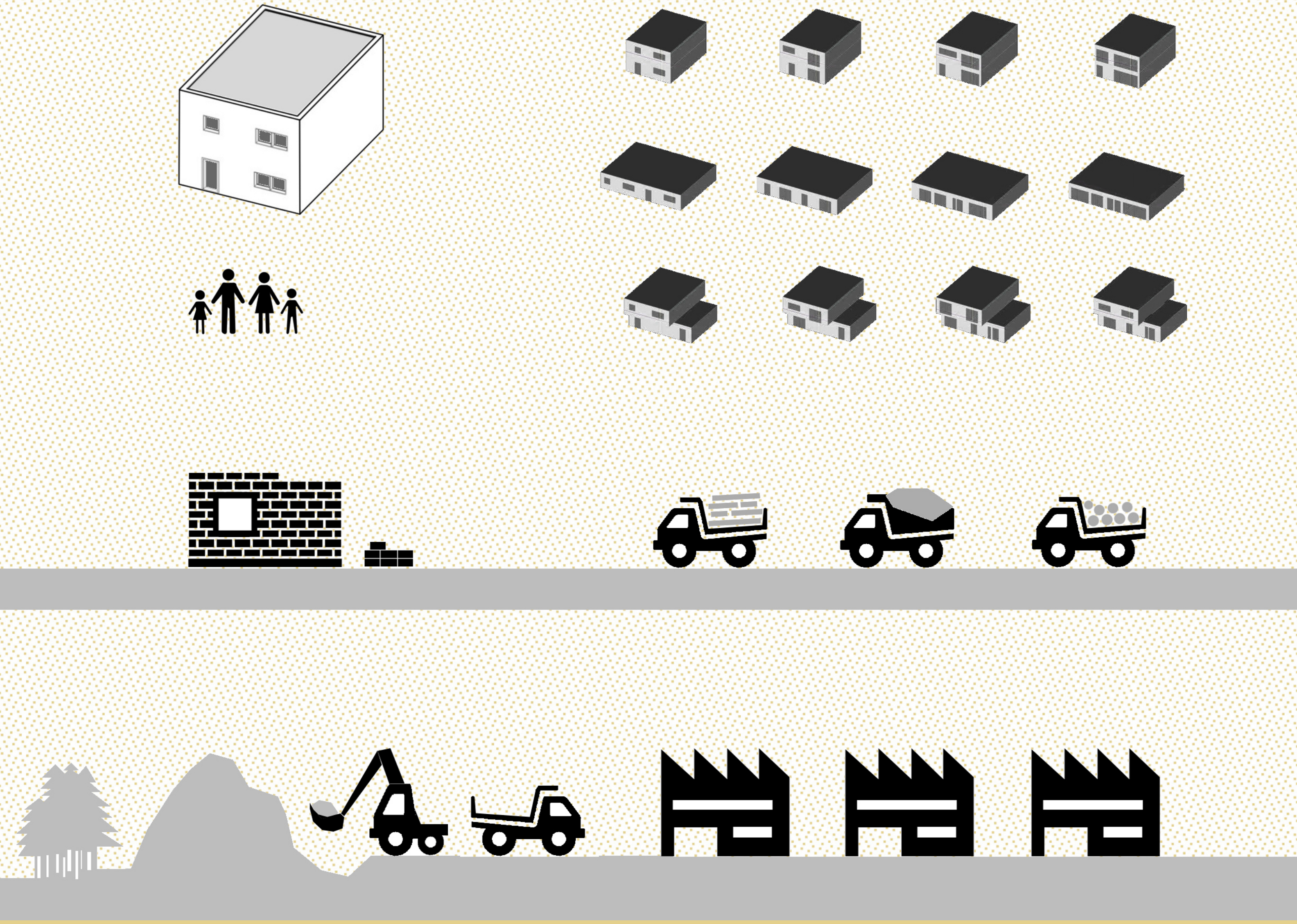

Helena Isabel Pereira Monteiro

COMPREHENSIVE LIFE CYCLE ASSESSMENT OF NEW HOUSES IN PORTUGAL: BUILDING DESIGN, ENVELOPE, AND OPERATIONAL CONDITIONS

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

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UNIVERSIDADE DE COIMBRA

Comprehensive life cycle assessment of new houses in Portugal:

Building design, envelope, and operational conditions

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Abstract

Residential buildings are accountable for a significant share of final energy consumption and environmental impacts. Although new houses are expected to hold significantly lower impact than existing dwellings, European building directives, regulations, and most actions at building level still focus on operational energy reduction, disregarding building embodied impacts. To support more sustainable building practices, a life cycle (LC) perspective is needed. Life Cycle Assessment (LCA) has been implemented to study residential buildings, showing the importance of building construction options, the envelope thermal performance, and energy systems, which jointly characterize the embodied and operational impacts. However, new houses in south Europe and Portugal have seldom been addressed from a LC perspective, and the few LCA performed failed to consider that, in mild Mediterranean climate, the operational impact (for heating and cooling) is highly dependent on user behavior. Additionally, architectural design options have not been addressed from a LC perspective. This thesis goal is to assess the influence of alternative building envelope, design, and operational conditions on the environmental impact of new single-family houses in Portugal considering alternative user behavior.

A framework combining LCA and building dynamic simulation was developed and implemented to investigate how operational and embodied impacts of Portuguese single-family houses vary among options at different levels: building envelope (insulation thickness, ventilation level, building components), design (orientation, window sizing and placement, and building shape), and operation (user operational pattern, heating systems selection, electricity generation mix). Insulation thickness tipping points that minimize the house LC impact were identified for different Portuguese locations.

The results showed that embodied energy of new houses (construction and maintenance) can represent two to seven times the operational heating and cooling energy (operational pattern OP50, with heat pump or wood pellets boiler, respectively) for most Portuguese locations (Coimbra, Lisboa, Porto and Faro). Even under more demanding Portuguese weather conditions (e.g., Évora, Bragança) embodied impacts are likely to surpass the operational impact of thermal needs due to user behavior (OP25-OP50, using a heat pump system). Therefore, careful attention should be paid to building design and building components selection. Comparative results showed that design options (orientation, window sizing and placement, and building shape) can have a higher influence in the overall LC impact of new houses than the thermal improvements of the envelope (increasing the thermal insulation or reducing ventilation levels). Additionally, selecting building components with lower embodied impact and similar thermal performance (e.g., wooden exterior wall instead of a double brick wall) can have a higher influence on reducing overall environmental impacts than focusing only on envelope thermal improvement. Results also showed that the LC impact of new Portuguese dwellings is very sensitive to operational conditions, namely operational patterns and the heating system selected. Nonetheless, current building regulations miss important LC impacts when focusing only on operational energy, especially for new houses in Portugal, and in other south European locations with mild Mediterranean climate, since the contribution of thermal energy requirements can be potentially small (due to user behavior and the regional electricity generation mix).

Keywords: residential building; dwelling; house; life cycle assessment; LCA; environmental impact; energy; building envelope; design; operation; energy performance.

Resumo

Os edifícios de habitação são responsáveis por uma parte significativa do consumo energético e dos impactes ambientais. Embora se espere que os novos edifícios de habitação tenham um impacte ambiental significativamente menor do que os edifícios existentes, as diretivas e regulamentação Europeia existente e a maioria das ações estão focadas no desempenho térmico do edifício na fase de utilização, não tendo em conta os impactes ambientais incorporados no próprio edifício (na sua construção e manutenção). Para apoiar a conceção de novos edifícios de habitação com menor impacte ambiental, é importante considerar uma perspetiva de ciclo de vida (CV). Com a implementação da metodologia de Avaliação de Ciclo de Vida (ACV) em estudos de edifícios de habitação, as opções construtivas, o desempenho térmico da envolvente, e os sistemas energéticos tem sido identificados como opções relevantes que influenciam duplamente os impactes incorporados no edifício e os impactes da fase de utilização. No entanto, a ACV de edifícios de habitação em Portugal é escassa, e os poucos estudos existentes para novos edifícios não consideram que, em clima Mediterrânico moderado, os impactes ambientais da fase de utilização dependem significativamente do comportamento dos habitantes. Adicionalmente, os estudos existentes não consideram opções de desenho arquitetónico numa perspetiva de CV. O objetivo desta tese é avaliar a influência de diferentes opções construtivas da envolvente do edifício, do desenho arquitetónico, e das condições operacionais no impacte ambiental de moradias unifamiliares em Portugal considerando diferentes padrões de utilização.

Um modelo de CV que combina a ACV com a simulação dinâmica de edifícios foi desenvolvido para analisar como variam os impactes ambientais incorporados e os da fase de utilização de uma moradia unifamiliar em Portugal, considerando diferentes opções construtivas da envolvente (nível de isolamento térmico, nível de ventilação, e paredes exteriores), alternativas arquitetónicas (orientação, tamanho e localização dos vão envidraçados, e forma do edifício), e condições operacionais (padrão de utilização, sistemas de climatização e mix energético). Com base no modelo desenvolvido foram identificados níveis de espessura do isolamento térmico que reduzem o impacte ambiental de CV da moradia para diferentes localizações em Portugal.

Os resultados da ACV mostraram que a energia incorporada em edifícios de habitação unifamiliar (construção e manutenção) pode representar duas a sete vezes a energia operacional de climatização (padrão operacional OP50, com bomba de calor ou caldeira a pellets, respetivamente) para a maioria das localizações (Coimbra, Lisboa, Porto e Faro). Mesmo sob condições climáticas mais exigentes (por exemplo, Évora ou Bragança), os impactes incorporados podem ultrapassar o impacte operacional dependendo dos padrões de utilização (OP50-OP25 com sistema de bomba de calor). Por conseguinte, deve ser dada especial atenção ao desenho arquitetónico e à seleção dos elementos construtivos em novos edifícios. Os resultados mostram que as opções arquitetónicas (orientação, localização e dimensão dos vãos envidraçados e a forma do edifício) podem influenciar mais significativamente o impacte ambiental de CV do que opções de melhoria térmica da envolvente (aumentar o nível de isolamento térmico ou diminuir nível de ventilação). Adicionalmente, a seleção de elementos construtivos com menor impacte ambiental incorporado e com desempenho térmico semelhante (por exemplo, uma parede exterior de madeira em vez de uma parede de tijolo dupla) pode reduzir mais o impacte ambiental de CV do que a melhoria térmica da envolvente. Os resultados mostram também que o impacte ambiental de CV de novas moradias em Portugal é muito sensível às condições operacionais, nomeadamente aos padrões de utilização e ao sistema de aquecimento selecionado. Todavia, esta tese mostra que os regulamentos de construção atuais (que se focam na energia de utilização) não contabilizam uma parte importante do impacte ambiental de CV dos novos edifícios de habitação, especialmente em Portugal e em outros locais do sul da Europa com clima mediterrâneo moderado, onde a contribuição de CV das necessidades de climatização pode ser potencialmente pequena (devido ao comportamento dos utilizadores e ao mix elétrico regional.

Palavras-chave: habitação; moradia; casa; avaliação de ciclo de vida; ACV; impacte ambiental; energia; envolvente exterior; desenho arquitetónico; utilização; desempenho energético.

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"The man who moves a mountain begins by carrying away small stones"

Confucius

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Acronyms

AP: Acidification potential.
AD: Abiotic depletion.
BAU: Business-as-usual
CO_2: Carbon dioxide
COP: Coefficient of performance
EER: Energy efficiency ratio
EOL: End-of-life
EH: Electric heater; resistance heating
EP: Eutrophication potential
EPS: Expanded polystyrene
ETICS: Exterior thermal insulation composite system
EU: European Union
GHG: Greenhouse gas
GWP: Global warming potential
HP: Heat pump
HVAC: heating, ventilation, and air conditioning
LC: Life cycle
LCA: Life cycle assessment
LCI: Life cycle inventory
LCIA: Life cycle impact assessment
LWA: Lightweight agregate (ex.: Leca ®)
NGCB: Natural gas condensing boiler
NRPE: Non-renewable primary energy
OLD: Ozone layer depletion
OP: Operational pattern
OP100: Continuous operational pattern
OPx: Scheduled intermittent operational pattern

PH: Passive house standard
PO: Photochemical oxidation
PUR: Rigid polyurethane foam
VLE: Very low energy
WPB: Wood pellets boiler
XPS: Extruded polystyrene

1. INTRODUCTION

1.1. Research rationale

Human activities and urban development are known to have a high impact on the environment, causing world-wide environmental problems that may impair the sustainability of the planet and compromise future generation needs. In this context, a transition to more sustainable societies is critical and it calls for joint actions to reduce energy demand, increase energy efficiency, and minimize the overall environmental impacts.

The building sector accounts for 40% of final energy in most developed countries (IEA, 2013; UNEP, 2009), and the residential buildings alone are accountable for 68% of final energy use in European buildings (Eurostat, 2012). Most efforts to promote a more sustainable built environment have primarily focused on reducing residential building operational energy. The Energy Performance of Buildings Directive and its recast (EPBD, 2002, 2010) have set the bar towards improving the energy efficiency of buildings, aiming for new buildings to be "nearly-zero energy" during use phase. Additionally, over the last decades, various building standards and energy certification schemes (e.g., the passive house standard) were developed, suggesting the integration of passive construction and active systems to support new (low-energy) houses development in European countries.

However, efforts and policies that focus only on operational energy reduction have major limitations. Operational heating and cooling reduction, which is directly affected by the buildings characteristics, is usually achieved with an increase in the energy required and environmental impacts associated with the production of a building and its materials (the embodied energy and impacts). Focusing only on operational energy neglects the environmental impacts embodied in construction materials and maintenance activities, and it may result in overall higher environmental impacts, which goes against the main aim of energy efficiency policies. To support new low-energy houses, a more holistic perspective is needed and a life cycle (LC) approach must be used not only to account for the magnitude of non-operational phases but also to identify key areas for improvement.

Over the last two decades, Life Cycle Assessment (LCA) has been used in the building context and buildings started to be assessed as systems, throughout their life cycle (Buyle, Braet, & Audenaert, 2013; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Chau, Leung, & Ng, 2015; Sartori & Hestnes, 2007). Most of LC studies of dwellings have primarily addressed energy and greenhouse gas (GHG) emissions of houses in cold climate areas (Adalberth, 1997a, 1997b; Citherlet & Defaux, 2007; Gustavsson & Joelsson, 2010; Gustavsson, Joelsson, & Sathre, 2010; Hacker, De Saulles, Minson, & Holmes, 2008; Mahdavi & Doppelbauer, 2010; B. Peuportier, 2001; Thormark, 2002). However, for a more comprehensive assessment, other environmental impacts should also be included, as suggested by some studies (Blengini & Di Carlo, 2010b; Citherlet & Defaux, 2007; Nemry et al., 2010b; Ortiz, Bonnet, Bruno, & Castells, 2009). Focusing on LC studies of residential buildings as a whole, the literature review performed (presented in Chapter 2) shows that the relative significance of different LC phases has been changing in recent years due to the thermally improved performance of new dwellings and energy efficiency measures. The operational stage, which represented 60-95% of LC energy one decade ago (Blanchard & Reppe, 1998; Keoleian, Blanchard, & Reppe, 2001; Sartori & Hestnes, 2007; Utama & Gheewala, 2008), has been decreasing in magnitude, while other LC processes have been increasing both in magnitude and in relative importance (Blengini & Di Carlo, 2010b).

New south European dwellings, in particular Portuguese houses have seldom been addressed from a LC perspective until recently. Additionally, the influence of user behavior (operational patterns) on thermal energy demand of new houses has not been considered by previous LC studies (Monteiro & Freire, 2012). Houses in south Europe and in mild Mediterranean climate generally require both heating and cooling loads to maintain comfort conditions. Since climate conditions are not as harsh as in cold climates, the interior comfort levels may be more flexible and dependent on cultural and personal habits and on economic constraints. In Portuguese dwellings, Heating, Ventilation, and Air Conditioning (HVAC) operational patterns are mainly intermittent during the day and non-simultaneous in all rooms; when compared to integral and continuous comfort conditions, user behavior results in a *prebound effect* (Sunikka-blank & Galvin, 2012), which could significantly alter the overall LC results (Majcen, Itard, & Visscher, 2013), and therefore its influence needs to be considered.

Material production, which in many LC studies is the second most relevant LC process of dwellings (Sartori & Hestnes, 2007), might be the most important process in houses in the south European context or where HVAC use and operational burdens are reduced (Blengini & Di Carlo, 2010a; Gustavsson & Joelsson, 2010; Monteiro & Freire, 2012; Verbeeck & Hens, 2010). To support the development of more sustainable houses in the Portuguese context, the environmental impacts need to be addressed from a life cycle perspective, in order to understand which processes hold most impacts and to possibly prevent problem-shifting (among processes or impacts). As income and comfort levels vary among householders, it is important to understand the magnitude of the environmental LC tradeoffs of alternative building options, considering different operational conditions for a new house.

Published LC studies of new dwellings (reviewed in Chapter 2) generally consider alternative construction components for a building (Dodoo, Gustavsson, & Sathre, 2012; Gervásio, Santos, Martins, & Simões da Silva, 2014; Rossi, Marique, Glaumann, & Reiter, 2012; Rossi, Marique, & Reiter, 2012) or compare thermally improved dwellings (e.g., Passive houses; very low energy houses) with legal standard or existing alternatives (Blengini & Di Carlo, 2010b; Dahlstrøm, Sørnes, Eriksen, & Hertwich, 2012; Lewandowska, Noskowiak, & Pajchrowski, 2013; Sartori & Hestnes, 2007; Stephan, Crawford, & de Myttenaere, 2012; Verbeeck & Hens, 2007, 2009, 2010). Regarding construction of new dwellings, it was possible to identify that exterior walls have an important role in embodied impact of dwellings (Blanchard & Reppe, 1998; Haapio & Viitaniemi, 2008b; Keoleian et al., 2001; Nemry et al., 2008, 2010b; Verbeeck, 2007b; Verbeeck & Hens, 2010), and that the building thermal properties may be determinant since they directly influence the operational (heating and cooling) impact (Blengini & Di Carlo, 2010b; Verbeeck & Hens, 2007, 2010). However, the relevance and influence of building design options (such as: window sizing, orientation, and building shape) have not been addressed from a LC perspective (Buyle et al., 2013), although these options are likely to affect both new houses thermal performance and embodied impacts.

In order to raise awareness and inform decisions regarding new houses, it is important to understand how construction, design, and operational conditions jointly influence the embodied and operational environmental impact of a house. New houses are expected to last many decades and hold the opportunity to shift the building sector impacts if careful planning, design, systems integration and user's needs are considered. Single-family houses (detached and semi-detached) are the most common typology of residential buildings in EU-25 (Eurostat, 2012; Nemry et al., 2008, 2010b) and in Portugal (Eurostat, 2012; INE, 2013). Therefore, a comprehensive environmental assessment of embodied and operational impacts of new houses can help to measure, understand and reduce the building sector burdens.

1.2. Aim and research objectives

This thesis aims to investigate the environmental impact of new houses development in the Portuguese context, considering different construction options, design alternatives and operational conditions. The audience of this research includes building designers (architects and engineers), and householders. Given the complexity of a building, this research aims to assess how the environmental LC impacts of new houses are influenced by building construction options (building envelope thermal properties and building components), design options, climate and operational conditions in the Portuguese context. A comprehensive environmental assessment of building embodied and operational impacts is performed for a representative single-family house integrating LCA and building dynamic simulation.

To represent the Portuguese dwellers heating and cooling habits, and their *prebound effect*, alternative HVAC operational patterns based on actual average energy consumption and continuous thermal comfort condition were selected. The research questions and the specific objectives of this thesis are summarized in Table 1:

Table 1. Research questions and objectives

Research questions	Specific objectives	Chapter Section
1. How alternative building envelope construction options (building thermal performance and building components) influence the LC impact of a Portuguese house?	To implement a life cycle inventory framework for Portuguese residential buildings, based on common building components, applicable to different houses relying on the same construction techniques.	**3**
	To assess the magnitude of embodied and operational impacts directly influenced by alternative construction options.	**4.1**
	To assess the LC influence of varying building thermal performance through different insulation levels (0-12 cm of XPS) and total ventilation levels (0.3 to 1.2 ac/h).	**4.1.1**
	To identify the LC thermal insulation thickness tipping point per operational pattern, and how tipping points vary with alternative HVAC systems.	**4.1.1** **4.1.3**
	To assess the LC influence of alternative building components (focusing on exterior walls) jointly with varying insulation level, identifying tipping points.	**4.1.2**
2. How design options (window sizing, orientation and building shape) influence the house LC results?	To assess the operational and LC influence of:	**4.2**
	- building orientations, identifying the range of results between the orientation with the highest and the lowest operational needs;	**4.2.1**
	- window sizing jointly with window placement (varying orientations);	**4.2.2**
	- building shapes with varying window sizing.	**4.2.3**
3. How location influences LC impacts and recommendations?	To assess the LC impact of the base case house for 6 alternative Portuguese locations considering varying insulation levels.	**4.3**
	To verify if this thesis findings can be extended for other Portuguese locations to draw recommendations.	
	To understand how the thermal insulation thickness tipping point varies with location.	
5. How operational conditions influence the LC impact of a new house and of a 25-year “equivalent” existing house?	To compare the LC energy of a new house with a 25-year “equivalent” existing house (non-insulated, single-glazing, high ventilated), acknowledging the influence operational conditions may have in the LC performance of both houses.	**4.4**
	To compare alternative operational patterns influence: continuous comfort condition (OP100), partial comfort condition (OP25,OP50), and intermittent scheduled comfort (OPx).	**4.3** **4.4.1**
	To assess the influence of alternative heating systems and the electricity generation mix.	**4.4.2**

1.3. Contribution

This PhD research expands the existing knowledge using LCA and building simulation to assess new houses for the Portuguese context, where heating and cooling operational patterns are dependent on user behavior due to mild Mediterranean climatic conditions. Though the focus is on Portuguese houses, the findings and several of the technological options are relevant for other south-European and Mediterranean locations.

More specifically it contributes to:

- Increase awareness about how embodied and operational energy are influenced by multiple factors (construction, design and operational options) when low operational levels, such as the Portuguese ones, are considered;
- Provide a life cycle inventory framework for Portuguese residential buildings, based on common building components, which can be applied to different houses relying on the same construction techniques and can be further expanded in the future.

Most of this Doctoral thesis is based on the following articles published, in review, or submitted to ISI-indexed journals:

- Monteiro, H., & Freire, F. (2012). Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. Energy and Buildings, 47, 572–583. doi:10.1016/j.enbuild.2011.12.032.
- Monteiro, H., Fernández, J. E., & Freire, F. (2016). Comparative life-cycle energy analysis of a new and an existing house: the significance of occupant's habits, building systems and embodied energy. Sustainable Cities and Society, 26, 507–518. doi:10.1016/j.scs.2016.06.002.
- Monteiro, H., Fernández, J. E., & Freire, F. (2017). Life cycle assessment of a single-family house in South Europe: addressing alternative construction strategies and heating systems.
- Monteiro, H., Freire, F. (2017). Life cycle assessment of building design options for a south European house: orientation, window sizing and building shape influence. (In final preparation for submission).

This PhD research also contributed to the following articles:

- Soares, N., Bastos, J., Pereira, L. D., Soares, A., Amaral, A. R., Asadi, E., Rodrigues, E., Lamas, F.B., Monteiro, H., Gaspar, A. R. (2017). A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. Renewable and Sustainable Energy Reviews. doi.org/http://dx.doi.org/10.1016/j.rser.2017.04.027.

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- Monteiro, H., & Freire, F. (2010). Environmental life cycle assessment of alternative exterior wall systems for a house in Portugal: Comparison of two LCIA methods. In A. B. Gültekín, H. S. Gokçe, M. Çavus, & R. Kiliç (Eds.), International Sustainable Buildings Symposium (ISBS) Proceedings, 26 – 28 May 2010 (pp. 753–759). Ankara, Turkey: Gazi University Technology Faculty, Construction Education Department.
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- Monteiro, H., Fernandez, J. E., & Freire, F. (2012). Thermal dynamic simulation to assess the influence of passive strategies on the energy performance of a Portuguese house. In Congress of Innovation on Sustainable Construction (CINCOS'12), Proceedings, (pp. 775-782). Aveiro.
- Monteiro, H., Fernandez, J. E., & Freire, F. (2012). Life-cycle energy analysis of a single family house: assessing alternative passive construction options. In: Energy for Sustainability 2015 - Designing for people and the planet, 2015. Coimbra. Proceedings of Energy for Sustainability 2015 Designing for People and the Planet. 2015.

1.4. Thesis outline

This thesis has five chapters, including this introduction. Chapter 2 reviews the state of the art regarding life cycle studies of residential buildings and provides the background for this research. Chapter 3 presents the life cycle model implemented and the life cycle impact assessment (LCIA) methods and categories used, it describes the life cycle inventory framework, the Portuguese house characteristics including the construction, design alternatives and operational conditions considered under this study. In Chapter 4, the operational and the LCIA results are presented and discussed. Chapter 5 draws the conclusions together, responds to the research questions, summarizes key findings, and provides recommendations regarding new houses building design and further research.

2. REVIEW OF LIFE CYCLE (LC) STUDIES OF DWELLINGS

This chapter aims to provide background for this research presenting a literature review focused on published life cycle studies of residential buildings. It shows the need for further research in the south European and Mediterranean climate, more specifically regarding the LCA of new houses in the Portuguese residential building context, which had seldom been addressed considering users behavior influence. Identifying the climatic context and the building options covered, the main findings of previous LC studies of residential buildings are highlighted, and the contribution of different processes and LC phases are identified. Focus is given to studies covering new dwellings, and dwellings in the Mediterranean context. Although most LC studies at building scale are based in specific case-studies with dissimilar contexts and different assumptions, general trends were identified in order to synthesize the existing knowledge. Literature covering new houses in the mild Mediterranean and in the Portuguese context is sparse and the existing studies did not considered the influence alternative operational user behavior may have in the overall LCA of a house. Generally, new houses embodied and operational impacts are both significant, but their LC contribution seems highly sensitive to construction options, and operational options (e.g., energy systems adopted, local or regional aspects, electricity production mixes). Interestingly, the influence of architectural building design has been overlooked from a LC perspective.

2.1. Introduction: from operational assessment to LCA of dwellings

In developed countries, the building sector accounts for 40% of final energy consumption and up to 30% of energy-related GHG emissions (IEA, 2013; UNEP, 2009), with the residential subsector being the largest building consumer (IEA, 2013). The urgency of developing a more sustainable built environment has been internationally recognized. Many organizations, initiatives, and research groups have been working to promote guidelines, building practices, and policies for building stakeholders that lead to improvements in the built environment at different scales (e.g., International Council for Research and Innovation in Building and Construction (CIB), United Nations Environment Programme - Sustainable Buildings and Climate Initiative (UNEP-SBCI), International Energy Agency (IEA), European Commission (EC), EC-Joint Research Center, International Initiative for a Sustainable Built Environment, World Green Building Council, the Portuguese Platform for Sustainable Construction, Energy for Sustainability (EfS-UC), etc.).

To support an envisaged shift towards a low-energy economy, EU policies and national regulations addressing building energy consumption have been enacted (EPBD, 2002, 2010; RCCTE, 2006; REH and RECS, 2013). In less than 5 years, new EU buildings are expected to have very low energy (VLE) consumption to promote cost-effective "nearly-zero energy buildings" during use phase (EPBD, 2010). To support the development of more efficient residential buildings, many studies and projects have focused on developing VLE dwellings and assessing both passive construction measures (that maximize the environmental thermal benefits and reduce the building energy loads) and alternative active systems (with high efficiency or based on renewable energy sources).

Over the last decades, VLE houses were developed with European funding mostly in north and central Europe along with some building energy certification schemes and construction standards. Developed for cold climate, the *Passive house* standard was disseminated throughout Europe thanks to European projects such as CEPHEUS (CEPHEUS, 2001; Feist, Peper, & Görg, 2001; Schnieders & Hermelink, 2006), Passive-On (2007), and PEP-project (2006). According to this standard, a *Passive house* assures indoor comfort in summer and winter without needing a conventional heating system thanks to five strategies: high thermal insulation, an air-tight building envelope, efficient windows, the minimization of thermal bridges, and a heat recovery ventilation system (CEPHEUS, 2001). These measures were shown to be of great importance to reduce operational heating and they are commonly found in VLE dwellings. The standard was also adapted for Mediterranean climate where heat recovery ventilation systems may not be needed (CEPHEUS, 2001). Table 2 presents the requirements of a *Passive house* for cold and Mediterranean climate based on project Passive-On (2007). The *Passive house* set a building reference that aims to guide the development of more sustainable dwellings.

At the same time, in the residential building context, some research studies have optimized passive options in order to minimize operational energy and total costs (investment and operational costs) of residential buildings for specific locations: Sydney (Bambrook, Sproul, & Jacob, 2011), Jordan (Jaber & Ajib, 2011), Helsinki (Hasan, Vuolle, & Sirén, 2008), Boulder, Chicago, Phoenix, Miami, and São Francisco (Bichiou & Krarti, 2011; Tuhus-Dubrow & Krarti, 2010). The passive options optimized were numerous (Bichiou & Krarti, 2011; Tuhus-Dubrow & Krarti, 2010), covering both construction options (insulation type and thickness, windows type, shading systems, ventilation strategies) and building design options (glazing size, glazing-wall ratio, building orientation). Some of these studies use a genetic algorithm optimization approach coupled with an energy simulation tool to identify, from an immense population (of solutions), a pareto-optimum (non-dominated solutions) that minimize energy and costs. Both building construction and design options were shown to have a significant effect on the building operational energy. Generally the lowest operational energy and cost were achieved with the rectangular or trapezoidal shaped plans, but it was also suggested that when all construction and design criteria were optimized the building shape had marginal influence on the operational results (Tuhus-Dubrow & Krarti, 2010).

Table 2. Passive house requirements and typical measures for Mediterranean and Central Europe

Passive House	Cold climate	Mediterranean climate
Standard limits:		
Useful energy for heating	< 15 kWh/m²year or Pmax <10W/m²	< 15 kWh/m²year
Useful energy for cooling	< 15 kWh/m²·year or Pmax <10W/m²	< 15 kWh/m²year
Operational primary energy	< 120 kWh/m²year	< 120 kWh/m²year
Interior operative temperature		
Winter	> 20ºC	> 20ºC
Summer	< 26ºC	Nat. Ventilated: EN 15251 (Adaptive) Mechanical ventilation:< 26ºC (Fanger)
Typical measures:		
Envelope insulation (U-value)	0.1 W/m²·K	0.15-0.32 W/m²·K
Windows	Low-e triple glazing (< 0.75 W/m²·K); Frame (< 0.8 W/m²K) Solar transmission factor: > 50%	Low-e double glazing; Frame with thermal break; Mostly facing South with selective shading
Ventilation	Mechanical with heat recovery	Natural (preferably) or mechanical
Air-tightness	< 0,6 ac/h*	Depend on ventilation: mechanical ventilation (0.6 ac/h *); natural ventilation for winters above 0º C (1.0 ac/h)
Appliances	Select efficient household appliances (A++) from market	

* Pressurization test according to EN 13829

However, assessing only operational phase is rather limited, since it does not represent the full environmental impact of buildings. Beyond operational energy, buildings are responsible for significant natural resources extraction, primary energy consumption, worldwide environmental emissions and waste generation (UNEP, 2009). To shift towards more sustainable economies and help mitigate the undesired environmental problems of the building sector, buildings should be addressed as a system through a life cycle perspective (Cabeza et al., 2014; Chau et al., 2015; Keoleian et al., 2001; Sartori & Hestnes, 2007; Soares et al., 2017).

