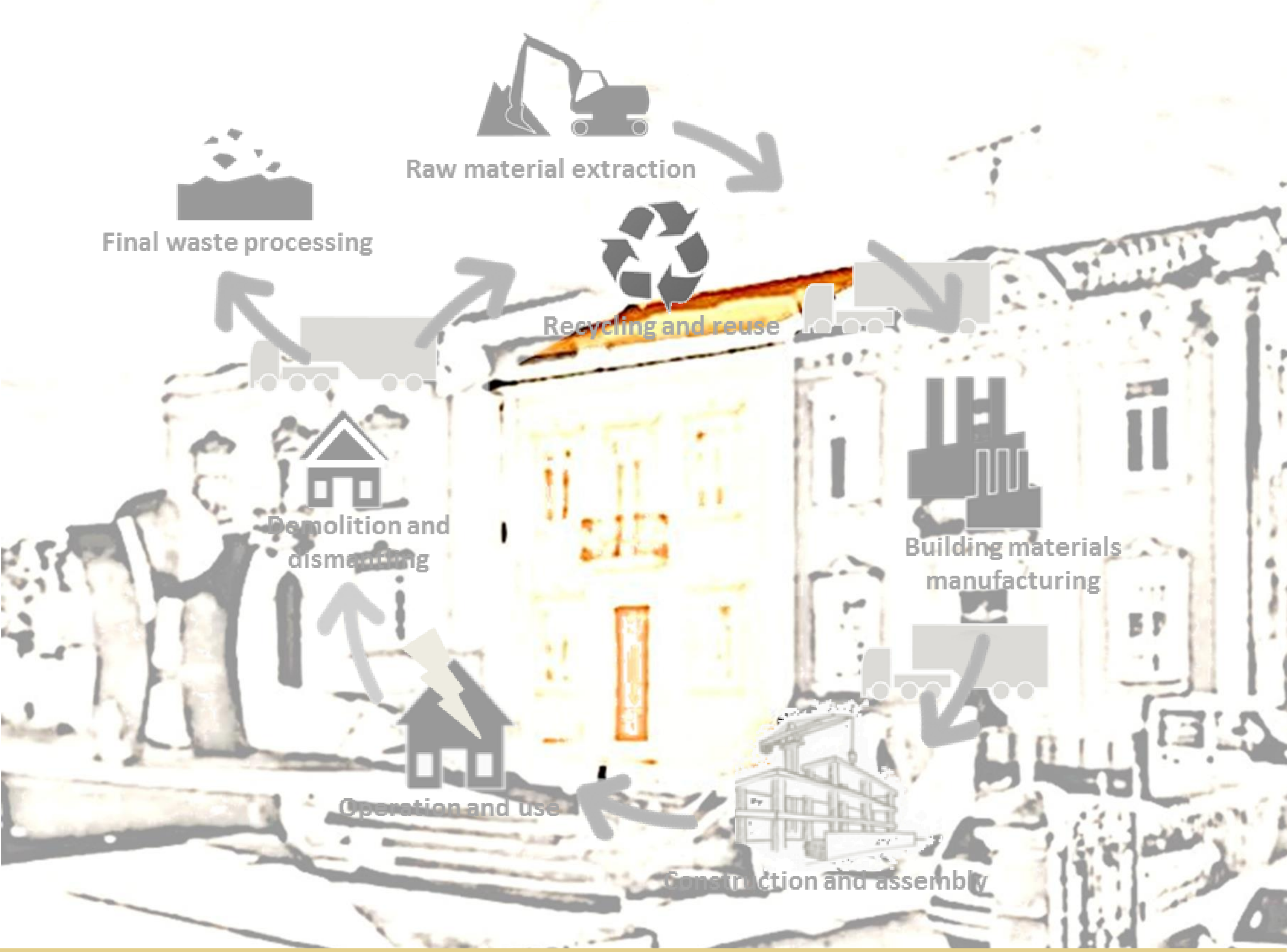

CARLA RODRIGUES

ENVIRONMENTAL ASSESSMENT OF BUILDING RETROFIT

ALTERNATIVE SCENARIOS FOR THE ROOF RETROFIT OF A SINGLE-FAMILY HOUSE

MSc Dissertation

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ENVIRONMENTAL ASSESSMENT OF BUILDING RETROFIT

ALTERNATIVE SCENARIOS FOR THE ROOF RETROFIT OF A SINGLE-FAMILY HOUSE

A dissertation presented by Carla Rodrigues in partial fulfillment of the requirements for the Degree of Master of Energy for Sustainability Specializing in Buildings and Urban Environment

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Abstract

According to the EU report on Energy roadmap 2050, building retrofit plays an important role to reduce the environmental loads currently associated with the building stock. However, research on retrofit of existing buildings is still limited, especially regarding major refurbishment works. This dissertation has three main goals. Firstly, to perform a comprehensive life-cycle assessment (LCA) of the roof retrofit of a Portuguese single-family house characterizing the various life-cycle processes in terms of energy and environmental impacts. Secondly, it aims to study the influence of the roof retrofit solution, and particularly the insulation material choice, in the overall life-cycle (LC) performance of the building. Thirdly, it aims to identify opportunities for improving the LC environmental sustainability of building retrofit for a single-family house in Coimbra. A LC model was developed to assess alternative scenarios for roof retrofit of the single-family house. 27 alternative scenarios were defined combining three types of frame materials (wood, steel and lightweight concrete slab), three types of insulation material (rock wool, expanded polystyrene and polyurethane foam) and three insulation levels (40, 80 and 120 mm). The main processes of the LC model are: removal of the original roof, construction phase and use phase (heating, cooling and maintenance). The functional unit selected for this study is 1 m^2 of living area over a period of 50 years. LC impact assessment results were calculated for six categories (primary energy, climate change, ozone depletion, terrestrial acidification, freshwater eutrophication and marine eutrophication) showing that wood scenarios had the lowest impacts in all the categories. The use phase (maintenance and operational energy) accounted for about 60% to 70% of the LC impacts in all categories The results also showed that, for insulation thicknesses greater than 80 mm, the reduction in energy consumption during use phase, due to a further increase of 40 mm, is not significant (less than 5%), while there is an increase of about 6% to 20% of the environmental impacts associated with the embodied phase, leading to an increase in the overall LC impacts of less than 5%. This dissertation shows the importance of addressing the entire life-cycle of building retrofit to reduce environmental impacts in other phases, namely in the selection of construction materials and insulation levels.

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

Resumo

De acordo com o relatório da UE sobre o roteiro de energia para 2050, a reabilitação de edifícios desempenha um papel importante para reduzir os impactes ambientais atualmente associados ao parque edificado. No entanto, ainda são escassos os estudos realizados sobre reabilitação de edifícios numa perspectiva ambiental de ciclo de vida (CV), especialmente em relação a grandes obras de reabilitação. Assim, esta dissertação tem três objetivos: 1) elaborar uma avaliação de ciclo de vida (ACV) da reabilitação de uma casa unifamiliar em Portugal e caracterizados os diferentes processos do CV em termos de energia e impactes ambientais; 2) estudar a influência da escolha da solução construtiva para a cobertura e, particularmente, a escolha do material de isolamento térmico, no desempenho global de CV do edifício; 3) identificar oportunidades de melhoria da sustentabilidade ambiental da reabilitação da casa. Foi desenvolvido um modelo de CV para avaliar cenários alternativos para a reabilitação da cobertura de uma casa unifamiliar. A análise de cenários foi estabelecida segundo: materiais de estrutura (madeira, aço galvanizado e laje aligeirada de betão leve), material de isolamento térmico (lã de rocha, poliestireno expandido extrudido e espuma de poliuretano) e níveis de isolamento (40, 80 e 120 mm). As principais fases do modelo de CV são: remoção da cobertura original, construção das soluções alternativas e utilização (operação e manutenção). A unidade funcional seleccionada para este estudo é de 1 m^2 de área útil por um período de 50 anos. Os resultados de avaliação de impacte ambiental de CV foram calculados para seis categorias. A fase de utilização representa cerca de 60% a 70% dos impactes de CV em todas as categorias ambientais. Para espessuras de isolamento superiores a 80 mm, os ganhos em eficiência energética devido a um aumento de 40 mm de isolamento não são significativos (inferior a 3%), quando comparados com o aumento de cerca de 20% dos impactos ambientais incorporados. Verifica-se um aumento nos impactos globais de CV de cerca de 5% em ambos os materiais de isolamento devido à redução dos impactes na fase de utilização. Esta dissertação mostra a importância de avaliar a reabilitação de edifícios numa perspectiva de CV para reduzir os impactos ambientais noutras fases para além da fase de utilização, nomeadamente na selecção de materiais e níveis de isolamento durante a fase construção.

Palavras-chave: Reabilitação de edifícios; impactes ambientais; avaliação de ciclo de vida; materiais de isolamento térmico; simulação energética de edifícios

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List of abbreviations

CED	Cumulative Energy Demand
CC	Climate change
COP	Coeficient of Performance
EPDB	Energy Performance of Buildings Directive
eq.	Equivalent
FE	Freshwater eutrophication
LC	Life-cycle
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LS	Light steel frame
LWC	Lightweight concrete slab
ME	Marine Eutrophication
OD	Ozone Depletion
RCCTE	Portugues code of buildings thermal behavior caracteristics
RW	Rock wool
PUR	Polyurethane foam
TA	Terrestrial Acidification
W	Wood frame
XPS	Expanded Poliestyrene

1| INTRODUCTION

1.1. Context and motivation

According to the EU report on Energy roadmap 2050 [1], building retrofit plays an important role to reduce the environmental loads currently associated with the building sector. The existing buildings are one of the biggest contributors to the high level of energy consumption in the residential sector especially those built many years ago.

Additionally, in the “Roadmap for moving to a competitive low carbon economy in 2050” [2], the European Commission established a long-term objective of decreasing the CO_2 emission levels for the building sector by 88% - 91% in 2050, compared to 1990 levels. 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 the existing building stock and reduce its energy use in the long term [3].

The Portuguese building sector has been mainly focused on new construction and the existing buildings were left behind and even the small percentage which have been somehow renovated, usually was some minor refurbishment actions. In Portugal, only 23% of buildings completed in 2010 were related to retrofit of buildings, the largest of these (about 68%) correspond to expansion works and only about 3% to reconstructions [4]. The major retrofits in buildings accounts for only about 15% of the overall construction works in Portugal [4]. According to this estimates, in 2010, 38% of the buildings in Portugal needed major retrofit works and about 3% presented a high level of degradation. [4]

The building stock is getting exhausted of new construction leaving a big percentage of existing buildings empty. It is clear that path now is to retrofit the existing building stock. In this context, the study of building retrofit is vital to answer the needs of today reality by protecting the environment and revitalizing the building stock of our cities. Building retrofit promotes reliving spaces that were often abandoned, returns people to revitalize neighbourhoods and areas of the city that were being left behind.

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 building. As the energy requirements during use phase get near to zero, the embodied phase starts to play an important role when considering a life-cycle perspective. EU published the Energy Performance of Buildings Directive (EPDB) in 2002 [5] which was transposed to member states regulations in the latest years. To apply the EPBD in the Portuguese context, a new regulation with two building codes have been implemented in 2006. The code of buildings thermal behavior characteristics (RCCTE) [6] applied to residential buildings, very recently replaced by the code of energy performance for residential buildings (REH) [7], aims at achieving indoor comfort with lower energy consumption levels. A wider approach regarding different environmental issues is needed in order to assess the whole building performance during its life span. Recently, EU published a set of buildings standards regarding the sustainability in construction works (EN 15643-1/2/3/4). This series of European standards provide a framework with principles, requirements and guidelines to assess the environmental (EN 15643-2), social (EN 15643-3) and economic (EN 15643-4) performance of buildings.

Environmental assessments can be used to identify the most critical components to the environmental performance of existing buildings, in analysing the potential impact of different retrofit alternatives and the selection and implementation of more efficient measures for environmental improvements [8]. In the Portuguese building context,very few life-cycle assessment (LCA) studies have been performed. Moreover, studies regarding the buildings retrofit in Portugal were not found. The present dissertation addresses this gap through the development of a LCA of the retrofit of a Portuguese single-family house from the beginning of the 20th century.

1.2. Literature review

Life-cycle models and assessment are already widely spread in the research area of buildings. The first LCA studies on this field accounted mainly for primary energy analysis and few for greenhouse gas emissions [9], [10], [11]. In 2001, Peuportier [12] evaluated a wider range of environmental impact categories in a life-cycle study of a single-family house in France. In the same year, Adalberth [13] developed a screening LCA of a multi-family building comparing different building solutions and their influence in the overall life-cycle performance of the building. Until then all LCA studies related to buildings concluded that the use phase accounted for 70-90% of the total life-cycle energy consumption. Many LC studies have been performed in the past years, some more focused on the use phase [13, 14] and others on the overall life-cycle including building materials and solutions analysis [15, 16, 17, 18].

