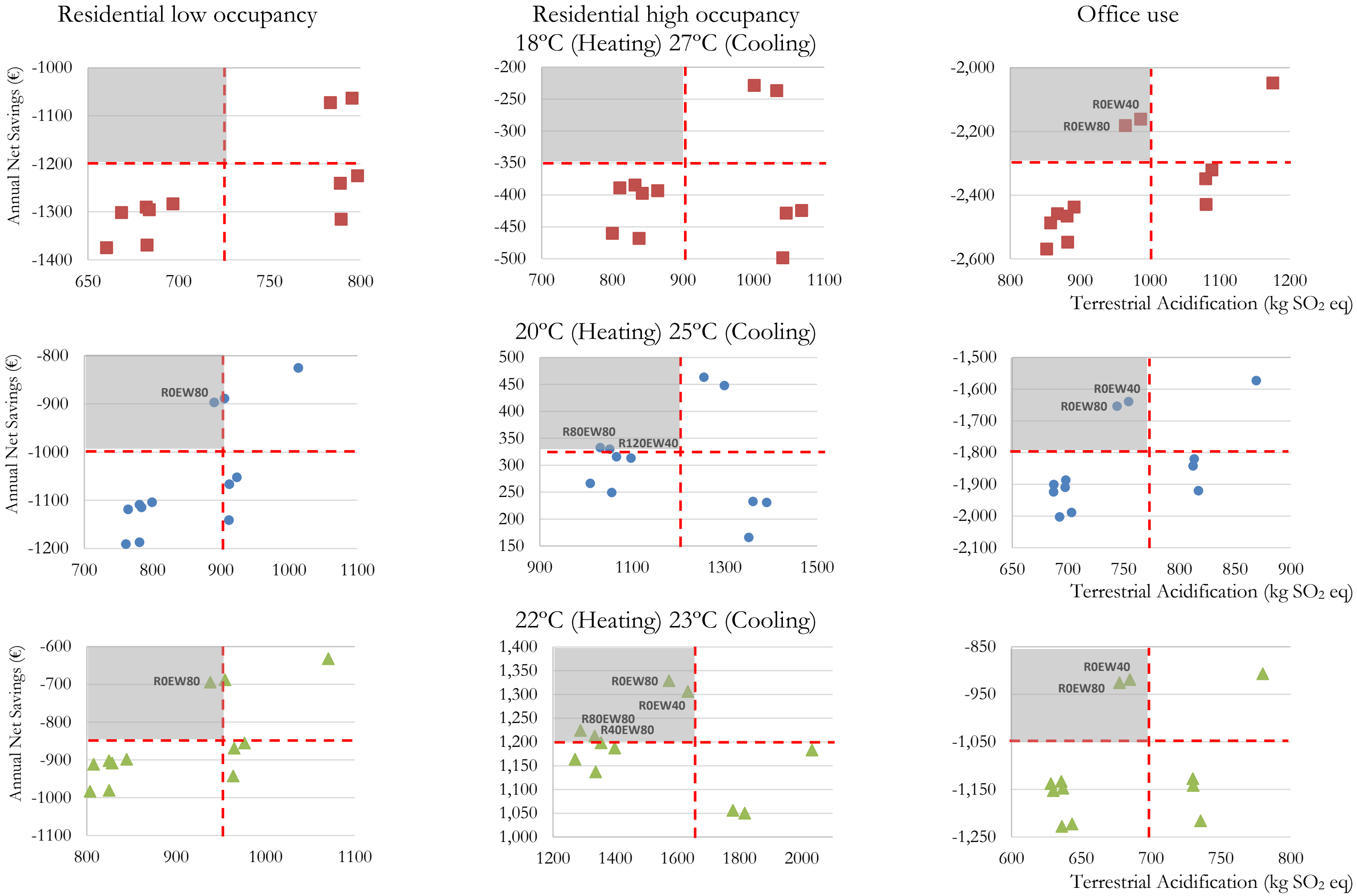

Figure A - 2 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-point scenarios for low and high residential occupancy, and office use (annual net savings in the y-axis and terrestrial acidification in the x-axis) R(roof) 0-120 EW(exterior wall) 40-80 (insulation thickness in mm)

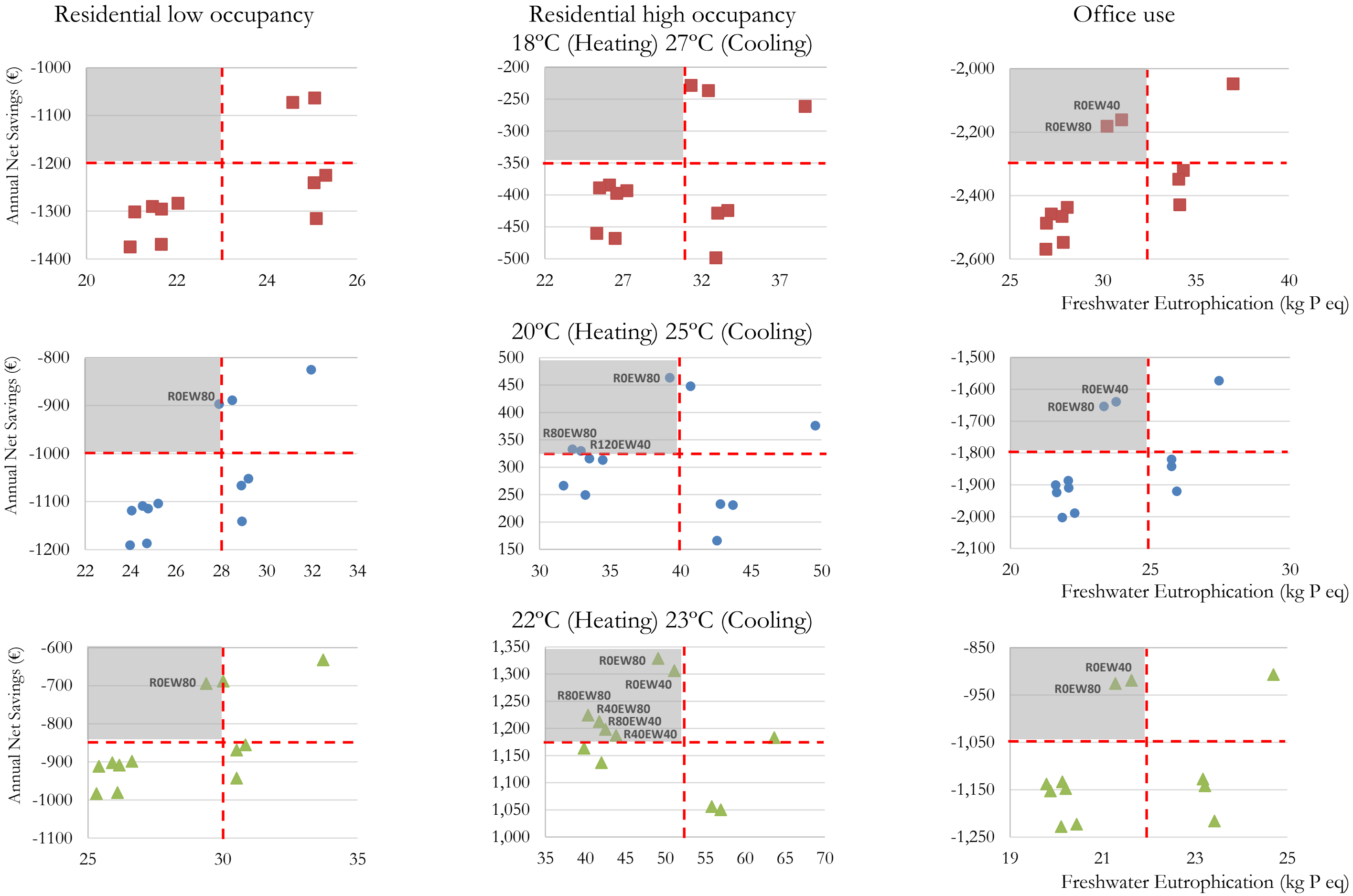

Figure A - 3 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-point scenarios for low and high residential occupancy, and office use (annual net savings (y-axis) and freshwater eutrophication (x-axis)) R(roof)0-120 EW(exterior wall)40-80 (insulation thickness in mm)