Life Cycle Assessment (LCA) is a science-based methodology (Baumann & Tillman, 2004; Guinée et al., 2002; ISO 14040, 2006; Jolliet et al., 2003; Rebitzer et al., 2004) to systematically account for the inputs, outputs and the potential environmental impacts throughout a product system life cycle (LC), usually from cradle-to-grave. Thanks to its holistic approach, LCA allows to unveil potential trade-offs between LC phases and between different environmental impacts allowing to compare and assess alternative functional equivalent systems. As an industrial ecology tool, LCA has gained increased international acceptance in industry, and it started to be used in the building context around two decades ago (Buyle et al., 2013; Keoleian et al., 2001) to asses both building materials and buildings as a whole. LCA is not a green label, but a process to quantify and acknowledge the building environmental impacts across different LC phases, to estimate the relative performance of alternative building options, and to possibly identify how and where improvements can be found.

Firstly published in 1997, the 14040 series of ISO standards define the LCA general framework (ISO 14040, 2006; ISO 14044, 2006) describing the four interrelated stages for a LCA application: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of results. These standards have been used as a starting point for LCA applications in the building sector. Additionally, ISO has also standardized Type III Environment declarations (ISO 14025, 2006), which are also known as Environmental Product Declarations (EPD). EPDs have been voluntarily applied to some construction products to communicate their environmental performance, and, on the long run, are expected to be useful to compare the environmental performance of alternative products available on the market. A deeper discussion about initiatives to environmental certificate or environmentally inform construction materials and building components goes beyond this review and can be found in Silvestre (2012).

Moreover, in the European context, the technical committee on sustainability of construction works CEN/TC 350 has been developing standardization work on LCA of building products (EN

15804 (CEN, 2012)) and of buildings (EN 15978 (CEN, 2011)), defining specific stages or modules that can be used in LCA studies to more easily allow comparability among studies. Figure 1 presents the building LC modules according to EN 15978. According to ISO 14040 (2006), a LCA study may define the LC processes and phases included depending on its goal and scope, and therefore many published LC studies of buildings only include some LC phases and processes having dissimilar system boundaries. Each LCA study is a comprehensive and complex process based on assumptions, foreground and background data and it inherently has a degree of uncertainty. Even though, LC studies of buildings have the ability to unveil hidden impacts for a specific building context (Buyle et al., 2013; Cabeza et al., 2014; Chau et al., 2015) usually neglected by studies focused only on operational energy assessments.

Beyond LCA studies, various sustainable building assessment, rating, and certification schemes have been developed both internationally (e.g., BREEAM by the UK British Building Establishment (BRE), LEED by US Green Building Council, SBTool by the International Initiative for a Sustainable Built Environment(iiSBE)) and in Portugal (e.g., LiderA; SBTool-PT) and their adoption is voluntary. Several reviews of these sustainable building assessment tools can be found in literature (Andrade & Bragança, 2016; Haapio, 2008; Haapio & Viitaniemi, 2008a; Silvestre, 2012; Vierra, 2014). Generally, certification schemes allow evaluating, classifying, and communicating the sustainable performance level of a building pondering environmental aspects (e.g., use of resources, the environmental impacts) jointly with social and economic aspects for specific countries. Although assessment schemes that aggregate multiple (environmental and/or other) aspects may simplify decision and communication of results (through weighting, classification or benchmarking), these are known to encompass higher uncertainty and subjectivity than LCA, and therefore are out of the scope of this literature review, which will focus on LCA studies of dwellings. Nevertheless, the environmental aspects considered under these sustainable building assessment and certification schemes are usually based on a LC perspective or on LCA data (Andrade & Bragança, 2016; Haapio & Viitaniemi, 2008a).

The importance of using LCA to support building assessments and new building developments has also been highlighted by a number of European projects that boosted research on LCA of buildings mainly to help introduce LCA methodology in the building context. ENSLIC-Building (2010), IMPRO-Building (Nemry et al., 2008, 2010b), EeBGuide project (EeBGuide, 2012), PRESCO (Bruno Peuportier & Putzeys, 2005), and LoRE-LCA project (Bribián, Capilla, & Usón, 2011; Tritthart et al., 2010) summarized existing LCA tools for buildings, provided common LCA methodology guidelines, presented some LCA case studies, and developed new tools to be used by designers and building stakeholders. For instance, ENSLIC project (ENSLIC-Building, 2010;

Malmqvist et al., 2011) aimed to promote LCA among building practitioners and with some case studies demonstrated the potential that LCA holds to compare building alternatives identifying different processes influence on the LC environmental impact of buildings. To increase LCA usability in the building sector it suggested a simplified LC tool based on CO_2 emissions.

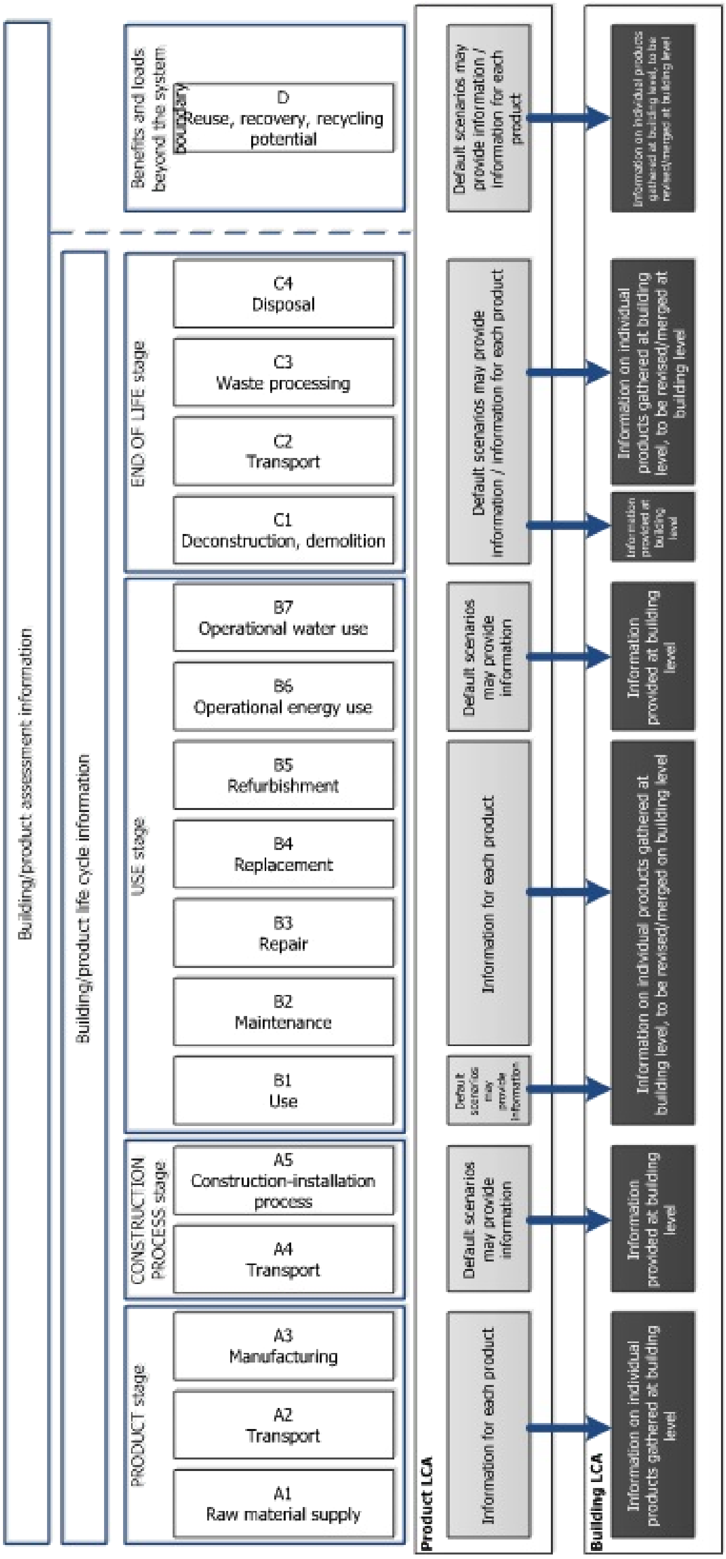


Figure 1. LCA of buildings as a whole based on EN 15978 (CEN, 2011)
from http://www.eebguide.eu/eebblog/wp-content/uploads/2012/10/EeBGuide_BUILDINGS_figure2.jpg

The IMPRO project (Nemry et al., 2008, 2010b) aimed to model the EU-25 building stock to comprehensively assess the environmental impacts of alternative LC phases (such as: construction, maintenance, operation, and demolition) for alternative building typologies (single-family, multifamily, and high-rise) located in three European climatic zones (southern, central, and northern Europe). Additionally, the study highlighted technical improvement options for existing buildings and their environmental reduction potential regarding the EU building stock. For the first time, the same system boundary and study assumptions were used to assess 72 dwellings placed in these different climatic zones. Although it was concluded that the major potential for reducing EU dwellings environmental impacts is associated with refurbishment of existing dwellings since these represent the majority of EU buildings, new dwellings were shown to be much better than existing ones, being able to influence the future reality on the long term.

This doctoral thesis was based on two important findings drawn from the IMPRO-project: i) In south Europe, thermal operational energy of dwellings is significantly lower than in central and north Europe. ii) New dwellings have significantly lower operational energy when compared to existing dwellings. Thus, it would be reasonable to consider that new dwellings in south Europe or in a Mediterranean location can easily have low operational energy consumptions (for heating and cooling), and in such building context using LCA is even more important to identify the most significant processes across the building life cycle.

LC studies of residential buildings are fairly fragmented and spread over international publications. Review studies on LCA and LC energy of buildings (Abd Rashid & Yusoff, 2015; Cabeza et al., 2014; Chau et al., 2015; Karimpour, Belusko, Xing, & Bruno, 2014; Sartori & Hestnes, 2007; Weißenberger, Jensch, & Lang, 2014) agree that the comparison among literature studies is not linear since buildings characteristics (size, shape, location, climate, occupation) and methodological assumptions (functional unit, lifespan, LCIA method, exclusions and simplifications) widely vary from case to case (Buyle et al., 2013), but generally, some trends can be identified. Though a building is a complex unique product, research studies reinforce that LCA can give important insights assessing the significance of different LC phases and processes and comparing alternative building options, materials, and components, thus supporting improvements at design phase (Anderson, Wulfhorst, & Lang, 2015; Buyle et al., 2013; Cabeza et al., 2014; Chau et al., 2015; Dixit, Fernández-Solís, Lavy, & Culp, 2012; Khasreen, Banfill, & Menzies, 2009; Ortiz, Castells, & Sonnemann, 2009).

LCA of buildings as a whole provide more findings regarding general building concepts and options than about specific materials (Buyle et al., 2013), which is aligned with this thesis goal. Thus, the major focus of this literature review is to examine existing LC studies of residential buildings as whole in order to:

- Present an overview of the state of the art of the literature and identify gaps that justify this research;
- Examine and learn from the main outcomes of existing LC studies of new dwellings in the Mediterranean context;
- Identify building options previously addressed that were identified as significant from a LC perspective;
- Highlight the need for further LC research in the south European mild Mediterranean context, more specifically regarding new Portuguese residential buildings, and the influence that user behavior may have in the balance between embodied and operational impacts.

2.2. Overview of LC studies of dwellings

Early examples of life cycle (LC) studies for residential buildings concluded that use phase had a preponderant weight in the overall LC impact of houses (Adalberth, 1997a, 1997b; Blanchard & Reppe, 1998; Keoleian et al., 2001). Adalberth (1997a) proposed a methodology to account for LC energy of buildings from cradle to grave and applied it to three Swedish single-family houses prefabricated in a factory (Adalberth, 1997b). Among other results, Adalberth (1997b) concluded that the building use phase required 85% of the total LC energy, while construction materials amounted to 15%. Keoleian (Blanchard & Reppe, 1998; Keoleian et al., 2001) evaluated LC energy, GHG emissions, and costs of a single-family house in Michigan (USA) and an equivalent energy efficient house (including 11 energy efficiency measures) to find opportunities for conserving energy throughout pre-use, use, and demolition phases. Assuming a 50-year lifespan, the new efficient house was shown to hold 563 $MJ/m^2 \cdot year$, having 60% lower LC energy that the standard house (1274 $MJ/m^2 \cdot year$). The authors stressed the importance of energy efficiency measures (e.g.: reducing infiltration, replacing the envelope fiberglass insulation for cellulose with an increased thickness, replace basement concrete walls for wood walls, and selecting efficient HVAC system and appliances) to significantly lower LC energy of residential buildings. The study also concluded that use phase was the most significant LC phase accounting for 91% and 74% of the LC primary energy of the standard house and of the energy-efficient house, respectively. The end-of-life (demolition and transport) energy (3 MJ/m^2·year) was shown to be insignificant when compare to the other LC phases (Keoleian et al., 2001).

Since then, a number of LC studies of dwellings (Blengini & Di Carlo, 2010a; Bribián, Usón, & Scarpellini, 2009; Citherlet & Defaux, 2007; Gustavsson & Joelsson, 2010; Gustavsson et al., 2010; Hacker et al., 2008; Mahdavi & Doppelbauer, 2010; Nemry et al., 2008, 2010b; Ortiz, Pasqualino, Díez, & Castells, 2010; B. Peuportier, 2001; Thormark, 2002; Utama & Gheewala, 2008) as well as review papers on LCA in the building context (Abd Rashid & Yusoff, 2015; Buyle et al., 2013; Cabeza et al., 2014; Chau et al., 2015; Karimpour et al., 2014; Lee, Tae, & Shin, 2009; Ortiz, Castells, et al., 2009; Ramesh, Prakash, & Shukla, 2010; Sartori & Hestnes, 2007; Sharma, Saxena, Sethi, Shree, & Varun, 2010; Soust-Verdaguer, Llatas, & García-Martínez, 2016; Weißenberger et al., 2014) have been published.

Many studies have been carried out for cold climate dwellings in developed countries (north and central European ones) and for that climate concluded that operational phase held most of the building LC burdens. Moreover, studies of existing dwellings from different countries (UK (Cuéllar-Franca & Azapagic, 2012), Sweden (Gustavsson & Joelsson, 2010), Belgium (Verbeeck & Hens, 2010), Italy (Asdrubali, Baldassarri, & Fthenakis, 2013; Blengini, 2009), Spain (Ortiz, Bonnet, et al., 2009; Ortiz, Castells, & Sonnemann, 2010a), Portugal (Rodrigues & Freire, 2014, 2017)) also agree that operational energy is dominant (due to heating and cooling), representing 60-90% of the total environmental impacts of existing dwellings (Chau et al., 2015; Nemry et al., 2010b). Ramesh et al. (2010) reviewed 73 case studies from 13 countries and concluded that LC energy demand in conventional dwellings ranged from 150 to 400 kWh/m^2·year. Similarly, most of the conventional dwellings reviewed by Sartori and Hestnes (2007) felt in the range 290 to 480 kWh/m^2·year, with embodied energy holding shares from 2-38% of the LC energy among studies. Thus, reducing heating and cooling needs of the existing building stock seems to be of great importance, and many studies advocated that future efforts should keep focusing in operational phase (Blengini, 2009; Cabeza et al., 2014).

Various LC studies of dwellings only addressed energy and/or greenhouse gas (GHG) emissions (e.g., Adalberth 1997a; Adalberth 1997b; Peuportier 2001; Thormark 2002; Citherlet and Defaux 2007; Hacker et al. 2008; Gustavsson et al. 2010; Ramesh et al. 2010; Mahdavi and Doppelbauer 2010; Gustavsson and Joelsson 2010; Ramesh et al. 2012; Oregi et al. 2015). Generally, these studies defend that these categories are good proxy indicators of the environmental impact of carbon-related processes, and additionally using a single category helps simplifying decision (ENSLIC-Building, 2010; Malmqvist et al., 2011). Conversely, more comprehensive LCA studies including multiple environmental categories highlighted that accounting for primary energy or GHG emissions although representative of some environmental categories (global warming potential (GWP); acidification potential (AP); abiotic depletion (AD)) may not fully represent the overall environmental impact of a building (Blengini & Di Carlo, 2010b; Monteiro & Freire, 2012; Nemry et al., 2008, 2010b), namely other categories such as: eutrophication potential (EP), photochemical oxidation (PO), and ozone layer depletion (OLD) and toxicity categories. Although LCA is a science-based methodology since there is no mandatory LCIA method, some studies also suggest that the environmental categories selected and LCIA methods used may partially influence the LC study results (Monteiro, 2010; Monteiro & Freire, 2011, 2012). Generally toxicity categories are known to encompass higher uncertainty and LCI databases still lack robust toxicological and physicochemical data (Finnveden et al., 2009) and therefore toxicity categories are not commonly used in the building context.

The importance of the functional unit selected in LCA of buildings has been highlighted by some LC studies (Bastos, Batterman, & Freire, 2015; Cuéllar-Franca & Azapagic, 2012; Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015; Soust-Verdaguer et al., 2016; Stephan, Crawford, & de Myttenaere, 2013b). Depending on the functional unit, the LC results may be very different especially when dissimilar assumptions are made, for instance, regarding the house size, the expected lifespan, and its occupation. When the functional unit is the whole building over its life span, the LC impacts are likely to increase with the size of the building and with its lifespan. However, when results are presented per unit of living area (or volume), a bigger house is likely to present lower LC impact (per m^2 or m^3) than a smaller house (B. Peuportier, 2001). Additionally, a house with a longer lifespan is likely to have lower embodied impacts per year than a house with a shorter lifespan (Haapio & Viitaniemi, 2008b). Considering the function of providing lodgment per person, a house occupied by a bigger family is likely to present lower impact per person than if it is occupied by a smaller family and, for the same family size, a smaller house may have lower LC impact per person than a bigger house (Cuéllar-Franca & Azapagic, 2012). From literature, a per person functional unit have been mainly used in LC studies including the transportation of dwellers during the building lifespan (Bastos et al., 2015; Stephan et al., 2013b).

In LCA studies, the LCIA can be based on processes (bottom-up); input-output (IO) data (top-down); or IO hybrid analysis (both process and IO data). The process-based approach is the most used in LCA studies of buildings and provides detailed information at the product level, allowing to compare specific construction alternatives (Monteiro, Fernández, & Freire, 2016; Rodrigues & Freire, 2014; Stephan & Stephan, 2016). Still, process-based analysis suffers from a "truncation error" (Crawford, 2008; Suh & Huppes, 2002) associated with its limited system boundary. Indirect impacts and small materials or services embodied in construction are usually disregarded, overlooking embodied energy. Top-down IO analysis is based on a relation between domestic economic data for different industry sectors and the energy intensity data per sector. IO analysis provides broader results for macro-scale but encompasses higher uncertainty suffering from an "aggregation error" (Crawford, 2008; Treloar, 1997), making it difficult to characterize impacts for different processes within the same sector. The IO-hybrid approach was developed in an effort to overcome the limitations of process-based LCA and IO analysis (Treloar, 1997). Authors that have applied the IO-hybrid approach (Crawford, 2011a; Crawford & Stephan, 2013; Nässén, Holmberg, Wadeskog, & Nyman, 2007; Stephan & Stephan, 2014; Treloar, 1997) stated that, due to more comprehensive system boundaries, an IO-hybrid LCA can result in significantly higher embodied energy values than equivalent process-based studies. For instance, Nässén et al., (2007) compared an IO analysis of the Swedish building sector with average results from 18 Scandinavian process-based LCA studies. Results showed that, including indirect services from other sectors, embodied energy was 94% higher in the IO analysis (6.0 GJ/m^2) than in the process-based studies (3.1 GJ/m^2). Crawford, (2008) also identified a gap around 59% between process-based (6.9 GJ/m^2) and IO-based hybrid analysis (17 GJ/m^2) for an Australian house. Other studies relying in Australian IO-data even pointed out that IO-hybrid analysis produced embodied energy figures around 11-19GJ/m^2, which can be 3.78 (Crawford, 2011a, 2011b), 3.94 (Stephan & Stephan, 2014), or 4.36 (Crawford & Stephan, 2013) times higher than process-based LCA (5-7.5GJ/m^2) for the same dwellings. However, it is difficult to implement an IO-hybrid analysis when there is no regional IO data available (Finnveden et al., 2009).

Table 3 presents a summary of the LC studies of dwellings found, identifying the building location, the type of dwelling covered, describing the main alternative building options assessed, the LC phases included, and the LCIA methods and categories considered. Table 4 presents the energy and GHG emissions (or GWP) selected results of new dwellings previously assessed.

Table 3. Summary of LC studies of dwellings
(continues in the next 2 pages)

Reference	Year	Location	Case study		N	Alternatives studied	Life span (years)	Area (m²)	Functional Unit	Type of LC study	LCIA Method	LCIA categories	Pre-use	Use - HVAC	Use - Others	Maintenance	EOL
Blengini (Blengini, 2009)	2009	Italy:Turin	MF	Exis	2	waste disposal: recycling or landfill	40	6110	m²·year	LCA	CML	PE; GWP; OLD; AP; EP; PO	x	x	x	-	x
Blengini and Di Carlo (2010a, 2010b)	2010	Italy: Piedmont	H	New	2	Low-energy house; Equivalent legal standard house	70	250 192*	m²·year	LCA	CML, EI99, EF, EPS2000	PE; NRPE; GWP; GWP_{nb}: OLD; AP; EP; PO	x	x	x	x	x
Bribián et al. (2009)	2009	Aragon, Spain	H	New	1	Single-family house complying with thermal code (3 cm EPS) Increasing thermal insulation thicknesses (0-20 cm)	50	222 108*	m²·lifespan	LCECA	IPPC	PE; GHG	x	x	x	-	-
Peuportier (2001)	2001	France	H	New	3	Standard house (concrete block wall; 8 cm XPS walls; 6 cm XPS roof) Solar house (wooden walls; 12 cm paper insulation; 10 cm XPS roof) Wooden house (wooden walls; 20 cm mineral wool in walls and roof)	80	112 212 155	m²·lifespan	LCA	CML	Energy, AD, GWP, AP, EP, PO, OLD, ET, HT, malodorous air, Water.	x	x	x	?	x
Citherlet and Defaux (2007)	2007	Lausanne, Switzerland	H	New	3	Standard legal house in Switzerland Energy efficient (Minergie label house) Low-energy house	50	266	m²·year	LCA	CED; CML	NRPE; GWP; AP; PO	x	x	x	x	x
Haapio and Viitaniemi (2008b)	2008	-	H	New	78	Insulation (cellulose, fiberglass, rock wool), cladding (brick, steel, stucco, wood), window frames (aluminum, wood) roof materials (clay, concrete, steel).	60 to 160	?	Full building	LCA	EIE	PE; GWP; Solid waste emissions, Pollutants to air and to water, NRU	x	-	-	x	x
Verbeeck and Hens (2007, 2009, 2010)	2007	Belgium	H MF	New Exis	5 4000	Dwellings: terraced; semi-detached; detached; non-compact house; an apartment flat. Lightweight wood frame; cavity wall; massive wall. Insulation types and levels; glazing; shading; air-tightness; HVAC systems; renewable energy systems.	30 60 90	143 147 153 149	m³·lifespan	LCA LCECA LCC optimization		PE; GWP; Cost; NOx, SOx, non-methane VOCs and particulates	x	x		x	-
Rodrigues and Freire (2014)	2014	Portugal: Coimbra	H	Exis	27	Roof retrofit scenarios: insulation material (RW, XPS;PUR); insulation levels (40; 80; 120mm); roof frame (wood; light steel; lightweight concrete)	50	279 70 (attic)	m²·lifespan	LCA	CED; Recipe	NRPE; CC; OLD; TA; FE; ME	x	x	x	x	-
Gervásio et al. (2014)	2014	Portugal: Coimbra	H	New	3 2	Light weight steel framing; Steel structure with hot rolled profiles; Traditional reinforced concrete and brick work; Early design stage simplified methodology (conceptual stage) vs. preliminary design stage LCA.	50	240 202	Full building	LCA	CML	GWP; OLD; AP; EP; PO; AD_e; AD_f	x	x	x	x	x
Thiers and Peuportier (2012)	2012	France: Formerie; Montreuil	H MF	New Exis	2 4	Passive attached house; Renovated MF social housing (36 dwellings); Heating systems: heat pump; wood pellet condensing boiler; wood pellet micro generation unit; district heating.	80	2500 132	m²·year	LCA	CML	CED, AD; GWP; AP; EP; PO; HT; ET; Odour; radioactive and no radioactive Waste; Water	x	x	x	x	x
Ortiz et al.(Ortiz, Castells, et al., 2010a; Ortiz, Castells, & Sonnemann, 2010b)	2010	Spain and Columbia	H		2	Typical houses: Spanish ($_{SH}$) and Colombian ($_{CH}$) windows; insulation; users behavior; energy supply (electric, electric +gas)	50	160_{SH} 140_{CH}	m^{2H}·lifespan	LCA	CML2	AD; GWP; AP; OLD; TE; HT	x	x	x	x	x
Nemry et al. (2008, 2010b)	2008	EU-25: southern; central; northern.	H MF HR	New Exis	72	Building types (53 new and 19 existing) were identified that represent altogether 80% of the whole building stock in the EU-25 in terms of living area.	40 20		m²·year	LCA	CML	PE; GWP; AP; EP; OLD; PO	x	x		x	x
Mosteiro-Romero et al. (2014)	2014	New jersey, US); Chur, Switzerland	H	New	2	LEED-H single-family house Minergie-P single-family house	65	255* 191*	m²·lifespan	LCA	CED; IMPACT 2002+, BEES;	NRPE; GWP AP; EP; OLD	x	x	x	x	x

Reference	Year	Location	Case study		N	Alternatives studied	Life span (years)	Area (m^2)	Functional Unit	Type of LC study	LCIA Method	LCIA categories	Pre-use	Use - HVAC	Use - Others	Maintenance	EOL
Rauf and Crawford (2015)	2015	Australia: Melbourne	H		1	Detached house - Service life assessment: embodied and recurrent embodied energy	1-150	291	Full building a year	LCEA IO hybrid		PE	**x**	-	-	**x**	-
Rossi et al.(2012; 2012)	2012	Brussels; Coimbra; Luleå	H		6	Steel frame and masonry frame house in 3 locations (Belgium, Portugal and Sweden)	50	192		LCECA		PE; GHG	**x**	**x**	**x**	-	**x**
Gustavsson and Joelsson (2010)	2010	Stockholm; Sweden	H MF	New Exis	11	Conventional single-family and low-energy passive houses and apartment buildings when using different types of energy supply systems for space heating, household electricity and heating domestic hot water. Concrete- and wood-framed apartment buildings.	50	144 120 1190 2802	m^2·lifespan	LCECA	CED	PE; GHG	**x**	**x**	**x**	-	-
Brunklaus et al. (2010)	2010	Sweden	MF	New Exis	7	3 passive house multifamily buildings and 4 conventional multifamily buildings; User behavior and choices (demand side); producers choices (supply side).	50		m^2·year	LCA		E; GWP; AP; EP; PO	**x**	**x**	**x**	**x**	-
Blom et al.(2011)	2011	Netherland	MF	Exis		Building characteristics Consumer behavior		73		LCA	CML	PE; GWP; AP; EP; OLD; PO; HT;TE; FE					
Adalberth (1997b)	1997	Sweden	H	Exist	3	Standard houses (built in 1991)	50	130	m^2·lifespan	LCEA		PE	**x**	**x**	**x**	**x**	**x**
Adalbert (2001)	2001	Sweden	MF	Exist	4	4 multifamily buildings	50		m^2·lifespan			GWP, AP, EP, HT	**x**	**x**	-	-	**x**
Blanchard and Reppe (1998); Keoleian et al. (2001)	1998	USA	H	Exist New		standard house and energy efficient house; 11 energy efficiency strategies: increase wall insulation; increase roof insulation; reduce infiltration; wood basement; high performance windows; energy efficient appliances; fluorescent lighting; shading; air-air heat exchanger; waste what water heat recovery; roof shingles made with recycle material.	50	228	Full building	LCECA LCC	CED	PE; GHG; costs	**x**	**x**	**x**	**x**	**x**
Dahlstrøm et al.(2012)	2012	Norway	H	New Exis	8	Conventional and passive house (single-family house); wooden, 2-storey. 4 heating and DHW scenarios: electricity; wood and electricity; solar collector and electricity; electricity and heat pump; 3 electricity generation mixes: Norwegian; Nordel; UCTE	50	187	m^2·lifespan	LCA	ReCiPe	PE; CC, OLD;HT; PO; TA; EP; GHG; DHH; DE; DRA	**x**	**x**	**x**	**x**	**x**
Cuéllar-Franca and Azapagic (2012)		UK	H	Exist	3	3 common types of houses in UK: Detached house, Semi-detached house Terraced house	50	130 90 60		LCA	CML	AD; GWP; AP; EP; OLD; PO; HT;TE; FE; ME	**x**	**x**	**x**	**x**	**x**
Proietti et al.(2013)		Perugia, Italy	H	New		Energy efficient house (passive house) with careful selection of materials and systems (heat pump with heat recovery; PV system).	70	252	m^2·year	LCA	CML EI99	PE; NRPE; GWP; AP; EP; PO; EI99 pts	**x**	**x**	**x**	**x**	**x**
Rosselló-Batle et al. (2015)	2015	Spain	H MF		92	Detached house; terraced house; duplex multifamily dwelling. Construction options: 10 exterior walls including 5 insulation materials (mineral wool, EPS, XPS, PUR injected or panels; 3 roofs; 3 window frames (wooden, aluminum, PVC).	50	135	m^2·year	LCE	-	PE	**x**	**x**	-	-	-
Hanandeh (2015)	2015	Irbid, Jordan	H	New	6	Popular exterior-wall construction alternatives for a single-family house: single hollow concrete block, double hollow concrete block with and without insulation, limestone cladding, insulated limestone wall, multilayer with limestone cladding and insulation.	50	144	Full building	LCA	ReCiPe ESM 2006	CC; AP; HT; WD	**x**	**x**		**x**	**x**

Reference	Year	Location	Case study		N	Alternatives studied	Life span (years)	Area (m^2)	Functional Unit	Type of LC study	LCIA Method	LCIA categories	Pre-use	Use - HVAC	Use - Others	Maintenance	EOL
Fouquet et al. (2015)	2015	Chambery, France	H	New	3	Single-family Passive houses with identical shape: a timber house, a cast concrete house, and a concrete block house. 2 EOL scenarios for timber house: landfilling or incineration with energy recovery (avoiding natural gas consumption)	100	122	Full building	LC	IPCC	GWP	x	x	x	x	x
Lewandowska et al. (2013)	2013	Poland	H	New Exist	4	detached single-family houses (3-bedroom with 4-people family): passive house with electric heating or traditional house with gas-heating; 2 material structure (masonry building or wooden building maximizing wood usage).	100	98	Full building over life span	LCA	EI99	ecopoints	x	x	x	x	x

Legend:
MF: multi-family residential building; H: house (single or double family house); HR: high-rise residential building; New: new building; Exis: existing building; K:10^3 times; *heated area;
LCA: Life cycle assessment (with multiple environmental categories); LCEA: Life cycle energy analysis; LCECA: Life cycle energy and carbon analysis; LCC – Life cycle cost;
Methods: CML; Recipe; EI99H/A: Eco-Indicator 99; EF: Ecological Footprint; EPS2000: Environmental Priority Strategy; BEES: Building for Environmental and Economic Sustainability; EIE: Environmental Impact Estimator; CED: Cumulative Energy Demand; GHG: Green House Gas emissions ($CO_{2\,eq}$); IO hybrid: Input-output hybrid life cycle assessment; IPCC: Intergovernmental Panel on Climate Change (IPCC, 2007); ESM 2006:Ecological Scarcity Method 2006;
Categories: PE: primary energy; NRPE: non-renewable primary energy; GWP: global warming potential; GWP_{nb}: GWP excluding biogenic contribution; AD: abiotic depletion; AD_e: AD elements (non-fossil); AD_f: AD fossil resources; AP: acidification potential; EP: eutrophication potential; PO: photochemical oxidation; OLD: ozone layer depletion; ET: ecotoxicity; HT: human toxicity; HH: human health; FE: fresh water aquatic ecotoxicity; DHH: damage to human health; DE: damage to ecosystems; DRA: damage to resource availability; NRU: Natural resource use; WD: Water depletion.
LC processes: **x** (included); **-** (not included).