Many LCA studies have been performed not only in residential buildings [10, 12, 13, 14, 18, 19, 20, 21, 22, 23, 24, 25, 26] but also in commercial/services buildings [27, 28, 29, 30]. Many review papers have also been published [31, 32, 33, 34]. Moreover, some studies have also started to deal with a wider scope of the built environment such as neighborhoods or blocks [36].

LCA studies in residential buildings had different goals. Some compared different types of buildings [4, 5, 26], or in different locations [25, 27, 28], or with different envelope solutions [23]. Adalberth [13] compared four buildings with different constructive solutions and analyzed the importance of knowing which phase in the life-cycle has greater environmental impact, if there were similarities between environmental impacts and energy use; or if there were differences between subsisted environmental impacts due to the selection of the construction. Considering an occupation phase of 50 years for the dwellings, this study concluded that the greatest environmental impact occurs during the use phase. Also, 70–90% of the environmental categories arise in this phase. Approximately 85% and 15% of energy consumption occurred during the occupation and manufacturing phases, respectively.

Rossi *et al* [38] performed an assessment of three buildings in three different climates (Belgium, Portugal and Sweden). A different life-cycle scenario was taken into account for each location, in which the monthly temperatures, buildings insulation thicknesses, energy mix, heating and cooling systems are defined. This study compared the influence of several parameters in the LCA of residential buildings: indoor and outdoor temperatures, building insulation thicknesses, the use of different materials, the energy mix and the heating/cooling system.

Many other studies have been focused in comparing conventional and low energy houses [3 ,10, 22, 29, 30]. These studies have emphasized the importance of each stage of a building life-cycle. Although some studies have concluded that operation energy is by far the most important contributor to life-cycle impacts of conventional buildings[3, 5, 22, 24, 32], Blengini and di Carlo [15] concluded that progressing towards low energy buildings may change the relative importance of the different LCA stages (construction, operation, end of life). Many other studies have been performed focused on evaluating different solutions for the building envelope such as exterior walls [23] or roofs [42, 43].

A life-cycle perspective is still lacking in studies assessing building retrofit. The main focus of LCA studies of buildings have been on new buildings. The few studies that have addressed retrofit were only of residential buildings and mainly to evaluate energy efficiency measures, such as thermal insulation of the building envelope [34, 36]. The main goal of those studies was to improve the energy performance of buildings during the use phase neglecting most of the time the embodied impacts during production and assembly of materials or constructive solutions (construction phase). However, according to Sartori & Hestnes [32] the construction phase becomes increasingly significant as measures are implemented to reduce operating energy use which means that this phase should be studied even more in detail. Moreover, those studies were mainly developed in cold climates which have different performances than those in a Mediterranean or hot climate.

It is generally assumed that energy efficiency measures for buildings will improve the environmental performance in their life-cycle [11, 12, 32]. However, the relative importance of the material processes increases as much more insulation materials and low-energy components are needed to comply with the energy building standards. Thus, the role of the life-cycle phases may change [7, 9, 35]. As the full impacts of materials and patterns of use become better mapped, questions are raised about the usefulness of upgrading from the low- energy to the ‘passive house’ standard for dwellings [30, 34].

Another specificity of the building sector is the high influence of occupants on the performance. LCA is used to perform optimization studies during the design phase, but the assumptions regarding occupants’ behavior (e.g. thermostat set point temperature, water consumption etc.) was generally not described (e.g. Verbeeck and Hens [22]) though the assumed occupants level of occupancy could influence the optimization results.

The results of a LCA in the building sector should never be generalized, as they necessarily reflect the complex combination of the building unique features, locally adopted construction techniques, behavioral pattern of occupants and site-specific climate conditions [40]. However, many sensitivity analyses can be made in order to reduce generalization. For instance, change location or constructive solutions, management of the heating/cooling system, define different set point temperature, study the life style of the family (occupied hours of a building), etc. It has been prove that the occupancy level of a building influences the use phase energy consumption and the role of the different phases of the life-cycle of a building [47]. Studies have been made regarding this subject but not in a life-cycle perspective, only regarding energy consumption optimization of buildings [48], [49].

Most studies have considered a conventional occupants' behavior or use monitoring results to adapt the model. The approach proposed by Peuportier *et al* [50] complements life-cycle assessment with a sensitivity study in order to account for the variability in real occupancy scenarios, but does not require monitoring results so that it can be performed during the design phase. Application of this method is illustrated by a case study regarding two attached passive houses built in France. The results show the essential influence of occupants on the performance, but varying the occupancy scenario does not modify the ranking between the compared alternatives.

Hernandez and Kenny [46] described a simple methodology which integrates life-cycle energy analysis and comfort expectations with building energy evaluation. It discussed the potential contribution of the occupants' preferences not only in the energy use of buildings in operation, but also the embodied energy associated with equipment and systems. The method is demonstrated in a case study considering a house in a maritime climate with the options of either mechanical or natural ventilation, and some differences in thermal and ventilation preferences. It was observed that as 'zero heating' demand is approached; the embodied energy of materials and systems become significant. The differences in occupants' expected temperature and ventilation levels can be important issues to consider when selecting heating and ventilation systems for minimum life-cycle energy use.

1.3. Research goals

This dissertation aims to incorporate the environmental issues into the retrofit decision-making process by assessing the environmental impacts of different roof retrofit scenarios. Based on literature review gaps, three main goals were defined for this dissertation:

Firstly, to perform a comprehensive life-cycle assessment (LCA) of the roof retrofit of a Portuguese single-family house located in Coimbra characterizing the various life-cycle processes in terms of energy and environmental impacts.

Secondly, to study the influence of the roof retrofit solution, and particularly the insulation material choice, in the overall life-cycle performance of the building. Is there an optimum insulation thickness for the roof with respect to environmental impacts and energy efficiency?

Thirdly, to identify opportunities to improve the life-cycle environmental sustainability of building retrofit for a family household in Coimbra (mediterranean climate).

1.4. Dissertation outline

This dissertation is organized in five chapters including this introduction (Chapter 1). This first chapter describes the context and motivation for this work by explaining what has been done in this subject and how this research can fullfill some of those gaps. The resarch goals are also presented in this chapter. Chapter 2 presents the methodology and methods, giving the framework of life-cycle assessment in the buildings context and describing the life-cycle impact assessment methods used in this study. Chapter 3 describes the case-study and the retrofit scenarios studied. Chapter 4 analyses and discusses the main results. Finally, chapter 5 summarizes the main conclusions and proposes topics for further research.

This dissertation research followed a work done under the scope of the discipline of Industrial Ecology during the first year of the master. From this research, one paper was published (oral presentation) in CINCOS'12 (Congresso de Inovação na Construção Sustentável; Rodrigues, Luiz, Tadeu & Freire, 2012a) and another paper was published in

Construlink entitled “Roof retrofit of an historic building: an environmental assessment” (in portuguese, “Reabilitação da cobertura de um edifício histórico: uma avaliação ambiental”; Rodrigues, Luiz, Tadeu & Freire, 2012b). More recently, an abstract has been accepted for the forthcoming international conference CISBAT 2013 (Rodrigues & Freire, 2013). An article entitled “Environmental assessment of alternative scenarios for the roof retrofit of a house” is is being finalized to be submitted to the Building and Environment journal (Elsevier). The published documents can be found in the list of publications (page 49).

2| METHODOLOGY

The methodology used in this dissertation integrates environmental and energy assessment. A life-cycle model was developed and implemented for the environmental assessment. The results for the environmental impacts were calculated using an impact assessment method called ReCiPe [51]. A single issue method called CED was used to calculate the total primary energy. A thermal dynamic simulation was carried out to calculate the building energy needs during the use phase. The details of the methodology used in this research are presented in sections 2.1 and 2.2.

2.1. Life-Cycle Assessment

Life-Cycle Assessment (LCA) is a methodological tool used to evaluate the environmental aspects and potential impacts throughout a product life (cradle-to-grave) from raw material acquisition through production, use and disposal. During the 1990s the application of this tool has experienced major changes. It was initially developed to compare clearly defined end product alternatives, as it was rapidly incorporated into higher strategic levels, including decision- and policy-making at the firm/corporate levels [52].

LCA is currently used for assessing a wide range of products and activities, from ecolabeling to product design as well as energy systems, food production and transportation alternatives; it now clearly extends beyond only an assessment of end products. A LCA gives quantitative information about the product contribution to, for instance, climate change and depletion of resources, which can be compared with the same information from other buildings.

The general framework of LCA methodology is defined by ISO standards (ISO-14040, 2006 [53]; ISO-14044, 2006 [54]) and it has four interrelated phases: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and interpretation of results [55].

Goal and scope definition: The purpose of the study, definition of the functional unit, system boundaries, necessary data, etc. The functional unit is a reference parameter that describes the primary function of a product (or service) in order to characterize the product performance while executing its function.

Life-Cycle Inventory (LCI): The inventory analysis involves collecting data and calculation procedures in order to quantify all the inputs and outputs of the system being studied. Quantified inputs for each stage of the building will include the use of energy, raw materials and construction materials, etc.

Life-Cycle Impact Assessment (LCIA): Classification and evaluation of the results of the inventory analysis relating its results to the associated environmental effects by using a collection of impact categories (acidification of soils, ozone layer depletion, resource depletion, etc.)

Interpretation: The results of the preceding phase are evaluated together in accordance with the objectives defined in the study in order to be able to establish conclusions and final recommendations. Different techniques are used to do this including sensitivity analysis on the data, an analysis of the relevance of the different stages of the process and an analysis of alternative scenarios.

There are different software applications that perform LCA studies including various databases that are used within the phase of LCI. Each study can be carried out using data from a single database or by combining information from different databases, depending on the quality of data that have been identified. For this study the software SimaPro (www.pre.nl) was used to perform the environmental impact calculations using data from the Ecoinvent database v2.2.

The application of LCA to the built environment has seen interest grow in its application. LCA assess complex products, as buildings, in order to understand their environmental "hot stops". LCA provides a quantitative basis for environmentally improved design options. Architects and engineers are becoming increasingly sophisticated in making buildings better by taking a holistic long-range view. LCA looks at the up- and downstream burden throughout the entire building life-cycle with a special focus on embodied environmental impacts. Embodied impacts become progressively more critical as operating energy consumption is reduced through optimization of design and building management.

2.1.1. Life-Cycle Impact Assessment methods

LCIA is defined by a set of elements, both mandatory and optional. The four mandatory elements are the selection of the impact categories, the inventory data assignment for each category (classification), the calculation of each impact category indicators using characterization factors (characterization), and the analysis of the results.

During classification the inventory results are organized into impact categories; for instance, CO_2 emissions are associated to global warming potential (GWP). The characterization factors represent the relative contribution of a substance to an impact category. Each LCIA applies different characterization factors to the substances included in each impact category, for instance CO_2eq for GWP.

Normalization is an optional element of the LCIA phase, which shows the degree of contribution of each category of impact on the global environmental problem. In reality, in this phase the results from characterization are divided by the normalization factors of each impact category. The normalization factors represent the real or predicted magnitude of the corresponding impact category for a geographic area and over a certain time span. Usually each method of impact evaluation applies different normalization factors to the impact categories considered in that method [56], [57], [58].

The different LCIA methods lead to different results (values, impact categories, units). The LCIA methods can be single category (eg primary energy, exergy, global warming potential) or multi-category, with specific impact categories. The multi-category LCIA methods can be problem-oriented or damage-oriented. Problem-oriented methods (e.g. CML 2001) have midpoint impact categories and model problems at an early stage in the chain of cause and effect, enabling more transparent results and less uncertainty [23].

In this study, the variability among LCIA results was evaluated by applying the same inventory life-cycle to two methods: a general method for single problem - the cumulative energy demand (CED) to account for the life-cycle primary energy requirements, and an environmental method, ReCiPe, to evaluate multiple environmental impacts.

Single issue method – Cumulative Energy Demand

The Cumulative Energy Demand (CED) has been used since the seventies as an indicator for energy systems. The assessment of the environmental impacts related to a product or process is based on one parameter: the total energy demand for production, use and disposal expressed in primary energy [59]. Energy resources that can be found in nature, such as coal, crude oil and natural gas are called primary energy resources.

The CED method calculates the total primary energy (PE) use (MJeq) throughout the life-cycle based on the Higher Heating Value (HHV) and distinguishes renewable (R) and non-renewable (Non-R) energy sources [60]. It constitutes a widely used indicator to assess energy life-cycle performance of buildings.