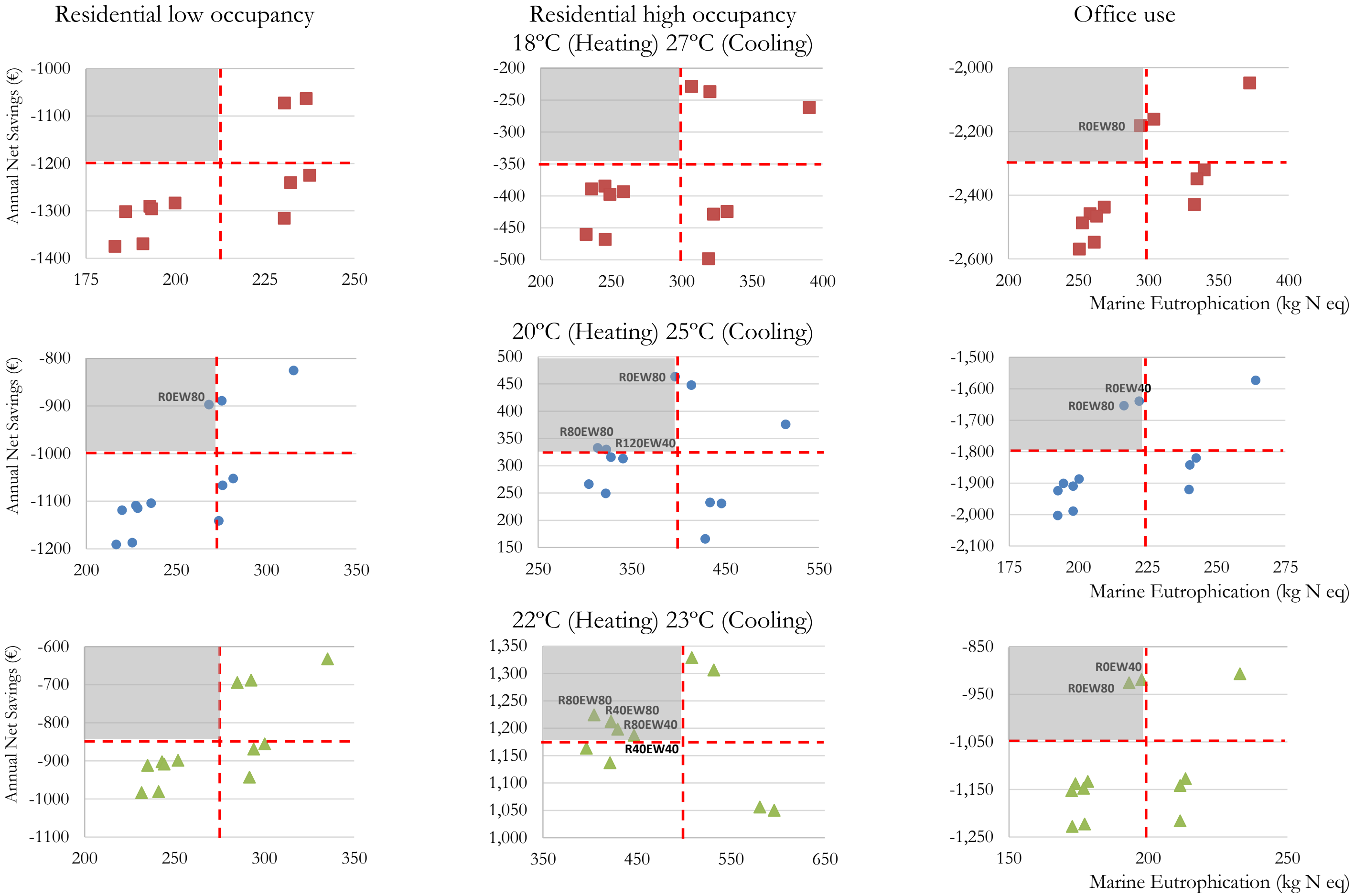

Figure A - 4 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-point scenarios for low and high residential occupancy, and office use (annual net savings in the y-axis and marine eutrophication in the x-axis) R(roof) 0-120 EW(exterior wall) 40-80 (insulation thickness in mm)