Table 4. LC energy and GHG emission of new dwellings assessed in the literature (continues in the next page)

Reference	Year	Location	Case study	N	Alternatives studied	Lifespan (years)	Area (m^2)	Unit	Pre-use	Use: HVAC	Use: HVAC and others	Maintenance	EOL	Total	Notes
Blengini and Di Carlo (2010a, 2010b)	2010	Piedmont, Italy	H	1	Low-energy house	70	**250**								Pre-use results include maintenance.
								NRPE MJ/m^2·y	132	38	123	-	-21	235	Heating hold 15% of NRPE.
								kg CO_2/m^2·y	10.8	2.6	7.9	-	-1.3	17.4	Heating hold 11% of LC GWP.
				1	Standard legal house			NRPE MJ/m^2·y	105	370	500	-	-15	590	Heating hold 63% of NRPE
								kg CO_2/m^2·y	9.4	22	30	-	-1	38.4	Heating hold 57% of LC GWP.
Bribián et al. (2009)	2009	Aragon, Spain	H	1	House complying with thermal code (3 cm EPS)	50	222 108*								
								kg CO_2/m^2·y	12	12	13	-	-	25	
								kWh/m^2·y	34	56	62	-	-	96	
					Varying thermal insulation thicknesses (0-20 cm)			kg CO_2/m^2·y	10-14	14-10	15-11	-	-	25-30	
								kWh/m^2·y	32-48	68-45	75-52	-	-	94-103	
Peuportier (2001)	2001	France	H	3	Standard construction house	80	112								Embodied carbon included credits for CO_2
								kg CO_2/m^2·y	3.1	-	21.9			25	uptake of wood, and end-of-life emissions.
					Solar house	80	212	kg CO_2/m^2·y	-2.2		22.8			25	
					Wood house	80	155	kg CO_2/m^2·y	-1		10.4			9.4	
Citherlet and Defaux (2007)	2007	Lausanne, Switzerland	H	3	Standard legal house in Switzerland	50	266								Approximate results inferred from reference
								NRPE MJ/m^2·y	66	306	506		8	580	figures. (Suiss Electric mix)
								kg CO_2/m^2·y	4.5		22.6		0.9	28	
					Energy efficient (Minergie label house)			NRPE MJ/m^2·y	70	95	295		8	475	
								kg CO_2/m^2·y	4.8		4.0		0.9	10.5	
					Low-energy house			NRPE MJ/m^2·y	63	55	140		8	200	
								kg CO_2/m^2·y	4.2		4.5		0.9	9.8	
Thiers and Peuportier (2012)	2012	France: Formerie;	H	3	Passive attached house:	80	132								
					With heat pump			kWh/m^2·y	30	1	16		1	49	
					With wood pellet condensing boiler			kWh/m^2·y	30	6	16		1	53	
					With wood pellet micro generation unit			kWh/m^2·y	30	14	17		1	62	
Ortiz et al. (2010a, 2010b)	2010	Spain	H	2	Typical Spanish house	50	160	kg CO_2/m^2·y	3.9	13.7	41.5		0.5	46.8	Heating:2.9 ; cooling: 10.8
		Columbia			Colombian house		140	kg CO_2/m^2·y	4.7	0	9.9	0.6	0.4	15.6	Use phase 64%
Nemry et al. (2008, 2010b)	2008	Southern Europe	H	2	New single-family houses (10 cm insulation):	40	135								Use phase: heating: 98%; cooling 2%.
					Z1_SI_005 (pitched roof)			kg CO_2/m^2·y	10.9	20.9	-	0.9	0.9	33.6	
								MJ/m^2·y	168	440		14	-1	621	
					Z1_SI_006 (flat roof)			kg CO_2/m^2·y	11.8	20.9	-	0.5	0.5	33.9	
								MJ/m^2·y	162	440		14	-1	615	

Reference	Year	Location			N	Alternatives studied	Lifespan (years)	Area (m²)	Unit	Pre-use	Use: HVAC	Use: HVAC and others	Maintenance	EOL	Total	Notes
Mosteiro-Romero et al. (2014)	2014	US: New jersey;	H	New	2		65									
						LEED-H single-family house		255	NRPE kWh/m²	2596	13716		x	64	16376	
									kg CO_2/m²	553	2147			30	2730	
		Swiss: Chur				Minergie-P single-family house		191	NRPE kWh/m²	4836	5433			218	10487	
									kg CO_2/m²	852	279			255	1386	
Rossi et al.(2012; 2012)	2012		H	New	6	Steel frame and masonry frame house in 3 locations:	50	192								Embodied carbon included maintenance and EOL
						Coimbra, Portugal			kg CO_2/m²·y	4.6		38.7			43.3	
						Luleå, Sweden			kg CO_2/m²·y	4.8		2.8			7.6	
						Brussels, Belgium			kg CO_2/m²·y	4.6		24.1			28.7	
Adalberth (1997b)	1997	Sweden	H		3	Single-family house 1	50	130	kWh/m²·y	20.4	76	141	8	0.8	170	
						Single-family house 2		129	kWh/m²·y	19.6	83	148	7.6	0.6	176	
						Single-family house 3		138	kWh/m²·y	16.2	64	128	6.8	0.6	152	
Blanchard and Reppe (1998); Keoleian et al. (2001)	1998	USA	H				50	228								
									MJ/m²·y	132	-	1271	-	3	1274	Maintenance is included in use phase.
									kg CO_2/m²·y						89	
				New		Energy efficient house (including 11 measures)			MJ/m²·y	146		414		3	563	
									kg CO_2/m²·y						32	
Proietti et al. (2013)		Perugia, Italy	H	New		Energy efficient house (passive house) with careful selection of materials and systems (heat pump with heat recovery; PV system).	70	252								EOL : -20% of NRPE PV: -
									MJ/m²·y	225		251	x	-77		
										16						EOL:-5% of GWP

Legend: EOL: End of Life; H: house or single family house.
The results presents are inferred from reference figures.

2.2.1. New dwellings

Whereas one decade ago operations were responsible for 85 to 95% of LC energy of houses (Blanchard & Reppe, 1998; Keoleian et al., 2001; Sartori & Hestnes, 2007; Utama & Gheewala, 2008), recent studies using a process-based approach (Bribián et al., 2009; Dodoo, Gustavsson, & Sathre, 2011; Pinto, 2008) showed that, in current building practice, embodied energy can represent 30% of LC energy. Generally, heating has been the most important process, followed by material production (Sartori & Hestnes, 2007). This subsection covers LC studies on new buildings and their main findings.

Most LCA studies of new dwellings focused on assessing recent “exemplary buildings” such as VLE houses and passive houses, in which operational energy is substantially reduced (Berggren, Hall, & Wall, 2013; Blengini & Di Carlo, 2010a, 2010b; Brunklaus et al., 2010; Citherlet & Defaux, 2007; Dodoo et al., 2011; Dodoo, Gustavsson, & Sathre, 2014; Gustavsson & Joelsson, 2010; Gustavsson et al., 2010; Proietti et al., 2013; Sartori & Hestnes, 2007; Stephan, Crawford, & de Myttenaere, 2013a). Some studies compared low-energy dwellings with standard or existing ones (Blengini & Di Carlo, 2010b; Dahlstrøm et al., 2012; Lewandowska et al., 2013; Sartori & Hestnes, 2007; Stephan et al., 2012; Verbeeck & Hens, 2007, 2009, 2010). Other studies assessed new dwellings with alternative construction options, such as: concrete and wooden construction (Dodoo et al., 2012; B. Peuportier, 2001); concrete and steel frame structures (Gervásio et al., 2014; Rossi, Marique, Glaumann, et al., 2012; Rossi, Marique, & Reiter, 2012); alternative thermal insulation materials (Audenaert, De Cleyn, & Buyle, 2012) and different insulation levels (Bribián et al., 2009; Gervásio, Santos, Simões Da Silva, & Lopes, 2010).

Examining the low-energy dwellings, a novel trend was identified (Blengini & Di Carlo, 2010b): the relative significance of LC phases and processes is changing, and the proportional contribution of embodied impacts is becoming more significant. Embodied energy (construction plus maintenance) can represent around 50-70% of the LC energy (Blengini & Di Carlo, 2010a; Citherlet & Defaux, 2007; Gustavsson & Joelsson, 2010; Verbeeck & Hens, 2010). Generally, LC studies on low-energy dwellings show that operational energy reduction is achieved with an increase in embodied impacts and that the balance between these two phases is important to be studied. It is critical to understand to what extent the additional embodied impacts reduce the achieved operational savings, and if they result in a lower LC impact.

In cold climate, the heating primary energy reduction achieved in VLE houses usually offsets the increase in embodied energy, although the magnitude of energy savings is intimately related to the heating system used as shown by some studies (Dodoo, Gustavsson, & Sathre, 2010; Verbeeck & Hens, 2010). The same conclusion was valid in a north Italian location: according to Blengini (Blengini & Di Carlo, 2010a) a VLE house built in Turin had lower LC impact than a standard one, but, whereas heating requirements were reduced by a ratio of 10:1, the house LC energy was only reduced by a ratio of 2.1:1. Sartori and Hestnes (Sartori & Hestnes, 2007) reviewed results from different houses (conventional, four low-energy, and a self-sufficient house) in Germany, and concluded that the LC energy of the self-sufficient building was higher than some low-energy alternatives. So, alternative building options must be carefully assessed, since options that allow operational energy consumption to be close to zero may not have the lowest LC impact.

Many of the reviewed LC studies considered the influence of both construction and operational alternatives in new dwellings. Even so, the studies are presented below based on their main emphasis (or their main conclusions), in order to sum up the existing knowledge regarding the influence of alternative envelope construction options and the influence of alternative operational conditions.

- **Envelope and construction influence**

Peuportier (2001) performed an environmental LCA of three French houses considering a lifespan of 80 years: a high insulated wood house (155 m^2, 35 kWh/m^2·year heating needs), a house with a solar heating system (212 m^2, 90 kWh/m^2·year heating needs), and a typical house with concrete blocks (112 m^2, 70 kWh/m^2·year heating needs). A sensitivity analysis was performed considering the materials selection (wood *vs*. concrete), two different wood-transportation scenarios (a national *vs*. an importation with higher transport distance), and changing the heating energy source (gas *vs*. electricity). The results showed the wood high-insulated house had almost half of the LC impacts of a typical concrete block house on a square meter basis; wood frame structure allowed significant CO_2 storage, and reduced the waste produced at demolition phase. The difference between wood and concrete houses in terms of CO_2 emissions was about 18%, but if accounted the end-of-life (wood incineration), this value may be reduced. Impacts related to the transport of building products were not very relevant (accounting 2.4% of LC CO_2 emissions in wood importation scenario). From this study it was also concluded that, comparisons about building components using different buildings are difficult to be clearly presented especially when few alternative buildings are presented. Therefore, comparing construction alternatives using a base case dwelling or equivalent buildings may be more useful.

The LC primary energy and carbon emissions of alternative concrete-frame and wood-frame multifamily buildings in Sweden have been compared by Dodoo et al. (2012) assessing the influence of thermal mass on space heating energy use production. Three versions were assessed for each construction type: an existing dwelling, a new dwelling meeting the current code, and a dwelling meeting the passive house standard. Results showed that, due to thermal mass, a concrete-frame building only had marginally lower space heating demand than a wood-frame alternative in a nordic climate. A wood-frame building was showed to have overall lower LC primary energy than a concrete one, thanks to its lower embodied energy and to the end-of-life benefits of recovering wood for bio-energy. Additionally, this study showed that a wood-frame current dwelling had lower LC energy than a concrete-frame passive house, despite the lower operational energy of the passive house. This was possible due to the low burdens of the operational heating system selected, as showed in other studies (Gustavsson & Joelsson, 2010; Joelsson & Gustavsson, 2009)

Fouquet et al. (2015) assessed three single-family passive houses located in Chambery in France: a timber house, a cast concrete house, and a concrete block house. The Passive houses with alternative envelope construction had identical life span (100 years), area (122 m^2), shape, and insulation, and their heating loads were covered by electric heating (12.3 $kWh/m^2 \cdot year$ for the timber house; 14.3 $kWh/m^2 \cdot year$ for the cast concrete house, and 15.9 $kWh/m^2 \cdot year$ for the concrete block house). The aim was also to identify the importance of considering biogenic carbon in VLE houses with timber construction. For the timber house, two end-of-life scenarios were considered - landfilling or incineration with energy recovery (avoiding natural gas consumption) - whereas for the other two houses landfilling was assumed. The study concluded that cast concrete house had the highest GWP impact, followed by the concrete block wall house. The timber house had the smallest GWP impact (less than 35% in 100 years) independently of the end-of-life scenario. Focusing only on embodied impact with no biogenic carbon the timber house held around 4 kg CO_2 eq/$m^2 \cdot year$, whereas the cast concrete house held around 6 kg CO_2 eq/$m^2 \cdot year$. Regarding biogenic carbon, it was shown that it is important to be considered especially in LCA of timber houses with alternative end-of-life scenarios. The authors (Fouquet et al., 2015) defended that landfilling wood after a 100 year lifespan has lower impact than wood incineration because it can prolong the carbon sequestration since the CO_2 stored in wood is only partially emitted when landfilled (as CO_2 and CH_4), whereas if wood is incinerated CO_2 is fully released. This latter finding contradicts Petersen and Solberg (2005).

➢ **Operational conditions influence**

Some literature studies also highlighted that the LC performance of new, passive or low-energy houses depends not only on the building construction but also (and mostly) on the operational conditions and assumptions (Blom et al., 2011; Brunklaus et al., 2010; Citherlet & Defaux, 2007; Gustavsson & Joelsson, 2010; Lewandowska et al., 2013; Stephan et al., 2013a). These studies show that a building is a complex product and that efforts and improvements in one LC phase (i.e., construction) can be fade away by careless options in another phase (i.e., use phase), which strengthens the idea that in new (or low-energy) dwellings the balance between pre-use and use phases is very important to be studied.

Citherlet & Defaux (2007) studied three variants of a Swiss house: a Swiss standard house; a low-energy house (with the Minergie label); a passive house (with increased insulation, a ventilation heat recovery system, solar collectors and photovoltaic panels). The use phase of the houses was studied assuming two alternative electricity production mixes (Swiss and UCTE). LC results were calculated based on three CML 92 categories as well as Non-Renewable Primary Energy (NRPE) requirements. Under a cold climate, the low-energy house was showed to have an improved LC performance (90% lower operational final energy than the standard new house). Considering the Swiss electrical mix, the results showed that NRPE was reduced by 33% in the Minergie house and 66% in the passive house in comparison to the standard house. Concerning CML 92 impacts, the two low-energy houses presented a similar performance with significant reductions (e.g. 62% for GWP, 29% for PO, and 10% for AP) in comparison to the Swiss standard house. The results highlighted the influence of the electricity generation mix: the Swiss mix had generally three times lower impact than the UCTE mix. Citherlet & Defaux (2007) even stated that the embodied impacts should be considered especially when the final energy demand (operation) is lower than 150 $MJ/m^2{\cdot}y$ for Swiss mix electricity production, and lower than 50 $MJ/m^2{\cdot}y$ for UCTE mix.

Gustavsson & Joelsson (2010) showed that embodied energy can be up to 45% and 60% of the LC primary energy for a Swedish conventional and a low-energy dwelling, respectively. They also highlighted that the LC primary energy and CO_2 emissions from both low-energy and existing buildings depended strongly on the energy supply and heating system adopted. Depending on the systems, an existing house (with biomass-based district heating with cogeneration) could have a lower impact than a low-energy house (with electric heating). Dodoo et al. (2010) also concluded that the type of heat supply system had greater impact on the primary energy of a multi-family wood-frame building than the final heat reduction measures of refurbishing an existing building to a passive house standard. The study advocated the use of district heating based on biomass cogeneration plant for Swedish dwellings.

Identical conclusions were found by Brunklaus et al., (2010), who also highlighted that Swedish houses (both new and existing) are strongly influenced by choices made by different actors (dwellers, building designers, and material producers). Thus lowering overall LC burdens of housing calls for jointly actions at different levels. Blom et al. (2011), who studied an apartment building with gas and/or electricity consumption, also showed that changes in user behavior can significantly affect household operational impacts: a reduction up to 60% of the operational impact was achieved thanks to a lower operational use of electric appliances and domestic hot water. The study highlighted that electricity consumption dominated the environmental impacts in dwellings with a low heat demand. Thus, two important strategies were suggested to reduce overall impacts of VLE dwellings: lowering electricity demand through user behavior and lowering electricity generation impacts (Blom et al., 2011).

Other authors (Lewandowska et al., 2013) performed a LCA of four detached single-family houses (passive and conventional houses with alternative masonry or wooden constructions) in Poznan, Poland. The study included the following activities over 100-year lifespan: operational energy (for HVAC, electric appliances, lighting and hot water), replacements, renovations, maintenance, land occupation, and waste management. Passive houses had a 3.6 lower heat demand than conventional dwellings but heating was covered by electric resistance heaters, while conventional houses had a gas-heating system. The results were presented in an aggregated environmental indicator (ecopoints) and they showed that operational energy consumption represented 82-85% of the LC impact over 100 years, while material production only represented up to 6% (in the masonry passive house). Operational energy was the most significant aspect in the LC of the four Polish houses assessed. Unlike most LC studies of new houses, in this study the alternative construction and energy thermal standard did not significantly alter the results. As a result of the different heating system used, the Passive houses (with electric heating) had higher use phase impact than the conventional houses (with gas-heating), namely due to the high environmental impact of electricity generation in Poland, which was 90% based on coal (Lewandowska et al., 2013). This study also showed that the aim of the passive house standard may be counteracted if a high impact heating system is used and that local conditions such as the electricity generation mix may deeply affect the conclusions of a LC study.

Using an input-output hybrid life cycle inventory approach, Stephan et al. (2013) studied the LC energy demand of a suburban Belgian passive house. Results showed the embodied, operational and commuting transport energy were responsible for 40%, 33% and 27% of the total LC energy, respectively. A parametric analysis showed that embodied energy represented the highest energy share in all passive house variations studied (up to 77% of the total embodied and operational energy) and that a significant variation on the total LC energy of the passive house (-30%) could be achieved integrating measures at different levels (building components; active systems using gas or electricity; users operational behavior; transport choices). But, due to embodied energy magnitude, the passive house only had slightly lower LC energy than a standard new house and, depending on the energy source, the LC results of the passive house could be worse than the standard house's (Crawford & Stephan, 2013; Stephan et al., 2013a).

Research from two inter-related Belgian projects (Verbeeck, 2007a; Verbeeck & Hens, 2007, 2009, 2010), developed a global methodology to optimize VLE houses considering three criteria (energy use, GWP, and costs). Five representative residential buildings were defined based on Belgian statistical data: a terraced house; a semi-detached house; two detached houses (one with square plan and the other with fragmented plan); and an apartment. For each building, a non-insulated reference scenario (typifying existing dwellings) was established and a large number of energy saving measures, building envelope construction options, and operational active systems (ventilation and heating systems) were assessed in comparison with the non-insulated scenarios over a 30-year life span. The goal of the analysis was to determinate the tradeoffs between energy use, GWP and costs. Results showed that in new Belgium dwellings complying with the legal thermal regulations, embodied energy represent up to 1/3 of the total LC energy, and only in new VLE houses the embodied energy sometimes surpassed the operational energy. The authors defended that in Belgium climate efforts should be focused on the reduction of operational energy. Optimizing LC energy and GWP, the following hierarchy of LC energy saving measures, independently of their cost, was presented for Belgian dwellings (cold climate): firstly, investing in a high insulation level (U=0.35 to 0.40W/m^2.K), air-tight windows, and well-designed natural ventilation system; secondly, selecting an efficient heating system, at least a high efficient boiler (or condensing boiler) or an air-to-water heat pump; finally, to reduce the ventilation losses through a heat recovery ventilation system, applying a ground-to-water heat pump and/or installing a solar driven system as a thermal solar collector or a photovoltaic system (Verbeeck, 2007b). Verbeeck (2007b) also stated that none of the energy and GWP optimized VLE solutions was economically cheaper than the reference building, and therefore without financial incentives the jointly adoption of the most effective measures to minimize primary energy and LC GWP may be restricted to a small number of consumers.

These studies (Verbeeck, 2007b; Verbeeck & Hens, 2007) showed that the tradeoffs among different construction and operational options are important to be studied to support the adoption of key options, but identifying the optimum technological solutions available, while worthwhile from a research point of view, may not support reality integration. Furthermore, after a dense assessment of non-dominated solutions the general building measures proposed are not very surprising since they are aligned with typical measures proposed for passive houses.

Most LC studies of new houses were performed for cold climate locations, where usually dwellers have continuous thermal comfort during the heating season. Operational heating and cooling loads included in LC studies of new dwellings are generally obtained by thermal calculation procedures based on steady-state models or on thermal dynamic building simulations (Chau et al., 2015). Dynamic building simulation has been advocated a good way to predict energy consumption of alternative construction options (Chau et al., 2015; Ortiz, Castells, et al., 2010b; Ortiz, Pasqualino, et al., 2010; B. Peuportier, 2001). However, some studies focused on operational energy stated that users behavior has not been adequately considered in most energy assessments of buildings (Hernandez & Kenny, 2010a) and that occupants behavior may be an important variable to determine the real operational energy (Daniel, Soebarto, & Williamson, 2015; Hernandez & Kenny, 2010b; Majcen et al., 2013; Sunikka-blank & Galvin, 2012). In cold climate dwellings, thanks to occupant behavior, inefficient dwellings were found to consume much less energy than predicted by energy simulation, but conversely, some very energy-efficient dwellings consumed more energy than predicted (Majcen et al., 2013). Due to the lack of detailed data, only a few studies used real energy consumption data (Chau et al., 2015).

2.2.2. Dwellings in Mediterranean and Portugal

Until 2012, most LCA studies of dwellings were performed for cold climate and the mild Mediterranean and Portuguese dwellings have seldom been addressed (Anastaselos, Giama, & Papadopoulos, 2009; Bribián et al., 2009; Monteiro & Freire, 2010b, 2011; Nemry et al., 2008; Ortiz, Bonnet, et al., 2009). Meanwhile, the number of LCA studies of dwellings have been growing rapidly. Recently, some LC studies were performed for Mediterranean and Portuguese dwellings (Bastos, Batterman, & Freire, 2014; Bastos et al., 2015; Gervásio et al., 2014; Monteiro et al., 2016; Monteiro & Freire, 2012; Ortiz, Castells, et al., 2010a; Proietti et al., 2013; Rossi, Marique, & Reiter, 2012). From those studies, some presented results for cold winter locations (e.g., northern Italy (Blengini & Di Carlo, 2010a; Rossi, Marique, Glaumann, et al., 2012)), other focused on existing buildings (Bastos et al., 2014) and covered retrofit options (Ferreira, Duarte Pinheiro, & De Brito, 2015; Gaspar & Santos, 2015; Rodrigues & Freire, 2014, 2017; Rosselló-Batle et al., 2015; Silva, Mateus, Marques, Ramos, & Almeida, 2015), another focused mainly on specific building components such as: green roofs (Fioretti, Palla, Lanza, & Principi, 2010), thermal insulation materials (Pargana, Pinheiro, Silvestre, & De Brito, 2014), exterior walls (Baglivo, Congedo, & Fazio, 2014; Ortiz, Pasqualino, et al., 2010; Silvestre, De Brito, & Pinheiro, 2011) and solar systems integration (Silva et al., 2015). A few other studied LCA methodological developments (Gervásio et al., 2014; Silvestre, De Brito, & Pinheiro, 2014; Silvestre, Lasvaux, Hodková, de Brito, & Pinheiro, 2015) or supported the development of sustainable assessment/certification tools for buildings (Mateus, 2009; Mateus & Bragança, 2011; Pinheiro, 2008). In the following paragraphs studies focused mainly on LCA of Mediterranean and Portuguese dwellings are reviewed.

- **Envelope and construction influence**

Bribián et al. (2009) presented a simplified LC study of a new Spanish house (complying with the thermal building code) located in Aragon. The study included only pre-use and use phase (heating, cooling, and domestic hot water production). Results showed that pre-use phase held 95 kWh/m^2·year and 25 kg CO_2/m^2·year which was around 30% of the LC energy and 45% of the CO_2 emissions of the house, respectively. An improved thermal performance was studied base in an incremental thickness of EPS insulation (0-20cm). LC carbon emissions and primary energy results suggested that thicknesses above 3-5 cm did not add significant LC benefits for the house in Aragon. This study showed that the thermal insulation level should be adapted to the climatic conditions using a LC perspective. Blengini and Di Carlo (2010a, 2010b) assessed a VLE house in northern Italy, encompassing all LC phases, and briefly compared it with a standard new house assuming a 70-year lifetime. LCIA results were presented for midpoint environmental categories (Blengini & Di Carlo, 2010a) and for single score end-point indicators (EI'99, Ecological footprint, EPS2000) (Blengini & Di Carlo, 2010b), which are known to be more uncertain, but are expected to simplify the decision process. Although the VLE house presented a reduction of LC impacts relative to the standard house, the magnitude of the reduction varied significantly with the end-point indicator used (e.g. reduction of 60% for NRPE, 52% for EI'99, and 38% for EPS2000). Results showed the VLE house had four times lower NRPE and ten times lower heating NRPE than the standard house. Focusing only on use phase, the VLE house seemed to have a greater benefit than considering all life cycle.

While heating was the most important LC process of the standard legal house, in the VLE house material-related impact was the most significant. Structure and finishing materials had the highest NRPE contribution (30%); maintenance and EOL were also identified as significant, holding 15% and -8% of the NRPE, respectively. According to Blengini & Di Carlo (2010b), a relevant aspect about low-energy dwellings is that these have higher embodied burdens, which may reduce or even cancel their real operational benefit.

Nemry et al. (2008, 2010b) modeled alternative residential buildings (single-family, multifamily, and high-rise) to assess the environmental impacts of the residential building stock of European Union (EU-25). Among other results the study showed the LC impacts of dwellings in Southern Europe were significantly lower than those associated with buildings in Central and Northern Europe mainly due to the lower heating energy consumption. New single-family houses (built in the last decade) in Southern Europe (data averaged from locations with 564 to 2500 heating degree days and based on EU-25 building stock from Malta, Spain, Portugal, Italy, Greece, France and Cyprus) were shown to have 50% to 70% overall lower overall LC impacts than existing houses operation over 40 years. Under this study, two single-family houses built after 2006 with brick masonry construction and reinforced concrete slabs structure were modeled to represent typical new south European single-family houses. Operational phase (mainly due to heating) was identified to be the most significant phase, whereas construction phase represented around 1/3 of the LC impact. The end-of-life phase was shown to be of much lower significance. The study concluded the relative importance of each LC phase varied from one impact category to the other, and therefore a comprehensive LCA with multiple environmental impact categories was advocated. Regarding GWP, the new south European houses assessed were shown to hold: 32.7-33.3 kg/m^2·year in their LC, with 20.9 kg/m^2·year from operational HVAC, 10.9-11.8 kg/m^2·year from construction, 0.7-0.9 kg/m^2·year from maintenance activities, and 0.5-0.9 kg/m^2·year from end-of-life management. The study concluded that for new single-family houses, the use phase environmental burdens were dominated by thermal losses through ventilation, followed by the exterior walls and the roof. Regarding the embodied burdens, the most significant building components were, in a descending order: exterior walls, basement, floors, and ceilings. In this study (Nemry et al., 2008, 2010b), continuous interior thermal comfort conditions during the heating season were assumed, and the influence of different operational conditions and cultural user behavior were not accounted.

Recently a study (Rosselló-Batle et al., 2015) focused on the relationship between the initial embodied energy and the thermal energy demand for heating and cooling a dwelling located in the Mediterranean Balearic Islands (Spain), considering three building typologies (detached house, terraced house, and a duplex in a multifamily building), and several construction options: ten exterior walls including five alternative insulation materials, three roofing systems, and two window frames. Regarding all construction alternatives, the embodied energy of the detached house varied from -180 MJ/m^2 to +723.6 MJ/m^2 in comparison to the base case; though, the embodied energy of the base case was not clearly presented. Regarding the insulation materials, assuming the same thickness (12 cm), the use of PUR or XPS panels instead of mineral wood had higher embodied energy but it was offset by the lower thermal operational energy during the lifespan; whereas the house with EPS or projected PUR had generally overall higher primary energy than with mineral wool insulation. The replacement of the slopped roof by a flat roof showed reduction of both operational and embodied energy. Additionally, the correction of thermal bridges was shown to have significant impact on heating needs reduction: for instance in the detached house it represented a heating reduction above 20% and a cooling reduction above 4%. The results for single-family houses showed the additional embodied energy of the wall-to-floor slab joints insulation was offset in less than five years by the heating operational savings. The results also showed that the house typology had a big impact in the house primary energy. The duplex apartment dwelling had significantly lower embodied and operational energy than the detached house: a 75 kWh/m^2 (or 271 MJ/m^2) reduction in pre-use phase, and an operational heating reduction of 75% (15 $kWh/m^2 \cdot year$ or 54 $MJ/m^2 \cdot year$), and an annual cooling reduction of 50% (8 $kWh/m^2 \cdot year$ or 28.8 $MJ/m^2 \cdot year$). This study reinforces the idea that the balance among embodied and operational impact of alternative building options is very important to be studied in new dwellings considering specific local conditions (climatic and operational). Furthermore it suggests that more than building typology, the building shape may influence overall LC results.