LCIA midpoint method – ReCiPe

ReCiPe is an LCIA method that is harmonized in terms of modeling principles and choices and which offers results at both the midpoint and endpoint level. The acronym also represents the initials of the institutes that were the main contributors to this project and the major collaborators in its design: RIVM and Radboud University, CML, and PRé. This method has focused on an analysis of the differences and similarities between two main approaches to a LCIA. In particular, the focus was on the first part of a LCIA when impact categories and category indicators are chosen and characterization models are selected or developed to convert LCI results into category indicator results. These two main approaches were: 1. the method proposed as the baseline method for characterization in the Handbook on LCA (Guinée *et al*, 2002 in [51]) ; we will refer to this as the midpoint approach; 2. the method advanced in the Eco-indicator 99 (Goedkoop & Spriensma, 1999 in [51]); this will be referred to as the endpoint approach [51].

The initial goal of this new method was to integrate oriented approach to environmental problems (problem oriented approach) of 2001 with the CML-oriented approach to the damage (damage oriented approach) of EcoIndicator 99. The problem-oriented approach considers impact categories at a midpoint level where the uncertainty of results is relatively low; however, it can be obtained a large number of impact categories associated with the various types of environmental problems. The damage oriented approach considers types of results to an endpoint level; the results are presented in three categories of impact however the uncertainty of results is considerably higher.

The ReCiPe integrates these two approaches presenting the categories of environmental impact to a level midpoint and endpoint. This method considers the following three perspectives [51]: Individualist (I) is a perspective based on a short-term view, considering types of environmental impact and there is a more consensual technological optimism regarding the ability of technology to solve problems; Hierarchist (H) is based on the policies in common with respect to time and other issues and Egalitarian (E) is the perspective that reflects greater caution considering a long term perspective and considers environmental impacts that are not yet fully proven, but for which there is already some evidence available.

The ReCiPe method considers eighteen categories of environmental impact at midpoint and three at endpoint level. This study considered ReCiPe method at a midpoint level, and among the eighteen categories of environmental impact available, the following were selected for this study: climate change (CC), ozone layer depletion (OLD), terrestrial acidification (TA), freshwater eutrophication (FE) and marine eutrophication (ME). The categories selected for this study are the most frequently discussed in the literature related to buildings [11, 12, 17, 18, 25, 39, 60]. This study only considered the hierarchical perspective, it is this that is defined by default in the method Recipe [52].

The description of the each the selected categories is presented in Table 1. Toxicity categories normally are not addressed because they have high uncertainty and lack scientific robustness [19], [57]. The ReCiPe method has already some improvements in this area so it was decided to include in the calculations four toxicity categories; however, the lack of scientific robustness has been taken into account in the interpretation of results.

In LCA studies of buildings, the attributional approach (ALCA) is the most frequently used and it was adopted in this study [57]. This is due to two reasons: first, the primary goal is to evaluate different retrofit solutions for the same house, in order to identify environmentally preferable solutions, and secondly, it is assumed that the changes that occur do not affect the market [23].

Table 1. Description of the environmental impact categories referred to ReCiPe method.

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

2.2. Energy Assessment – Thermal Dynamic Simulation

Thermal dynamic simulation is a method that calculates the energy performance of buildings based on dynamic models. The dynamic models allows incorporating schedules, systems, set-point temperatures in order to calcute results closer to the real performance of buildings.

Energy assessment in a life-cycle perspective allows balancing embodied and operation energy. The integration of thermal dynamic simulation in LCA studies is relevant to assess and possibly improve the performance of a building project on a global basis. Many studies have already used thermal dynamic simulation for energy performance calculation. Thermal dynamic simulation plays an important role especially as the buildings achieve low energy or passive house standards or to compare the performance of different energy efficiency and/or retrofit measures [3, 14, 33]. This method allows modeling the building according to very specific characteristics such as schedules, systems, set-point temperatures, etc.

EnergyPlus is a whole building energy simulation program that is used to model energy and water use in buildings. Modeling the performance of a building with EnergyPlus enables the optimization of the building design to use less energy and water. EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use. EnergyPlus includes many innovative simulation capabilities: time-steps less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems. Despite all the capabilities of this energy simulation program, for the purpose of this research, the software Energy Plus [62] was used mainly to model schedules according to the family lifestyle in order to calculate the annual energy needs of the building to incorporate into the LCA.

3| LIFE-CYCLE MODEL AND INVENTORY

3.1. Goal and scope definition

The main goal of this study is to perform a comprehensive LCA of the roof retrofit of a Portuguese single-family house characterizing the various life-cycle processes in terms of energy and environmental impacts in order to identify opportunities for improving the LC environmental sustainability of the roof. It also aims to study the influence of the roof retrofit scenario, and particularly the choice of the insulation material, in the overall LC performance of the building.

A life-cycle model was developed to the single-family house (with a living area of 279 m^2 organized in 4 floors) from the 1900's, located in Coimbra, Portugal. The main features of the original building are massive stone walls, single glazing wood windows and a traditional wooden frame roof. The roof retrofit process incorporates the replacement of frame material, interior and exterior coverings as well as the incorporation of a thermal insulation layer.

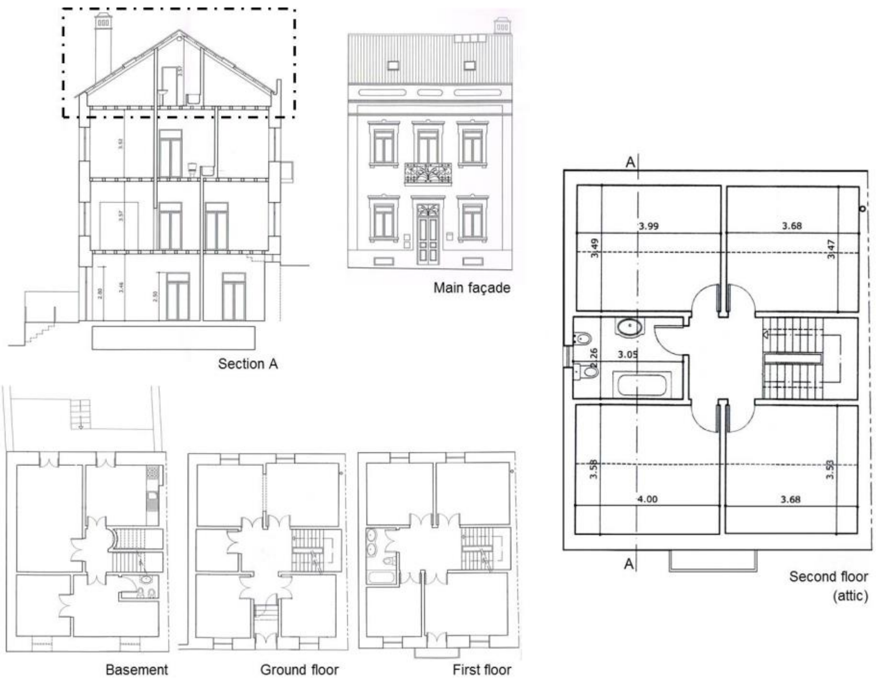


Fig. 1. Main façade, section and plans of the single-family house

This dissertation focused only on the second floor (attic) because is the floor which energy performance is more influenced by the retrofit of the roof (representing about 20% of total energy requirements for heating and about 60% for cooling). Moreover, it was concluded that the reduction of energy requirements due to roof´s insulation on the lower floors is less than 2%. The floors plans, section and main façade are provided in figure 1. The occupancy type assumed was a 4-people family with a low occupation level, according to the Portuguese occupation pattern for residential buildings.

The functional unit selected for this study was 1 m^2 of living area over a period of 50 years, following many authors that have assumed the life span of buildings of 50 years (e.g. [13], [26], [33], [63], [64]).

3.2. Inventory analysis of the roof retrofit

Figure 2 presents the LC model which includes the following phases: removal of the original components (such as roof and some demolition waste), construction of the new roof and use (heating, cooling and maintenance). The next 3 subsections describe the three phases in detail. The heating and cooling system defined for the house was a 12 kW heat pump with a coefficient of performance (COP) of 3.6 for heating and 3.2 of cooling.

The LCA was performed following the ISO 14040 [53] and 14044 [54]. The model and life-cycle inventory were implemented in software SimaPro 7 (www.pre.nl). Ecoinvent database v2.2 was used to obtain inventory data regarding material processing and activities during each phase of the assessment. In order to quantify transportation distances from the building site to the recovery (recycling, incineration) sites as well as from the production site to the building site, a market search was carried out. For each material or component was determined the extraction or production plant nearest to the building site. Energy requirements for the use phase were simulated with an energy dynamic model using software Energy Plus [62].

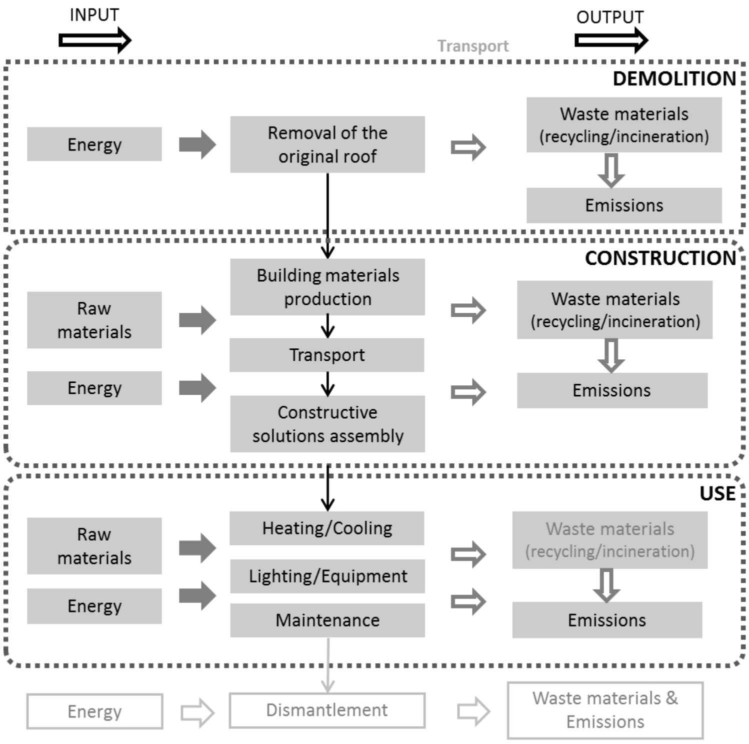


Fig. 2. Main processes of the model and system boundaries

3.2.1. Demolition Phase

The removal of the original components includes dismantling and transport for recycling (roof tiles) or incineration (wood). For this study was considered that the original wood roof was completely removed and replaced by a new roof. No special treatment was considered to the wood that has been reuse.

3.2.2. Construction Phase

The construction phase of the retrofit process includes the production of materials ("cradle to gate") and transport to the site as well as all the other processes involved in this phase: carpentry/joinery, assembly of the wood/steel/concrete structure, insulation and tiles placement and interior coating (gypsum plaster board or stucco). 27 roof retrofit scenarios were defined combining three types of frame material, three types of insulation material, and three insulation levels, as presented in Table 2. These scenarios were based only in solar passive measures. Due to the nature of the building, their exterior features must be preserved, so all the scenarios have the same volumetric, slope and outer coat in ceramic tile.

Table 2. Roof retrofit scenarios

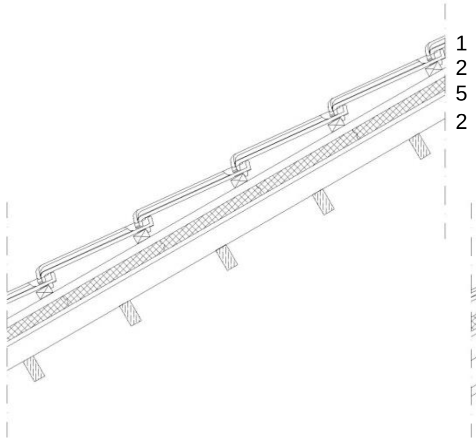
Retrofit Options		**Number of scenarios**
Frame material	Wood (W); Light Steel (LS); Lightweight Concrete (LWC)	3
Thermal Insulation	Rock wool (RW); Polyurethane Foam (PUR); Expanded Polystyrene (XPS)	3
Insulation level (mm)	40; 80; 120	3
Total number of retrofit scenarios		27 (3 x 3 x 3)

Frame material options

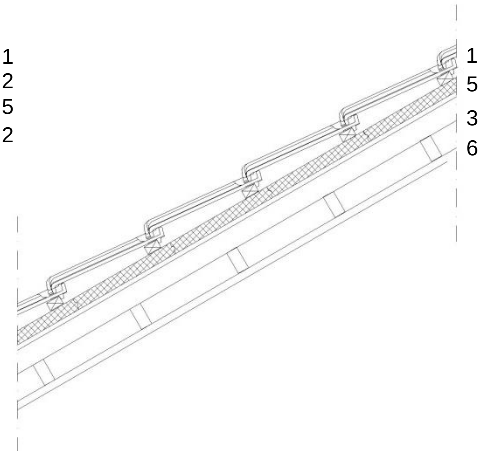
The wood frame option was assumed to be the base case scenario for the roof retrofit, but other two options were studied and compared through a scenario analysis. Figure 3 presents schematic drawings of the alternative roofs retrofit. These drawings were based in information given by manufactures [67, 68, 69, 70,71]. Three frame material options were selected: wood frame, light steel frame and lightweight concrete slab. These options were defined to have similar heat transfer coefficients (U-values) with the same thermal insulation material (rock wool with 40 mm), placed outside the structure. Therefore the heating and cooling requirements were the same for the various frame material options [65].