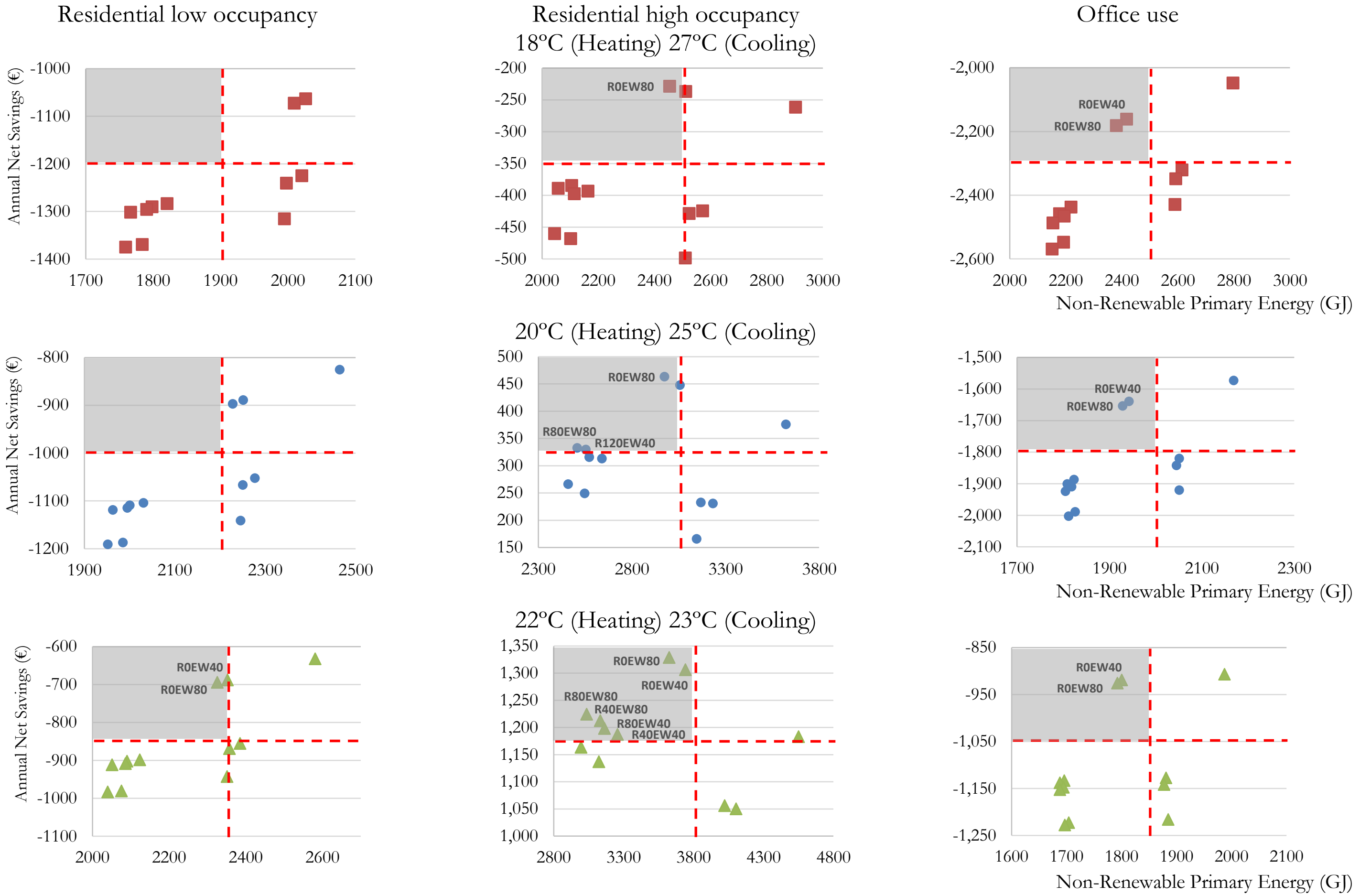

Figure A - 5 Eco-efficiency assessment of exterior-wall and roof retrofit insulation strategies assuming alternative set-point scenarios for low and high residential occupancy, and office use (annual net savings (y-axis) and non-renewable primary energy (x-axis)) R(roof) 0-120 EW(exterior wall) 40-80 (insulation thickness in mm)

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Appendix IV Streamlined environmental and cost life-cycle approach for building retrofits: a case of residential buildings in South European climates– Supplementary Information

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A4.1 Detailed information on the building design parameters

Table A - 1 Summary of attributes for the residential building-retrofit streamlined model and their ranges or options LSF=Light Steel Frame; LWC=Lightweight Concrete

Building attributes	
Location	987 - 2015 HDD
Region	North, Central or South
Time period	1900 - 2000
Existing exterior-wall type	Stone masonry wall system; other single- or double-leaf wall system
Existing roof framing	Wood frame or LSF
House type	Detached; Semi-detached or Row
Floor area	(40 - 500 m²)
Number of stories	1 - 6
Orientation	N; S; E; W; SE; SW; NE; SW
Floor aspect ratio	1.1 - 1.3
Window-to-wall ratio	0.1 - 0.3
Window distribution (percentage of window area in the front façade)	0.1 - 0.5
Roof geometry	Gable or Hip
Roof pitch	1/12 - 12/12
Floor height	(2.5 - 4 m)
Building service life	30 - 100 years

Energy attributes	
Number of occupants	1 - 6
Heating set-point (day)	18 - 25ºC
Heating set-point (night)	18 - 25ºC
Cooling set-point (day)	25 - 30ºC
Cooling set-point (night)	25 - 30ºC
Heating system efficiency (COP)	2 - 4.2
Cooling system efficiency (EER)	2 - 3.5
Operational energy fuel	Electricity

Assembly attributes	
Exterior walls – retrofit type	Interior or exterior insulation
Exterior walls – finishes	Plaster-, gypsum-, or board-based
Exterior walls – insulation material	(several insulation material options)
Exterior walls – insulation thickness	10 - 200 mm
Roof – retrofit type	Wood; LSF or LWC
Roof/Ceiling – finishes	Ceramic-, cement-, or clay-based
Roof – insulation material	(several insulation material options)
Roof – insulation thickness	10 - 200 mm
Windows – frame and glazing	Frame: wood, PVC or aluminum; Glazing: single, double or triple

Cost attribute	
Discount rate	1-8%

A4.2 Streamlined energy metamodel

Table A - 2 Heating stepwise regression metamodel coefficients SD=Semi-detached

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	-2.42E+05	1.32E+03	-183.3	<.0001
Type of house{SD left&Row-Detached&SD right}	-4.31E+03	9.27E+01	-46.54	<.0001
Type of house{SD left-Row}	4.14E+03	1.10E+02	37.53	<.0001
Type of house{Detached-SD right}	4.67E+03	1.23E+02	38.04	<.0001
Bedrooms	-1.90E+03	8.17E+01	-23.2	<.0001
Orientation	3.60E+01	1.38E+00	26.1	<.0001
EW Rvalue	-9.16E+03	6.57E+01	-139.5	<.0001
R Rvalue	-2.66E+03	6.37E+01	-41.81	<.0001
Window Area	9.23E+04	5.79E+03	15.95	<.0001
Window Distribution	-1.13E+04	9.32E+02	-12.16	<.0001
Window type	1.67E+03	7.68E+01	21.75	<.0001
HDD	2.96E+01	1.36E-01	217.96	<.0001
Heating set point NIGHT	7.66E+03	1.22E+02	62.62	<.0001
Heating set point DAY	5.15E+03	1.00E+02	51.37	<.0001
Type of house{SD left&Row-Detached&SD right}*(Bedrooms-4.01319)	5.93E+02	8.11E+01	7.31	<.0001
Type of house{SD left-Row}*(Orientation-44.5915)	1.93E+01	2.14E+00	9.02	<.0001
Type of house{Detached-SD right}*(Orientation-44.5915)	-3.41E+01	1.90E+00	-17.95	<.0001
Type of house{SD left&Row-Detached&SD right}*(EW Rvalue-2.184)	1.34E+03	7.32E+01	18.35	<.0001
Type of house{SD left-Row}*(EW Rvalue-2.184)	-2.59E+03	1.14E+02	-22.73	<.0001
Type of house{Detached-SD right}*(EW Rvalue-2.184)	-1.07E+03	9.16E+01	-11.71	<.0001
Type of house{SD left&Row-Detached&SD right}*(R Rvalue-2.29619)	-3.33E+02	6.48E+01	-5.13	<.0001
Type of house{Detached-SD right}*(Window Area-0.13921)	-3.58E+04	6.92E+03	-5.17	<.0001
Type of house{Detached-SD right}*(Window Distribution-0.36105)	1.18E+04	1.56E+03	7.55	<.0001
Type of house{Detached-SD right}*(HDD-1436.31)	1.96E+00	1.82E-01	10.76	<.0001
Type of house{SD left-Row}*(Heating set point NIGHT-20.6676)	4.35E+02	7.40E+01	5.87	<.0001
Type of house{SD left&Row-Detached&SD right}*(Heating set point DAY-20.2745)	-9.42E+02	3.63E+01	-25.96	<.0001
Type of house{Detached-SD right}*(Heating set point DAY-20.2745)	5.71E+02	3.77E+01	15.17	<.0001
(Bedrooms-4.01319)*(Orientation-44.5915)	1.82E+01	1.73E+00	10.5	<.0001
(Bedrooms-4.01319)*(EW Rvalue-2.184)	-4.15E+02	8.17E+01	-5.08	<.0001
(Bedrooms-4.01319)*(R Rvalue-2.29619)	-6.83E+02	7.99E+01	-8.54	<.0001
(Bedrooms-4.01319)*(Window Area-0.13921)	-2.46E+04	4.67E+03	-5.26	<.0001
(Bedrooms-4.01319)*(HDD-1436.31)	1.30E+00	1.73E-01	7.55	<.0001
(Bedrooms-4.01319)*(Heating set point NIGHT-20.6676)	-3.88E+02	4.54E+01	-8.55	<.0001
(Orientation-44.5915)*(Window Distribution-0.36105)	9.18E+01	1.55E+01	5.93	<.0001
(Orientation-44.5915)*(HDD-1436.31)	-3.97E-02	3.06E-03	-13	<.0001
(Orientation-44.5915)*(Heating set point DAY-20.2745)	-4.57E+00	6.37E-01	-7.17	<.0001
(EW Rvalue-2.184)*(R Rvalue-2.29619)	7.80E+02	6.71E+01	11.63	<.0001
(EW Rvalue-2.184)*(Window Area-0.13921)	-5.18E+04	3.79E+03	-13.68	<.0001
(EW Rvalue-2.184)*(HDD-1436.31)	-1.14E+00	1.37E-01	-8.36	<.0001
(EW Rvalue-2.184)*(Heating set point NIGHT-20.6676)	-7.36E+02	1.17E+02	-6.29	<.0001