- **Operational conditions influence**

A LCA of a typical Spanish semi-detached house (Ortiz, Bonnet, et al., 2009) concluded that LC studies can play an important role in supporting decision-making at building sector. In this study, material production, transport, maintenance and operational energy consumption (heating, ventilation, cooling, hot water, lighting, electrical appliances and cooking) were taken into account. Considering six CML impact categories, operation had the highest environmental impacts (70-92%). Focusing in GWP results, the house accounted for 2340 kg $CO_{2\,eq}/m^2$ over 50 years, with the embodied GWP holding 196 kg $CO_{2\,eq}/m^2$ (8.4%). Regarding operational phase, it accounted for 41.5 kg $CO_2/m^2\cdot$year, and cooling was the most significant process (26%) followed by lighting (21%), hot water (21%) and electrical equipment (16%). Unlike in cold climate, the Mediterranean house heating only represented 7% of the operational GWP. These results show how operational processes can significantly vary its relative importance with climatic conditions. The use of building energy simulation tools were defended to be the best way to predict heating and cooling energy consumption for a specific climatic location.

The same Spanish house was compared to a Columbian house considering a functional unit of one square meter of living area over 50 years (Ortiz, Castells, et al., 2010a, 2010b). Two scenarios were assumed with different energy supply systems (total electricity and natural gas plus electricity) and the two dwellings had very different operational energy requirements due to different consumption patterns: heating and cooling were not considered in the Columbian reality, resulting in a lower value. Focusing in GWP results, the Columbian house accounted for significantly lower LC results, holding 780 kg $CO_{2\,eq}/m^2$, with embodied impact holding 238 kg CO_2/m^2 (32%). Regarding use phase, it represented 64% of the Columbian house GWP. Maintenance represented 4%, and the end-of-life (landfill) only accounted for 1% in both houses. The operational energy impact was shown to be lower in Colombia due to bio-climatic conditions, user behavior, and the significantly lower impact of the Columbian electric energy mix (when compared to the Spanish). Even though, the use of natural gas to replace part of electricity consumptions was shown to be a favorable measure for both houses: the source of energy used deeply influenced the primary energy (and the associated environmental impacts). Although this study (Ortiz, Castells, et al., 2010a) did not considered the influence alternative operational heating and cooling habits may have in the same house under the same climate conditions, it shows that a detailed LCA of buildings needs to consider not only accurate climatic data but the energy sources used, the national electric mix, and typical dweller operational habits.

Rossi et al. (2012; 2012) studied one residential building for three different European locations: Brussels in Belgium, Luleå in Sweden, and Coimbra in Portugal (mild Mediterranean climate). Alternative structural construction, different heating systems and local electricity generation mix (for 2008 year) were considered for each location. Operational phase was also identified as the most significant LC phase in the three locations, but results showed that the electricity generation mix of a country highly influenced the operational carbon emissions of the house, being able to reverse the conclusions regarding the carbon footprint of the building; for instance, the operational energy in Sweden (328 kWh/m^2·year) was higher than in Portugal (175 kWh/m^2·year) but it accounted for the lowest operational carbon emissions: (2.9 kg CO_2/m^2·year in Sweden *vs.* 39 kg CO_2/m^2·year in Portugal).

The jointly effect of dynamic (zoned and intermittent) operational patterns and thermal mass (inertia) was assessed for three super-insulated multifamily buildings both for hot and cold climate in one study (Stazi, Tomassoni, Bonfigli, & Di Perna, 2014). The authors concluded that in highly insulated envelopes, thermal mass had low influence on operational energy savings (marginal benefit). Additionally, thermal mass (masonry alternative) had a bigger effect on comfort levels (less discomfort hours for intermittent cooling) but it had 20% higher environmental LC impacts (using ecoindicator'99 method).

Proietti et al. (2013) assessed an energy-efficient house meeting the passive house standard located in Perugia, Italy. The study included pre-use, operation, maintenance, and end-of-life (including selective dismantling and recycling) stages. The house had a reinforced concrete and steel structure, a secondary wood structure and wooden building components. Regarding the operational systems, a heat pump HVAC system (5.75 kW_t) with heat recovery was used and a photovoltaic (PV) system (6.4 kW_P) that covered operational energy was included. The pre-use phase was accountable for 319 MJ/m^2·year of primary energy (225 MJ/m^2·year of NRPE) and 16 kg $CO_{2\,eq}$/m^2·year. Including all household energy uses and excluding the PV renewable energy generation, the actual electricity consumption was 21.5 kWh/m^2·year accounting for 251 MJ/m^2·year (20% of the LC NRPE), with HVAC being responsible for 11.1 kWh/m^2·year. Maintenance held 10-18% of the LC impact. Assuming selective dismantling and recycling, the end-of-life held a benefit of 1/3 of pre-use energy and a reduction of 5-20% of the house LC impact. The annual PV electricity production was 28.4 kWh/m^2·year, which held a 50-65% benefit when compared to the house LC impact (without PVs). The authors conclude that new houses can have significantly reduced LC impact (when compared to existing dwellings) if careful selection of construction materials (renewable material incorporation), active systems and end-of life procedures are undertaken.

Dwellings in Portugal

Some LC studies of Portuguese dwellings were found (Bastos et al., 2014, 2015; Gaspar & Santos, 2015; Gervásio et al., 2010; Monteiro et al., 2016; Monteiro & Freire, 2010a, 2011, 2012, Rodrigues & Freire, 2014, 2017), most of which were published in the last 5 years. Some already recognize that Portuguese dwellers have typically lower operational patterns when compared to other European countries due to usual intermittent and partial heating and cooling habits (Gaspar & Santos, 2015; Gervásio et al., 2014; Pinto, 2008; Rodrigues & Freire, 2017). But only a few studies address new dwellings (Bastos et al., 2015; Gervásio et al., 2014; Pinto, 2008) and without considering the operational user behavior influence jointly with alternative building design, envelope options and operational conditions on overall LC results.

Pinto (2008) addressed construction options (masonry exterior walls with varying coatings and thermal insulation materials and glass curtain walls) for buildings (office and residential) assuming 10% of the Portuguese thermal standard comfort levels (RCCTE, 2006), but without addressing building design influence on overall LC results. This study already identified that in the Portuguese context embodied impacts can be five to six times higher than the heating impact. Construction, heating, and end-of-life represented around 75-80%, 12-18%, and 7% of the overall impact, respectively (CO_2 emissions and primary energy). The dwelling assessed held 29.4 kg $CO_2/m^2{\cdot}$year and 460 MJ/ $m^2{\cdot}$year. The study also concluded that depending on the interior set-points thermal operational energy could be significantly reduced (e.g., a 45% reduction was achieved in a building in Lisbon just by changing from 20-25ºC set-points to 18-17ºC).

Gervasio et al. (2010) performed an LC energy analysis of single-family house (165 m^2) with a light weight steel frame construction over a 50 year lifespan. The study assumed an 80% steel recycling rate at end-of-life and credited the system for avoiding primary steel production (due to the production of secondary steel from recycled scrap). Embodied energy was around 800 GJ and a benefit of around -23% LC energy was credited to the system due to recycling. The study also assessed the influence of alternative thermal insulation on the balance between embodied and operational energy. Results showed that operational energy (only heating and cooling) could represent around 50-80% (1900-2400 GJ) of the dwelling LC energy depending on the envelope thermal performance. The adoption of an increased envelope insulation was recommended (e.g., exterior wall U-value: : 0.158 $W/m^2{\cdot}$ºC, roof U-value: 0.188 $W/m^2{\cdot}$ºC and window U-value: 1.9 $W/m^2{\cdot}$ºC). This study did not assume typical Portuguese operational patterns and light weight steel frame construction is not frequently used in Portuguese residential building practice.

Monteiro and Freire (2010a, 2012) assessed a Portuguese single-family house, and compared seven exterior walls solutions in terms of primary energy, and multiple environmental impact categories using three different LC impact assessment methods – cumulative energy demand, CML 2001 and EI'99. The study showed that the rank of the alternative walls may change depending on the LCIA method and environmental category chosen: OLD and PO results may diverge from carbon related environmental categories, which generally presented identical ranking of alternatives among them (NRPE; GWP; AP, AD). In a scenario analysis, the same house with different exterior walls (wood wall vs. facing brick wall) but with similar U-values, achieved a reduction of 7% of LC energy. The wood wall solution had the lowest LC energy and environmental impacts in most environmental categories. This study used the Portuguese building thermal regulation (RCCTE) to calculate the house heating and cooling energy requirements but included two alternative operational patterns assuming two reduction factors (0.5 and 0.1) to represent different occupancy and comfort levels of Portuguese householders and to frame alternative user behaviors in Portuguese context. The results showed that the operational pattern influenced the most significant LC phase and process: in Portuguese houses with reduced HVAC levels, material production becomes the most important process. This is a new finding regarding most of the previous LCA studies and this thesis was based on the preliminary results presented in Monteiro and Freire (2012).

Some recent Portuguese LC studies have mainly focused in developing new methods to support decision (Gervásio et al., 2014; Santos, Martins, Gervásio, & Simões Da Silva, 2014; Silvestre, de Brito, & Pinheiro, 2013) or to further study methodological aspects of LCA of construction works (Silvestre et al., 2013, 2014, 2015). Silvestre et al. (2013) developed a method to perform environmental, energy and economic assessment of building components (or assemblies) from cradle-to-cradle in accordance with European standards, and applied it to support decision regarding the choice to exterior walls. The method used weighting to quantify each environmental category in the same unit (eco-costs) and the overall costs of each exterior wall were obtained to more easily support a material assembly selection.

Gervásio et al. (2014) developed a LC methodology based on a macro-components approach to more easily account for potential environmental impacts in the early stages of building design. The methodology provided a range of macro-components (pre-defined building construction solutions) integrating LC embodied data. A residential building was assessed using both the simplified LC methodology at an early design stage and LCA jointly with dynamic energy simulation based on complete data from design stage. The study included material production, construction, use phase, the end-of-life management and the benefits/loads of recycling. Three structural constructions scenarios were assessed (a light weight steel frame construction; a steel structure with hot-rolled profiles; and a reinforced concrete structure with brickwork walls) and the overall LC primary energy of the three house was 36.5 MJ/m²·y, 59.3 MJ/m²·y, and 50.5 MJ/m²·y, respectively. Results per LC phase were only presented for the light weight steel frame scenario, though this scenario is not very common among Portuguese residential buildings. This study referred that in Portugal, user behavior plays a key-role in energy consumption, and have assumed an occupancy schedule (to account for typical internal gains) and a limited operational period of the HVAC system (from 17:00 to 23:00 h). However, these assumptions were kept constant along the study and therefore the influence of alternative user behavior was not studied. With the occupancy and operational schedule assumed, material production of the light-weight steel frame house dominated all impact categories holding from 60-85% of the LC impacts. Operational had a much lower significance representing 5-25% of the LC impacts. The recycling and recovery of materials was considered to provide a large benefit (credits) in the end-of-life of the light weight steel frame house, being the second most significant LC process for most categories; for instance, it accounted for -20% of LC fossil primary energy in that building. In Gervásio et al. (2014) only total LC results are disclosed to rank the three constructive solutions. As material recovery and recycling activities will take place far in the future encompassing a high uncertainty, including credits in the end-of-life (to represent future potential avoided burdens of recycling and material recovery) needs to be transparently presented (to prevent misleading conclusions), especially when alternative solutions are compared. Additionally, presenting alternative end-of life scenarios may help understand how the environmental impacts of a building may vary due to the uncertain end-of-life. For instance, Silvestre et al. (2014) methodologically detailed and explained the system boundaries of two approaches defined by the European Standards EN 15804 (CEN, 2012) and EN 15978 (CEN, 2011) than can be used in LCA studies to model building material waste flows at end-of-life stage, regarding the reuse, recovery and/or recycling potential (benefits beyond the system boundaries) in order to promote a cradle-to-cradle thinking (Silvestre et al., 2014).

Bastos et al. (2014) compared the LC energy and GHG emissions of three multifamily residential buildings from 1940 located in Lisbon using two alternative functional units: per square meter per year, and per person per year. The building construction, retrofit and operational phase were accounted. An econometric model based on occupancy and building characteristics was used to account for household operational energy consumption. The use phase was shown to account for most (69–83%) of the primary energy requirements and GHG emissions of the buildings (over a 75-year lifespan). The smaller multifamily building was shown to have the highest impact per square meter (283-324 MJ/m^2·year; 18 kg CO_{2eq}/m^2·year) whereas it had the lowest impact per occupant (11 554-13 237 MJ/person·year) due to its higher occupancy per useful area. Thus, the authors highlight that depending on the functional unit selected, the ranking of different residential buildings assessed may differ. Another LC study (Bastos et al., 2015) compared an urban apartment building with a suburban semidetached house located in Lisbon metropolitan area. The study included the daily transportation of the dwellers during the lifespan in order to assess the influence of building location. As both dwellings had similar size, construction materials and occupancy, the major difference among them was attributable to user transportation impact. Results showed that commuting user transportation could represent more than half of the NRPE of a detached house located in a suburban area (ranging from 63-512 MJ/m^2·year and from 3.7-30 kg CO_{2eq}/m^2·year) depending on the location. The detached house use phase accounted for 276 MJ/m^2·year and 20 kg CO_{2eq}/m^2·year, whereas construction only held 65 MJ/m^2·year and 5.6 kg CO_{2eq}/m^2·year.

Gaspar and Santos (2015) compared the LC energy of two scenarios: a major renovation of an existing Portuguese house, and the demolition of the existing house and construction of a new building. Though the focus was on the refurbishment of an existing dwelling, which was shown to present 18% lower LC energy than the demolition and new building scenario. This study also concluded that for both scenarios (refurbished and new house) embodied energy surpassed operational energy, and that the prevailing logics of cold climate houses should not be directly transposed to other building or climatic contexts (Gaspar & Santos, 2015).

A dwelling LC impact depends not only on the building characteristics, but also on the joint effect of the energy conversion efficiency, energy source and supply chain (Gustavsson & Joelsson, 2010; Ortiz, Castells, et al., 2010a) and users (Monteiro, Fernandez, & Freire, 2012). In warm summer Mediterranean locations, climate conditions are not as harsh as in cold climate: interior comfort conditions and operational patterns are more easily dependent on user behavior. The regional electric production mix (share of renewable) may also play an important role in characterizing the potential impacts of use phase (Ortiz, Castells, et al., 2010a, 2010b; Rossi, Marique, Glaumann, et al., 2012; Rossi, Marique, & Reiter, 2012). Despite the existing studies, the options available (building construction practices; systems and electricity supply chains) vary from region to region. For instance, in Portugal, district heating, which seems to have the lowest impacts in Swedish housing, is not usually an option. Therefore, LCA studies should be applied to different contexts in other to evaluate each context idiosyncrasies and to identify overall preferable building practices.

In Portugal, as possibly in other south European countries, dwellers operational heating and cooling habits are mostly partial and intermittent due to cultural and economic constraints (INE-I.P./DGEG, 2011). In this context, we are likely to assist to a high gap between expected (assuming continuous interior thermal comfort) and actual energy consumption of dwellings. Real heating and cooling data tend to be lower thanks to users' behavior (INE-I.P./DGEG, 2011). This phenomenon also is named the *prebound effect* (Sunikka-blank & Galvin, 2012). Therefore, as suggested by studies focused on operational energy (Daniel et al., 2015; Hernandez & Kenny, 2010b; Majcen et al., 2013; Sunikka-blank & Galvin, 2012), and a sensitivity analysis study on interior set points (Pinto, 2008), user behavior may significantly affect the contribution of operational burdens (Monteiro & Freire, 2012) and indirectly the relative significance of embodied burdens.

The literature covering new houses in mild Mediterranean climate and in Portuguese context is sparse and the existing studies did not consider the influence alternative operational user behavior may have in a house LC results, jointly with different envelope, design and operational options. In new houses embodied and operational impacts are both significant, but their LC contribution seems highly sensitive to construction options, energy systems adopted, as well as local or regional aspects (electricity production mixes). This literature review showed that LC impacts are highly inter-related, as options in one phase can significantly influence other phases, for example, material selection affect burdens of many phases (embodied energy, transport emissions, service life and maintenance schedules and recycling potential). In low-energy houses there is not a single process that dominates the building environmental LC performance, but several similarly important (Blengini & Di Carlo, 2010b). Furthermore, LC studies of VLE houses have shown that using multiple environmental categories is important to assess whether the benefits of lowering operational energy requirements can be confirmed in a broad environmental LC perspective, preventing problem shifting.

New houses are expected to have lower operational energy than existing houses and at the same time offer better comfort conditions; however, current building regulations neglect embodied energy. Therefore, it is essential to assess the relative importance of the embodied impacts (in construction) when compared to operational heating and cooling impact considering current Portuguese operational habits and assessing different operational conditions influence, because under mild Mediterranean climate, building envelope and design options might be the solution to achieve a significant operational energy reduction.

2.2.3. Building envelope options

Some LC studies of residential buildings have considered alternative envelope and construction options for the same dwelling. Thus, an overview of the main findings of previous studies of dwelling regarding these options influence can be found below.

Envelope thermal performance

Construction options affecting the thermal performance of the building envelope were assessed from a LC perspective, namely different insulation layers of exterior wall and roofs, and higher air-tightness of windows (Bribián et al., 2009; Gervásio et al., 2010; Pinto, 2008; Rodrigues & Freire, 2014, 2017). Generally studies suggest that the thermal insulation level should be adapted to the climatic conditions using a LC perspective. Bribián et al. (2009) suggested that EPS (0.037 W/m·k) insulation thicknesses above 3-5 cm do not add significant LC benefits in a Spanish house located in Aragon. Pinto (2008) suggested that for Lisbon the adequate insulation level would be 10 cm (rock wool or XPS). Gervásio et al. (2010) suggested opaque building envelope U-values around 0.16-0.19 $W/m^2 \cdot ºC$ (14 cm rock wool insulation plus 6-10 cm EPS insulation) for a lightweight steel house in Coimbra. But, none of these studies explored how thermal insulations tipping points varied with alternative user behavior.

Building components

Regarding the building components magnitude, exterior walls have been identified as a very significant building component, especially in studies addressing single-family houses (Blanchard & Reppe, 1998; Haapio & Viitaniemi, 2008b; Keoleian et al., 2001; Nemry et al., 2008, 2010b; Verbeeck, 2007b; Verbeeck & Hens, 2010). Walls, floors, foundations and roof were shown to be (in descending order) the building components with the highest embodied primary energy (Blanchard & Reppe, 1998; Keoleian et al., 2001). Similar results were found by Happio (Haapio & Viitaniemi, 2008b) and Nemry (Nemry et al., 2008, 2010b) who also identified the exterior walls and roof as the components that hold most of the embodied impact of new houses in EU-25. Additionally, building ventilation was identified as a major source of heat losses having a big influence on operational energy.

Haapio and Viitaniemi (Haapio & Viitaniemi, 2008b) conducted an environmental assessment of 78 single-family houses focusing on buildings envelopes, to analyze how different structural solutions and building materials affect the environmental impact of a whole building. In this study, operating energy was not included, and the interiors and the structure of the buildings were assumed to be identical. The envelopes studied were different in term of: insulation type (cellulose and fiberglass, fiberglass and rock wool), cladding materials (brick, stucco, steel, wood cladding), window frame materials (wood, aluminium), and roof materials (concrete tile, clay tile, steel). The environmental impact estimator was the method chosen and Athena LCA tool was used, considering six impact categories: primary energy, GWP, solid waste emissions, pollutants to air, pollutants to water and resources use. The solution with lowest environmental impact point include cellulose and fiberglass as exterior and interior wall insulation, respectively, wood cladding, wood frame windows, and steel or concrete tile as roof material. Varying the length of the service life from 60 to 160 years, results showed that buildings with a higher life span had lower impacts per year. According to Haapio and Viitaniemi (2008b), since the buildings life span is often decades, maintenance and renovations should be scheduled to assess their environmental impact in the overall LC of a building.

Using an IO-hybrid life cycle inventory approach, Crawford et al. (2010) presented the LC energy of eight envelope building components (two roofs, two floors, and four exterior walls) to be used in Australian dwellings. Results ranked the alternatives as follows: a timber frame concrete tile roof had 18% lower NRPE than a timber frame steel sheet roof; a concrete slab on ground floor had 32% lower NRPE than an elevated timber floor; regarding the exterior walls, a polystyrene timber frame wall had the lowest NRPE followed by the brick veneer timber frame, the brick veneer steel frame, and lastly the timber weatherboard wall. The authors argued that IO hybrid results are significantly higher when compared to existing and previous presented process-based data, so further research should be focused on producing an IO hybrid inventory data for building materials and components.

Some publications have focused on exterior walls. For instance, Ortiz et al. (2010) assessed the construction phase of an apartment block considering typical Spanish exterior and interior wall scenarios. The CML method was used to assess acidification, GWP, ionizing radiation, and OLD impacts as well as energy and resource consumption. The steel elements, in particular galvanized steel, were responsible for high environmental impacts. Another study indicated that houses with wood-based wall systems required 15–16% less primary energy and 20-50% less GHG emissions over a 100-year lifespan than thermally comparable houses with alternative concrete- or steel-based walls (Upton, Miner, Spinney, & Heath, 2008).

Five factory-built wood-frame exterior wall assemblies were assessed for a house in Quebec (Canada) concerning energy and three LCIA methods: TRACI; Impact 2002; and EI'99 (Frenette, Bulle, Beauregard, Salenikovich, & Derome, 2010). Midpoint results were calculated for the mentioned methods and endpoint results were presented for Impact 2002 and EI'99. The goal of

Frenette et al. (2010) was to support the selection of an appropriate environmental index to be included in a multi-criteria decision analysis evaluation. The results showed the two alternatives with wood cladding and blown cellulose insulation had the lowest LC impacts in all categories except for OLD, whereas the alternatives with brick veneer cladding had generally 1.5 to 3 times higher embodied impacts. Regarding the different LCIA methods used, slightly different rankings of alternatives were observed for some midpoint category results, namely, respiratory organic, eutrophication, and minerals. Nevertheless, Frenette et al. (2010) concluded that endpoint results generally presented a similar ranking of alternatives, and that it seemed acceptable to use climate change category as a single environmental index.

Mateus (2009) developed a database for building components (36 walls, 16 floors, and 36 construction materials) based on ecoinvent data. The CML 2 environmental results were presented per m^2 of building component surface for cradle to gate and for one end-of-life scenario separately. The environmental data was included in a sustainability assessment methodology developed for buildings that aggregates all embodied environmental impacts in one environmental indicator, which is used jointly with a social and an economic indicator to assess the overall sustainable performance of the buildings. Despite the database developed, due to the broader aim of the methodology developed, alternative envelope options have not been compared to assess their overall influence in the LCA assessment of a building.

Silvestre (2012) performed an environmental assessment of 60 alternative exterior walls with alternative construction materials partially based on inventory data modelled for Portuguese producers. In this study, wooden framed walls were not assessed, even so, a significant variation was found between embodied impacts. Compared to the base case wall (W1: concrete hollow block masonry with 8 cm exterior stone wool insulation layer (ETICS)) the embodied GWP of the alternatives studied ranged from -37% to +79% (impact without operational stage). Regarding the single pane walls, the alternatives with glass fiber reinforced concrete presented the worst environmental performance (5 categories), whereas alternatives with ETICS were identified to have the best environmental performance. Regarding the double brick cavity walls the alternative with the lowest environmental impact had cement mortar as exterior and interior cladding and LWA insulation layer completely filling the cavity between the two panes. Conversely, in a study focused on insulation materials (Pargana et al., 2014), LWA was shown to be the insulation material with generally higher impact when compared to other alternatives (e.g., EPS and PUR). In Silvestre (2012), the exterior wall environmental LCA performed was aggregated being converted to an eco-cost unit to be used in an innovative LC cradle to cradle environment, energy, and economic assessment methodology (3E cost C2C), however due to this aggregation, the different environmental impact of the construction alternatives assessed resulted in minor eco-cost difference amongst alternatives.

Rodrigues and Freire (2014) compared the embodied energy of three pitched roofing scenarios (wood frame, light steel frame and lightweight concrete slab) with the same thermal insulation and concluded that the wooden framed roof had generally 40-60% lower embodied impact than the concrete slab roof for climate change, freshwater eutrophication, acidification and ozone depletion.

Materials

Regarding materials, the use of wood in building components (roofs; walls, windows, floorings) is usually identified as a better alternative to other materials (e.g., brick, concrete, vinyl, linoleum, aluminum) with regard to waste generation, GHG and SO_2 emissions (Petersen & Solberg, 2005), and energy related impacts (Salazar & Meil, 2009). A review study (Petersen & Solberg, 2005) advocated that careful attention should be payed to wood preservative treatments, since these may have toxicological impacts; the same study also argued that to take the most out wood materials, wood should not be landfilled at end-of-life (Petersen & Solberg, 2005) mainly due to the methane emissions of cellulosic materials degradation (under anaerobic conditions) in landfills (Upton et al., 2008).

Pargana et al. (2014) compared alternative thermal insulation materials (EPS, XPS, PUR, LWA (expanded clay lightweight aggregate), ICB (expanded cork agglomerate)) based on a functional equivalent unit that provides a thermal resistance of 1 ($m^2 \cdot K$)/W. The inventory performed was adapted (from ecoinvent database) to Portuguese building material production based on local material producer data (whenever possible) and using the Portuguese electricity generation mix (of 2011). Results showed that EPS and PUR had a lower impact (in all categories) and generally presented better results than the other alternatives. ICB had a low NRPE, GWP and ADP, due to its low consumption of fossil fuels and because it is based on a renewable raw material, but it had a high eutrophication impact due to production phase. XPS had similar results to PUR, except for its higher GWP and Photochemical oxidation. XPS boards with thickness above 8 cm have slightly higher impact than thinner boards of XPS due to the different blowing agents used. LWA generally had the highest impact due to fossil energy during production and due to its high reference flow associated with the functional unit selected (Pargana et al., 2014).

Structures

Some studies compared alternative structural construction: wooden *vs.* concrete (Dodoo et al., 2012; Lippke, Wilson, Perez-garcia, Bowyer, & Meil, 2004; B. Peuportier, 2001), wooden *vs.* steel

(Lippke et al., 2004; Rodrigues & Freire, 2014), or concrete *vs*. steel (Gerilla, Teknomo, & Hokao, 2007; Gervásio et al., 2014; Rodrigues & Freire, 2014; Rossi, Marique, Glaumann, et al., 2012; Rossi, Marique, & Reiter, 2012). Generally, studies concluded that a wood-frame dwelling has lower primary energy and GWP than a concrete-frame or a steel frame dwelling (Dodoo et al., 2012; Petersen & Solberg, 2005; B. Peuportier, 2001) due to the lower embodied impacts of wood as a natural material, biogenic carbon storage, and/or the greater bioenergy recovery benefits that can be accounted in the end-of-life (Dodoo et al., 2012). Regarding the comparison of concrete-frame and a lightweight steel-frame construction, the results are not so obvious, since they are highly dependent on the end-of life assumptions and credits included for recycling of steel. Gervásio et al. (2014) showed that assuming a high recycling share of steel (and crediting the system for it), a dwelling with lightweight steel construction had overall lower impact than a dwelling with reinforced concrete structure and brick masonry construction. However, structural construction of dwellings is deeply influenced by the current regional construction practices (Nemry et al., 2008, 2010b).

2.3. Concluding remarks

The major focus of this literature review was to examine LC studies of residential buildings as a whole, and summarize their findings regarding the influence of general building concepts and options. From the studies reviewed, it was possible to identify the need for further research in the south European mild Mediterranean context, more specifically in the Portuguese context regarding new houses development, which had seldom been addressed.

Based on existing literature it was possible to highlight that user behavior operational patterns influence has not been properly addressed by previous LC studies and that it may be important to be studied from a LC perspective especially in countries with mild climate conditions and typical low operational patterns as Portugal. Numerous studies on new houses or houses with very low operational energy consumption highlight that to reduce the overall LC impact of new dwellings not only construction options need to be considered but also operational conditions, such as: active systems used and local energy generation chains.

From the literature reviewed it was possible to identify that regarding construction of new dwellings, exterior walls play an important role in embodied impact of dwellings, and the thermal properties of the dwelling are also a determinant factor mainly because they directly influence operational (heating and cooling). Additionally, as acknowledged by Buyle et al. (2013), LC studies of new dwellings generally fail to consider the influence of building design options such as building orientation, window area, or building shape. However, these options should be assessed from a life cycle perspective in order to support the overall improvement of new houses in the Portuguese context.

3. A LIFE CYCLE MODEL FOR NEW HOUSES

LCA is a renowned and accepted methodology for accounting the environmental impacts of a product system along its life cycle. As shown in the literature reviewed, LCA has recently been applied to investigate the energy and environmental impacts of buildings, allowing to quantify the trade-offs between the various LC phases or processes and between alternative building solutions. In order to assess the life cycle environmental impacts of new houses in the Portuguese context and to answer this thesis research questions, a life cycle model was developed based in the LCA methodology (ISO 14040, 2006; ISO 14044, 2006). This chapter describes the LC model developed under this research to assess new houses in Portugal. In section 3.1 the goal and scope is presented along with the system boundaries and the functional unit selected. In section 3.2 the Life Cycle Inventory (LCI) is described identifying the LCI approach and the LCI framework implemented for new houses. In section 3.3 the life cycle impact assessment (LCIA) methods and the environmental categories included are presented. In section 3.4 the simplifications of the LC model developed are explained. In section 3.5 the base case house selected is detailed along with the building alternatives, the specific data requirements, and the assumptions made to address the research questions.

3.1. Goal and scope

The main goal of this research is to investigate the primary energy and the environmental impacts associated with new houses development in the Portuguese context, identifying improved alternatives from a life cycle perspective. The LC model here described aimed to comprehensively and quantitatively assess the life cycle impact of alternative building options, at the building scale, informing building design of new houses from a new perspective, not covered in the Portuguese building energy assessments.

The LC model developed was based on detailed understating of the major components and processes of the system under study (a single family house). The life cycle impacts of the system were determined by an attributional LCA including an inventory process-analysis (described in the next section), which allowed not only identifying the most significant processes, but also to compare different options regarding the building envelope, the house design, and its operational conditions, and evaluate their influence in the total LC results to answer this thesis research questions.