Table 3 presents the inventory for the alternative frame materials scenarios for the roof, per total roof area (84 m^2) and per functional unit (1 m^2). Scientific literature and technical information was gathered from producers and contractors in order to calculate the quantities of materials. An additional 5% of materials have been considered to include losses on site due to cutting and fitting processes. These elements have been modeled based on Kellenberger *et al* [66], which presented average European LCI data for the production of building materials.

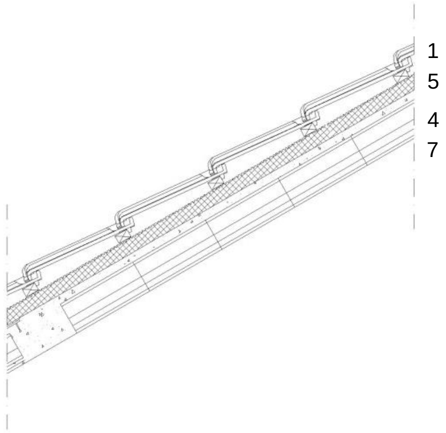
A. Wood Frame



B. Light-Steel Frame



C. Lightweight Concrete Slab



1. Roof tiles (+ underlay system)*
2. Wood frame
3. Light steel frame
4. Hollow concrete slab
5. Thermal insulation + vapor barrier
6. Gypsum plaster board
7. Stucco

*An underlay system is considered when the insulation option is rock wool.

Fig. 3. Schematic drawings of the alternative roofs: 3 types of frame materials (wood, light steel, lightweight concrete slab)

Thermal insulation thickness and material options

Another scenario analysis was performed to study the influence of thermal insulation thickness and material both in construction and use phase. For this analysis, three insulation material options were considered: rock wool (RW) expanded polystyrene (XPS) and polyurethane foam (PUR). Three insulation levels (40, 80 and 120 mm) were studied for each insulation material. The insulation thickness and material options inventory is presented in Table 4.

Table 3. Frame material options inventory

	Roof Layers		Units	Thickness (mm)	by Roof Area: Total Weight (kg)	by Roof Area: Total Volume (m^3)	by Functional Unit: Weight (kg/m^2)	by Functional Unit: Volume (m^3/m^2)
Original Roof	Exterior Coating	- ceramic tiles	840		2940	-	35	-
		- vapor control layer	-	2	15	-	0.17	-
	Existing Wood Frame	- secondary structure[1]	48+26+50	80*40/40*40	949	1.4	11.3	0.016
		- rafters	12	80*160	630	0.9	7.5	0.011
		- trusses	3	160*160	553	0.8	6.6	0.009
	Interior Coating	- wood panels	-	20	176	0.7	2.1	0.008
Wood (W)	Wood Frame	- secondary structure[1]	48+26+50	80*40/40*40	1138	1.6	13.6	0.019
		- rafters	12	80*160	756	1.1	9.0	0.013
		- trusses	3	160*160	664	0.9	7.9	0.011
	Thermal Insulation	- Rock wool	-	40	*(see Table 4)*			
	Interior Coating	- gypsum plaster board	-	25	2117	4.4	12	0.05
Light Steel (LS)	Light Steel Frame	- steel battens	32	0.6	108	-	1.3	-
		- main structure	20	2	999	-	11.9	-
		- OSB	-	15	794	1.3	9.5	0.02
	Thermal Insulation	- Rock wool	-	40	*(see Table 4)*			
	Interior Coating	- gypsum plaster board	-	25	2117	4.4	12	0.05
Lightweight Concrete (LWC)	Lightweight Concrete Slab	- pre-stressed beams	30	-	2336	0.8	27.8	0.01
		- formwork concrete[3]	538	-	4515	-	53.8	-
		- complementary concrete	-	-	8568	5.4	102.0	0.06
		- reinforcement steel	-	-	556.4	-	6.6	-
	Thermal Insulation	- Rock wool	-	40	*(see Table 4)*			
	Interior Coating	- stucco	-	20	4234	3.4	50	0.04

[1] Secondary Structure: Sticks, Battens & Counter Battens [2] Extruded Polystyrene [3] Hollow Concrete

Table 4. Insulation thickness and material options inventory

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

*Source: ITE 50 [65]

Transport

The transportation of the construction materials to the building site was implemented assuming lorry (3,5 – 16t) and van (<3,5t) transportation, with European fleet average characteristics. The inventory data associated with this process were obtained from Spielmann et al. and Hischier et al [12, 13]. The construction material weights and shipping distances for the alternative roofs are presented in Table 5.

Table 5. Building materials: weight and transportation distances

Construction Materials		**Mass** (ton)	**Distance** (km)
Frame material			
Wood (100%)		0.9	90
Wood (30%)		0.3	90
Steel	light steel	1.1	115
	other	0.6	10
Concrete	reinforced	6.9	10
	not reinforced	8.6	10
Other components			
Roof Tile		2.9	50
RW - Rock Wool	40mm	0.5	145
	80mm	0.9	145
	120mm	1.4	145
XPS – Expanded Polystyrene	40mm	0.1	78
	80mm	0.25	78
	120mm	0.37	78
PUR – Polyurethane Foam	40mm	0.1	110
	80mm	0.3	110
	120mm	0.4	110
Vapor Control Layer		0.01	120
Oriented Strand Board		0.8	90
Gypsum Plaster Board		2.1	58
Stucco		4.2	90

3.2.3. Use Phase – Thermal Dynamic Simulation

The use phase includes heating, cooling and maintenance requirements. The occupancy level was defined considering a typical low occupation level of Portuguese residential houses with loads mainly during the night time on weekdays and weekends during all day. A 12 kW heat pump, with a coefficient of performance (COP) of 3.6 for heating and 3.2 for cooling, was adopted for the house heating and cooling system. The occupant behavior related to lighting, hot water and appliances was considered the same for all design options.

The Portuguese climate is classified as a maritime temperate climate with a Mediterranean influence under the classification of the Köppen-Geiger system. The building is located in the city of Coimbra where the temperatures in the winter are between 15ºC during the day and 5ºC during the night. In the summer, the temperatures are between 29ºC during the day and 16ºC during the night. Solar radiation levels in this city are about 1650 kWh/m^2/year [73].

The annual heating and cooling requirements were calculated based on a dynamic model in the Energy Plus [62]. The heating season begins in November and ends in March and the cooling season begins in May and ends in September. The heating and cooling set-points where define to be 20ºC and 25ºC, respectively, and the natural ventilation rate of 0.6 air changes per hour was considered, according to the Portuguese building thermal regulation (RCCTE) [7]. The single-family house was simulated for the previously described scenarios in order to assess the influence of the insulation level on the energy performance of the building.

The energy needs for the attic corresponds to 15% to 20% of total heating needs and 55% to 65% of total cooling needs of the all house, depending on the scenario. The internal gains used for the simulation were the number of people, lights and equipment. The number of people vary from 0 to 5 according to the occupation schedule define for each day of the year. Lights were estimated in 5 W/m^2 and equipment (computers, television, hair dryer and other small equipment) in 300 W (according to the schedule defined for each equipment).

Occupancy level

The average annual end-use energy consumption of Portuguese households for space heating (2010), which is about 1.4 kg of oil equivalent (koe)/m^2.year ($\approx$ 16 kWh/m^2) [74], the second lowest level in Europe. From 2009 to 2010 the energy consumption for space heating in the Portuguese dwelling decreased in 40%, from 2.2 koe/m^2 to 1.4 koe/m^2.

The very low occupation level defined to this study takes into account the trend where the occupants have an increase sense of reducing the energy consumption. It was assumed to be mainly during the night on weekdays and all day on weekends, with a restricted use of HVAC systems (25% of use in the heating season and 5% in the cooling season). Table 6 presents the energy requirements for the alternative insulation level scenarios.

Table 6. Energy requirements for the single-family house (SFH, 280 m^2) and for the 2nd floor (70 m^2) per insulation level and material in kWh/(m^2.year)

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

Maintenance

The main maintenance activities included in this study are those associated with the conservation of the interior and exterior finishes of the building during the predicted life span (50 years). The maintenance activity schedule for the roof has been established based on data from [66] and material producers. Table 7 presents the main assumptions for the inventory of maintenance activities including interior painting of walls, varnishing of wood surfaces and plaster board replacement.

Table 7. Inventory of Maintenance

Component	**Activity**	**Density** (kg/L)	**Area** (m^2)	**Volume** (L)	**Mass** (kg) **with x coats**	**Every x years**	**Times in life**
Roof floor	plaster board	-	71	-	852	20	2
	interior paint	1.0	71	10	21	20	2
	interior varnish	1.5	64	6	28	10	4

3.3. Model simplifications

Some simplifications were considered in the life-cycle model. Regarding the construction phase, equipment used and transportation of workers to the workplace were not included because the relevance of these processes is minor in residential buildings [16]. The end-of-life phase of the new roof (scenarios dismantling and waste treatment) was not included because it is considered of minor importance for single-family homes and, according to a recent European study [16], represents less than 4% of the total environmental impacts of dwellings in southern European countries. Additionally, it is difficult to predict this phase since the buildings have a long lifetime. In the end-of-life scenario for the demolition phase was considered that residues were separated and treated in the same place. Moreover, all the waste was removed and transported to the incineration or recycling plant in only one trip.

4| RESULTS AND DISCUSSION

4.1. Introduction

This section presents the main results of the life-cycle impact assessment (LCIA) of the roof retrofit scenarios. A scenario analysis was perfomed concerning their main differences: insulation and frame materials. Firstly, the LCIA results are presented for the base scenario. Secondly, the construction phase is analyzed in detail regarding the three frame materials. Thirdly, the insulation scenarios (materials and thicknesses) are analyzed in a whole life-cycle perspective. The balance between embodied phase ("cradle to gate") and use phase is also assessed as well as the tipping point where life-cycle impacts reaches a minimum value.

Total LC results addressed the four main phases: removal of the original roof, construction of the new roof, maintenance and operational energy (heating, cooling, lights and equipment). The results are presented in two types of figures: i) LCIA results and ii) normalized results and contribution analysis. LCIA results show the absolute values of the environmental impacts. Normalized results allow us to show the relative magnitude of the environmental impacts on a common scale to all impact categories [58]. The reference value used to calculate ReCiPe normalized results is relative to European context for the year 2010 (Europe ReCiPe) [56]. Contribution analysis show the contribution of each phase in the overall LC of the building. LCIA and contribution anlysis results are presented for primary energy and five environmental impact categories. Normalized results are presented for the five environmental impact categories analyzed.

4.2. LCIA: base scenario

Figure 4 and 5 presents the LCIA, normalized and contribution analysis results of the base scenario (wood frame and rock wool with 40 mm) for the roof retrofit of the single family-house. The results show that use phase is responsible for more than half of the impacts in all the categories, accounting for 60% to 80% of total LC impacts. Operational energy (heating, cooling, lights and equipment) is the most significant process and accounts for about 50% to 75% of total LC impacts. Maintenance accounts for only 7% to 15%. The construction phase is the second highest contribution and accounts for 20% to 30% of total LC impacts. Finally, removal phase is relatively insignificant compare to the other LC phases, accounting for only about 2%.

Use phase is the most significant contributor to freshwater eutrophication and terrestrial acidification. On the other hand, construction phase has the highest impacts for ozone depletion. For normalized results, freshwater eutrophication is the most significant being followed by descending order by terrestrial acidification and climate change.