(EW Rvalue-2.184)*(Heating set point DAY-20.2745)	-8.71E+02	8.92E+01	-9.76	<.0001
(R Rvalue-2.29619)*(Heating set point DAY-20.2745)	-5.00E+02	3.00E+01	-16.67	<.0001
(Window Area-0.13921)*(Window Distribution-0.36105)	3.18E+05	4.42E+04	7.19	<.0001
(Window Area-0.13921)*(Heating set point DAY-20.2745)	1.49E+04	1.58E+03	9.43	<.0001
(Window type-3.55182)*(Heating set point NIGHT-20.6676)	3.50E+02	4.12E+01	8.51	<.0001
(HDD-1436.31)*(Heating set point NIGHT-20.6676)	-3.46E+00	7.55E-02	-45.9	<.0001
(Heating set point NIGHT-20.6676)*(Heating set point DAY-20.2745)	1.18E+03	2.83E+01	41.53	<.0001

Table A - 3 Heating standardized regression coefficients, sorted by absolute value SD=Semi-detached

Term	Standardized coefficient
Heating set point NIGHT	0.43192
HDD	0.384379
Heating set point DAY	0.334961
EW Rvalue	-0.27817
Type of house{SD left&Row-Detached&SD right}	-0.12841
Type of house{Detached-SD right}	0.108095
(Heating set point NIGHT-20.6676)*(Heating set point DAY-20.2745)	0.105333
R Rvalue	-0.08665
(HDD-1436.31)*(Heating set point NIGHT-20.6676)	-0.08368
Type of house{SD left-Row}	0.079493
Type of house{SD left&Row-Detached&SD right}*(Heating set point DAY-20.2745)	-0.06027
(EW Rvalue-2.184)*(Heating set point DAY-20.2745)	-0.05681
Type of house{SD left-Row}*(EW Rvalue-2.184)	-0.04945
Orientation	0.04902
Window Area	0.047562
Bedrooms	-0.04654
(EW Rvalue-2.184)*(Heating set point NIGHT-20.6676)	-0.04083
Type of house{SD left&Row-Detached&SD right}*(EW Rvalue-2.184)	0.040601
Window type	0.037871
Type of house{Detached-SD right}*(Orientation-44.5915)	-0.03547
(R Rvalue-2.29619)*(Heating set point DAY-20.2745)	-0.03541
Type of house{Detached-SD right}*(Heating set point DAY-20.2745)	0.031092
Window Distribution	-0.03075
(EW Rvalue-2.184)*(Window Area-0.13921)	-0.02699
Type of house{Detached-SD right}*(Window Distribution-0.36105)	0.025718
Type of house{Detached-SD right}*(EW Rvalue-2.184)	-0.02508
(EW Rvalue-2.184)*(R Rvalue-2.29619)	0.024553
(Orientation-44.5915)*(HDD-1436.31)	-0.02318
(Window Area-0.13921)*(Window Distribution-0.36105)	0.02048
(Bedrooms-4.01319)*(Orientation-44.5915)	0.020045
Type of house{Detached-SD right}*(HDD-1436.31)	0.019419
(Window Area-0.13921)*(Heating set point DAY-20.2745)	0.017934
(Bedrooms-4.01319)*(Heating set point NIGHT-20.6676)	-0.01738
Type of house{Detached-SD right}*(Window Area-0.13921)	-0.01693
Type of house{SD left-Row}*(Orientation-44.5915)	0.016752
(Bedrooms-4.01319)*(R Rvalue-2.29619)	-0.0163
(EW Rvalue-2.184)*(HDD-1436.31)	-0.01488

(Window type-3.55182)*(Heating set point NIGHT-20.6676)	0.014813
Type of house{SD left&Row-Detached&SD right}*(Bedrooms-4.01319)	0.014563
Type of house{SD left-Row}*(Heating set point NIGHT-20.6676)	0.013943
(Bedrooms-4.01319)*(HDD-1436.31)	0.0137
(Orientation-44.5915)*(Heating set point DAY-20.2745)	-0.01334
(Orientation-44.5915)*(Window Distribution-0.36105)	0.011105
Type of house{SD left&Row-Detached&SD right}*(R Rvalue-2.29619)	-0.01083
(Bedrooms-4.01319)*(Window Area-0.13921)	-0.01041
(Bedrooms-4.01319)*(EW Rvalue-2.184)	-0.01006
Intercept	0