The LC model includes the building LC processes for three stages: Construction or pre-use, Operation, and Maintenance of the building components. Construction and Maintenance present the material-related embodied impacts of the building, whereas Operation presents the thermal operational impact for heating and cooling the building. Figure 2 presents a flow chart of the LC model developed and its systems boundaries (identifying the processes included and processes out of the scope of this study). In parenthesis are the reference to building processes identified in the EN 15978 (CEN, 2011). Under Construction or Pre-use stage (A1-A5) are the impacts resulting from raw material extraction (A1) and its transport to factory (A2), building material manufacture (A3), transport of materials to the building site (A4), and on-site construction (A5) excluding the impact of machinery used, transport of workers and the municipal infrastructures. Under use stage Operation (B6), the impacts of household energy use for heating and cooling are considered because they are directly influenced by the building physical characteristics, but other household energy uses (non-related to the house characteristics) and water usage (B7) have not been included. Under Maintenance (B2-B4), are the impacts resulting from activities of maintenance (B2), repair (B3), and replacement (B4) of building components and materials along the building lifespan. The end-of-life stage (C1-C4) and the potential loads or benefits from building materials recovery or recycling (D) were not taken into account (this simplification is further explained in section 3.4).

A single-family house, presented in section 3.5, was selected as a base-case for this study. Based on Portuguese household building stock (INE, 2013, 2015) the house selected is expected to be representative of average recently built single-family houses and having similar shape and size to many houses built over the last three decades. The house was considered to be inhabited by a family of four people (i.e., two adults and two children) and it was assumed to have an average life span of 50 years. This life span is based on most LC studies of buildings (e.g., (Cuéllar-Franca & Azapagic, 2012; Gustavsson & Joelsson, 2010; Sartori & Hestnes, 2007)) as shown in Chapter 2.

In this research, all house alternatives have the same living area, volume, and life span, so the building life cycle inventory was accounted for the following functional unit: to build and operate one house (inhabited by a 4-people family) during its expected life span (50 years). In order to allow a comparison to other LC studies and to other buildings, the house LC impacts are also provided for the following functional unit: per useful area a year (m^2/year).

3.2. Life cycle inventory (LCI)

The life cycle inventory (LCI) includes data collection and calculation procedures to quantify the inputs (resources, materials and energy) and the outputs (emissions and waste) associated with the functional unit (presented in section 3.1). Under this section the LCI approach chosen is justified among the existing LCI analysis (subsection 3.2.1), and the steps followed to implement the LCI building framework for new houses are presented (subsection 3.2.2).

3.2.1. LCI analysis

Depending on the goal and scale of the LC study, there are three life cycle inventory analysis that can be used: *i*) a process-based, also called bottom-up; *ii*) an Input-Output (IO) also called top-down; *iii*) and an IO-hybrid analysis, which relies on both process-based and IO data. In this research, due to its comparative nature, an attributional LCA approach was followed building on a detailed process-based inventory.

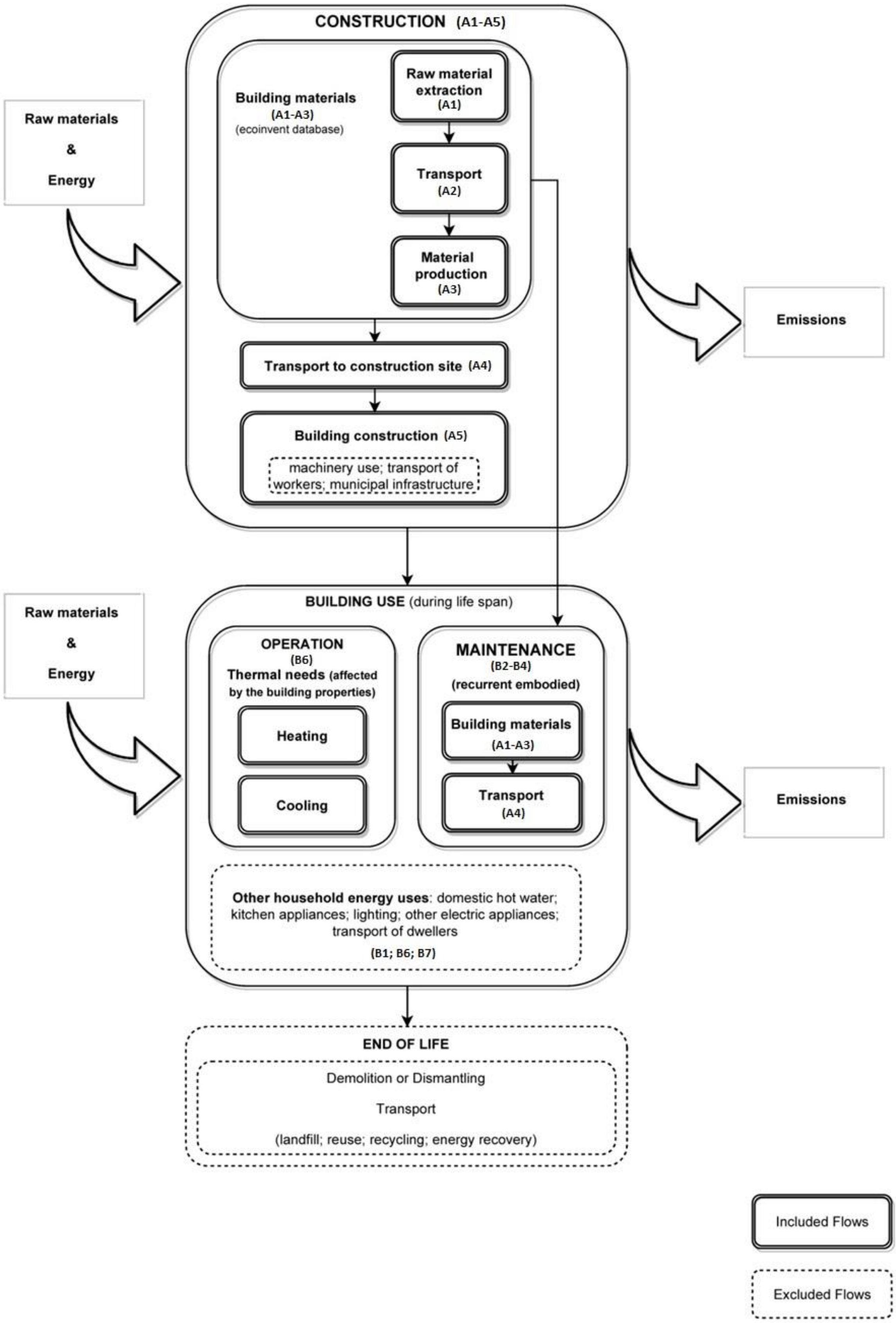


Figure 2. Life cycle model flow chart and system boundaries

As highlighted in Chapter 2, the process-based analysis is the most used in LCA studies at building scale and provides detailed information at product level which allows comparing specific building construction (Monteiro et al., 2016; Stephan & Stephan, 2016) and design alternatives as the ones here under study. Still, process-based analysis is known to suffer from a "*truncation error*" (Crawford, 2008; Suh & Huppes, 2002). To determine the total impacts of a system, the final output is traced upstream by accounting the inputs of the preceding processes. In this bottom-up process, many impacts from indirect services and less relevant materials or flows embodied in the building construction and in the construction sector are usually excluded (cut-off criteria) to enable LCA practitioners to conduct LCA without having to model 100% of the product system, which overlooks the embodied burdens. Although incomplete, the process-analysis is considered to be more accurate than the IO analysis (Treloar, 1997), which encompasses higher uncertainty and suffers from an "*aggregation error*" (Crawford, 2008; Treloar, 1997) making it difficult to characterize impacts for different processes within the same industry sector. The IO-hybrid approach was developed to overcome the limitations of process-based LCA and IO analysis (Treloar, 1997). However, it is difficult to implement and rely on IO-hybrid analysis when there is no regional IO data available. So, due to the comparative nature of this research study, based in alternatives from the same industry sector, which have identical system boundaries and incompleteness level, a process-based analysis was used. The "truncation error" is expected to be similar between the alternatives studied and to have a minor effect in the comparative findings.

Even though, in order to assess the effect of a potential underestimation of the embodied energy in the total LC results of the process-based analysis as suggested by authors that have applied an IO-hybrid analysis to buildings (Crawford, 2011a; Crawford & Stephan, 2013; Nässén et al., 2007; Stephan & Stephan, 2014; Treloar, 1997), a sensitivity analysis with an IO-hybrid scenario for embodied energy was included in section 4.4.3. Following (Gustavsson & Joelsson, 2010), based on Swedish IO-data from (Nässén et al., 2007) we multiplied the process-based embodied energy values by an average IO-based hybrid coefficient: 1.94 (Nässén et al., 2007). We used Sweden IO-data, since we consider that from the literature reviewed Nässén et al.'s might have closer results to Portuguese context than the IO Australian database. For instance, the Portuguese's electrical mix primary energy conversion factor (1.59 (Garcia, Marques, & Freire, 2014) is closer to Sweden's (1.92 (Nässén et al., 2007) than to Australia's (3.4 (Stephan & Stephan, 2014)).

3.2.2. LCI building framework

This section presents the LCI building framework implemented to account for the embodied environmental impacts (from Construction (A1-A5) and Maintenance (B2-B4)) and the thermal operational impacts (from Operation B6) of the single-family house and building alternatives, following the system boundaries previously presented (in section 3.1). In this framework, the embodied impacts were traced through a building construction and maintenance inventory and the operational impacts were obtain combining dynamic building simulation results (heating and cooling final energy of the building alternatives) with an operational systems inventory. The total LC results were obtained summing the embodied (from construction and maintenance) and the operational impacts. Figure 3 outlines the LCI building framework. This framework was developed using the following software tools: *SimaPro v.7.3*, *DesignBuilder © v3.0*, and *Microsoft Office Excel.*

- *SimaPro v.7.3* (PRé, 2013) was used to trace the LCA environmental impact of construction materials, maintenance activities, and HVAC systems, which were based on background data from the European environmental LCI database *ecoinvent 2.2* (Frischknecht et al., 2005). *Simapro* was chosen because it is a leading LCA software trusted by industry and academics that allows process-based LCA modeling and provides access to one of the most complete LCI databases (*ecoinvent*). Furthermore it allows to export the LCA results to *Excel* and it was available for this research. The *Ecoinvent* database was used as background data for the following reasons: i) it presents an extensive process-based environmental LCI database (covering construction materials, transport systems, and energy systems) developed for Swiss and European context by the Swiss Centre for Life Cycle Inventories (Frischknecht et al., 2005) with well documented and externally validated process-data reports; ii) a LCI database of construction processes and materials adapted to Portuguese reality and externally validated was not available to be used.

- *DesignBuilder © v3.0* (DesignBuilder Software Ltd, 2014b) was used to perform the dynamic building simulation and calculate the annual operational heating and cooling loads. *DesignBuilder* is a modeling and thermal building simulation tool with a graphical user interface and it is based on the EnergyPlus thermal dynamic calculation engine. Both DesignBuilder © and Energyplus have been tested and validated under the comparative standard method of test BESTEST and ANSI/ASHRAE Standard 140-2011 (DesignBuilder Software Ltd, 2014a; US Department of Energy; National Renewable Energy Laboratory, n.d.).

- *Microsoft Office Excel* was used to implement the inventory framework at building scale and allowed to customize the same inventory data to alternative houses (e.g.: with different shapes and component areas).

The steps followed to create the LCI building framework, summarized in Figure 3, are described hereby.

1. A building component LCI database of Construction and Maintenance embodied impacts was modeled based on building component's surface area (per m^2, for most components), or per unit (for doors and structural elements) or per thickness and surface area (per $cm \cdot m^2$, for insulation materials). The following building components categories were inventoried: exterior walls; exterior wall's insulation layer; roof; roof's insulation layer; ground floor; ground floor insulation layer; first floor; first floor insulation layer; interior walls; windows; columns, beams and foundations; exterior doors; interior doors. This building component LCI database was built upon the preliminary work presented in Monteiro (2010) and Monteiro and Freire (Monteiro & Freire, 2012) and it has similarities to other contemporaneous studies such as Gervásio et al. (2014) and Mateus (2009), but it is adapted to this research goals, covering the base case house and the building alternatives presented in section 3.5.:

    1.1. Building materials included in building components were accounted on a mass unit (kg, for most materials) or on a volume unit (m^3, for wood and concrete), and they were coupled with the respective LCI environmental data. The building materials background data (A1-A3 in EN 15978 (CEN, 2011)) were taken from *ecoinvent 2.2* database and its reports (Kellenberger et al., 2007; Spielmann, Dones, Bauer, & Tuchschmid, 2007) using *SimaPro v.7.3*;

    1.2. Transportation assumptions (distance traveled and means of transport used) were defined for each building material based in likely scenarios for the Portuguese context (e.g., local producer's availability). Thus, based on the material amounts inventoried, the transportation process (A4) was accounted for each building material on a "tons per km" unit, and it was coupled with respective LCI environmental data. Transportation background data was taken from *ecoinvent 2.2* and Spielmann et al. (2007);

    1.3. To account for on-site construction processes (A5), a construction waste factor was assumed for each building material following other studies (Nemry et al., 2008, 2010a, 2010b).

1.4. The environmental impacts of Construction stage (A1-A5) were summed for material and aggregated for each building component for each environmental category considered.

1.5. Maintenance assumptions (amount and frequency of maintenance, repair and replacement activities, presented in section 3.5.2.) were defined for building components and materials. Depending on the life span (in this study, 50 years) the total maintenance amount of each building material was determine per building component and was coupled with the respective LCI environmental data. The maintenance materials background data were taken from *ecoinvent 2.2*. Transportation assumptions were assumed for maintenance materials and the maintenance's transportation process was accounted (as explained in point 3). Maintenance stage (B2-B4) impact (from material production and transport) was accounted for each building component.

2. At building level, the areas or units of all building components considered (in point 1) are inventoried based on the building design characteristics (e.g., house shape and size), the living area, volume, the expected life span, and the number of dwellers are identified, as exemplified in Table 5.

Table 5. LCI building framework at Building level (input-data)

BUILDING LEVEL					
Life span (years)	50				
Number of occupants	4				
Area (m²)	133				
Volume (m³)	356				
BUILDING COMPONENTS	**Type (modeled solution)***	**Area [m²]**	**Thickness [cm]**	**Units**	**Leghth [m]**
Exterior walls	Double hollow brick wall	220			
Insulation EW	XPS CO_2	220	**6**		
Roof	Roof	74.4			
Insulation R	XPS CO_2	74.4	**6**		
Ground floor	Ground floor	80			
Insulation GF	No insulation	0	**0**		
1st Floor	1st Floor	76.4			
Insulation 1F	XPS CO_2	0	**6**		
Interior walls	Interior wall	110			
Windows	Window A double glazing (1 m²)	1		11	
Columns	Column			9	6
Beams	Beam			4	10
Foundations	Foundation			9	
Exterior doors	Door Exterior wooden			1	
Interior doors	Door Interior wooden			8	

* Components that are linked/selected (from the building component LCI database modeled).
In light-grey boxes are the input-data at building level from base case house (H1W1).

3. To obtain the house embodied burdens, the building components areas are multiplied by the building component environmental impacts achieved for Construction and Maintenance stages and summed together for each environmental category considered. Based on the input-data entered at building level, the LCI building framework delivers the LC results for the following functional units: per building over the life span; per living area over the life span (m^2); per living area a year (m^2/year); per volume a year (m^3/year); per person a year (person/year). In this research the LC results are presented for the first, to address the functional unit selected (section 3.1), and for the second to allow compare results to other LC studies of dwellings.
4. At building scale, each house alternative was modeled and simulated on *DesignBuider © v3.0*. The *DesignBuilder* settings (the model input data) were based on the building and building components physical characteristics under study (described in section 3.5.1) and in the operational conditions assumed (described in section 3.5.3). In order to simplify the model, the internal heat gains from users, lighting, and household appliances use were lumped into a single value per m^2 of living area (as suggested in (RCCTE, 2006)). Climate data was selected from the *DesignBuilder* weather database according to the location assumed. The annual final energy for heating and cooling each house alternative was obtained and it was included in the LCI building framework to account for the operational stage impact.
5. The LCI building framework allowed the selection of alternative HVAC systems, with each system relying on a specific energy source. The impacts of each system were modeled based on a final energy consumption unit (kWh) and included the impacts embodied in the production of each system and in its energy source supply chain. Systems and energy source supply chains were based on background data from ecoinvent 2.2, except for systems relying in electricity. For those systems (e.g., heat pump, electric heating) specific impacts from the Portuguese supply chain (electricity generation, distribution and supply at low voltage) were assumed based on background data from Garcia et al. (2014). Operational LC impacts were obtained multiplying the annual impact for the building life span.
6. The total LC impacts for each house alternative were obtained summing the embodied and the operational LC impacts for each environmental category.

Therefore, this LCI framework allowed to:

- obtain the embodied burdens of different buildings relying in the same constructive components;
- change one building component or insulation level for an alternative one, assessing its influence in the LC embodied results, for the same building;
- present LC results for alternative units.

At the same time this framework could also allow to: model additional building components and expand the assessment beyond this research study; change the generic background data used (ecoinvent 2.2) by other environmental data available (e.g., based on local producers' data); change maintenance and/or transportations assumptions, to better fit other building components and case studies.

The base case building and alternatives studies are detailed in section 3.5.

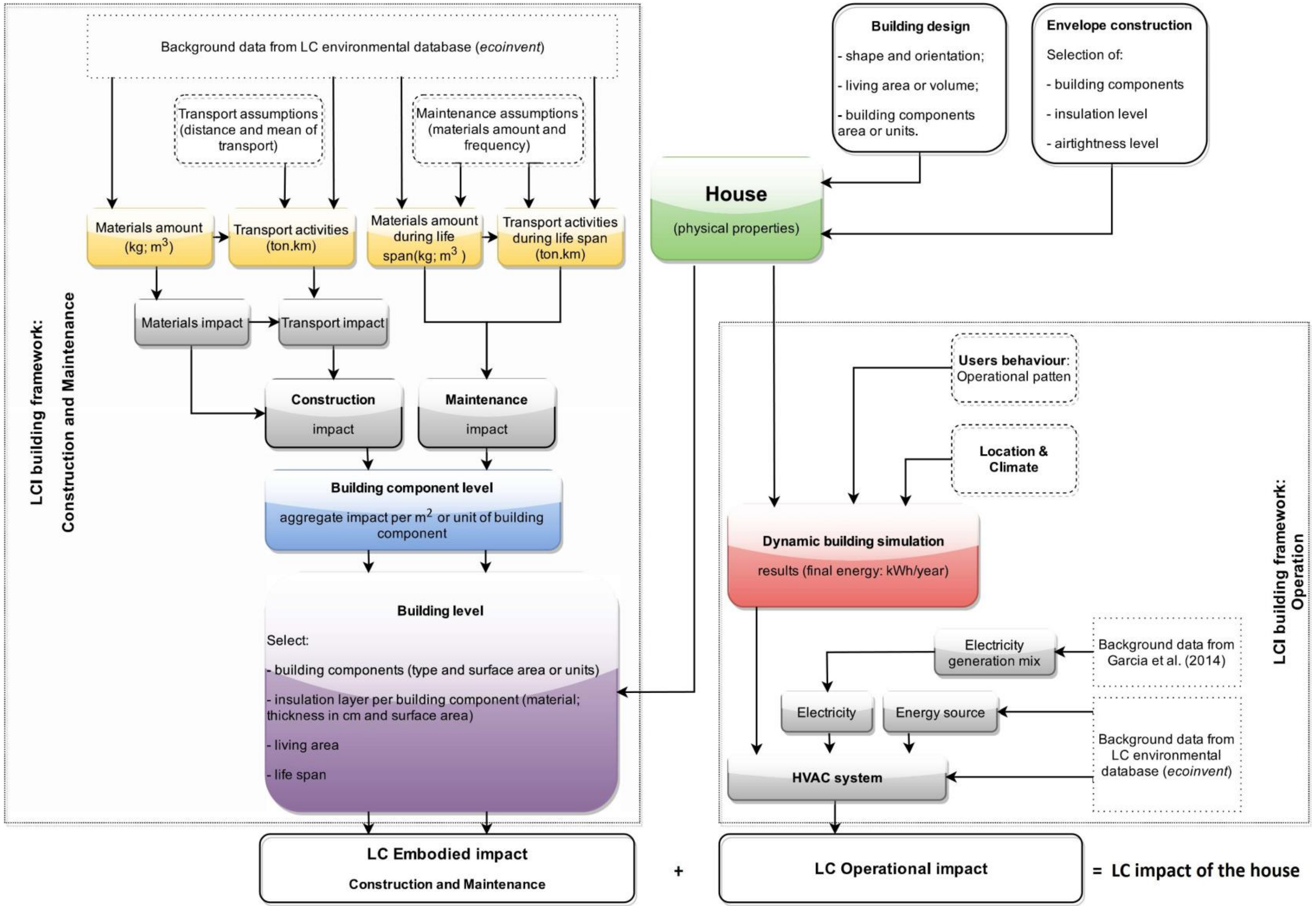


Figure 3. Life cycle inventory building framework

3.3. Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase of an LCA, the extent and the significance of the potential environmental impacts of a system are evaluated through a LCIA method. According to ISO 2006, the LCIA phase includes the following three mandatory steps: i) the selection of the impact categories and their corresponding category indicators; ii) classification: assignment of inventory substances (inputs and outputs) to each impact category; iii) characterization: all inventoried substances (from products and activities) are multiplied by category indicators' equivalency factors, which are defined for each substance and impact category; all substances results for a category indicator are summed and the result for an impact category is obtained.

Additionally, the LCIA may include three optional steps that aim to ease the decision making: i) normalization of the impact category results based on relative information for a given context (e.g., European) presenting the magnitude of the environmental impacts in that context; ii) grouping, or ranking the impact categories in broader categories; iii) weighting and aggregating mid-point impact categories possibly in a single environmental indicator.

Various LCIA methods have been developed to convert the inventory data substances (inputs and outputs) into potential environmental impacts organized into specific impact categories. There are single-issue methods, which address only one environmental issue (for example primary energy, exergy, GHG emissions) and multi-category LCIA methods with specific sets of impact categories. From the latter group, there are two different types of LCIA methods: the midpoint methods and the endpoint methods. The use of different LCIA methods leads to distinct type of results (impact categories and units), and depending on the method (environmental categories), a different ranking of the alternatives can be achieved in comparative LC studies (Monteiro & Freire, 2011, 2012). Methods that aggregate and weight environmental categories simplify comparisons and interpretations, but incorporate higher levels of uncertainty in the modeling of the cause-effect chain at an endpoint assessment, being less transparent than midpoint methods (Barnthouse et al., 1998; Finnveden et al., 2009). Additionally the weighting procedure is based on value choices and it is considered less reliable.

In order to enable a more transparent assessment and limit the uncertainties, two LCIA methods were used in this research in the LC inventory model:

i) the Cumulative Energy Demand (CED) – to account for LC non-renewable primary energy requirements (NRPE). The CED method calculates the total primary energy use (MJ eq) based on the higher heating value, distinguishing renewable and non-renewable energy sources

(Frischknecht et al., 2007). Non-renewable primary energy constitutes a simple and widely used indicator and it is considered to be a good proxy for other environmental impacts in LC studies of buildings. Literature showed that NRPE has very close results to environmental categories whose impact are mainly due to fossil energy use, namely abiotic depletion, global warming potential and acidification (Monteiro & Freire, 2012; Oregi et al., 2015). Other categories, as eutrophication and Ozone Layer Depletion (OLD), still present some correlation with NRPE, but are more sensitive to specific substances (for instance, OLD is very sensitive to chlorofluorocarbons or hydrofluorocarbons) and therefore might have varying results depending on the building materials and systems selected (Monteiro & Freire, 2012).

ii) the CML 2001 method which focuses on a high number of environmental impact problems at an early stage in the cause-effect chain (mid-point level). CML has ten impact categories in the baseline version. However environmental impact categories related to toxicity, are usually not addressed due to missing scientific robustness of the underlying characterization procedures (Barnthouse et al., 1998; Finnveden et al., 2009; Monteiro & Freire, 2012; Nemry et al., 2008, 2010b). Therefore, in this study the environmental impacts are only presented for the six widely used environmental categories, which are briefly described in Table 6: Abiotic Depletion (AD), Global Warming Potential (GWP), Acidification potential (AP), Eutrophication Potential (EP.), and OLD. The LCIA results presented in this research were taken from characterization phase. The results were not normalized, since normalization does not affect the results of the comparative assessment.

Table 6. CML 2001 impact categories selected

Impact categories	Indicator	Description
Abiotic depletion (AD)	kg antimony (Sb) eq	The category indictor is related to extraction of minerals and fossil fuels due to inputs in the system is based on concentration reserves and rate of deaccumulation.
Global Warming Potential (GWP)	kg CO_2 eq	It is related to emissions of greenhouse gases to air. The characterization model was developed by the Intergovernmental Panel on Climate Change (IPCC) for a time horizon of 100 years.
Ozone Layer Depletion (OLD)	kg CFC-11 eq	It is output-related. The characterization model was developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gasses.
Photochemical Oxidation (PO)	kg ethylene (C_2H_4) eq	It relates to the formation of reactive substances (mainly ozone) also called as "summer smog".
Acidification Potential (AP)	kg SO_2 eq	It relates to emissions of acidifying substances to air.
Eutrophication Potential (EP)	kg PO_4^{3-} eq	It is also known as nitrification. It includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil.

Description based on information from Frischknecht et al. (2007))

3.4. Model simplifications

As identified in Figure 2 a few LC model simplifications were adopted. The end-of-life was kept out of the scope of this study for two reasons. Firstly, according to literature, it is expected to have a small life cycle magnitude when compared to the processes assessed (Nemry et al., 2008, 2010; Oregi et al., 2015; Winistorfer, Chen, Lippke, & Stevens, 2005). For instance, it represents around 1-3.5% in Mediterranean buildings (Nemry et al., 2008). Secondly, future waste treatment scenarios (within a 50-year life span) encompass high uncertainty, being difficult to predict, since total demolition, selective demolition or major retrofits may occur and waste treatment processes available may be very different (Oregi et al., 2015).

Furniture, plumbing, sanitary equipment, heat distribution pipes were not inventoried since these are not affected by the alternative building construction options assessed, they do not affect the comparative nature of our findings. Energy used on construction site were also not included because it is considered of minor importance (Gervásio et al., 2014; Nemry et al., 2008, 2010). Though, as a consequence total embodied energy is slightly underestimated in the LC model.

Indirect embodied impacts from municipal infrastructure serving the house, land use changes, and the transport of construction workers and the dwellers during the lifespan of the building were out of the scope. Although these impacts might be worth of assessment studies at a different scale, our LC model boundary was limited to the building exterior boundaries. Likewise shading from building surroundings (other buildings or trees) was not considered in the model.

3.5. Base case house and building alternatives

In this section, the base case house selected is introduced following common Portuguese household building stock characteristics, and the building alternatives considered are described. Details and building assumptions are presented to characterize the three building LC stages – Construction (section 3.5.1), Maintenance (section 3.5.2) and Operation (section 3.5.3) – providing input data to the LCI building framework at building level, at building components level and at operational use (HVAC systems) level. In section 3.5.1, the base case construction is described and building envelope and building design alternatives are presented. The building components maintenance assumptions can be found in section 3.5.2. In section 3.5.3, the building operational conditions and options (operational patterns; HVAC systems; electricity generation mix; location) are described.

- **Base case house**

Single-family houses are very significant residential buildings. They represent more than 50% of the EU-25 and Portuguese housing stock (Eurostat, 2012; Nemry et al., 2008). The Portuguese household building stock is mainly characterized by small residential buildings: the average number of conventional dwellings per building is 1.65 and over 50% of the dwellings are single-family houses (Carmo, 2014; INE, 2013, 2015) and have up to 2 floors (Carmo, 2014). In Portugal, the 3-bedroom typology is the most common among existing (33%) and newly constructed residential buildings (e.g.: 48%, in 2011), and the average area per dwelling is around 107 m^2. Most households (45%) are composed by a 3-5 people family (INE, 2013, 2015). Besides, more than 63% of the buildings have less than 35 years, and the business-as-usual construction practice during that period has been: double hollow brick walls with concrete slabs and concrete structure (Carmo, 2014; INE, 2015). Furthermore, most Portuguese dwellings (73%) are occupied by the homeowners.

Based on Portuguese household building stock data (INE, 2013, 2015) a representative base-case single-family house was selected for this research. The base-case house has two floors, 133 m^2, and a 3-bedroom typology. It has a parallelepiped shape and all the openings are placed in two opposite facades: West facing (front facade) and East facing (back facade). Axonometric drawings of the building can be found in Figure 4. The base-case house was assumed to be located in Coimbra, center of Portugal. The house was assumed to be occupied by a 4-people family and to have an expected life span of 50 years.

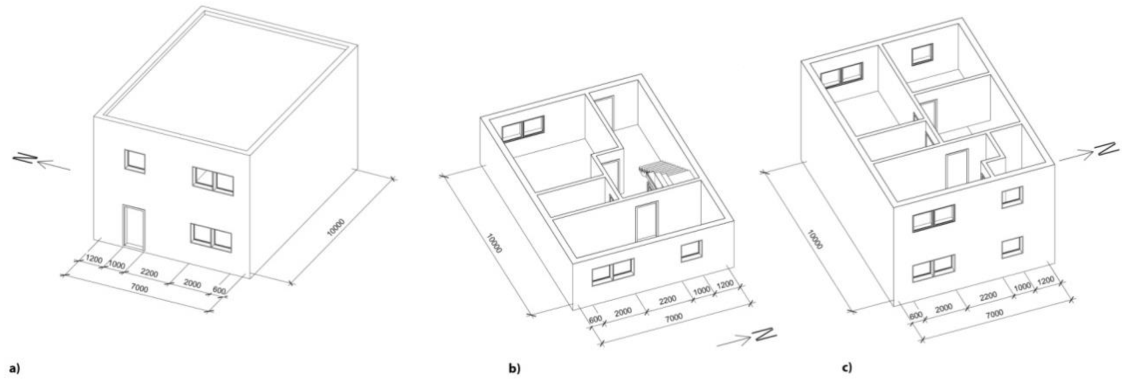


Figure 4. Axonometric drawings of the base case house

3.5.1. Construction stage

The construction stage holds the house initial embodied burdens which were traced through the LCI building framework previously described (section 3.2.2). In this research a parametric analysis with building envelope measures and building design options was performed: five envelope insulation levels, four total ventilation levels (including infiltration), two window-glazing types, and three exterior wall systems, eight building orientations, four window sizing with two orientation and three building shapes. The base case house construction and its alternatives are described below.

To more easily present the LC results and the variations among the building alternatives under study, a base-case heavy-weight construction that represents a likely combination of options for a new house was assumed and it is identified in Table 7. This construction type also represents materials and techniques used in Portugal during the last 2-3 decades, for instance, double hollow brick masonry exterior walls, concrete columns, reinforced concrete slabs, ground floor slab on grade, interior brick walls, and aluminum frame windows with exterior shutters.