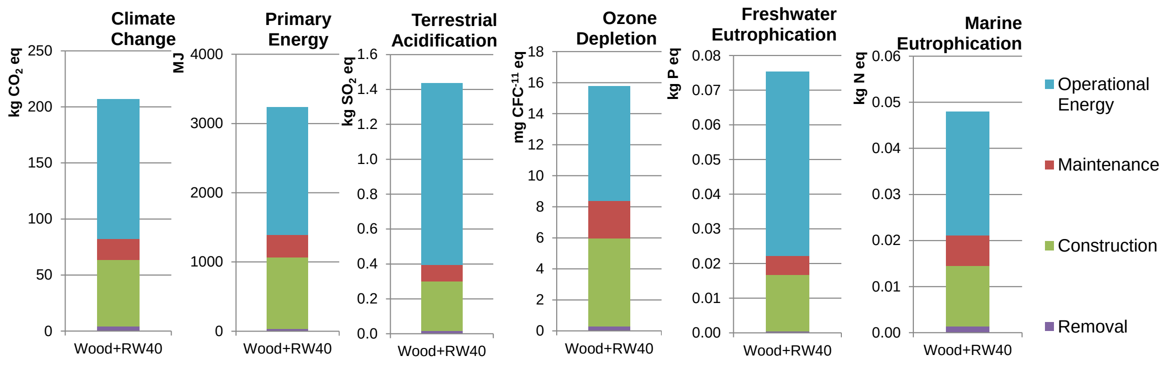


Fig. 4. Life-Cycle Impact Assessment of the base scenario (wood frame and 40 mm of rock wool; per functional unit: 1 m^2 of living area over a period of 50 years)

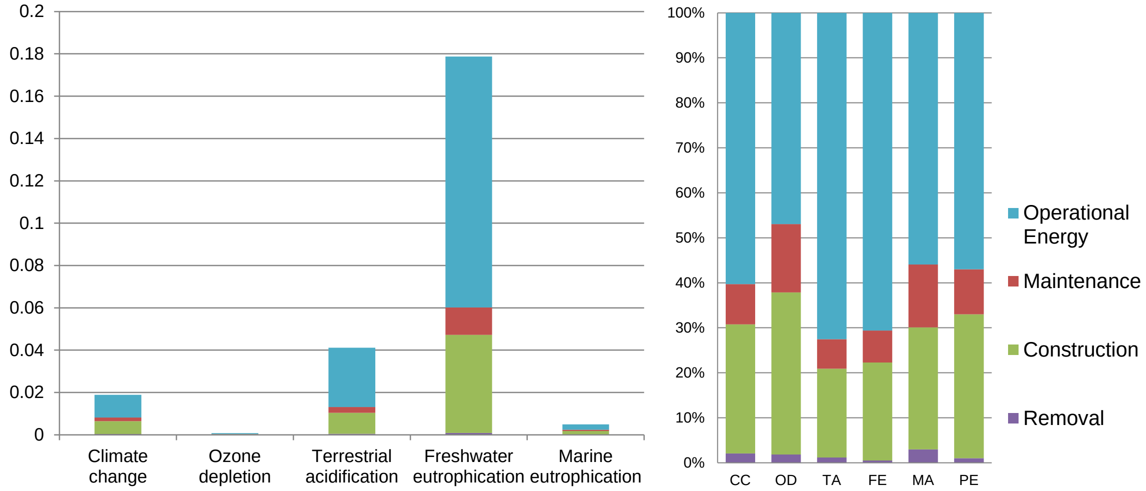


Fig. 5. ReCiPe normalized results for base scenario (wood frame and rock wool 40 mm; left) and contribution analysis (right; per functional unit: 1 m^2 of living area over a period of 50 years)

4.3. Frame material options

Three alternative roof retrofit scenarios with different frame materials (wood (W), light steel frame (LS) and lightweight concrete slab (LWC)) and the same insulation solution (rock wool with 40 mm) were considered for this analysis. All the scenarios have the same heat transfer coefficient (U-values), so that LC heating and cooling requirements are also the same. The selected frame materials influence material production (different material composition), transport (different weights for different materials) and maintenance activities.

Figure 6 and 7 presents LCIA, normalized and contribution analysis results of the frame material options. The results show that W is the scenario with the lowest environmental impacts among all the categories. LWC is the scenario with the highest environmental impacts in 4 out of 6 categories. Concerning eutrophication impacts, LS is the scenario with the highest environmental impacts, as a result of the galvanized steel process (steel with zinc coating).

Use phase is the largest contributor phase to W and LS scenarios, for every category, accounting for 40% to 70%. For LWC scenario, the construction phase is the most significant LC phase for 3 out of 6 categories, accounting for 30% to 65% of total LC impacts. Construction phase contribution is nearly half of use phase to terrestrial acidification and freshwater eutrophication and nearly 20% to the other categories. The contribution of demolition and maintenance phases is much less significant.

Regarding primary energy analysis, use phase accounts for 60% of total energy requirements in W and LS scenarios. Concerning LWC scenario, there is no significant difference (only 2%) between the energy requirements for construction and use phase.

These results provide a useful perspective of the influence of the frame material in the performance of the different LC phases. Depending on the frame material option, the potential for reducing environmental impacts of building retrofit can shift from use phase to construction phase.

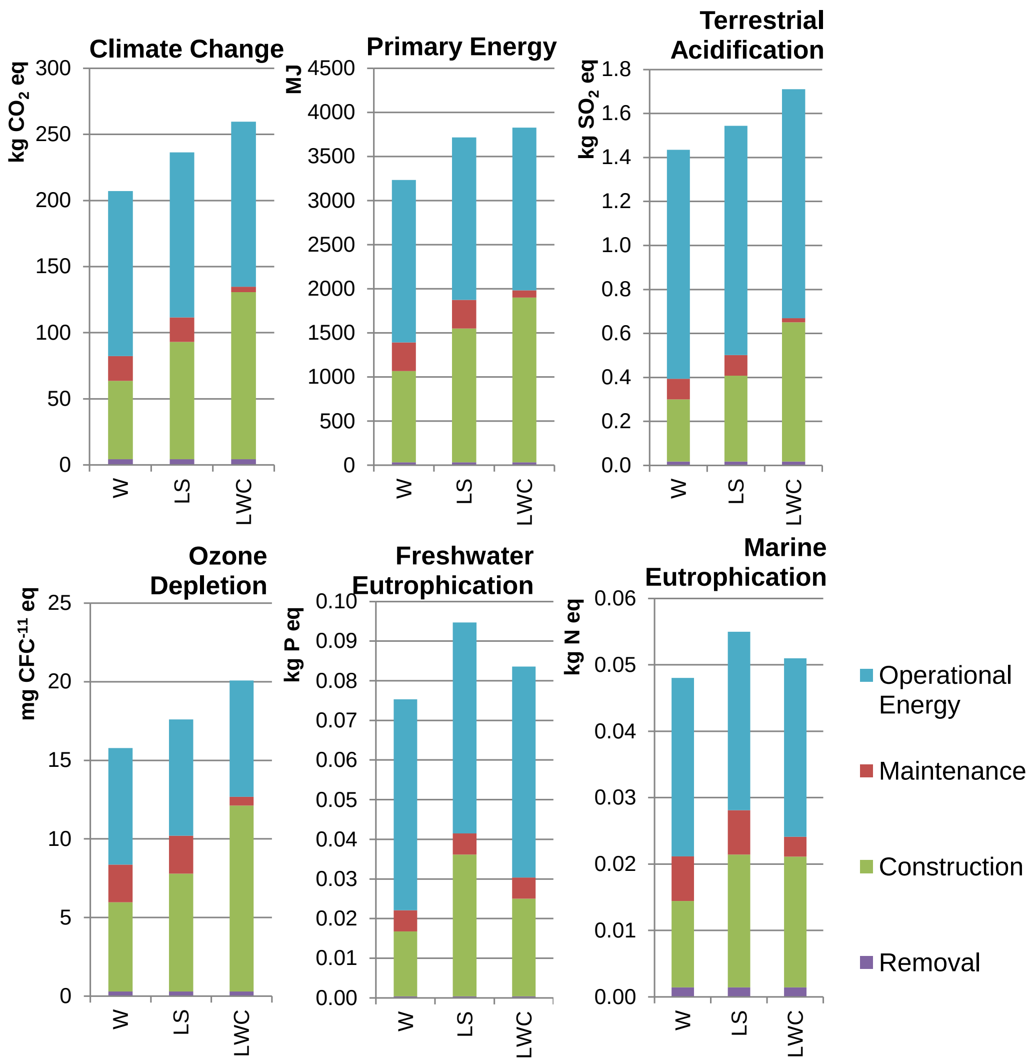


Fig. 6. Life-Cycle Impact Assessment of the frame materials options (wood, light steel and lightweight concrete slab; per functional unit: 1 m^2 of living area over a period of 50 years)

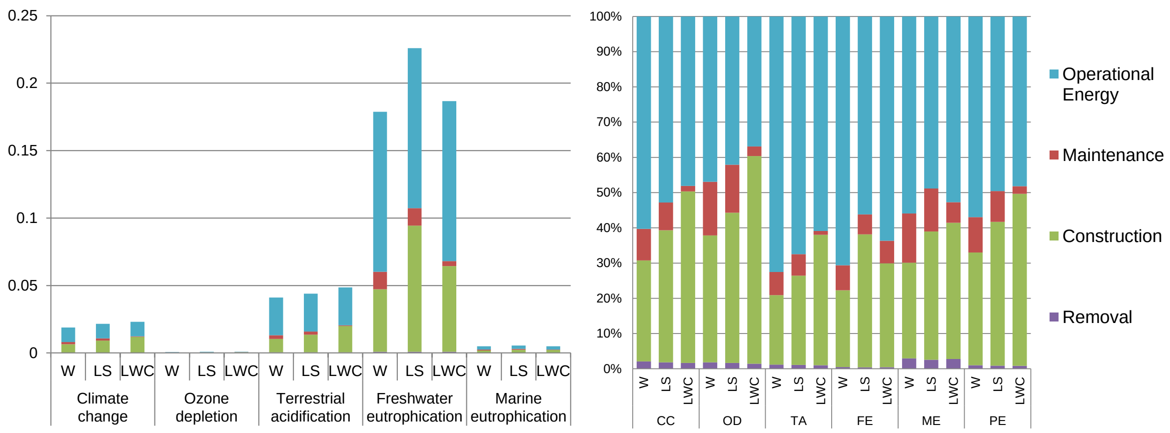


Fig. 7. ReCiPe normalized results (left) and contribution analysis (right) of the frame materials options (wood, light steel and lightweight concrete slab; per functional unit: 1 m^2 of living area over a period of 50 years)

Construction phase is the second largest contributor phase to the whole life-cycle of the building. Figure 8 shows the contribution of each process to the construction phase. The materials/processes with higher environmental impacts are transport, steel, concrete and zinc. Transport is the largest contributor to W scenario (25% to 50%) and to LS scenario (13% to 43%), followed by steel (10% to 30%). Lightweight concrete is the most significant contributor process to LWC scenario (26% to 54%), followed by steel (3% to 22%). The processes with lower environmental impacts are wood, oriented strand board (OSB) and stucco.