Table A - 4 Cooling stepwise regression metamodel coefficients SD=Semi-detached

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	9.42E+04	5.90E+02	159.58	<.0001
Type of house{SD left&Row-SD right&Detached}	-1.63E+03	3.17E+01	-51.42	<.0001
Type of house{SD left-Row}	1.00E+03	4.91E+01	20.4	<.0001
Type of house{SD right-Detached}	-2.25E+03	4.62E+01	-48.62	<.0001
Bedrooms	9.10E+02	3.25E+01	28	<.0001
Orientation	4.31E+01	5.59E-01	77.1	<.0001
EW Rvalue	-1.11E+03	2.61E+01	-42.43	<.0001
EW Q	4.83E-04	8.60E-05	5.62	<.0001
R Rvalue	-5.22E+02	2.51E+01	-20.82	<.0001
Window Area	2.74E+04	2.53E+03	10.83	<.0001
Window Distribution	3.40E+03	4.05E+02	8.39	<.0001
Window type	1.78E+03	3.09E+01	57.62	<.0001
HDD	-1.09E+01	5.43E-02	-200.3	<.0001
Cooling set point DAY	-1.37E+03	1.53E+01	-89.68	<.0001
Cooling set point NIGHT	-1.83E+03	2.73E+01	-67.27	<.0001
Type of house{SD left&Row-SD right&Detached}*(Bedrooms-4.01319)	-3.00E+02	3.51E+01	-8.54	<.0001
Type of house{SD right-Detached}*(Bedrooms-4.01319)	-1.87E+02	4.30E+01	-4.35	<.0001
Type of house{SD left&Row-SD right&Detached}*(Orientation-44.5915)	8.47E+00	5.99E-01	14.13	<.0001
Type of house{SD right-Detached}*(Orientation-44.5915)	1.97E+01	7.48E-01	26.29	<.0001
Type of house{SD left&Row-SD right&Detached}*(EW Rvalue-2.184)	3.74E+02	2.68E+01	13.95	<.0001
Type of house{SD left-Row}*(EW Rvalue-2.184)	2.45E+02	4.12E+01	5.94	<.0001
Type of house{SD right-Detached}*(EW Rvalue-2.184)	6.59E+02	3.61E+01	18.24	<.0001
Type of house{SD right-Detached}*(R Rvalue-2.29619)	-2.10E+02	3.29E+01	-6.39	<.0001
Type of house{SD left&Row-SD right&Detached}*(Window Area-0.13921)	-1.70E+04	2.55E+03	-6.68	<.0001
Type of house{SD right-Detached}*(Window Area-0.13921)	-5.77E+04	2.77E+03	-20.82	<.0001
Type of house{SD left&Row-SD right&Detached}*(Window Distribution-0.36105)	-2.21E+03	4.55E+02	-4.85	<.0001
Type of house{SD left&Row-SD right&Detached}*(Window type-3.55182)	-2.97E+02	3.16E+01	-9.41	<.0001
Type of house{SD left-Row}*(Window type-3.55182)	2.58E+02	4.93E+01	5.24	<.0001
Type of house{SD right-Detached}*(Window type-3.55182)	-3.07E+02	3.96E+01	-7.74	<.0001
Type of house{SD left&Row-SD	1.21E+00	5.60E-02	21.67	<.0001

right&Detached}*(HDD-1436.31)				
Type of house{SD left-Row}*(HDD-1436.31)	-5.64E-01	8.72E-02	-6.47	<.0001
Type of house{SD right-Detached}*(HDD-1436.31)	4.85E-01	7.39E-02	6.56	<.0001
Type of house{SD left&Row-SD right&Detached}*(Cooling set point DAY-24.7878)	2.75E+02	9.57E+00	28.7	<.0001
Type of house{SD right-Detached}*(Cooling set point DAY-24.7878)	2.06E+02	2.31E+01	8.91	<.0001
Type of house{SD left-Row}*(Cooling set point NIGHT-23.9532)	-2.07E+02	2.31E+01	-8.98	<.0001
Type of house{SD right-Detached}*(Cooling set point NIGHT-23.9532)	2.03E+02	3.60E+01	5.65	<.0001
(Bedrooms-4.01319)*(EW Rvalue-2.184)	-3.34E+02	3.14E+01	-10.64	<.0001
(Bedrooms-4.01319)*(R Rvalue-2.29619)	-2.51E+02	3.17E+01	-7.93	<.0001
(Bedrooms-4.01319)*(Window Distribution-0.36105)	1.59E+03	3.60E+02	4.42	<.0001
(Bedrooms-4.01319)*(HDD-1436.31)	4.22E-01	6.63E-02	6.36	<.0001
(Bedrooms-4.01319)*(Cooling set point NIGHT-23.9532)	-2.27E+02	1.84E+01	-12.37	<.0001
(Orientation-44.5915)*(EW Rvalue-2.184)	-2.97E+00	5.41E-01	-5.48	<.0001
(Orientation-44.5915)*(Window Distribution-0.36105)	3.63E+01	6.37E+00	5.7	<.0001
(Orientation-44.5915)*(Window type-3.55182)	4.66E+00	6.72E-01	6.94	<.0001
(Orientation-44.5915)*(HDD-1436.31)	-1.90E-02	1.21E-03	-15.7	<.0001
(Orientation-44.5915)*(Cooling set point DAY-24.7878)	-2.82E+00	1.92E-01	-14.72	<.0001
(EW Rvalue-2.184)*(EW Q-509259)	-9.19E-04	7.83E-05	-11.74	<.0001
(EW Rvalue-2.184)*(R Rvalue-2.29619)	1.47E+02	2.56E+01	5.72	<.0001
(EW Rvalue-2.184)*(HDD-1436.31)	8.42E-01	5.42E-02	15.52	<.0001
(EW Rvalue-2.184)*(Cooling set point DAY-24.7878)	2.18E+02	9.08E+00	24.05	<.0001
(EW Q-509259)*(Cooling set point NIGHT-23.9532)	-3.03E-04	4.40E-05	-6.89	<.0001
(R Rvalue-2.29619)*(HDD-1436.31)	4.82E-01	5.14E-02	9.39	<.0001
(R Rvalue-2.29619)*(Cooling set point DAY-24.7878)	1.09E+02	1.25E+01	8.68	<.0001
(R Rvalue-2.29619)*(Cooling set point NIGHT-23.9532)	-8.10E+01	2.28E+01	-3.56	0.0004
(Window Area-0.13921)*(Window Distribution-0.36105)	3.02E+05	1.49E+04	20.26	<.0001
(Window Area-0.13921)*(Window type-3.55182)	1.84E+04	1.79E+03	10.27	<.0001
(Window Area-0.13921)*(HDD-1436.31)	-4.44E+01	3.20E+00	-13.86	<.0001
(Window Area-0.13921)*(Cooling set point NIGHT-23.9532)	-9.03E+03	7.27E+02	-12.42	<.0001
(Window Distribution-0.36105)*(Cooling set point NIGHT-23.9532)	6.63E+02	1.78E+02	3.72	0.0002
(Window type-3.55182)*(HDD-1436.31)	-8.31E-01	6.96E-02	-11.93	<.0001
(Window type-3.55182)*(Cooling set point DAY-24.7878)	-1.89E+02	1.06E+01	-17.85	<.0001
(HDD-1436.31)*(Cooling set point DAY-24.7878)	8.58E-01	2.97E-02	28.94	<.0001
(HDD-1436.31)*(Cooling set point NIGHT-23.9532)	1.40E+00	4.62E-02	30.25	<.0001
(Cooling set point DAY-24.7878)*(Cooling set point NIGHT-23.9532)	2.26E+02	9.93E+00	22.78	<.0001

Table A - 5 Cooling standardized regression coefficients, sorted by absolute value SD=Semi-detached