The inventory of the base-case house building materials and components partially builds on a previous preliminary LCA study (Monteiro, 2010; Monteiro & Freire, 2010a, 2010b, 2012), which did not addressed the jointly influence of the alternatives here under study. In this research, to easily allow assessing and comparing different envelope and design alternatives, the LCI building framework was developed to account for the embodied impacts of different dwellings. Table 8 presents the building material transportation assumptions included in the LC model.

Table 7. Building components construction inventory (bill of materials): base-case house and alternative walls (1/2)

Building Components	Materials	Description	units	kg/u	Density (kg/m³)	On-site waste factor	Volume [m³/m²]	Mass [kg/m²] [kg/unit]	Transport distance [km]	Transport system	Base case[1] Building component area [m²] or units
Exterior wall (m²):											220.0
Double hollow brick wall – base case		(U=0.36 W/m².K)						301.1			
	Paint H_2O	exterior paint 3x (10 m²/l; 1.4 kg/l)				5%		0.4	30	Van <3.5t	
	Base plaster	exterior (0.02 m), 1650 kg/m³			1 650	5%	0.02	34.7	65	Lorry 3.5-16t, RER	
	Brick	masonry (0.11 + 0.15 m)	15.5	11.0		5%		179.0	65	Lorry 3.5-16t, RER	
	Cement mortar	horizontal and vertical				5%		52.0	65	Lorry 3.5-16t, RER	
	XPS/XPS CO_2*	0.06 m layer (0.035 W/m.K); Blowing agent CO_2 and aceton			30	5%	0.06	1.9	85	Lorry 3.5-16t, RER	
	Base plaster	interior (0.02 m), 1 650 kg/m³			1 650	5%	0.02	34.7	65	Lorry 3.5-16t, RER	
	Paint H_2O	interior paint 3x (12 m²/l; 1.3 kg/l)				5%		0.3	30	Van <3.5t	
Concret block wall								257.6			
	Paint H_2O	exterior paint 3x (10 m²/l; 1.4 kg/l)				5%		0.0	30	Van <3.5t	
	Acrylic filler	exterior (0.002 m); 1000 kg/m³			1000	5%		2.1	65	Van <3.5t	
	Adhesive mortar	Exterior (0.002 m);1600 kg/m³			1600	5%		3.4	65	Van <3.5t	
	EPS	0.06 m layer (0.04 W/mK)			30	5%	0.06	1.9	85	Lorry 3.5-16t, RER	
	Lightweight concrete block	10 concrete blocks (0.5 x 0.2 x 0.2 m)		18.5		5%		194.3	65	Lorry 3.5-16t, RER	
	Cement mortar	horizontal				5%		21.0	65	Lorry 3.5-16t, RER	
	Base plaster	interior (0.02 m), 1 650 kg/m³			1 650	5%	0.02	34.7	65	Lorry 3.5-16t, RER	
	Paint H_2O	interior paint 3x (12 m²/l; 1.3 kg/l)				5%		0.3	30	Van <3.5t	
Wooden wall								43.3			
	Acrylic varnish	exterior 2x (12m²/l; 0.95kg/l)				5%		0.17	30	Van <3.5t	
	Wood planks	Interior and exterior			550	5%	0.06	34.7	40	Lorry 3.5-16t, RER	
	XPS	0.06 m layer (0.035 W/m.K);			30	5%	0.06	1.9	85	Lorry 3.5-16t, RER	
	Wood studs joist	Studs, plates, headers: hard wood			550	5%	0.012	6.6	40	Lorry 3.5-16t, RER	
	Acrylic varnish	exterior 2x (12m²/l; 0.95kg/l)				5%		0.17	30	Van <3.5t	
Interior wall (m²) - hollow brick wall								168.5			110.0
	Paint H_2O	Interior paint 3x (12m²/l; 1.3kg/l)				5%		0.3	30	Van <3.5t	
	Base plaster	exterior (2 cm), 1650 kg/m³			1 650	5%	0.02	34.7	65	Lorry 3.5-16t, RER	
	Brick	16 hollow bricks (30x20x11 cm; 4.7 kg/u)	15.5	4.7		5%		76.5	65	Lorry 3.5-16t, RER	
	Cement mortar	horizontal and vertical binding				5%		22.0	65	Lorry 3.5-16t, RER	
	Base plaster	interior (2 cm), 1650 kg/m³			1 650	5%	0.02	34.7	65	Lorry 3.5-16t, RER	
	Paint H_2O	Interior paint 3x (12m²/l; 1.3kg/l)				5%		0.3	30	Van <3.5t	
Roof (m²)		(U=0.39 W/m².K)						550.0			74.4
	Gravel round				1 800	2%	0.05	91.8	170	Lorry 3.5-16t, RER	
	XPS	0.06 m layer (0.03 W/mK)			30	5%	0.06	1.9	85	Lorry 3.5-16t, RER	
	Fleece				65	2%	0.002	0.13	65	Van <3.5t	
	Bitumen				1 000	2%	0.004	4.1	80	Lorry 3.5-16t, RER	
	Anhydrite screed				1 000	2%	0.05	51.0	65	Lorry 3.5-16t, RER	
	Concrete	reinforced concrete C25/30			2 400	2%	0.153	367.2	40	Lorry 3.5-16t, RER	
	Reinforced steel	80 kg of steel for m³ of concrete				2%		12.2	130	Lorry 3.5-16t, RER	
	Stucco	interior (0.02 m), 1000 kg/m³			1 000	5%	0.02	21.0	65	Van <3.5t	
	Paint H2O	Interior paint 2x (12 m²/l; 1.3kg/l)				5%		0.2	30	Van <3.5t	
	Formwork residues	0.4 kg wood construction waste per m²				100%	0.001	0.4	40	Lorry 3.5-16t, RER	

Table 7. Building components construction inventory (bill of materials): base-case house and alternative walls (2/2)

Building Components	Materials	Description	units	kg/u	Density (kg/m³)	On-site waste factor	Volume [m³/m²]	Mass [kg/m²] [kg/unit]	Transport distance [km]	Transport system	Base case[1] Building component area [m²] or units
1st Floor (m²)								390.6			76.4
	Acrylic varnish	Interior 2x (14m²/l; 0.95kg/l)				5%		0.14	30	Van <3.5t	
	Wood planks				590	5%	0.02	12.4	40	Lorry 3.5-16t, RER	
	Wood studs joist	studs, plates, headers: hard wood			550	5%	0.003	1.8	40	Lorry 3.5-16t, RER	
	Anhydrite screed				1 000	2%	0.05	51.0	65	Lorry 3.5-16t, RER	
	Concrete	reinforced concrete C25/30			2 400	2%	0.153	367.2	40	Lorry 3.5-16t, RER	
	Reinforced steel	80 kg of steel for m³ of concrete				2%		9.8	130	Lorry 3.5-16t, RER	
	Stucco	interior (2 cm), 1000 kg/m³			1 000	5%	0.02	21.0	65	Van <3.5t	
	Paint H2O	Interior paint 2x (12 m²/l; 1.3kg/l)				5%		0.2	30	Van <3.5t	
	Formwork residues	0.4 kg wood construction waste per m²			650	100%	0.001	0.4	40	Lorry 3.5-16t, RER	
Ground Floor (m²)								791.8			80.0
	Acrylic varnish	Interior 2x (14m²/l; 0.95kg/l)				5%		0.143	30	Van <3.5t	
	Wood planks				590	5%	0.02	12.4	40	Lorry 3.5-16t, RER	
	Wood studs joist	studs, plates, headers: hard wood			550	5%	0.003	1.8	40	Lorry 3.5-16t, RER	
	Anhydrite screed				1 000	2%	0.03	30.6	65	Lorry 3.5-16t, RER	
	Concrete	reinforced concrete C25/30			2 400	2%	0.153	367.2	40	Lorry 3.5-16t, RER	
	Reinforced steel	80 kg of steel for m³ of concrete				2%		12.2	130	Lorry 3.5-16t, RER	
	Gravel round				1 800	2%	0.2	367.2	170	Lorry 3.5-16t, RER	
	Formwork residues	0.4kg wood construction waste per m²				100%	0.001	0.2	40	Lorry 3.5-16t, RER	
Columns and beams (m)		1 m long, 0.3 x 0.2 section									94.0
	Concrete	reinforced concrete C25/30			2 400	2%	0.063	146.9	40	Lorry 3.5-16t, RER	
	Reinforced steel	120 kg of steel for m³ of concrete				2%		7.3	130	Lorry 3.5-16t, RER	
	Formwork residues	wood construction waste per unit				100%	0.001	0.4	40	Lorry 3.5-16t, RER	
Foundations (unit)		unit: 0.3 x 0.4 x 2.0 m									9
	Concrete	reinforced concrete C25/30			2 400	2%	0.245	587.5	40	Lorry 3.5-16t, RER	
	Reinforced steel	120 kg of steel for m³ of concrete				2%		29.4	130	Lorry 3.5-16t, RER	
	Formwork residues	wood construction waste per unit				100%	0.003	1.2	40	Lorry 3.5-16t, RER	

Building Components	Materials	Description		Area [m²]	Mass [kg/unit]	Transport distance [km]	Transport system	Base case[1] Building component units
Window (unit) - double glazing with thermal break				1.0	29.4			11
	Aluminium frame	0.08 m frame (U=1.6W/m².K), 50.7 kg/m²		0.2944	14.9	65	Van <3.5t	
	Double glazing	double glazing (U=1.1W/m².K) (4+4mm)		0.7225	14.5	65	Van <3.5t	
	Plastic shuters	PVC			2.8	65	Van <3.5t	
Door Interior wooden (unit)		unit: 1.6 m²			44.6			8
	Interior wooden door			1.6	44.2	40	Van <3.5t	
	Acrylic varnish	Interior 2x (14m²/l; 0.95kg/l)	5%	3.2	0.5	30	Van <3.5t	
Door Exterior wooden (unit)		unit: 2 m²			122.9			1
	Exterior wooden door			2	77.6	40	Van <3.5t	
	Acrylic varnish	Exterior 2x (12m²/l; 0.95kg/l)	5%	4.0	0.7	30	Van <3.5t	

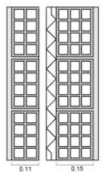
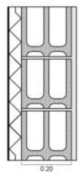
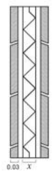
Table 8. Building materials transport assumptions (from producer/retailer to construction site)

Building material	Possible Producer	Distance [km]	Transport system
Acrylic filler	Weber (Aveiro)	65	Van <3.5t
Acrylic varnish	CIN	30	Van <3.5t
Adhesive mortar	Weber (Aveiro)	65	Van <3.5t
Anhydrite screed	Weber (Aveiro)	65	Lorry 3.5-16t, RER
Base plaster	Weber (Aveiro)	65	Lorry 3.5-16t, RER
Bitumen	Sika	80	Lorry 3.5-16t, RER
Brick		65	Lorry 3.5-16t, RER
Cement mortar	Weber (Aveiro)	65	Lorry 3.5-16t, RER
Concrete	Cimpor	40	Lorry 3.5-16t, RER
Concrete block		65	Lorry 3.5-16t, RER
Formwork residues		40	Lorry 3.5-16t, RER
Gravel round	Cimpor (Penafiel)	170	Lorry 3.5-16t, RER
Stucco	Weber (Aveiro)	65	Van <3.5t
Paint H_2O	CIN	30	Van <3.5t
Fleece	Importel (Aveiro)	65	Van <3.5t
Reinforced steel	Sardaço	130	Lorry 3.5-16t, RER
Wood planks		40	Lorry 3.5-16t, RER
Wood studs joist		40	Lorry 3.5-16t, RER
Exterior wooden door		40	Van <3.5t
Interior wooden door		40	Van <3.5t
Aluminium frame		65	Van <3.5t
Double glazing (U=1.1 W/m².K)		65	Van <3.5t
Single glazing (U=5.7 W/m².K)		65	Van <3.5t
Thermal insulation (EPS;XPS)		85	Lorry 3.5-16t, RER

- **Building envelope alternatives**

A parametric analysis with alternative envelope construction measures was performed to assess the influence of alternative thermal performance and alternative building components: five envelope insulation levels, four total ventilation levels (including infiltration), two window-glazing types, and three exterior wall systems. The three exterior wall systems here presented were selected based on a previous LCA of seven exterior wall systems (Monteiro, 2010; Monteiro & Freire, 2010a, 2010b, 2012), in order to represent distinct types of construction based in three alternative materials: brick blocks; concrete blocks; and wood. In this research the exterior wall assessment aimed to exemplify how changing a building envelope component can affect the overall LC results. Table 9 presents the building envelope alternatives assessed and the base case envelope construction (underlined). The alternative walls inventory (bill of materials) is presented in Table 7.

Table 9. Alternative building envelope measures

Passive construction	Alternatives studied		
Envelope insulation level, XPS or EPS thickness (cm),	0 3 6 9 12		
Total ventilation level, including infiltration (ac/h)	0.3 0.6 0.9 1.2		
Window type with aluminum frame	Single glazing with no thermal break; double glazing with thermal break		
Exterior wall construction type*	Double hollow brick masonry (XPS insulation) 	Concrete block masonry (EPS insulation) 	Wood walls (XPS insulation) 

* Partially based on data presented in (Monteiro, 2010; Monteiro & Freire, 2010a, 2010b, 2012).
Insulation layer: XPS (extruded polystyrene); EPS (expanded polystyrene).

- **Building design alternatives**

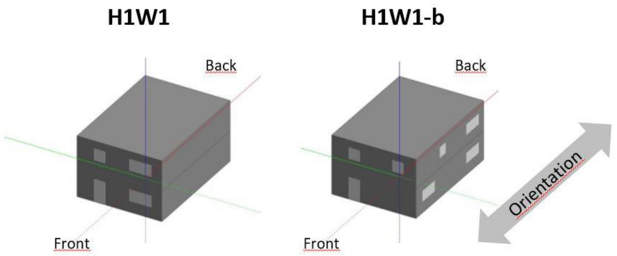
As shown in the literature review (Chapter 2), the influence of building design options on overall LC impact of dwellings has been disregarded by previous LC studies. In order to address this gap, in this research, the following building design options were assessed:

- Building orientation;
- Window placement and sizing (or window-to-wall ratio);
- Building shape.

Identical building envelope construction and components were assumed following the "base-case" construction previously presented: double hollow brick exterior walls; 6 cm insulation level; 0.6 ac/h ventilation level; double glazing window with thermal break aluminum frame, hollow brick interior walls and reinforced concrete structure. The operational and LC results of the building design alternatives assessed are presented in section 4.2.

- **Building orientation, window placement and sizing**

Firstly, the influence of building orientation with the window placement and sizing was considered. Eight building orientations were assessed for the base case house shape (H1) as presented in Figure 5. But as the base case house (hereafter identified as H1W1) has openings placed in two opposite façades which have around 45% and 55% of the glazing area each (5 m^2 in the front, and 6 m^2 in the back), the operational results for opposite orientations (+180º) are very alike. To further study the building orientation influence, an alternative house with the same window sizing but a different window placement, identified as H1W1-b, was also considered: windows placed in three facades (2 m^2 in the front, 2 m^2 in the back and 7 m^2 in the lateral façade). The two window placement alternatives and the building orientations assessed are identified in Figure 5, and their operation results are presented in section 4.2.1.



Orientation	(Front - Back)	
0º - Base case	West - Est (W-E)	W-E
45º	Northwest - Southeast	NW-SE
90º	North - South	N-S
135º	Northeast - Southwest	NE-SW
180º	East - West	E-W
225º	Southeast - Northwest	SE-NW
270º	South - North	S-N
315º	Southwest - Northeast	SW-NE

Figure 5. Building orientation and window placement (H1W1 and H1W1-b) alternatives

To study the window placement and sizing (window to wall ratio) influence, a sensitivity analysis was performed based on four incremental window sizes (W1 to W4) for the two window placement options: H1 (a house with openings almost evenly placed in two opposite facades, based on the base case) and H1-b (a house with openings placed in three facades but with the majority in the lateral façade, based on the previously presented H1W1-b). The design alternatives covered are further detailed in Table 10. Regarding building orientation, the LC results (section 4.2.2.) are only presented for the building orientations with the maximum and the minimum operational results identified in results section 4.2.1: W-E and N-S for the house with the window placement H1; W-E and E-W for the house with the window placement H1-b.

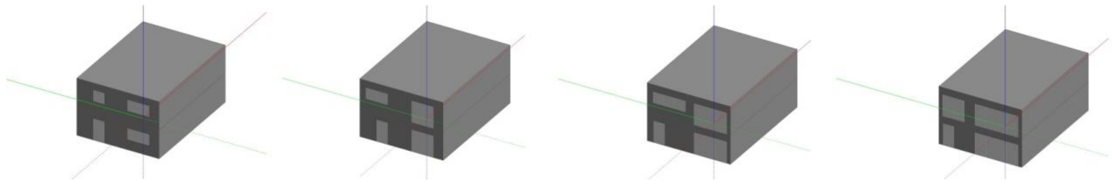
Table 10: Base case building shape (H1) with alternative window placement, sizing and orientation assessed

Window alternatives:	W1	W1-b	W2	W2-b	W3	W3-b	W4	W4-b
Front façade (m²)	5	2	10	4	15	6	20	8
Back façade (m²)	6	7	12	14	18	21	24	28
Lateral façade (m²)	0	2	0	4	0	6	0	8
Other lateral façade (m²)	0		0		0		0	
Total window area (m²)	11		22		33		44	
Window to wall ratio (WWR)	5%		10%		15%		20%	

Building orientations presented in LCIA results (front - back facade):

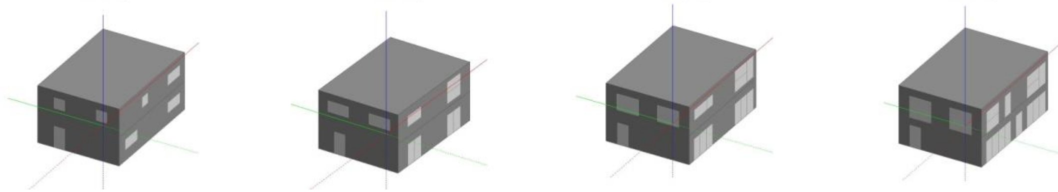
W-E and **N-S**, for **window placement H1**:

W1 **W2** **W3** **W4**



W-E and **E-W**, for **window placement H1-b**:

W1-b **W2-b** **W3-b** **W4-b**



- **Building shape and window sizing**

Secondly, to further understand how building design can affect the environmental impact of a house, the jointly influence of building shape and window sizing was assessed for 12 house design alternatives described in Table 11 and visually presented in Figure 6. Four window sizes (W1-W4) and three building shapes with the same living area and interior volume were considered: the compact base case shape (H1), a one-floor-terraced house (H2), and a two floor less compact house (H3). The scenarios assessed follow the base-case window placement previously presented: having the openings almost evenly placed in two opposite facades. In order to account for the different orientation influence, the building orientations with the maximum (W-E) and the minimum operational results (N-S) are considered for the 12 scenarios.

Table 11. Building design alternatives: building shapes and window sizing description

House shape			Window sizing							
			W1 (11 m^2)		**W2** (22 m^2)		**W3** (33 m^2)		**W4** (44 m^2)	
			WWR	WFR	WWR	WFR	WWR	WFR	WWR	WFR
H1	**Exterior wall (m^2)**	220	5%		10%		15%		20%	
	Roof (m^2)	74								
	Ground floor (m^2)	86								
	Exterior envelope (m^2)	294.4								
H2	**Exterior wall (m^2)**	161	7%	8%	14%	17%	20%	25%	27%	33%
	Roof (m^2)	147								
	Ground floor (m^2)	147								
	Exterior envelope (m^2)	308								
H3	**Exterior wall (m^2)**	224	5%		10%		15%		20%	
	Roof (m^2)	96.9								
	Ground floor (m^2)	86								
	Exterior envelope (m^2)	343								
All H1,H2,H3	**Living Area (m^2)**	133								
	Volume (m^3)	356								

Window to Wall Ratio (WWR); Window to Floor Ratio (WFR).

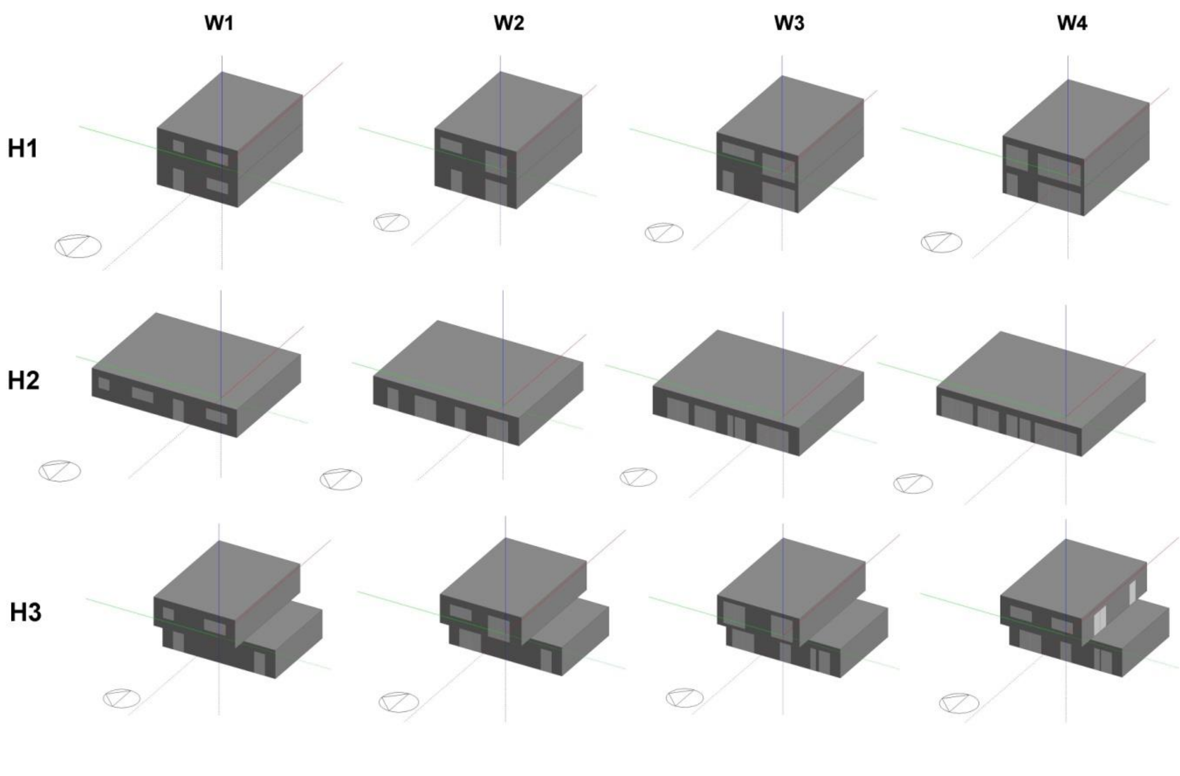


Figure 6. Axonometric models of the building design alternatives: house building shapes and window sizing

3.5.2. Maintenance stage

The building recurring embodied energy increment is caused by maintenance, replacement and repairing activities along the buildings life cycle. In this study, corrective maintenance activities aimed to preserve the physical characteristics of the base case house (and house alternatives) during the building lifespan were accounted. Table 12 presents the maintenance activities schedule assumed, which was based on data from literature (Blanchard & Reppe, 1998; Kellenberger et al., 2007; Künzel, Künzel, & Sedlbauer, 2006; Monteiro & Freire, 2012) and local construction material producers, and that characterizes the recurring embodied impacts of the house. The LC inventory background data was taken from ecoinvent 2.2 and incorporated in the LCI building framework described in section 3.2.2. Table 13 presents the transportation assumptions for materials used in Maintenance.

Table 12. Maintenance activities schedule

Material	%[1] of maintenance procedure	procedure life span (y)	frequency during life span
Renew finishing:			
Acrylic varnish, exterior 2x (12 m^2/L; 0.95kg/l)	100%	5	9
Acrylic varnish, interior varnish 2x (14m^2/L; 0.95kg/l)	100%	10	4
Paint H2O, exterior 3x (10 m^2/l; 1.4 kg/l)	100%	10	4
Paint H2O, interior 3x (12m^2/l; 1.3kg/l)	100%	20	2
ETICS system renew finishing:			
Acrylic filler, exterior (0.002), 1000 kg/m^3	100%	25	1
Adhesive mortar, exterior (0.002), 1600 kg/m^3	100%	25	1
Renew waterproofing:			
Bitumen	100%	25	1
Doors and windows:			
Exterior wooden door	0%	50	
Acrylic varnish exterior	100%	5	9
Interior wooden door	0%	50	
Acrylic varnish interior	100%	10	4
Corrections:			
Base plaster interior (0.02 m), 1650 kg/m^3	15%	25	1
Stucco interior (0.02 m), 1000 kg/m^3	15%	25	1
Brick, facing brick	10%	25	1
Thermal insulation (XPS)	0%	50	0
Other building materials	0%	50	0

[1] Relative to the same materials presented in the Building components LC inventory model (Table 1.)

Table 13. Maintenance transport assumptions

Building material	Possible producer	Distance [km]	Maintenance Transport system
Acrylic filler	Weber (Aveiro)	65	Van <3.5t
Acrylic varnish	CIN	30	Van <3.5t
Adhesive mortar	Weber (Aveiro)	65	Van <3.5t
Anhydrite screed	Weber (Aveiro)	65	Van <3.5t
Base plaster	Weber (Aveiro)	65	Van <3.5t
Bitumen	Sika	80	Van <3.5t
Brick		65	Lorry 3.5-16t, RER
Cement mortar	Weber (Aveiro)	65	Van <3.5t
Concrete	Cimpor	40	Lorry 3.5-16t, RER
Concrete block		65	Lorry 3.5-16t, RER
Formwork residues		40	Van <3.5t
Gravel round	Cimpor (Penafiel)	170	Lorry 3.5-16t, RER
Stucco	Weber (Aveiro)	65	Van <3.5t
Paint H_2O	CIN	30	Van <3.5t
Fleece	Importel (Aveiro)	65	Van <3.5t
Reinforced steel	Sardaço	130	Lorry 3.5-16t, RER
Wood planks		40	Van <3.5t
Wood studs joist		40	Van <3.5t
Exterior wooden door		40	Van <3.5t
Interior wooden door		40	Van <3.5t
Aluminium frame		65	Van <3.5t
Double glazing		65	Van <3.5t
Single glazing		65	Van <3.5t
Thermal insulation (EPS;XPS)		85	Van <3.5t

3.5.3. Operational stage

The building operational stage included the thermal operational energy (for heating and cooling) which is directly affected by the building characteristics (building envelope and design options) under study. The annual heating and cooling loads (final energy) were obtained by a model implemented in a dynamic thermal simulation tool (*DesignBuilder © v3.0*) and the environmental LC impacts of operation over the building lifespan were traced trough the LCI building framework presented in section 3.2.2. Shading from building surroundings (other buildings or trees) was not considered in the model, as the assessment was performed for a base case house at building scale.

Aiming to assess how different operational conditions can influence the LC results of a house in the Portuguese context, alternative operational scenarios were considered: four operational patterns in order to represent alternative Portuguese user behavior; four HVAC systems; two electricity generation mixes; and six Portuguese locations. Table 14 summarizes the operational alternatives considered, which are further described in the following subsections. A set of base case operational conditions, also presented in Table 14, were selected to be used when the operational conditions influence was not under study.

Table 14. Base case and alternative operational conditions

Operational conditions:	Base case	Alternative operational conditions	Results presented in section
Operational pattern	OP50	OP100*	4.1; 4.2; 4.4.1;
		OP25	4.1; 4.2; 4.4.1;
		OPx	4.4.1
HVAC system	Heat pump	Resistance heaters	4.1.3; 4.4.2
		Natural gas condensing boiler	4.1.3; 4.4.2
		Wood pellets boiler	4.4.2
Electricity generation mix	2012-year	5-year average (2008-2012)	4.4.2
Location	Coimbra	Évora, Bragança, Porto, Lisboa, Faro	4.3

- **Operational patterns**

In this study two operational patterns were simulated: OP100, which assumed continuous interior thermal comfort with average household internal gains; and OPx, which was based on a scheduled (intermittent) operational pattern and a low occupancy level. Both operational patterns are described below.

OP100 was based on Portuguese building thermal regulation assumptions (RCCTE, 2006), and it assumed interior temperature set-points between 20ºC (for heating) and 25ºC (for cooling), 24 hours a day, 365 days a year. Following the RCCTE (2006) recommendations, we included in the model 4 W per m^2 of living area (24h a day) to account for the average internal heat gains (from dwellers, lighting and use of appliances). Annual thermal gains are on average 4660 kWh (3300 kWh from household energy use and 1350 kWh from dwellers' thermal load). OP100 represents a continuous interior thermal comfort condition and an average occupation time. Table 15 presents the building simulation settings for the base case house under operational pattern OP100.

OPx dynamically represents partial and intermittent heating and cooling habits of a working-family assuming a short daily occupancy period. OPx was based on the dynamic operational scheduled HVAC ON presented in Table 16, and it assumed distinct occupation and operational schedules per floor. Interior comfort temperature set points between 20ºC and 25ºC (identical to OP100) were assumed only during the operational schedule HVAC ON. In order to consider the internal heat gains (from dwellers, lighting and electric appliances) an average 10W per m^2 of building living area were assumed per floor, during the operational/occupational schedule HVAC ON. The annual internal heat gains are 475 kWh lower in OPx than in OP100, and this is justified by the OPx lower occupancy and household energy use.