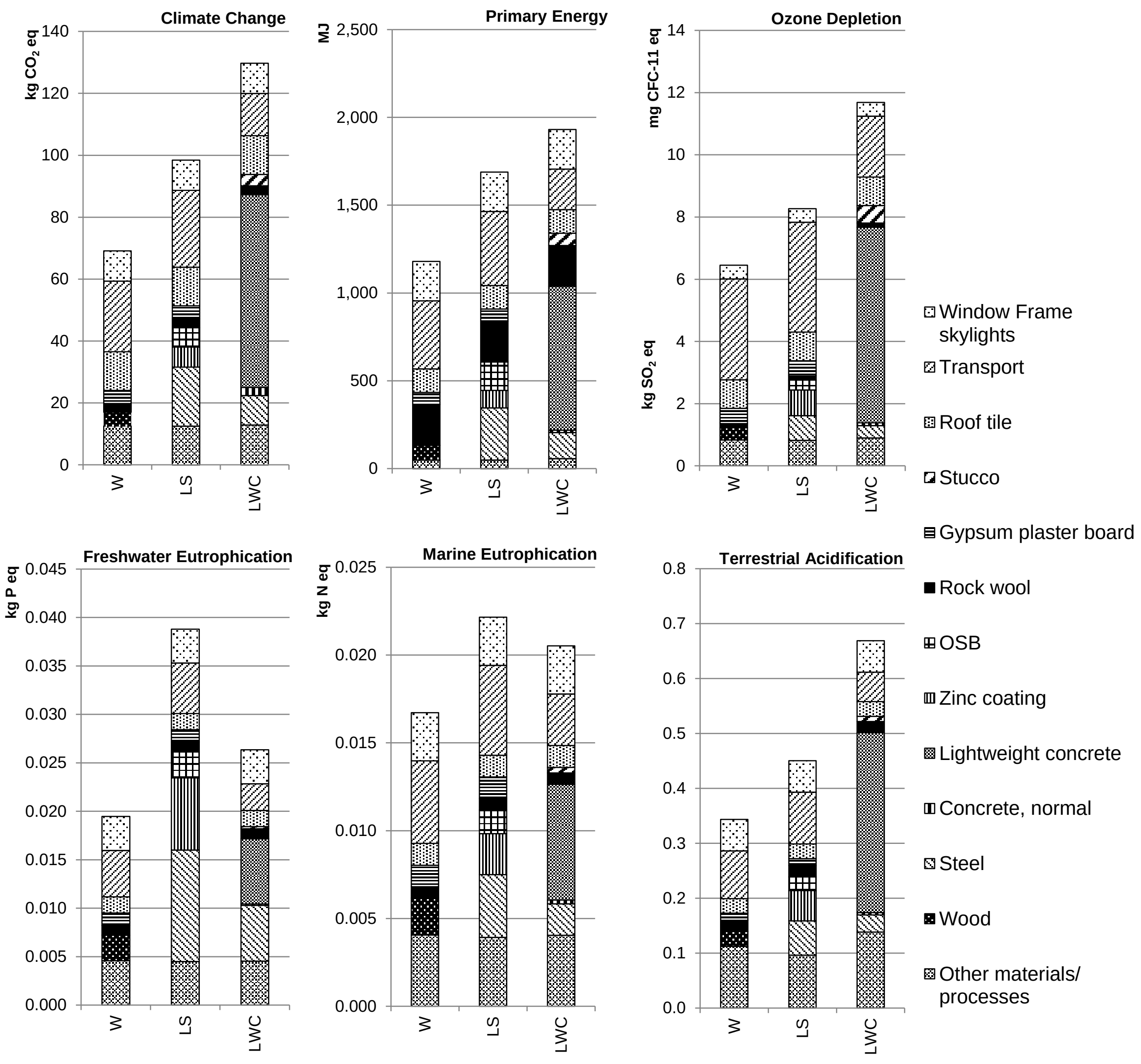


Fig. 8. Environmental and primary energy assessment of the construction phase: Frame material (wood, light steel and lightweight concrete slab) scenarios analysis (main processes; per functional unit: 1 m^2 of living area over a period of 50 years)

4.4. Thermal insulation options

As shown in the previous sections, the use phase has the highest LC impacts in all the assessed categories. This section analize the influence of increasing the thickness (40, 80 and 120 mm) of the insulation material or changing the insulation material (RW, XPS and PUR). The selected insulation thickness and material options influence material production, transport (different weights and distances for different insulation materials) and energy consumption during the use phase.

This section is organized in 3 subsections. The first subsection (4.4.1.) assesses the overall LC impacts of twelve insulation options. The other two subsections analyze in detail the performance of each LC phase for the different insulation levels (4.4.2.) and for the different insulation materials (4.4.3.).

4.4.1. Thermal insulation thickness and material options

Figure 9 presents the LC results for twelve insulation options to assess the tipping point where LC impacts reaches a minimum value and to compare operational energy (energy consumption during use phase) and embodied impacts (construction phase). The results are presented as total LC, operational energy and embodied impacts.

It can be observed that the tipping point for rock wool occurs for thicknesses lower than 80 mm in all the categories. It occurs for 40 mm for ozone depletion, marine eutrophication and primary energy, and 80 mm for climate change, terrestrial acidification and freshwater eutrophication. Regarding XPS and PUR, the tipping point occurs for thicknesses lower than 120 mm in half of the categories. Primary energy results show that the tipping point happens for 40 mm in all insulation materials.

Embodied impacts become more significant than operational energy impacts in thicknesses lower than 120 mm for climate change in XPS scenarios, ozone depletion in RW scenarios and marine eutrophication in PUR scenarios. As for all the other scenarios this always occurs in thicknesses greater than 120 mm (not commonly used in Mediterranean climates).

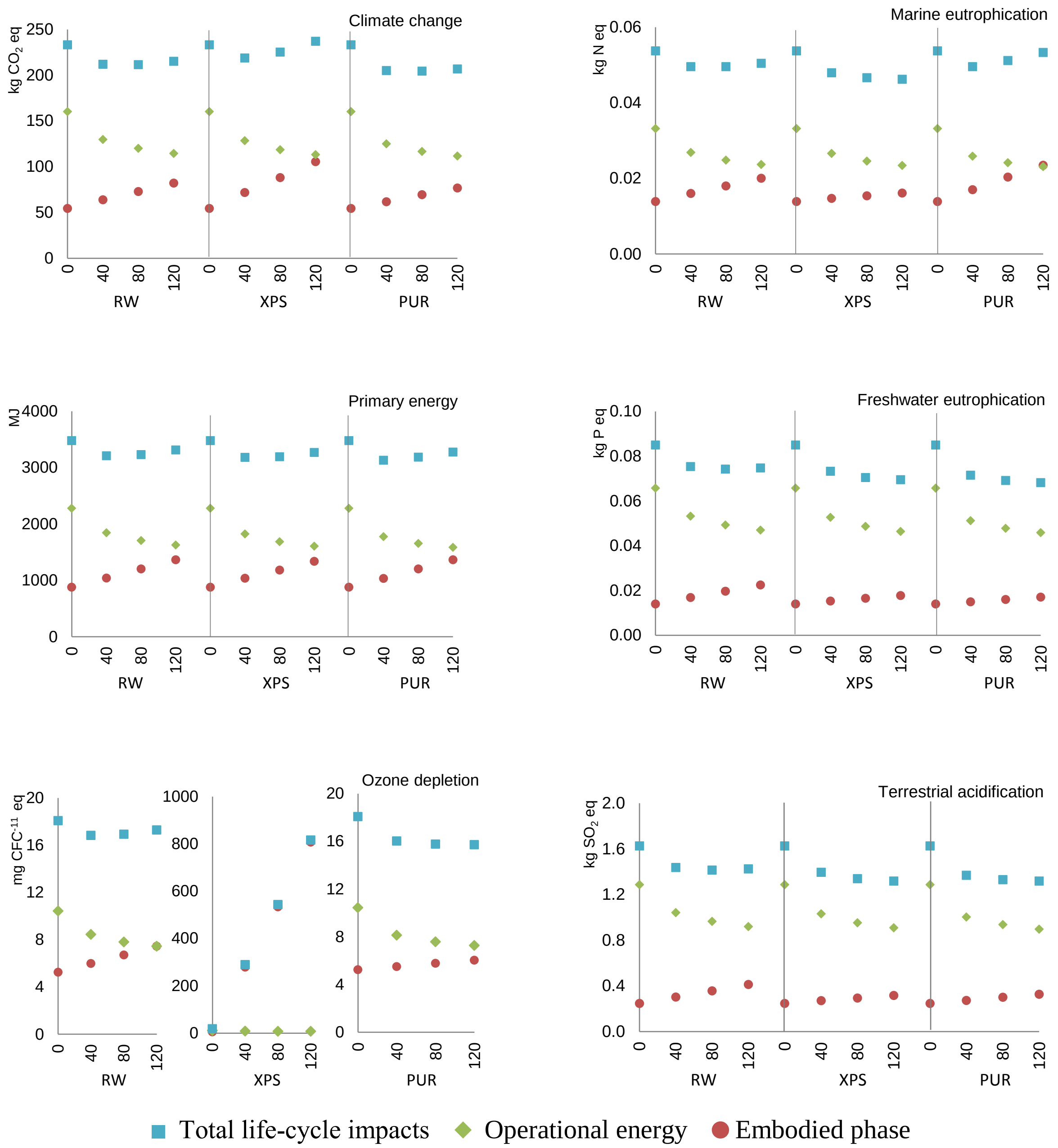


Fig. 9. Life-cycle environmental and primary energy assessment of the insulation scenarios (Rock wool, Expanded polystyrene and Polyurethane foam; 0, 40, 80 and 120 mm; per functional unit: 1 m^2 of living area over a period of 50 years)

The results also show that for insulation thicknesses greater than 80 mm, the reduction in energy consumption during the use phase, owing to a further increase of 40 mm of insulation, is not significant (less than 5%), while there is an increase of 6% to 20% of the environmental impacts associated with the embodied phase, leading to an increase in the overall LC impacts of less than 5%. The most important absolute benefit is obtained when a 40 mm insulation layer is applied to roofs with no insulation, leading to a decrease in energy consumption of about 30%. It can be assumed that the energy efficiency benefit of increasing the insulation thickness may not always offset the increase of environmental impacts due to production.

4.4.2. Rock wool thickness options

Three insulation levels were assessed to evaluate the impact of a further increase of 40 mm and 80 mm in the insulation level. LCIA, normalized and contribution analysis results for rock wool insulation levels are presented in figure 10 and 11.

The results show that the option of an insulation level of 80 mm has the lowest environmental impacts in 4 out of 6 categories. For the remain categories, the option of 40 mm has the lowest environmental impacts. There are no significant differences between insulation levels, since the impacts in the use phase, which is the main contributor, varies only about 5% among the options. The slight difference that can be found is primarily due to the construction phase.

LC impacts are dominated by the use phase (45% to 70% of total LC impacts) followed by construction phase (20% to 40%). The main contributor to the use phase is the heating requirements which accounts for 70% of total energy requirements. The cooling requirements accounts for only 8% and lights/equipment accounts for 22%.

Normalized results show that freshwater eutrophication is the most significant followed by terrestrial eutrophication and climate change.

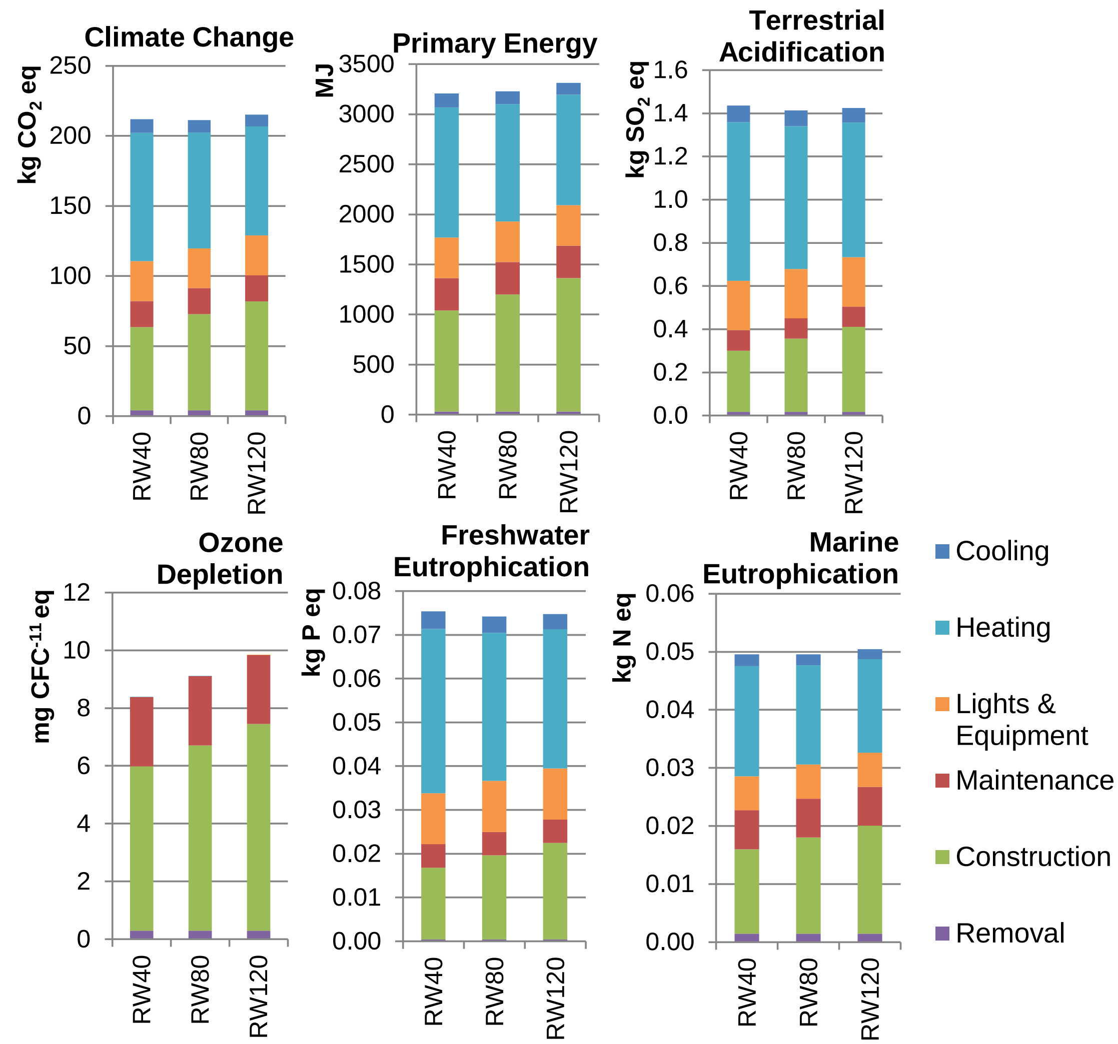


Fig. 10. Life-Cycle Impact Assessment of the alternative rock wool insulation thicknesses (40, 80 and 120 mm; per functional unit: 1 m^2 of living area over a period of 50 years)