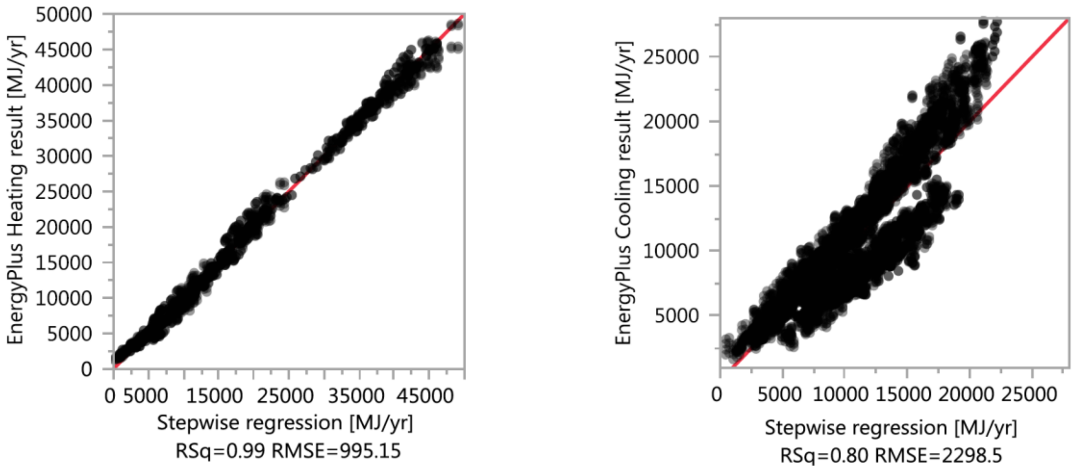
Term	**Standardized Coefficient**
HDD	-0.43475
Cooling set point DAY	-0.37994
Cooling set point NIGHT	-0.3268
Orientation	0.18073
Type of house{SD right-Detached}	-0.16013

Type of house{SD left&Row-SD right&Detached}	-0.14959
Window type	0.12426
(HDD-1436.31)*(Cooling set point NIGHT-23.9532)	0.107036
EW Rvalue	-0.10347
(HDD-1436.31)*(Cooling set point DAY-24.7878)	0.10254
Type of house{SD right-Detached}*(Window Area-0.13921)	-0.08401
Type of house{SD left&Row-SD right&Detached}*(Cooling set point DAY-24.7878)	0.073993
(Cooling set point DAY-24.7878)*(Cooling set point NIGHT-23.9532)	0.071303
Bedrooms	0.068767
Type of house{SD right-Detached}*(Orientation-44.5915)	0.063042
(EW Rvalue-2.184)*(Cooling set point DAY-24.7878)	0.060496
(Window Area-0.13921)*(Window Distribution-0.36105)	0.059849
Type of house{SD left-Row}	0.059229
R Rvalue	-0.05235
Type of house{SD left&Row-SD right&Detached}*(HDD-1436.31)	0.048556
Type of house{SD right-Detached}*(EW Rvalue-2.184)	0.047406
Window Area	0.04353
Type of house{SD right-Detached}*(Cooling set point DAY-24.7878)	0.042307
(Window type-3.55182)*(Cooling set point DAY-24.7878)	-0.0394
Type of house{SD left&Row-SD right&Detached}*(Orientation-44.5915)	0.035452
(Orientation-44.5915)*(Cooling set point DAY-24.7878)	-0.03518
Type of house{SD left&Row-SD right&Detached}*(EW Rvalue-2.184)	0.034827
(R Rvalue-2.29619)*(Cooling set point DAY-24.7878)	0.034205
(Orientation-44.5915)*(HDD-1436.31)	-0.03413
(EW Rvalue-2.184)*(HDD-1436.31)	0.033823
(Bedrooms-4.01319)*(Cooling set point NIGHT-23.9532)	-0.03336
(Window Area-0.13921)*(HDD-1436.31)	-0.03021
(Window Area-0.13921)*(Cooling set point NIGHT-23.9532)	-0.02889
Window Distribution	0.028431
Type of house{SD right-Detached}*(Cooling set point NIGHT-23.9532)	0.027044
Type of house{SD left&Row-SD right&Detached}*(Window Area-0.13921)	-0.02694
(EW Rvalue-2.184)*(EW Q-509259)	-0.0256
(Bedrooms-4.01319)*(EW Rvalue-2.184)	-0.02491
(Window type-3.55182)*(HDD-1436.31)	-0.02491
Type of house{SD left-Row}*(Cooling set point NIGHT-23.9532)	-0.02399
Type of house{SD left&Row-SD right&Detached}*(Bedrooms-4.01319)	-0.02265
(Window Area-0.13921)*(Window type-3.55182)	0.021941
(R Rvalue-2.29619)*(HDD-1436.31)	0.020889
Type of house{SD left&Row-SD right&Detached}*(Window type-3.55182)	-0.02077
(Bedrooms-4.01319)*(R Rvalue-2.29619)	-0.01849
Type of house{SD left&Row-SD right&Detached}*(Window Distribution-0.36105)	-0.01785
Type of house{SD right-Detached}*(Window type-3.55182)	-0.01643
Type of house{SD right-Detached}*(R Rvalue-2.29619)	-0.01553
(EW Q-509259)*(Cooling set point NIGHT-23.9532)	-0.01548
Type of house{SD right-Detached}*(HDD-1436.31)	0.014841
(Orientation-44.5915)*(Window type-3.55182)	0.014661
Type of house{SD left-Row}*(HDD-1436.31)	-0.01453
Type of house{SD left-Row}*(EW Rvalue-2.184)	0.014399
(R Rvalue-2.29619)*(Cooling set point NIGHT-23.9532)	-0.01433
(EW Rvalue-2.184)*(R Rvalue-2.29619)	0.014214
(Bedrooms-4.01319)*(HDD-1436.31)	0.013668
(Orientation-44.5915)*(Window Distribution-0.36105)	0.013527
EW Q	0.012705
(Orientation-44.5915)*(EW Rvalue-2.184)	-0.01248

Type of house{SD left-Row}*(Window type-3.55182)	0.011583
(Window Distribution-0.36105)*(Cooling set point NIGHT-23.9532)	0.010802
Type of house{SD right-Detached}*(Bedrooms-4.01319)	-0.01078
(Bedrooms-4.01319)*(Window Distribution-0.36105)	0.010668
Intercept	0

Limitations

When a single model is developed for the entire range of data, that model often produced negative predicted values (i.e. negative heating and cooling) for highly efficient buildings. A decision/regression tree analysis was performed revealing which attributes were most associated with the negative results and a second model was developed to better predict the energy needs in scenarios with those characteristics. Exterior-wall R-value, heating set-point day and HDD were the attributes that were influencing the most the negative predicted values for the heating model, and cooling set point day, and number of bedrooms for the cooling model. A second heating model was then conducted using the simulation trials with exterior wall R-value higher or equal to 2.8 m^2 K/W, heating set-point day lower than 19ºC and HDD lower than 1304. A second cooling model was also conducted using the simulation trials with cooling night set point higher or equal to 27ºC. Details on the form of the models (low heating and cooling energy) are presented in Figure A-6 and Tables A6-A9.



a.

b.