Table 15. Building simulation settings, operational pattern OP100

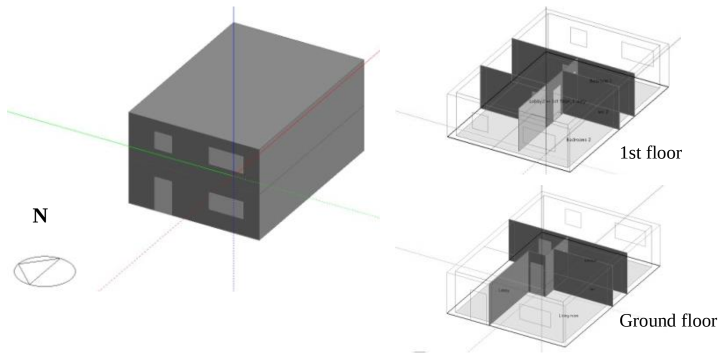
Building simulation settings	**Description**
3D build-up model (base case house)	
Living area (m²)	133.2
Conditioned volume	360
Heating set point air temperature (with no set back)	20ºC
Cooling set point air temperature (with no set back)	25ºC
HVAC Schedule; gains schedule	0:00-24:00 (24h/7 a year)
Location	Coimbra, Portugal
Latitude (º)/ Longitude (º)	40.2º / -8.4º
Elevation above sea (m)	140
Hourly Weather data	PRT_Coimbra_IWEC
Internal gains (lumped into a single value)	4 W per m^2 of living area
Air-tightness (infiltration)	Dependent on total ventilation scenario
Gains schedule	0:00-24:00 (24h/7 a year)

Table 16. OPx Operational Schedule (HVAC ON)

	Ground floor		**1st floor**	
	Schedule	**HVAC**	**Schedule**	**HVAC**
Weekday (245 days a year)	0 - 18h	OFF	0 - 6:30h	OFF
	18 - 23h	**ON**	6:30 - 9h	**ON**
	23 - 24h	OFF	9 - 21h	OFF
			21 – 24h	**ON**
Weekend/holyday (120 days a year)	0 - 8h	OFF	0 - 8h	OFF
	8 - 23h	**ON**	8 - 24h	**ON**
	23 - 24h	OFF		

When HVAC ON: heating set point at 20ºC and cooling set point at 25ºC. Presented in (Monteiro et al., 2016)

Based on Portuguese household energy statistical data (INE, 2013; INE-I.P./DGEG, 2011), partial and intermittent heating is common practice among Portuguese dwellers and cooling systems are not widespread in the residential sector. The average annual heating energy per home is 1885 kWh (or 17.4 kWh/m^2) if electrical heating is considered. This value suggests that Portuguese dwellers only spend around 20-25% of expected heating requirements (for a continuous interior thermal comfort condition as OP100). In fact, RCCTE only considered 10% of heating and cooling energy requirements calculated for OP100. Research studies that compared real energy consumption levels to building simulations identified that user behavior tend to change with energy efficiency: dwellers living in thermally inefficient buildings use lower operational patterns than dwellers living in thermally efficient buildings (Galvin & Sunikka-Blank, 2013; Sunikka-blank & Galvin, 2012). In this life cycle study, aiming to frame most Portuguese dwellers occupational and heating/cooling habits, two alternative operational pattern scenarios, proportionally related to OP100, were also considered: OP25, which held 25% of OP100's energy requirements, and typifies a moderate occupancy of the house with a modest HVAC level, being comparable to Portuguese statistical data; OP50, that included 50% of the simulated OP100's energy requirements, and it represents an average occupancy of the house with a medium HVAC level, following the trend suggested by (Galvin & Sunikka-Blank, 2013; Sunikka-blank & Galvin, 2012).

- **HVAC scenarios**

To assess the heating, ventilation, and air conditioning (HVAC) system influence in the operational assumptions sensitivity analysis, four alternative HVAC scenarios were selected as described in Table 17. The heating or HVAC systems selection is generally based on householder economic criteria. In this study, the heat pump system, which has higher efficiency and investment cost, was assumed as the (new house) base case scenario. Other system, the natural gas condensing boiler, is considered to be efficient among Portuguese construction stakeholders and thus it is likely to be installed in new houses. Wood pellets boilers, are also accepted for being economical to run-on, whereas electrical heating, which has low energy efficiency, but low investment cost, is one of the most common heating systems in existing houses. Furthermore, due to easy availability, electric heating is most likely to be used when other heating systems are not installed. This study does not intend to exhaustively study the HVAC systems influence, but instead to give insights of the ranges of their influence on the house LC impacts. The heating and cooling loads were converted to primary energy and environmental impacts based on the operation LCI building framework. Background data for the Portuguese electricity generation and supply mix was based on (Garcia et al., 2014), whereas for systems and other energy sources (natural gas and wood pellets) and supply chains was taken from generic European background data (ecoinvent 2.2.)

The heating systems influence was assessed firstly jointly with the varying insulation level (on section 4.1.3), and secondly in the operational conditions analysis section both for a new house and an equivalent existing house (on section 4.4.2).

Table 17. HVAC scenarios characterization

Heating system	Power	Energy source	Efficiency/COP	NRPE conversion factor[1]
Resistance heaters	6x2kW	Electricity (2012 mix)	1	1.59
Heat pump (air-water)	10kW	Electricity (2012 mix)	2.80[2]	0.58
Natural gas condensing boiler	10 kW	Natural gas	1.07	1.22
Wood pellets boiler	10 kW	Wood pellets	0.82	0.30

COP: coefficient of performance; NRPE: non-renewable primary energy; NRPE conversion factor: MJ of NPRE per 1 MJ of heat provided; [1] based on ecoinvent 2.2 data available and (Garcia et al., 2014); [2] heat pump cooling COP: 2.0. Note all scenarios assume cooling is provided by a heat pump system with COP 2.0.

- ## Electricity generation mix

From a life cycle perspective, the environmental impact of electric systems depends on the local electricity supply chain, which is determined by the national electricity generation mix, and the electricity on grid distribution and supply at low voltage. Over the last decade, the Portuguese electricity mix has been undergoing an important shift toward incorporating more renewable and less carbon intensive technologies (Garcia et al., 2014). To estimate the range of variation of LC impacts associated with the Portuguese electricity generation and supply chain mix, two scenarios were studied based on Portuguese environmental data from Garcia et al. (2014) presented in Table 18: the 2012 year Portuguese electricity generation and supply chain mix (base case scenario); a 5-year average (from 2008 to 2012) Portuguese electricity generation and supply chain mix, presenting the minimum (2010 year) and maximum (2008 year) values. The influence of the Portuguese electricity generation mix was assessed in the operational conditions analysis section (section 4.4.2) for a new house and an equivalent existing house.

Table 18. Life cycle impacts per kWh of Portuguese annual electricity supply mix based on Garcia et al. (2014)

Electricity generation and supply mix (year)	NRPE [MJ]	GWP [CO_2 eq]	AD [g Sb eq]	AP [g SO_2 eq]	EP [g PO_4-- eq]	PO [g C_2H_4 eq]	OLD [µg CFC-11 eq]
2008 (max)	**6.44**	**0.477**	**3.73**	**1.37**	0.72	**0.05**	**27**
2009	6.09	0.459	3.59	1.17	0.74	0.04	24
2010 (min)	<u>4.35</u>	<u>0.312</u>	<u>2.46</u>	<u>0.69</u>	<u>0.43</u>	<u>0.03</u>	21
2011	5.08	0.380	2.98	0.88	0.60	0.03	21
2012*	5.72	0.456	3.53	1.22	**0.86**	0.04	<u>18</u>
5-year (2008-2012) average	5.54	0.417	3.26	1.07	0.67	0.04	22

*Base case scenario (year 2012). For each environmental category: values in bold indicate the highest value and underlined values the lowest value.

- ## Location and climate

Building location affect the exterior conditions to which a building is exposed, therefore affecting the building thermal performance and its thermal operational needs (heating and cooling). At the same time, building thermal performance can be improved by a higher envelope thermal insulation in more demanding climates. In this study, the base case house was assumed to be located in Coimbra and to be oriented West-East (front-back facades, respectively). In order to assess how different Portuguese locations (and specific weather conditions) affect the operational and total LC results of a house, six alternative Portuguese building locations were compared: Coimbra, Porto, Lisboa, Faro, Bragança and Évora. Climatic data on each location was obtained based on *DesignBuilder* weather database and Table 19 characterizes the locations considered. The aim was to identify the range of operational impact variation due to alternative locations but at the same time to identify how thermal insulation typing points may change with building location in Portugal. Lastly, it matters to know if tipping points achieved with LC results vary from the tipping points suggested by operational final energy results. To address these issues six alternative Portuguese building locations were assessed for the base case house (H1W1) with three varying XPS insulation levels (3 cm, 6 cm, and 9 cm). The house operational and LCIA results of this analysis are presented in section 4.3.

Table 19. Alternative building locations: characterization and source of weather data

Location	Latitude [º]	Longitude [º]	Elevation [m]	Standard pressure [kPa]	Source of hourly weather data
Coimbra*	40.20	-8.42	140.0	99.7	ASHRAE/IWEC
Évora	38.57	-7.90	321.0	97.5	ASHRAE/IWEC
Bragança	41.80	-6.73	692.0	93.3	ASHRAE/IWEC
Porto	41.23	-8.68	77.0	100.4	ASHRAE/IWEC
Lisboa	38.77	-9.13	105.0	100.1	ASHRAE/INETI
Faro	37.02	-7.97	8.0	101.2	ASHRAE/IWEC

*Base case house location. The exposure to the wind was assumed to be normal for all scenarios.

- **Other household energy uses**

In this comparative study, operational stage included only the thermal operational energy (for heating and cooling). Although it is important to reduce the total household operational energy use in dwellings, other household energy reduction is mainly dependent on specific appliances efficiency and users behavior, not being influenced by the building characteristics under study.

Even though, in order to frame the magnitude of overall final energy consumed per dwelling, Table 20 presents other household energy needs (excluding heating and cooling) for two scenarios: *i*) a business as usual (BAU), based on average Portuguese statistic data on household energy consumption (INE-I.P./DGEG, 2011) and RCCTE (2006); *ii*) an hypothetical energy efficiency (EE) scenario. Based on this data, a sensitivity analysis on total LC energy is presented on section 4.4.3 for the base case new house, assuming the EE scenario, and for an equivalent existing house with the BAU scenario.

Table 20. Other household annual energy needs

	BAU scenario		EE scenario		
Other household energy needs[1]	**Energy source**	**Annual Energy kWh**	**BAU reduction**	**Energy source**	**Annual Energy kWh**
Domestic hot water (DHW)[1]	Natural Gas	2 300	-65%	Electricity	805
Cooking and kitchen appliances	Electricity	2 152	-35%	Electricity	1 399
Lighting	Electricity	248	-30%	Electricity	174
Other Electric appliances	Electricity	600	-20%	Electricity	480

BAU: business-as-usual; EE: energy efficient alternative; [1] Assumed a fan burner non-modulating boiler for BAU and a heat pump (air-water) for EE alternative.

4. RESULTS AND DISCUSSION

This chapter presents the main operational and LCIA results for a Portuguese single-family house with alternative building envelope and design options and operational conditions.

In section 4.1 the influence of alternative building envelope options affecting the thermal performance of the building (varying insulation and ventilation levels) and of different building components (exterior walls) are assessed considering different user behavior (two operational patterns). In section 4.2, the influence of alternative building design options (orientation, window sizing and placement, and building shape) are assessed for the base case house located in Coimbra, considering different user behavior (operational patterns). In section 4.3, the base case house is assessed for alternative Portuguese locations and different user behaviors to identify how operational and total LC results of a Portuguese house vary for different climate in Portugal. In section 4.4, the influence of alternative operational conditions (operational patterns, HVAC systems and the electricity generation mix) is assessed for the base case new house and for an equivalent 25-year old existing house (non-insulated and with single glazing). Section 4.5 discusses the joint influence of the building envelope, design and operational conditions in Portuguese houses.

4.1. Building envelope options

The influence of alternative building envelope options (presented in Table 9) on operational energy and on overall LC impact of a Portuguese single-family house is assessed. Firstly, the operational energy results assuming alternative thermal envelope options are compared to existing energy consumption statistical data from the Portuguese household context (INE-I.P./DGEG, 2011; INE, 2015), in order to frame the potential *prebound* effect due to Portuguese user behavior and explain the operational patterns selected (OP50 and OP25). Secondly, the house non-renewable primary energy (NRPE) and LCIA results are presented for the two operational patterns (OP50 and OP25). In section 4.1.1, alternative insulation and ventilation levels (which influence the building thermal performance) are assessed. In section 4.1.2, the influence of alternative exterior wall assemblies is assessed jointly with envelope insulation level. In section 4.1.3 the influence of insulation level is assessed assuming alternative HVAC systems for the same house. The LC results presented include three LC stages: construction (embodied impacts), maintenance, and operation (energy for heating and cooling).

- **Operational results and operational pattern**

Figure 7 presents the final energy requirements for heating and cooling the single-family house (presented in section 3.5, page 63) with double brick exterior walls, located in Coimbra, assuming 40 building envelope construction alternatives (five insulation levels, four ventilation levels, and two window types, presented in Table 9) and continuous interior thermal comfort (operational pattern OP100, presented in section 3.5.3, page 74) with the electric heater HVAC scenario (presented in Table 17).

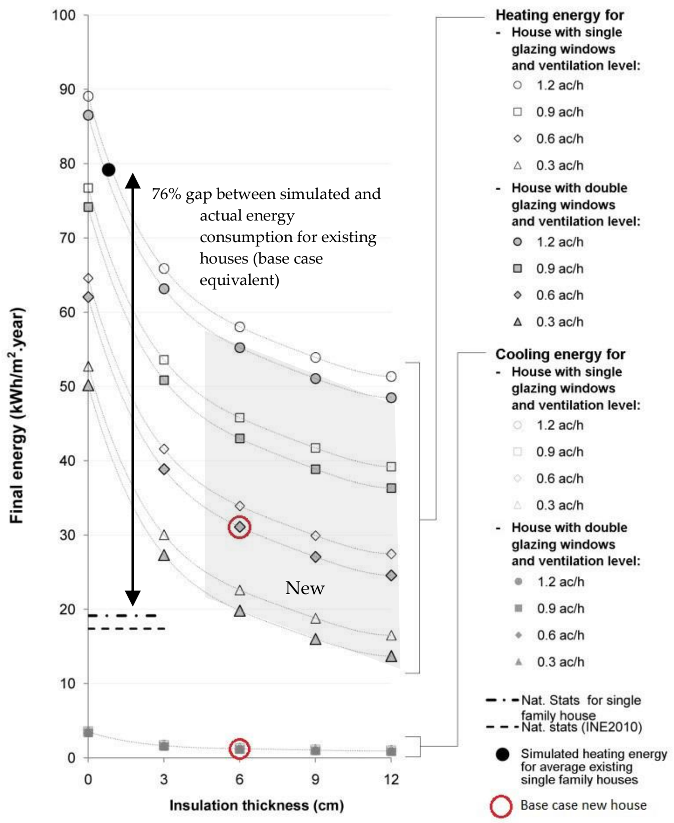


Figure 7. Annual final energy considering OP100 (kWh/m^2.year) for heating and cooling the single-family house with local electric heaters and air-conditioning units, respectively. Comparison with statistical data for the Portuguese building stock

Jointly with the operational results of the parametric analysis performed, Figure 7 presents the expected heating final energy for an average existing house based on Portuguese building stock characteristics (INE, 2013) for OP100 and the real (statistical) energy consumption data for heating a Portuguese dwelling (INE-I.P./DGEG, 2011) and a Portuguese single-family house (value inferred from statistical data, and the Portuguese building stock physical characteristics (INE, 2013)). Final energy results are presented in kWh/m^2·year. Although based on a rough estimation, the comparison between the real energy consumption in Portuguese homes and the simulated energy performance reflects a significant gap. This gap, also called the *prebound effect* (Sunikka-blank & Galvin, 2012), represents the way user behavior can reduce the expected (simulated) energy consumption levels. As identified to be true in other countries (Galvin & Sunikka-Blank, 2013; Rosenow & Galvin, 2013; Sunikka-blank & Galvin, 2012) it seems that Portuguese dwellers heat their homes partially, or at cooler temperatures, or have their heating on for less time than assumed in the simulated continuous comfort operational pattern (OP100).

Statistical data (INE-I.P./DGEG, 2011) show that in Portugal real measured household consumption can be on average 75% lower than simulated energy consumption for maintaining continuous optimum comfort conditions. This is possible also because climate conditions are not as harsh as in North and Central European locations. But as shown in (Galvin & Sunikka-Blank, 2013; Sunikka-blank & Galvin, 2012), another trend is likely to be found: occupants tend to use heating more economically in houses that are thermally worst. So, the *prebound* effect percentage may change with the thermal performance of the building, decreasing the benefit of energy efficiency measures. Real operational energy consumption data is limited and the potential *prebound effect* for the Portuguese household context and for the warm Mediterranean climate still needs to be better studied (and quantified). Thus, in this section, two alternative operational pattern scenarios that most likely frame Portuguese dwellers heating and cooling habits are considered:

- **OP25**, which represents a low occupancy and modest (and partial) heating and cooling level reinforced by Portuguese statistical data; it holds 25% of the simulated heating and cooling energy requirements for OP100;
- **OP50**, which assumes a medium occupancy and heating and cooling level, holding 50% of the simulated heating and cooling energy requirements for OP100.

This section does not intend to further assess the specific effect of the dynamic (zoned and intermittent) operational patterns, which widely vary from family to family. The additional influence of operational patterns is further studied in section 4.4.1.

Regarding the parametric assessment performed (for the 40 envelope alternatives), the thermal simulation results showed that heating was the dominant process in operational final energy of the house (located in Coimbra). For a non-insulated building, the use of thermal insulation, followed by the reduction of the ventilation level (infiltration) are the most favorable measures. The upgrade of window type from single to double glazing with thermal break is a significant measure if an insulated (with 6 cm or more) and air-tight building is considered, as the base case house assumed in this study. For this house, cooling energy represents only 7 to 2% of operational final energy. This low significance is also justified by the small window size. Although not very significant, it is worth mentioning that cooling energy increased in the lower total ventilation scenario 0.3 ac/h, when compared to 0.6 ac/h ventilation scenario, but this increase was completely offset by heating savings. This is justified by the fact that ventilation is a key factor to remove heat during cooler periods of the day (for example during night periods).

4.1.1. Ventilation and insulation levels

Four total ventilation levels (0.3-1.2 ac/h) and five insulation levels (0-12 cm) were assessed for the base case new house (house with double hollow brick walls and double glazing windows with thermal break). The heat pump system HVAC scenario was assumed for heating and cooling. The life cycle NRPE results are presented in Figure 8 for the operational patterns OP25 and OP50. Although a non-insulated house is an unlikely alternative for Coimbra (not complying with the thermal regulations), in this parametric analysis trend lines (polynomial, order 4) were applied for each ventilation alternative to clearly show the influence of varying insulation level from 0 to 12 cm. The LCIA results for the environmental categories assessed are presented in Figure 9, for OP25, and in Figure 10 for OP50.

- **Primary energy results**

Construction phase was the most important LC phase regarding NRPE (Figure 8). In OP25, construction represented 55-82% of the NRPE, surpassing operational energy (heating and cooling) for all alternatives. In OP50, construction represented 40-76% of NRPE, surpassing operation for houses alternatives with 3 cm XPS insulation thickness or higher. Operational phase was dominant in only two non-insulated house alternatives, representing 53-14% of NRPE amongst alternatives. Insulation thickness tipping-points, for which NRPE was minimized were identified for operational pattern: 3-6 cm for OP25, and 6-9 cm for OP50. However in OP50, the total LC benefit of having more insulation than 6 cm, was less than 1% for all ventilation scenarios. The insulation tipping-point did not change significantly with the ventilation level.

Compared with the worst case (0 cm insulation, 1.2 ac/h ventilation), insulating the house with 6 cm reduced operational NRPE in 39-61% (OP25 and OP50) but it only achieved a LC reduction of 8-9% (OP25) or 16-20% (OP50). Increasing air-tightness and lowering ventilation levels from 1.2 to 0.3 ac/h reduced operational NRPE in 38-68% (OP25 and OP50) and it achieved a LC reduction of 14-15% (OP25) or 20-23% (OP50). Assessing the jointly effect of the measures (6 cm insulation; 0.3 ac/h ventilation) a maximum NRPE reduction of 21% (OP25) and a 36% (OP50) was achieved. The base-case house (6 cm insulation and 0.6 ac/h ventilation) resulted in a 17% (OP25) and a 30% (OP50) NRPE reduction.

Maintenance had a small impact in non-insulated house alternatives, but a similar impact to operational energy in a well-insulated (6 cm) and air-tight (0.3 ac/h) house for OP25. When operational energy is reduced, other LC phase contribution is proportionally increased. Figure 8 shows that combining two simple passive construction measures (thermal insulation and air-tightness) may result in important LC NRPE savings, but the LC savings are lower than operational ones. Additionally, the expected LC savings are highly influenced by user behavior (or by the operational pattern) assumed. Thus, to avoid problem shifting, the operational patterns should reflect alternative ways of inhabit and acclimatize a house.

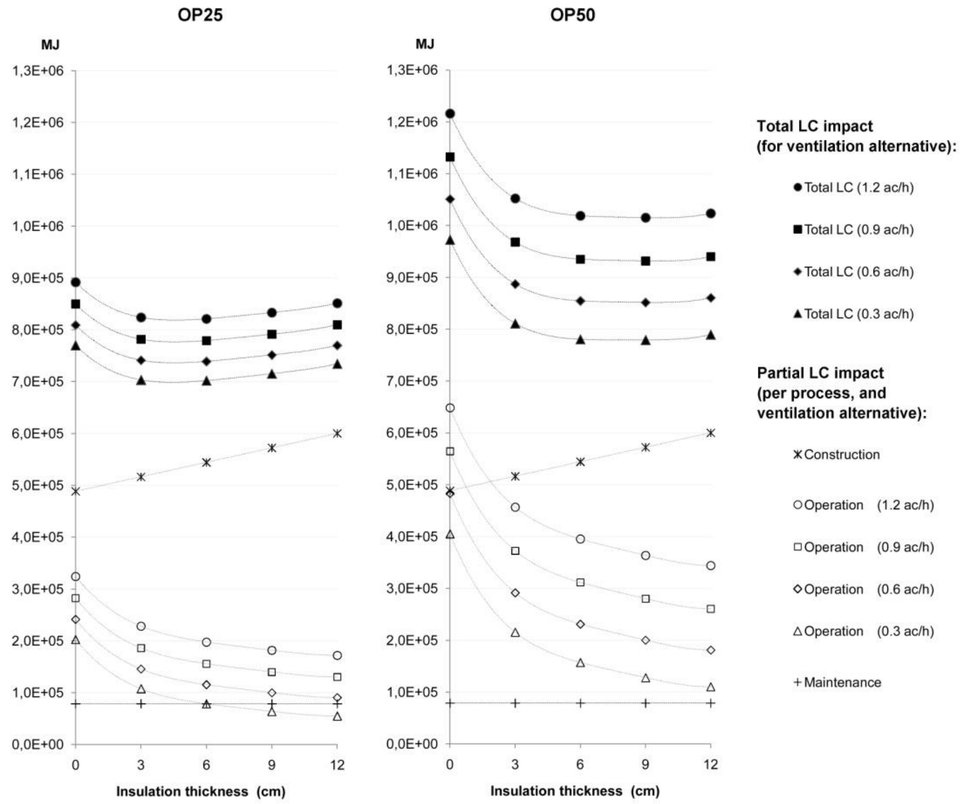


Figure 8. NRPE for base case house (brick house with a heat pump system) for OP25 and OP50: ventilation level (ac/h) *vs*. insulation level (0-12 cm)

Increasing the air-tightness of the building and reducing total ventilation (and infiltration) level to 0.3 ac/h (without compromising indoor air quality) is a more beneficial passive solution than increasing XPS insulation beyond 6 cm thickness. This should hold true for new houses with a fairly compact shape and small window area, as the base case, using a heat pump system under similar climate conditions. Increasing the insulation thickness generates gradually lower NRPE savings and can even result in higher NRPE (when insulation is above the tipping point, since embodied energy requirements offset operational energy savings).

- ## Environmental impact assessment results

Figure 9 and Figure 10 show that abiotic depletion, acidification, and GWP results correlate with NRPE (Figure 8). In OP25 the insulation tipping point was between 3-6 cm for most categories, being the exceptions eutrophication and OLD. Whereas in OP50, the tipping point varied widely: 3-6 cm for GWP and photochemical oxidation; 9-12 cm for abiotic depletion and acidification. For eutrophication the tipping point was above 12 cm, both in OP25 and OP50, since the insulation material had relatively low impact in this category.

Regarding OLD, the lowest impact was for a non-insulated house, both for OP25 and OP50. OLD embodied impact (58-99%) surpassed by far the operational one (for all alternatives) given that construction materials, especially XPS insulation, had a big contribution in OLD impact. XPS high impact is justified by the extrusion process assumed that uses hydrofluorocarbon (HFC-134a) (Althaus H-J, Bauer C, Doka G, Frischknecht R, Jungbluth N, 2010). Recently, some XPS producers have started to use CO_2 and HCF-152a as alternative blowing agents to HFC-134a and, new European inventory data became available (i.e., ecoinvent v3.1 (2014)). Additionally, a LCA study of insulation materials (Pargana, 2012; Pargana et al., 2014) has assumed this replacement for the Portuguese context. Based on that study, new production methods can drastically reduce the XPS OLD impact (from 1.64 E-04 kg CFC-11eq to 7.27E-08 kg CFC-11eq, per 1 kg of XPS material) and, in that case, the insulation tipping point would be above the 12-cm thickness for both OP25 and OP50. This example shows how building overall impact may be highly sensitive to specific material production processes used.

Regarding the comparison between construction and operational impacts, in OP25, construction was the most significant LC phase for all categories (an exception was found in eutrophication for two non-insulated alternatives). Furthermore, in photochemical oxidation, construction had a big impact (72-88%). In OP50, the contributions of construction and operation are dependent on the insulation and ventilation alternative selected. Combining two simple passive construction measures (an insulation level of 6 cm and an air-tight envelope (0.6 ac/h)) the embodied impacts had a LC contribution above 67%.

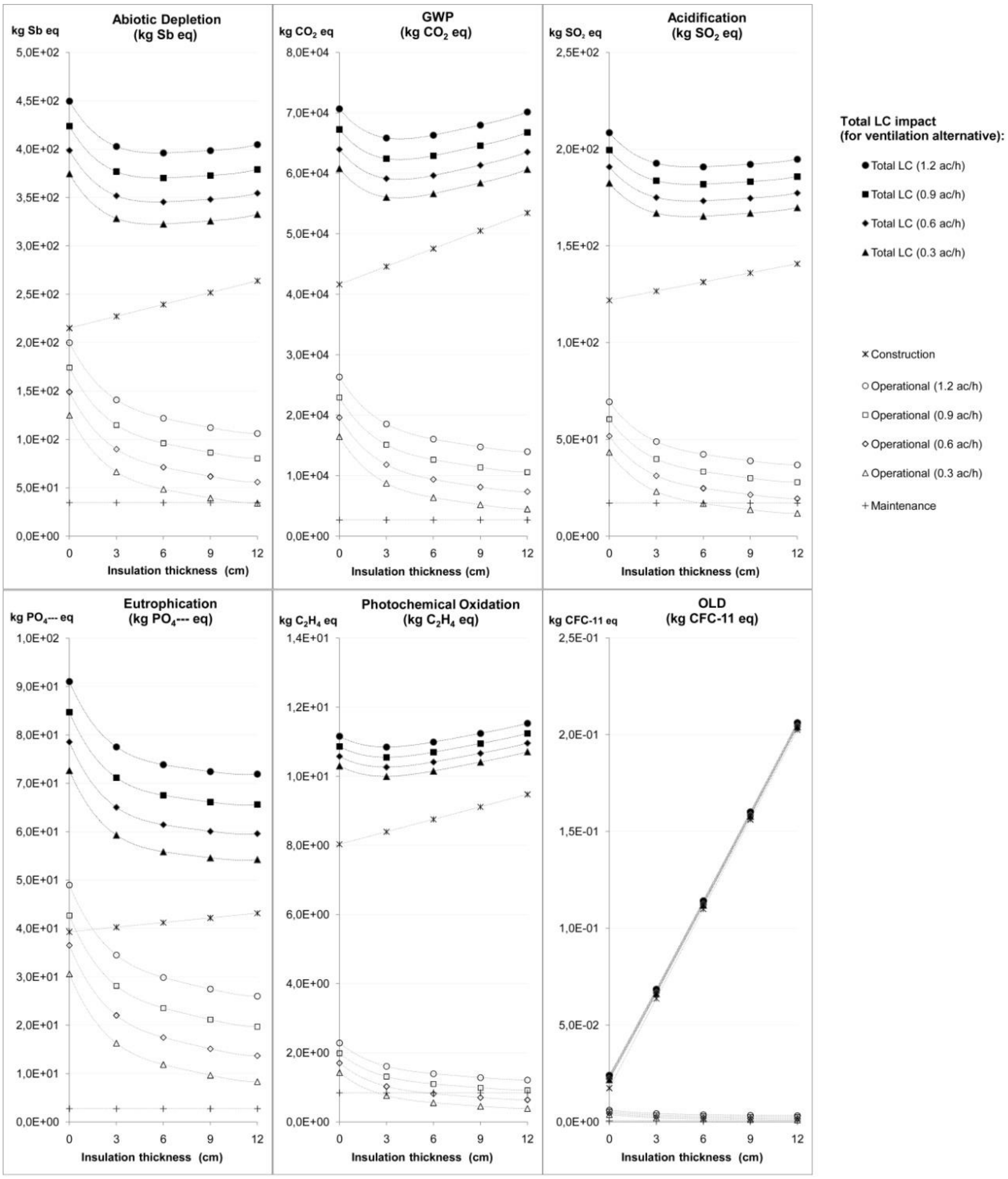


Figure 9. LCIA results for base case house (brick house with a heat pump system) for OP25: ventilation level (ac/h) *vs*. insulation level (0-12 cm)

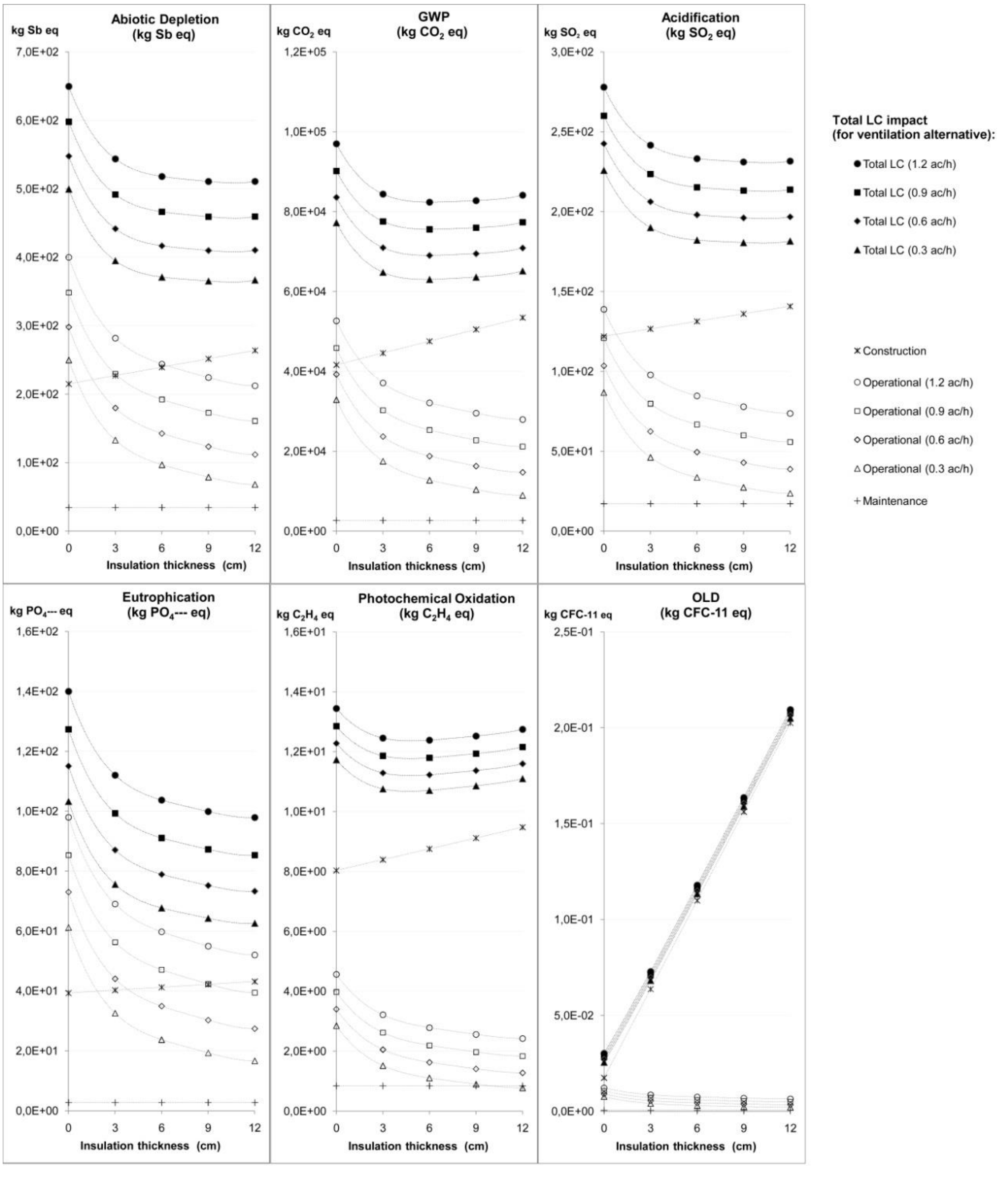


Figure 10. LCIA results for base case house (brick house with a heat pump system) for OP50: ventilation level (ac/h) *vs*. insulation level (0-12 cm)

4.1.2. Exterior wall alternatives and insulation level

In this subsection, three exterior wall alternatives, presented in Table 9 – double brick exterior walls, lightweight concrete exterior walls, and wooden exterior walls – were assessed jointly with different envelope insulation levels. Results are presented for the base case house with 0.6 ac/h ventilation level and the heat pump system HVAC scenario, for operational patterns OP25 and OP50. The insulation level parametric analysis covers thicknesses from 0 cm to 12 cm for the three exterior wall alternatives. Though, it should be noted that a wood wall with no insulation is an unlikely alternative and the non-insulated concrete wall (0 cm) assumes a base plaster finishing instead of the exterior thermal insulation composite system (ETICS) acrylic plaster layer.