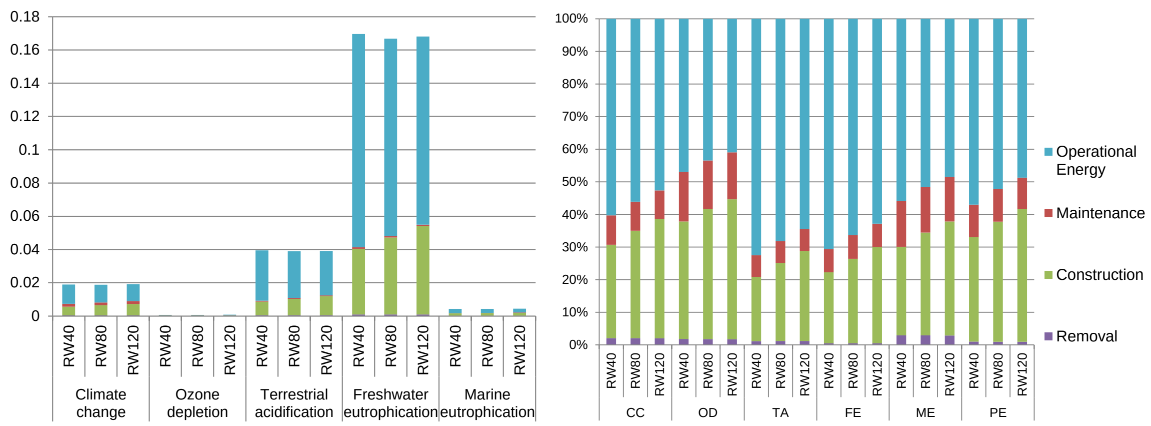


Fig. 11. ReCiPe normalized results (left) and contribution analysis (right) of the alternative rock wool insulation thicknesses (40, 80 and 120 mm; per functional unit: 1 m^2 of living area over a period of 50 years)

4.4.3. Thermal insulation material options

Figure 12 and 13 present the LCIA, normalized and contribution analysis results of the three thermal insulation material options. The results show that the PUR option has the lowest environmental impacts in 4 out of 6 categories. For the three insulation materials, the use phase has the highest environmental impacts (65% to 80% of total LC impacts), followed by the construction phase (20% to 35%). Although there were no significant differences observed among options, construction phase presents the main differences between insulation materials, primarily due to material production and shipping distances.

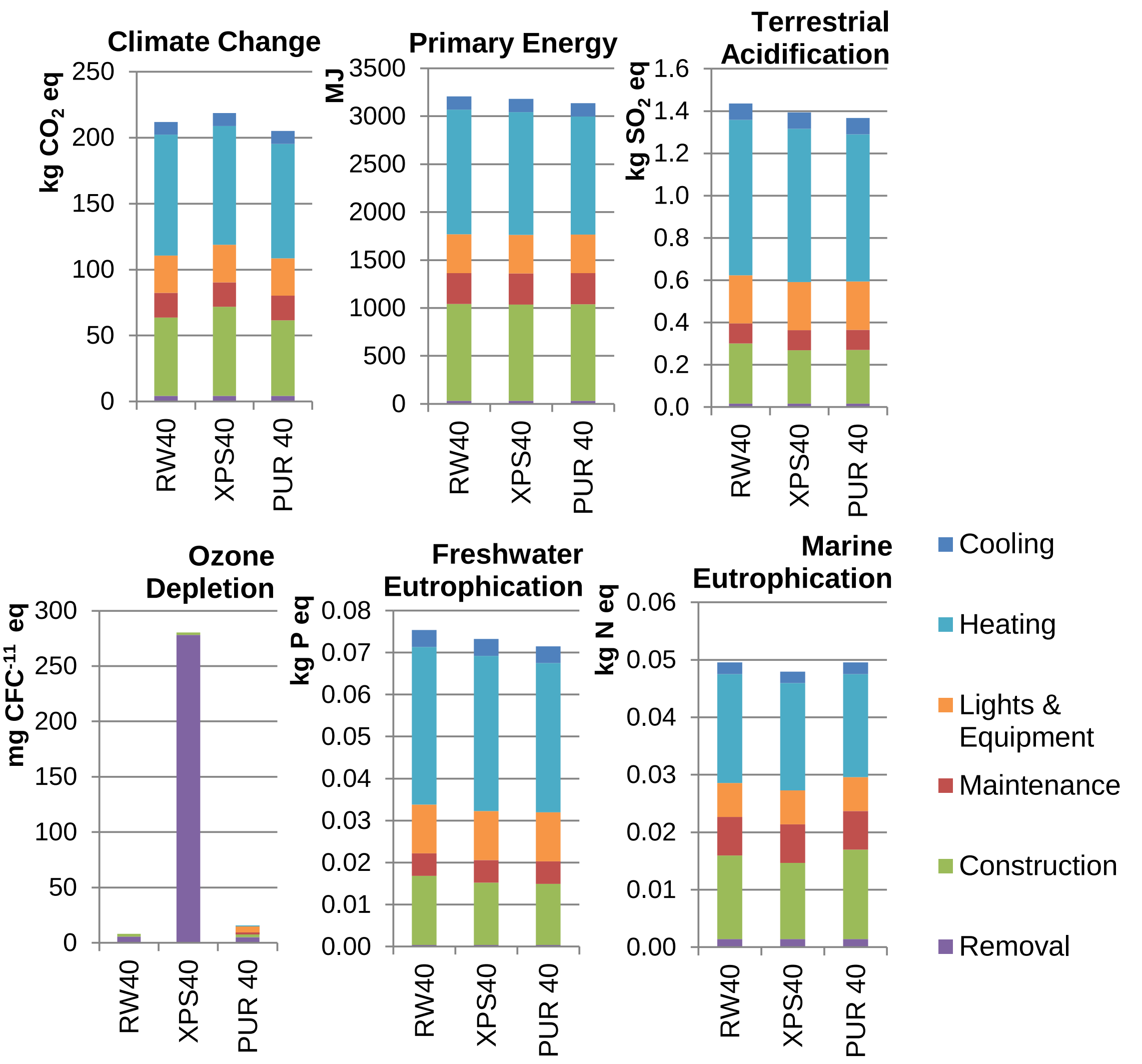


Fig. 12. Life-Cycle Impact Assessment of the insulation material options (Rock wool, Expanded Polystyrene and Polyurethane Foam (40 mm); per functional unit: 1 m^2 of living area over a period of 50 years)

Regarding XPS option, the use phase accounts for only 3% of the LC impacts while the construction phase accounts for 96%. The important contribution of XPS for the ozone depletion is due to the agent used in the extrusion process, the hydrochlorofluorocarbons (HCFCs). Recently some XPS producers have begun to use CO_2 as blowing agent in alternative to HCFCs [75], but this was not considered since there was not inventory data available for this XPS production process. Nonetheless, a preliminary analysis was performed, showing that the use of CO_2 instead of HCFCs can reduce the contribution ozone layer depletion of the construction phase from almost 97% to only about 11%.

Normalized results show that freshwater eutrophication is the most significant followed by terrestrial eutrophication. Moreover, RW presents the highest environmental impacts for those categories.

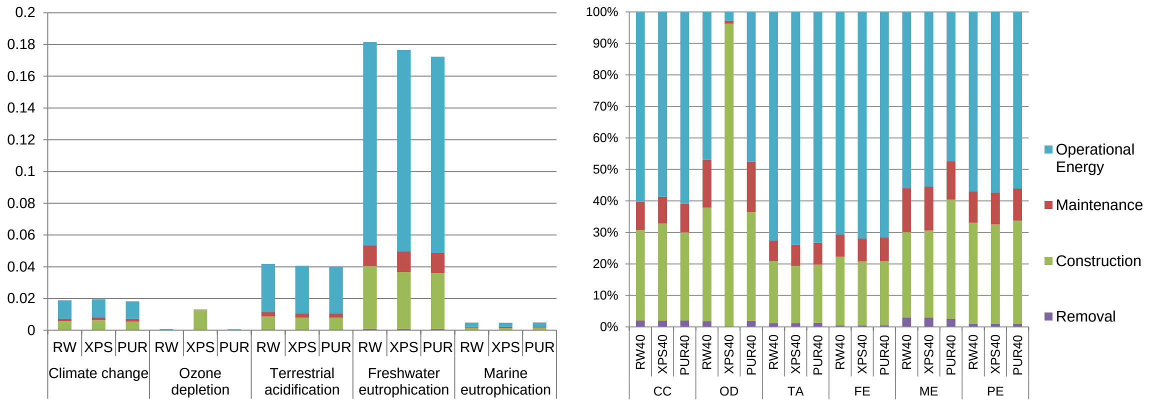


Fig. 13. ReCiPe normalized results (left) and contribution analysis (right) of the alternative insulation materials (Rock wool, Expanded polystyrene and Polyurethane foam (40 mm); per functional unit: 1 m^2 of living area over a period of 50 years)

5| CONCLUSION

This dissertation presents an energy and environmental assessment of different scenarios for the roof retrofit of a single-family house. The methodology used in this dissertation integrates environmental and energy assessment. A life-cycle model was developed including the implementation of a comprehensive inventory. Building energy analysis was carried out with thermal dynamic simulation. The integrated assessment performed in a life-cycle perspective allowed balancing embodied and operation energy.

A scenario analysis of roof frame, insulation materials and thicknesses was performed to evaluate the environmental performance of different roof retrofit scenarios for the single-family house. Twenty seven roof retrofit scenarios were assessed combining three types of frame material (wood frame, lightsteel frame and lightweigh concrete slab), three types of insulation material (rock wool, expanded polystyrene and polyurethane foam) and three insulation levels (40, 80 and 120 mm). Primary energy and five environmental categories were evaluated to identify critical aspects of those scenarios as well as to identify hot spots and improvement opportunities. Wood frame scenarios presented the lower environmental impacts in the construction phase. Lightweight concrete scenarios presented the highest environmental impacts in all the categories with the exception of freshwater eutrophication where lightsteel frame scenarios had the highest impacts. Although some materials, such as steel, concrete and zinc, had an important contribution in the construction phase, the use phase was still the largest contributor to all the scenario. The use phase (maintenance and operational energy) accounted for about 40% to 70% (varying between scenarios and categories) of the LC impacts.

The results showed that, for insulation thicknesses greater than 80 mm, the reduction in energy consumption during use phase, due to a further increase of 40 mm, is not significant (less than 5%), while there is an increase of about 6% to 20% of the environmental impacts associated with the embodied phase, leading to an increase in the overall LC impacts of less than 5%, in all insulation material options. Nonetheless, it should be emphasized that there is a very significant benefit associated with the improvement of the thermal envelope by adding 40 mm of insulation, for which there is a reduction of 30% in the energy consumption during the use phase. It can be assumed that the energy efficiency benefit of increasing the insulation thickness may not always offset the increase of environmental impacts due to material production and assembly. Additionally, in southern European countries the “over insulation” of buildings runs the risk of reducing the effectiveness of traditional passive cooling strategies (such as thermal mass or roof ventilation) and could have adverse effects on internal comfort. It was concluded that there is an optimal thickness of insulation in terms of environmental performance which can be found for every retrofit measure to be implemented in any building retrofit process.

The reduction of environmental impacts in buildings is commonly focused in energy efficiency measures during the use phase. This dissertation shows the importance of addressing the entire life-cycle of building retrofit to reduce environmental impacts in other phases, namely in the selection of construction materials and insulation levels.