RSq=Root-mean-square error

Figure A - 6 Test-set performance of low heating (a) and cooling (b) stepwise regression metamodel

Table A - 6 Low heating energy stepwise regression metamodel coefficients

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-134415	1840.324	-73.04	<.0001
Type of house{Row-Semi detached right&Semi detached left}	-776.443	139.0491	-5.58	<.0001
Type of house{Semi detached right-Semi detached left}	530.2155	64.76334	8.19	<.0001
Bedrooms	-854.079	66.65084	-12.81	<.0001
Orientation	49.63642	2.336514	21.24	<.0001
EW Rvalue	-1982.92	102.1532	-19.41	<.0001
R Rvalue	-1662.39	41.95144	-39.63	<.0001
Window Area	80964.96	3483.272	23.24	<.0001
Windows Distribution	-10399.9	775.414	-13.41	<.0001
Window type	1089.142	43.55024	25.01	<.0001
HDD	30.43123	0.266432	114.22	<.0001
Heating set point NIGHT	5933.656	94.06015	63.08	<.0001
Type of house{Row-Semi detached right&Semi detached left}*(Orientation-45)	14.64443	2.244148	6.53	<.0001
Type of house{Semi detached right-Semi detached left}*(R Rvalue-2.46255)	136.9148	48.33258	2.83	0.0047
Type of house{Semi detached right-Semi detached left}*(Windows Distribution-0.3564)	-19173.3	3110.783	-6.16	<.0001
Type of house{Row-Semi detached right&Semi detached left}*(HDD-1409.52)	-0.70906	0.267263	-2.65	0.0081
Type of house{Semi detached right-Semi detached left}*(HDD-1409.52)	0.461165	0.100788	4.58	<.0001
(Bedrooms-4)*(Orientation-45)	6.854183	1.023239	6.7	<.0001
(Bedrooms-4)*(Windows Distribution-0.3564)	-17328.1	3104.867	-5.58	<.0001
(Bedrooms-4)*(HDD-1409.52)	-0.40097	0.108687	-3.69	0.0002
(Orientation-45)*(R Rvalue-2.46255)	5.558338	1.150688	4.83	<.0001
(Orientation-45)*(Window Area-0.1406)	-523.52	77.68643	-6.74	<.0001
(Orientation-45)*(Window type-3.55)	3.341936	0.972027	3.44	0.0006
(Orientation-45)*(HDD-1409.52)	-0.0074	0.002137	-3.46	0.0006
(Orientation-45)*(Heating set point NIGHT-18.62)	18.01093	1.852146	9.72	<.0001
(EW Rvalue-3.304)*(R Rvalue-2.46255)	398.5648	98.7124	4.04	<.0001
(EW Rvalue-3.304)*(HDD-1409.52)	-1.80586	0.207369	-8.71	<.0001
(R Rvalue-2.46255)*(HDD-1409.52)	-1.18855	0.091861	-12.94	<.0001
(Window Area-0.1406)*(Window type-3.55)	16416.81	4447.911	3.69	0.0002
(Window Area-0.1406)*(HDD-1409.52)	59.95829	8.127587	7.38	<.0001
(Window Area-0.1406)*(Heating set point NIGHT-18.62)	55409.95	7618.814	7.27	<.0001
(Window type-3.55)*(HDD-1409.52)	0.780919	0.105594	7.4	<.0001
(Window type-3.55)*(Heating set point NIGHT-18.62)	350.147	77.43789	4.52	<.0001
(HDD-1409.52)*(Heating set point NIGHT-18.62)	2.721053	0.177658	15.32	<.0001

Table A - 7 Low heating energy metamodel standardized regression coefficients, sorted by absolute value

Term	Standardized coefficient
HDD	0.978351
Heating set point NIGHT	0.263769
Orientation	0.171262
R Rvalue	-0.13026
Type of house{Semi detached right-Semi detached left}*(Windows Distribution-0.3564)	-0.07398
EW Rvalue	-0.07103
(Bedrooms-4)*(Windows Distribution-0.3564)	-0.06723
Bedrooms	-0.06385
Window type	0.062629
Window Area	0.062075
(HDD-1409.52)*(Heating set point NIGHT-18.62)	0.052682
Type of house{Row-Semi detached right&Semi detached left}*(Orientation-45)	0.050529
Windows Distribution	-0.04048
Type of house{Semi detached right-Semi detached left}	0.039368
(R Rvalue-2.46255)*(HDD-1409.52)	-0.03917
(Orientation-45)*(Heating set point NIGHT-18.62)	0.036037
(EW Rvalue-3.304)*(HDD-1409.52)	-0.02748
Type of house{Row-Semi detached right&Semi detached left}	-0.0256
(Window Area-0.1406)*(Heating set point NIGHT-18.62)	0.024694
Type of house{Row-Semi detached right&Semi detached left}*(HDD-1409.52)	-0.02276
(Bedrooms-4)*(Orientation-45)	0.022423
(Window Area-0.1406)*(HDD-1409.52)	0.019299
(Window type-3.55)*(HDD-1409.52)	0.01883
(Orientation-45)*(R Rvalue-2.46255)	0.018062
(Orientation-45)*(Window Area-0.1406)	-0.01805
(EW Rvalue-3.304)*(R Rvalue-2.46255)	0.01447
Type of house{Semi detached right-Semi detached left}*(HDD-1409.52)	0.014331
(Bedrooms-4)*(HDD-1409.52)	-0.01247
(Window type-3.55)*(Heating set point NIGHT-18.62)	0.011668
(Orientation-45)*(HDD-1409.52)	-0.01066
Type of house{Semi detached right-Semi detached left}*(R Rvalue-2.46255)	0.009812
(Window Area-0.1406)*(Window type-3.55)	0.00945
(Orientation-45)*(Window type-3.55)	0.008648
Intercept	0

Table A - 8 Low cooling energy stepwise regression metamodel coefficients

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	12782.41	1821.735	7.02	<.0001
Type of house{Row&Semi detached left&Semi detached right-Detached}	-2220.92	89.13531	-24.92	<.0001
Type of house{Row-Semi detached left&Semi detached right}	-890.109	59.45029	-14.97	<.0001
Bedrooms	792.2576	52.41051	15.12	<.0001
Orientation	32.35158	1.340746	24.13	<.0001
EW Rvalue	-430.638	49.1053	-8.77	<.0001
R Rvalue	-249.087	66.52772	-3.74	0.0002
Window Area	44511.3	9343.027	4.76	<.0001
Windows Distribution	3805.747	1262.133	3.02	0.0026
Window type	1836.94	60.45458	30.39	<.0001
HDD	-8.70871	0.113446	-76.77	<.0001
Cooling set point DAY	-232.752	44.00882	-5.29	<.0001
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Orientation-38.0755)	16.67327	1.62067	10.29	<.0001
Type of house{Row-Semi detached left&Semi detached right}*(Orientation-38.0755)	-5.36442	1.229292	-4.36	<.0001
Type of house{Row&Semi detached left&Semi detached right-Detached}*(EW Rvalue-1.99068)	211.178	49.06673	4.3	<.0001
Type of house{Row&Semi detached left&Semi detached right-Detached}*(R Rvalue-2.51106)	-206.651	65.2617	-3.17	0.0016
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Window Area-0.14374)	-64245.6	9651.21	-6.66	<.0001
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Window type-3.55726)	-442.977	64.07746	-6.91	<.0001
Type of house{Row-Semi detached left&Semi detached right}*(Window type-3.55726)	-203.937	71.46168	-2.85	0.0043
Type of house{Row&Semi detached left&Semi detached right-Detached}*(HDD-1437.27)	1.521124	0.144749	10.51	<.0001
Type of house{Row-Semi detached left&Semi detached right}*(HDD-1437.27)	0.413143	0.12516	3.3	0.001
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Cooling set point DAY-28.9925)	280.5866	44.86137	6.25	<.0001
(Orientation-38.0755)*(Windows Distribution-0.34725)	77.9945	12.56381	6.21	<.0001
(Orientation-38.0755)*(Window type-3.55726)	6.553061	1.080749	6.06	<.0001
(Orientation-38.0755)*(HDD-1437.27)	-0.02494	0.001883	-13.25	<.0001
(R Rvalue-2.51106)*(Cooling set point DAY-28.9925)	93.74168	32.86025	2.85	0.0044
(Window Area-0.14374)*(Windows Distribution-0.34725)	497035.2	166066.5	2.99	0.0028
(Window Area-0.14374)*(Window type-3.55726)	14415.22	3343.008	4.31	<.0001
(Windows Distribution-0.34725)*(HDD-1437.27)	-5.11073	1.291708	-3.96	<.0001
(Window type-3.55726)*(HDD-1437.27)	-0.75813	0.10779	-7.03	<.0001
(Window type-3.55726)*(Cooling set point DAY-28.9925)	-248.649	34.07796	-7.3	<.0001
(HDD-1437.27)*(Cooling set point DAY-28.9925)	0.170969	0.059432	2.88	0.004