Although many European countries have developed those energy certification schemes for residential and commercial buildings, the indicators considered to obtain the energy qualification are not calculated using a LC approach. Nonetheless, some European standards have already been published regarding the sustainability issues in the building sector, the combination of LCA with the existing energy certification schemes has still a great potential to promote a European environmental certification scheme of buildings.

5.1. Limitations and future research

In the building sector, as in other sectors, the application of LCA has some drivers and barriers. One main driver is to establish environmental targets for buildings in Europe and in each country in specific, as EPDB [76], and the translated regulations, set energy targets to reduce the energy consumption in buildings. Nonetheless, there are some barriers to overcome the lack of accuracy in LCA studies regarding the complexity of modelling the LC of processes, data limitiations, subjectivity, variability in the models, etc.

The LC model in this dissertation did not include the end of life phase because it is difficult to predict this phase since the buildings have a long lifetime. Moreover, this study showed that for building retrofit the removal phase of the building component represents less than 10% of the overall LC impacts. Other studies also showed that the end-of-life phase of buildings has very low impact in current building practices and neglecting it did not impair the results [16]. However, with the regard of wood products, an extended end-of-life assessment could be performed in order to study different destinations for the wood waste since solutions with high wood content present upper levels of renewable primary energy because wood is considered a renewable energy source, and also have lower levels of CO_2 emissions due to carbon uptake during the growth of trees. The end of life issues and this kind of trade-offs will be assessed in future research, in the context of energy efficient building solutions.

This study highlighted the importance of the choice of materials and solutions during the design phase for the roof retrofit of a house. Future research will address other components of the building envelope, such as exterior walls, focusing on the performance of the building depending on the insulation option (interior, exterior or no insulation).

Another limitation of this dissertation, that will be addressed in the future, is not including the economic dimension. In the decision-making process is important to balance environmental and economic issues in a LC perspective. The calculation of heating and cooling requirements should also be improved by performing a sensitivity analysis on different occupancy levels in order to predict more accurate results according to users behavior.

References

[1] European Comission, “EU Energy Roadmap 2050,” 2011.

[2] European Comission, “COM(2011) 112 final, A Roadmap for moving to a competitive low carbon economy in 2050,” 2011.

[3] T. Boermans, K. Bettgenhäuser, M. Offermann, and S. Schimschar, “Renovation tracks for Europe up to 2050,” 2012.

[4] INE, “Estatísticas da Construção e Habitação 2010,” 2011.

[5] EPDB, “Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings,” *Official Journal of the European Union*, vol. L1/65–1/71, 2002.

[6] “RCCTE, Regulamento das Características de Comportamento Térmico dos Edifícios, Code of the Buildings Thermal Behaviour Characteristics – DL80/2006,” Ministry of Public Works, Communications and Transportation, 2006, pp. 2468–2513.

[7] RCCTE, “Regulamento das Características de Comportamento Térmico dos Edifícios - DL 80/2006,” *Ministry of Public Works, Transportation and Communication*, pp. 2468–2513, 2006.

[8] D. Crawley and I. Aho, “Building environmental assessment methods : applications and development trends,” *Building Research & Information*, vol. 27, no. 4–5, pp. 300–308, 1999.

[9] K. Adalberth, “Energy use during the life cycle of buildings: a method,” *Building and Environment*, vol. 32, no. 4, pp. 317–320, Jul. 1997.

[10] S. Blanchard and P. Reppe, “Life Cycle Analysis of a Residential Home in Michigan,” Ann Arbor, MI, 1998.

[11] G. A. Keoleian, S. Blanchard, and P. Reppe, “Life-cycle Energy Costs and Strategies for Improving a Single-Family House,” *Journal of Industrial Ecology*, vol. 4, no. 2, pp. 135–156, 2001.

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

[13] K. Adalberth, “Life-cycle assessment of four multi-family buildings,” *International Journal of Low Energy and Sustainable Buildings*, vol. 2, pp. 1–21, 2001.

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

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

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

[17] J. N. Hacker, T. P. De Saulles, A. J. Minson, and M. J. Holmes, “Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change,” *Energy and Buildings*, vol. 40, no. 3, pp. 375–384, Jan. 2008.

[18] A. Haapio and P. Viitaniemi, “Environmental effect of structural solutions and building materials to a building,” *Environmental Impact Assessment Review*, vol. 28, no. 8, pp. 587–600, Nov. 2008.

[19] F. Nemry, A. Uihlein, C. M. Colodel, C. Wetzel, A. Braune, B. Wittstock, I. Hasan, J. Kreißig, N. Gallon, S. Niemeier, and Y. Frech, “Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs,” *Energy and Buildings*, vol. 42, no. 7, pp. 976–984, Jul. 2010.

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

[21] N. Kohler, “Life Cycle Analysis of Buildings, Groups of Buildings and Urban Fragments,” in in *Sustainable Urban Environment. Volume 2: Environmental Assessment Methods*, M. Deakin, G. Mitchell, P. Nijkamp, and R. Vreeker, Eds. Routledge, 2007, pp. 348 – 371.

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

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

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

[25] B. Rossi, A.-F. Marique, M. Glaumann, and S. Reiter, “Life-cycle assessment of residential buildings in three different European locations, basic tool,” *Building and Environment*, vol. 51, pp. 395–401, May 2012.

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

[27] J. Basbagill, F. Flager, M. Lepech, and M. Fischer, “Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts,” *Building and Environment*, vol. 60, pp. 81–92, Feb. 2013.

[28] Y. G. Yohanis and B. Norton, “Life-cycle operational and embodied energy for a generic single-storey office building in the UK,” *Energy*, vol. 27, no. 1, pp. 77–92, Jan. 2002.

[29] C. K. Chau, F. W. H. Yik, W. K. Hui, H. C. Liu, and H. K. Yu, “Environmental impacts of building materials and building services components for commercial buildings in Hong Kong,” *Journal of Cleaner Production*, vol. 15, no. 18, pp. 1840–1851, Dec. 2007.

[30] M. Wallhagen, M. Glaumann, and T. Malmqvist, “Basic building life cycle calculations to decrease contribution to climate change – Case study on an office building in Sweden,” *Building and Environment*, vol. 46, no. 10, pp. 1863–1871, Oct. 2011.

[31] K. Van Ooteghem and L. Xu, “The life-cycle assessment of a single-storey retail building in Canada,” *Building and Environment*, vol. 49, pp. 212–226, Mar. 2012.

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

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

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

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

[36] N. Kohler and I. Bauproduktion, “Life-cycle analysis of the built environment,” *UNEP Industry And Environment*, pp. 17–21, 2003.

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

[38] B. Rossi, A.-F. Marique, and S. Reiter, "Life-cycle assessment of residential buildings in three different European locations, case study," *Building and Environment*, vol. 51, pp. 402–407, May 2012.

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

[40] G. A. Blengini and T. Di Carlo, "Energy-saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy)," *The International Journal of Life Cycle Assessment*, vol. 15, no. 7, pp. 652–665, May 2010.

[41] A. Dodoo, L. Gustavsson, and R. Sathre, "Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard," *Resources, Conservation and Recycling*, vol. 54, no. 12, pp. 1152–1160, Oct. 2010.

[42] C. W. Scheuer and G. A. Keoleian, "Evaluation of LEED ™ Using Life Cycle Assessment Methods," Ann Arbor, MI, 2002.

[43] S. Saiz, C. Kennedy, B. Bass, and K. Pressnail, "Comparative life cycle assessment of standard and green roofs.," *Environmental science & technology*, vol. 40, no. 13, pp. 4312–6, Jul. 2006.

[44] L. Kosareo and R. Ries, "Comparative environmental life cycle assessment of green roofs," *Building and Environment*, vol. 42, no. 7, pp. 2606–2613, Jul. 2007.

[45] I. Blom, L. Itard, and A. Meijer, "Environmental impact of building-related and user-related energy consumption in dwellings," *Building and Environment*, vol. 46, no. 8, pp. 1657–1669, Aug. 2011.

[46] P. Hernandez and P. Kenny, "Integrating occupant preference and life cycle energy evaluation: a simplified method," *Building Research & Information*, vol. 38, no. 6, pp. 625–637, Dec. 2010.

[47] A. S. Nordby, "Carbon reductions and building regulations : the case of Norwegian mountain cabins," *Building Research & Information*, no. December 2012, pp. 37–41, 2011.

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

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

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

[51] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. van Zelm, “ReCiPe,” *Ministry of Housing, Spatial Planning and Environment (VROM), Netherlands*, 2013. [Online]. Available: http://www.lcia-recipe.net/.

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

[53] ISO 14040, “Environmental Management Life Cycle Assessment Principles and Framework,” *International Organization for Standardization*, 2006.

[54] ISO 14044, “Environmental Management Life Cycle Assessment Requirements and Guidelines,” *International Organization for Standardization*, 2006.

[55] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B. P. Weidema, and D. W. Pennington, “Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications.,” *Environment international*, vol. 30, no. 5, pp. 701–20, Jul. 2004.

[56] A. W. Sleeswijk, L. F. C. M. van Oers, J. B. Guinée, J. Struijs, and M. a J. Huijbregts, “Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000.,” *The Science of the total environment*, vol. 390, no. 1, pp. 227–40, Feb. 2008.

[57] G. Finnveden, M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh, “Recent developments in Life Cycle Assessment.,” *Journal of environmental management*, vol. 91, no. 1, pp. 1–21, Oct. 2009.

[58] D. W. Pennington, J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg, and G. Rebitzer, “Life cycle assessment part 2: current impact assessment practice.,” *Environment international*, vol. 30, no. 5, pp. 721–39, Jul. 2004.

[59] R. Dones, C. Bauer, R. Bolliger, B. Burger, T. Heck, A. Röder, P. S. Institut, M. F. Emmenegger, R. Frischknecht, N. Jungbluth, and M. Tuchschmid, “Life Cycle Inventories of Energy Systems : Results for Current Systems in Switzerland and other UCTE Countries,” *Ecoinvent Report n.^{o}5*, no. 5, 2007.

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

[61] M. a J. Huijbregts, W. Gilijamse, A. M. J. Ragas, and L. Reijnders, "Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling.," *Environmental science & technology*, vol. 37, no. 11, pp. 2600–8, Jun. 2003.

[62] U.S. Department of Energy, "EnergyPlus v.7.2.0," 2012. [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/.

[63] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Building and Environment*, vol. 32, no. 4, pp. 321–329, Jul. 1997.

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

[65] C. Pina dos Santos and L. Matias, "ITE 50 - Coeficientes de Transmissão Térmica da Envolvente dos Edifícios," Lisbon, 2006.

[66] D. Kellenberger, H. Althaus, T. Künniger, M. Lehmann, and N. Jungbluth, "Life Cycle Inventories of Building Products," *Ecoinvent Report n.ºo7*, no. 7, 2007.

[67] ADENE, "Coberturas Eficientes," 2011.

[68] CS - Telhas, "Telha Marselha."

[69] Onduline, "Sub-telha Onduline."

[70] Dow Portugal, "Dow - soluções para a construção."

[71] Fibrosom, "Isolamentos térmicos/acústicos - Lã de rocha."

[72] M. Spielmann, C. Bauer, R. Dones, and M. Tuchschmin, "Life Cycle Inventories of Transport Services," *Ecoinvent Report n.º14, v2.0*, no. 14, 2007.

[73] GeoModel Solar, "SolarGis." [Online]. Available: http://solargis.info/.

[74] ADEME, "Energy Efficiency Indicators in Europe," *http://www.odyssee-indicators.org/online-indicators/*, 2010. [Online]. Available: http://www.odyssee-indicators.org/online-indicators/.

[75] H.-J. Althaus, C. Bauer, G. Doka, R. Frischknecht, N. Jungbluth, T. Nemecek, A. Simons, M. Stucki, J. Sutter, and M. Tuchschmin, "Documentation of changes implemented in ecoinvent Data v2.1 and v2.2," *Ecoinvent Report n.º16*, no. July, 2010.

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

List of Publications

1 | Rodrigues, C., Luiz, I., Tadeu, S. F., Freire, F. (2012a). "Environmental Assessment of Alternative Options for the Roof Retrofit of an Historic Building", CINCOS'12 - Congress of Innovation on Sustainable Construction 2012, Aveiro. (Dissertation CD)

2 | Rodrigues, C., Luiz, I., Tadeu, S.F., Freire, F. (2012b). "Roof Retrofit of an Historic Building: an Environmental Assessment". Construlink, 31 (10), pp 5-15. Available at http://www.construlink.com

3 | Rodrigues, C., Freire, F. (2013). "Life-cycle assessment of retrofit scenarios for a single-family house". CISBAT 2013, Clean Technology for Smart Cities and Buildings, 4-6 September 2013, Lausanne, Switzerland. (Dissertation CD)