Table A - 9 Low cooling energy metamodel standardized regression coefficients, sorted by absolute value

Term	**Standardized Coefficient**
HDD	-0.72474
Type of house{Row&Semi detached left&Semi detached right-Detached}	-0.36462
Orientation	0.278398
Window type	0.266406
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Window Area-0.14374)	-0.17709
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Orientation-38.0755)	0.141588
(Window Area-0.14374)*(Windows Distribution-0.34725)	0.14005
Bedrooms	0.131557
Type of house{Row&Semi detached left&Semi detached right-Detached}*(HDD-1437.27)	0.126588
Window Area	0.12651
Type of house{Row-Semi detached left&Semi detached right}	-0.12298
(Orientation-38.0755)*(HDD-1437.27)	-0.09233
EW Rvalue	-0.08239
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Cooling set point DAY-28.9925)	0.075846
Windows Distribution	0.065566
Type of house{Row&Semi detached left&Semi detached right-Detached}*(Window type-3.55726)	-0.06424
Cooling set point DAY	-0.06371
(Orientation-38.0755)*(Windows Distribution-0.34725)	0.058818
R Rvalue	-0.05225
(Window type-3.55726)*(Cooling set point DAY-28.9925)	-0.05103
(Window type-3.55726)*(HDD-1437.27)	-0.04732
Type of house{Row&Semi detached left&Semi detached right-Detached}*(R Rvalue-2.51106)	-0.04249
(Orientation-38.0755)*(Window type-3.55726)	0.042292
Type of house{Row-Semi detached left&Semi detached right}*(Orientation-38.0755)	-0.04079
Type of house{Row&Semi detached left&Semi detached right-Detached}*(EW Rvalue-1.99068)	0.040246
(Windows Distribution-0.34725)*(HDD-1437.27)	-0.03799
(Window Area-0.14374)*(Window type-3.55726)	0.030727
Type of house{Row-Semi detached left&Semi detached right}*(HDD-1437.27)	0.030043
Type of house{Row-Semi detached left&Semi detached right}*(Window type-3.55726)	-0.02585
(R Rvalue-2.51106)*(Cooling set point DAY-28.9925)	0.023681
(HDD-1437.27)*(Cooling set point DAY-28.9925)	0.020138
Intercept	0

A4.3 Streamlined cost model

Net Present Value (NPV) can be expressed symbolically as:

$$NPV(i, N) = \sum_{t=o}^{N} \frac{R_t}{(1+i)^t}$$

Equivalent Annual Cost (EAC) can be expressed symbolically as:

$$EAC = \frac{NPV}{A_{t,i}} \quad \text{where, } A_{t,i} = \frac{1 - \frac{1}{(1+i)^t}}{i}$$

$A_{t,i}$ = annuity factor

i = discount rate

N = number of periods (years)

R_t = net cash flow

t = year of the cash flow

Appendix V Environmental impact and cost of residential building retrofits – what matters? – Supplementary Information

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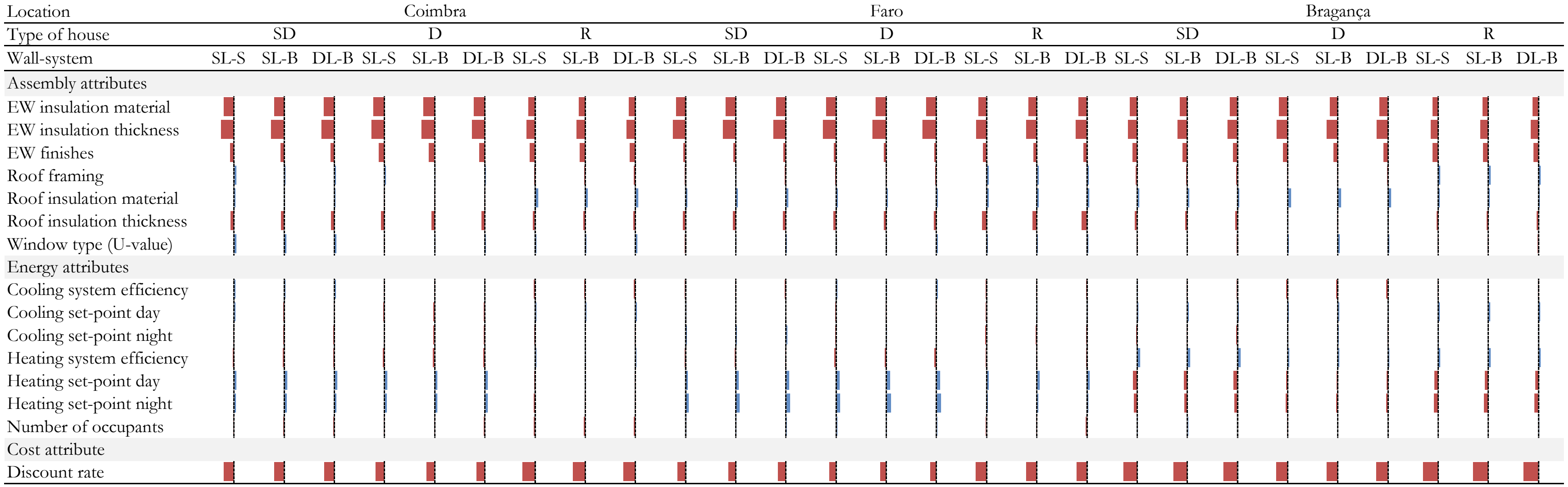

EW=Exterior-wall; SL-S= Single-leaf stone; SL-B= Single-leaf brick; DL-B=Double-leaf brick; SD=Semi-detached; D=Detached; R=Row

Figure A - 7 Spearman rank correlation coefficients (not normalized) characterizing the relative contribution of each attribute in the variance of eco-efficiency results for alternative types of house and wall systems in Coimbra (all assembly and energy attributes are unspecified). Each bar ranges from -1 to 1. Red bars represent negative correlation and blue bars represent positive correlation.