- **Primary energy results**

Figure 11 presents the NRPE for OP25 and OP50. Results showed that the operational energy of the three exterior wall house alternatives was similar, being mostly dependent on the envelope insulation level. This can be justified because all exterior wall house alternatives have high thermal inertia, due to the heavyweight core of the house (concrete structure, and brick interior walls), which remained unchanged. So, the LC differences among the exterior wall alternatives were mainly due to the insulation thickness level and due to the embodied and maintenance impacts typical of different wall assemblies.

Embodied energy surpassed operational energy for most alternatives except for the non-insulated houses. Regarding the contribution to overall NRPE, in OP25, construction held 51-78% and operation held 33-12%, whereas in OP50 operation held 21-50%, and construction held 39-70% amongst alternatives.

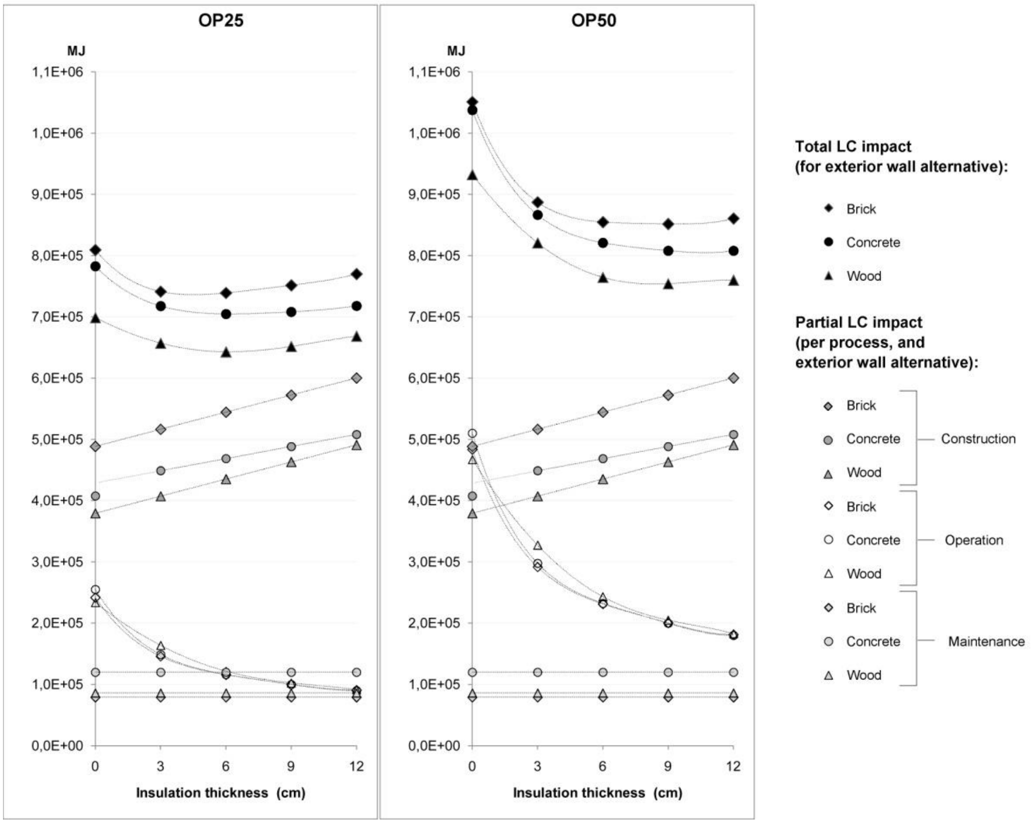


Figure 11. NRPE for OP25 and OP50 for 3 exterior wall house alternatives (brick, concrete and wood) with 5 insulation levels (0-12 cm)

Double brick wall house had the highest embodied NRPE (construction), whereas concrete wall house had 13-15% lower embodied energy (depending on the insulation level), and the wood wall house had 22-18% lower embodied energy. In CED method, wood is considered a renewable source of energy and it has a low embodied NRPE. Thus, the wood wall house presented the lowest NRPE, with a total reduction of 11-14% (OP25) or 7-11% (OP50) NRPE when compared to the base case brick house. The concrete wall house had a NRPE LC reduction of only 3-7% (OP25) or 1-6% (OP50) since the embodied energy reduction was partially offset by the higher maintenance requirements. The maintenance of concrete wall house held a higher LC energy than the other exterior wall alternatives mainly due to the acrylic plaster finishing of ETICS.

Insulation thickness tipping point varied with the exterior wall alternative and the operational pattern. In OP25, the tipping points were 6 cm for concrete and wood wall houses, and 3 cm for the brick wall house. In OP50, the tipping points were around: 12 cm for concrete wall, 9 cm for wood wall, and 6 cm for brick wall house. Furthermore, the adoption of an alternative exterior wall assembly (i.e., wooden wall) instead of the base case (double brick wall) had a higher contribution to reduce NRPE than an increase of the XPS insulation beyond 6 cm thickness.

- **Environmental impact assessment results**

Figure 12 and Figure 13 present the LCIA results for OP25 and OP50, respectively. Acidification closely correlated with NRPE. Abiotic depletion also showed similar results to NRPE, though operational phase had a little higher contribution in abiotic depletion. Other environmental categories presented some differences regarding the LC phase contributions, insulation tipping-points, and specific insulation material impacts.

In GWP, photochemical oxidation and OLD, dissimilar embodied impacts were associated with XPS (used in brick and wood wall alternatives) and EPS (used in the concrete wall ETICS). XPS has 3.8 times higher GWP impact and 2000 times higher OLD impact than EPS for the same insulation thickness. Whereas, EPS has 3.5 times higher photochemical oxidation impact than XPS. XPS OLD high impact is due to HFC-134a used during the extrusion process as explained in section 4.1.1. Insulation material impacts play a big role in the LCA of building envelope construction alternatives because they affect not only the insulation thickness tipping points but also the LC benefit of building envelope construction alternatives and the expected operational savings in different environmental categories.

Insulation thickness tipping points varied with exterior wall alternative, operational patterns, and impact categories. In OP25, the tipping point for the brick wall alternative was between 3-6 cm for most categories (except eutrophication and OLD); the tipping point for the wood wall was near 6 cm for most categories (except eutrophication and OLD); and the tipping point for concrete wall was above 12 cm for three categories (GWP, eutrophication, OLD), near 9 cm for two categories (abiotic depletion and acidification) and was inexistent in photochemical oxidation (since the solution that minimized LC burdens was to use no EPS insulation). For OP50, the tipping points for both the brick and the wood wall were near 6 cm for GWP and photochemical oxidation, 9-12 cm for abiotic depletion and acidification, and above 12 cm for eutrophication; the tipping points for the concrete wall were above 12 cm for five categories (except photochemical oxidation).

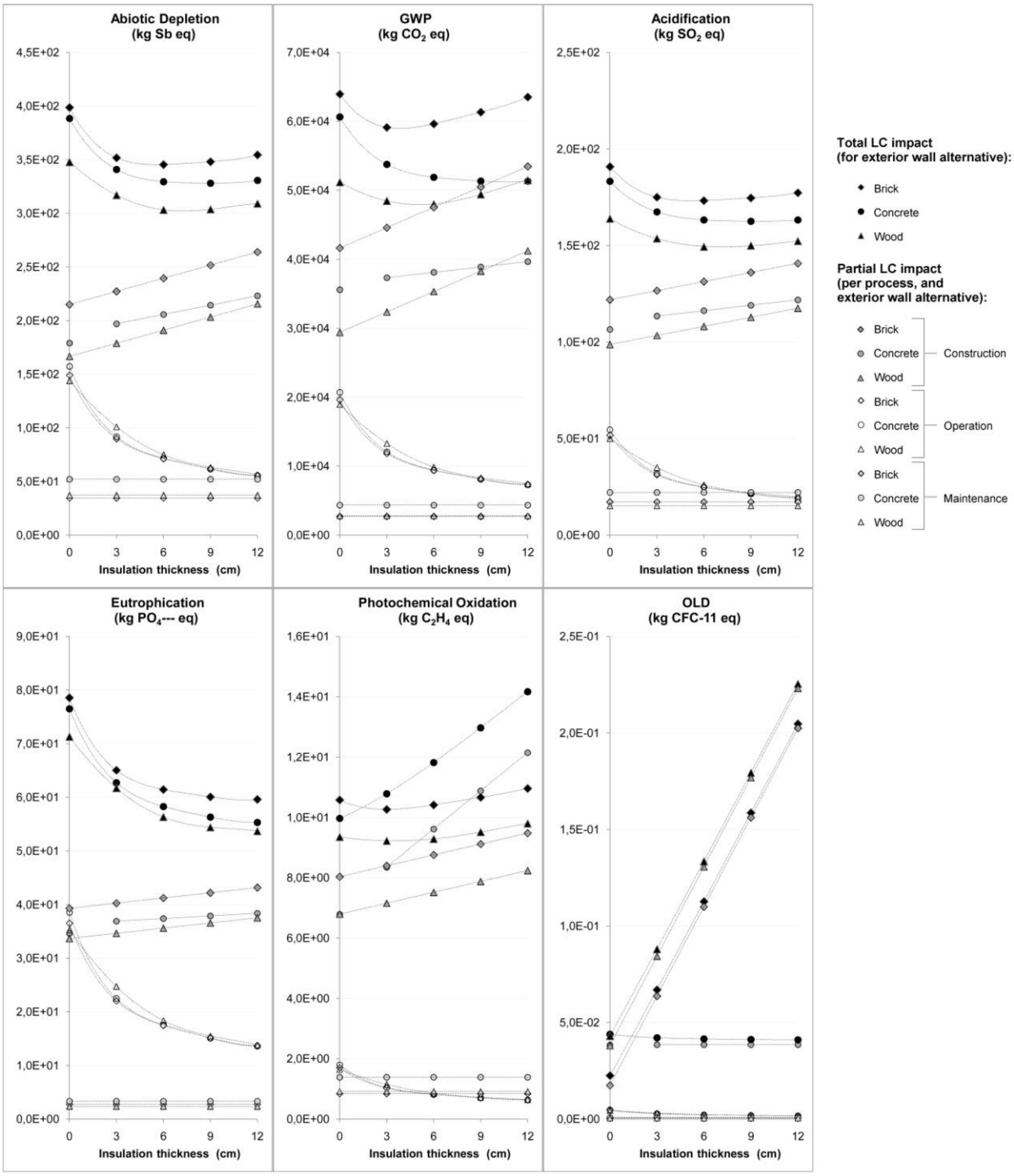


Figure 12. LCIA results for the house with 0.6 ac/h ventilation level and a heat pump system for OP25: 3 exterior wall construction alternatives with 5 insulation levels (0-12 cm)

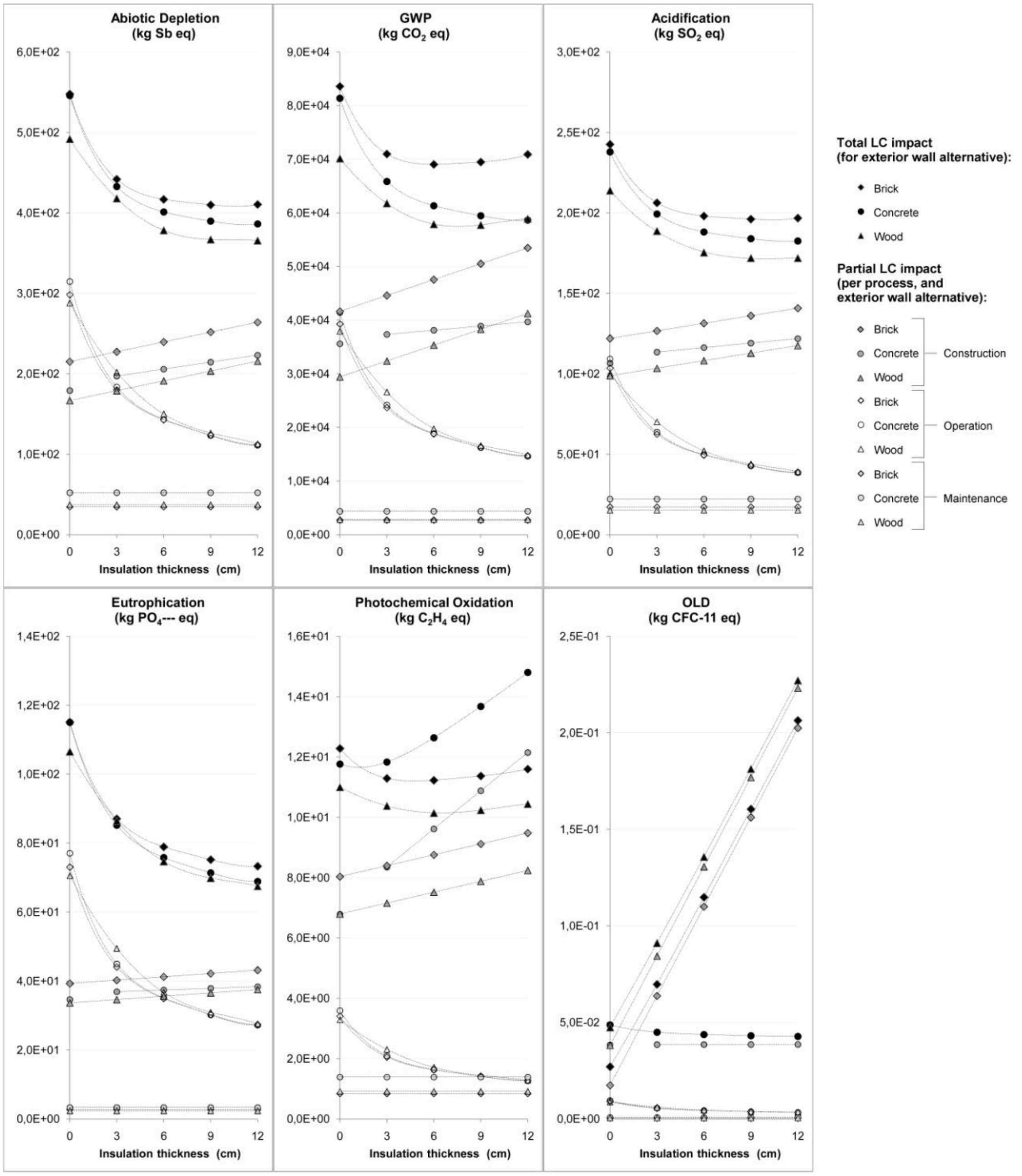


Figure 13. LCIA results for the house with 0.6 ac/h ventilation level and a heat pump system for OP50: 3 exterior wall construction alternatives with 5 insulation levels (0-12 cm)

Comparing the three exterior wall alternatives, double brick wall had the highest embodied and total LC burdens in four categories (abiotic depletion, GWP, acidification, eutrophication). Concrete wall had most embodied and LC burdens of photochemical oxidation, and wood wall held most embodied and LC impacts of OLD. Wood wall was the alternative with the lowest LC burdens in five categories, presenting a LC impact reduction of 7-20% (amongst those categories) when compared to the brick wall alternative (comparing both walls with the most beneficial insulation thickness, i.e. the closest alternative to the tipping point). Thus, the adoption of a wood wall construction alternative allows higher LC savings than the increase of thermal insulation beyond 6 cm thickness for the brick wall alternative. Nevertheless the concrete wall alternative also presents 5-20% reduction of most environmental impacts having a higher thermal insulation thickness tipping point, which may be desirable for Portuguese houses were operational heating impact is higher due to operational conditions (e.g., local climate, user behavior, HVAC system used, and energy supply chain).

The relative contributions of different LC stages change among the exterior wall alternatives, with the environmental category and with the operational pattern selected. But, with this case study, a clear trend was identified: construction phase generally represent most of building LC impacts (even in poorly insulated buildings) if realistic Portuguese energy consumption patterns are considered. In OP25, this was valid for the 15 alternatives presented in five environmental categories (the exceptions were two non-insulated alternatives in eutrophication category). Even in OP50, this was valid for all alternatives in two categories.

Assuming the base case 6 cm insulation level, which is a likely insulation level to be adopted in a new house in Coimbra, construction phase holds most of the house LC burdens both in OP25 and OP50. In OP25 construction held 62-81% of LC burdens, operation held 7-33%, and maintenance accounted for 5-16% in five categories (except OLD, which is explained below). While in OP50, construction held 48-76% of LC impacts, operation held 13-49%, and maintenance accounted for 3-13%. OLD is a particular category, in which embodied impacts were responsible for almost all LC burdens (88-98%), especially in the wall alternatives that incorporated XPS insulation as explained in section 4.1.1.

These results reinforce the idea that LCA is crucial to avoid problem shifting and to identify the most significant LC processes. Additionally, they highlight the different nature of Portuguese dwellings LC impacts when compared to cold climate houses. Under Coimbra climate and the Portuguese context, even a non-insulated house can have higher embodied impacts than the operational ones (for heating and cooling), and a new house (base case) is likely to have more embodied burdens in all impact categories. These results are justified by both the high performance of the heating and cooling system adopted (heat pump) and by the Portuguese electricity mix, which in the last years had a large contribution of renewable energy (Garcia et al., 2014). Therefore it is important to assess how LC results and the insulation benefit vary, if different HVAC systems are considered.

4.1.3. Insulation level using different HVAC systems

In this subsection, three alternative HVAC scenarios – a heat pump system (COP 2.8 / EER 2.0), local electric heaters, and a natural gas condensing boiler – were assessed jointly with different insulation levels assuming a 0.6 ac/h ventilation level. The house alternatives NRPE is presented in Figure 14 for OP25 and OP50, whereas the LCIA results are presented in Figure 15 for OP25, and in Figure 16 for OP50.

- **Primary energy results**

The HVAC scenario (and heating system) selected had a great influence on operational LC results and on insulation level LC benefit. NRPE results show that the heat pump was the most energy-efficient system of the three systems assessed. Compared to local electric heaters, the heat pump system presented a reduction of 61-62% of operational energy, whereas the natural gas condensing boiler achieved a reduction of 22-23%. Regarding the insulation thickness tipping point, for which the LC NRPE of the house is minimized, it widely varied with the heating system adopted and the operational pattern assumed. In OP25, the tipping point was: 9-12 cm (using electric heaters); 9 cm (natural gas boiler); 3-6 cm (heat pump system). In OP50, the tipping points were higher than in OP25, being around: 12 cm (electric heaters); 9-12 cm (natural gas boiler); 6-9 cm (heat pump). However, it is worth to note that in OP25, the total LC benefit of adding more insulation than 6 cm was less than 2% for both electric and natural gas heating. Likewise, in OP50 there is only a marginal benefit for the natural gas condensing boiler in having more than 9 cm insulation level.

Though embodied impacts were constant in both operational patterns, in OP25 construction was generally the most important LC phase, representing 41-78% of the LC NRPE amongst heating systems, while in OP50, its relative share decreased to 27-70%. The relative contribution of operational energy widely varied with the system selected and with the insulation level: being 12-52% (in OP25) and 21-69% (in OP50). Maintenance share was also affected though it remained less significant: 7-11% (in OP25) and 4-9% (in OP50). Considering the base case house (6 cm insulation level and 0.6 ac/h ventilation level), construction energy held 59% (electric heater), 63% (natural gas boiler) or 74% (heat pump) of NRPE in OP25, and 44% (electric heater), 50% (natural gas boiler) or 64% (heat pump) of NRPE in OP50. Therefore, even with electric heating, the initial (in construction) and recurrent (maintenance) embodied energy surpassed the operational NRPE.

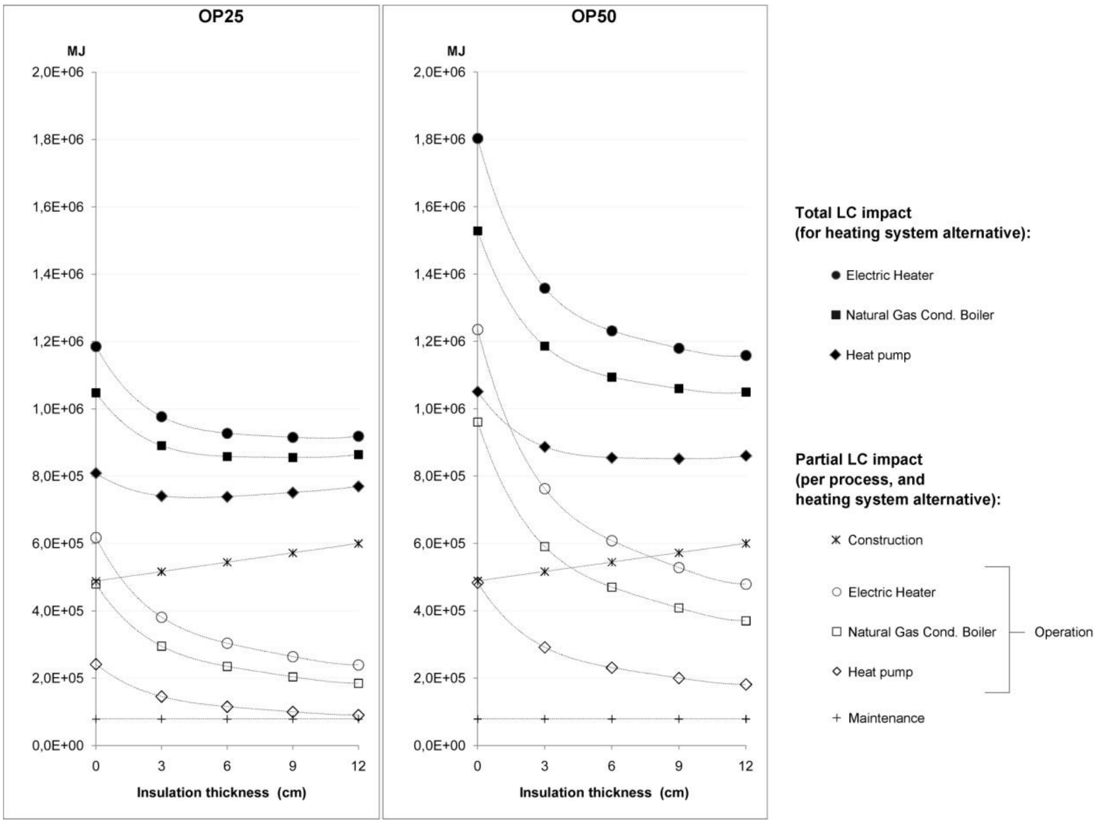


Figure 14. NRPE for base case house (brick house with 0.6 ac/h) for OP25 and OP50: alternative heating system *vs*. insulation level (0-12 cm)

- **Environmental impact assessment results**

LCIA results show that the heating system with the lowest impact varies among categories. The heat pump system presented the lowest abiotic depletion, GWP, and photochemical oxidation impacts. The natural gas condensing boiler had the lowest acidification and eutrophication impact. Electric heaters had the highest impact for all categories except for OLD. The heat pump system had the highest OLD impact due to partial emissions of refrigerant HFC-134a considered during operation, which represented around 80% of the operational stage. However, OLD impacts among heating systems were not significant when compared to the total LC of the house (less than 2%) since the embodied impact (mainly due to XPS production process) dominated this category, as discussed in section 4.1.1.

The insulation tipping points varied with the heating system adopted, the operational pattern assumed and the environmental category selected. In OP25, the tipping points for most categories were 3-6 cm for the heat pump system (except in eutrophication and OLD), 3-6 cm for the natural gas condensing boiler (except in abiotic depletion and OLD) and near 12 cm for the electric heater (except in OLD, GWP, and photochemical oxidation). In OP50, the insulation thickness tipping points for most categories were 6-9 cm for the natural gas condensing boiler (except in abiotic depletion, acidification and OLD), and over 12 cm (not identified in our study) for electric heater (except in photochemical oxidation and OLD). In OP50, the tipping points varied widely for the heat pump system depending on the category.

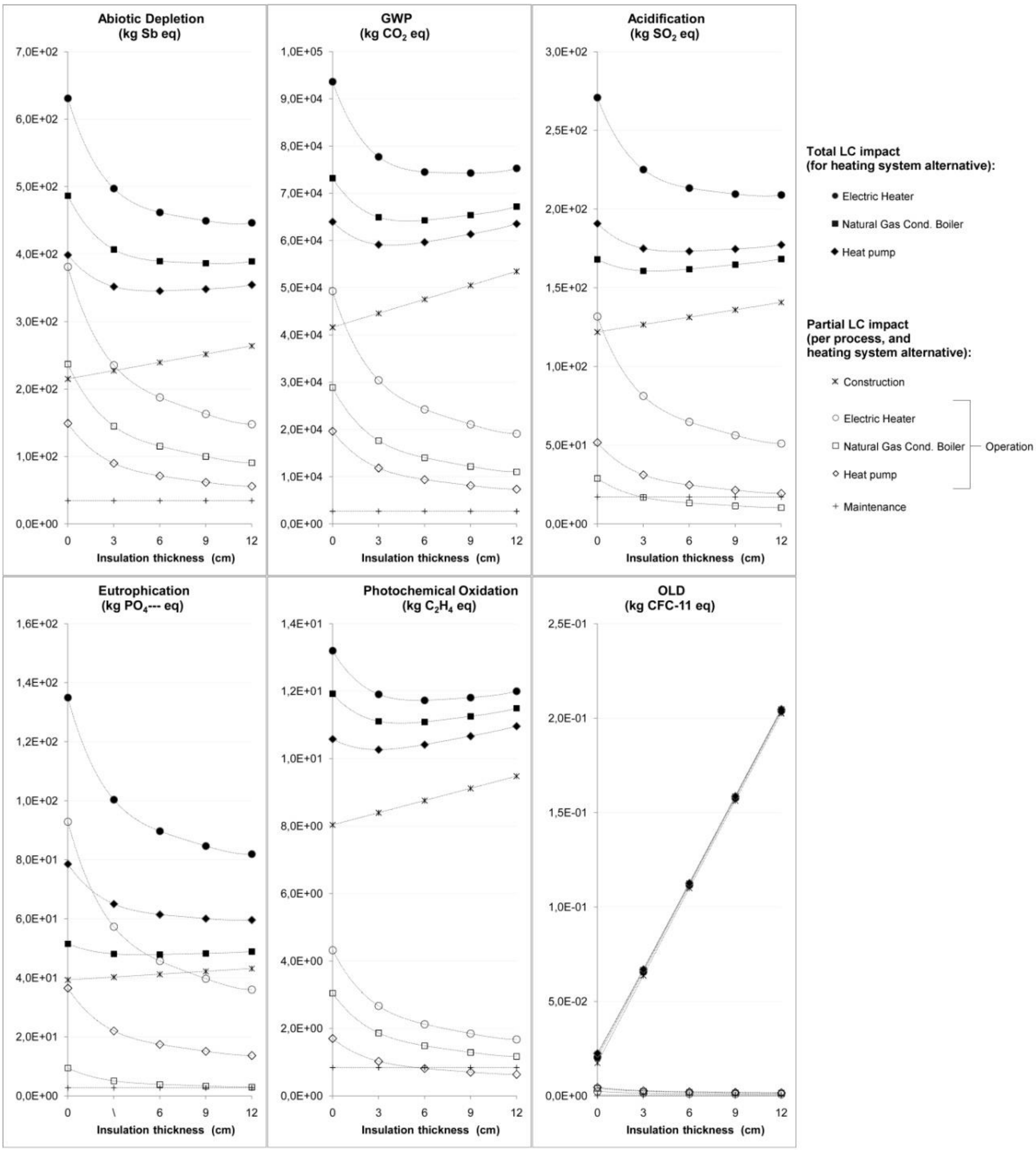


Figure 15. LCIA results for the base case house (brick house with 0.6 ac/h ventilation level) for OP25: heating systems *vs*. insulation level (0-12 cm)

The most important LC phase depends on the heating system, insulation level and operational pattern. For OP25, construction phase dominated most alternatives, except some with electric heating and with a low insulation level (0-3 cm). For OP50, a house with electric heating is expected to have higher operational impacts than embodied ones, while a house with a heat pump or natural gas condensing boiler and an insulated envelope is likely to have higher embodied energy. Considering the new house with 6 cm insulation (base case), using the heat pump or the natural gas boiler, in OP50 construction holds 47-80% of LC impacts, operation holds 15-46%, and maintenance accounts for 4-10% in five categories (except OLD); whereas in OP25 construction holds 62-86% and operation holds 8-30% of LC burdens.

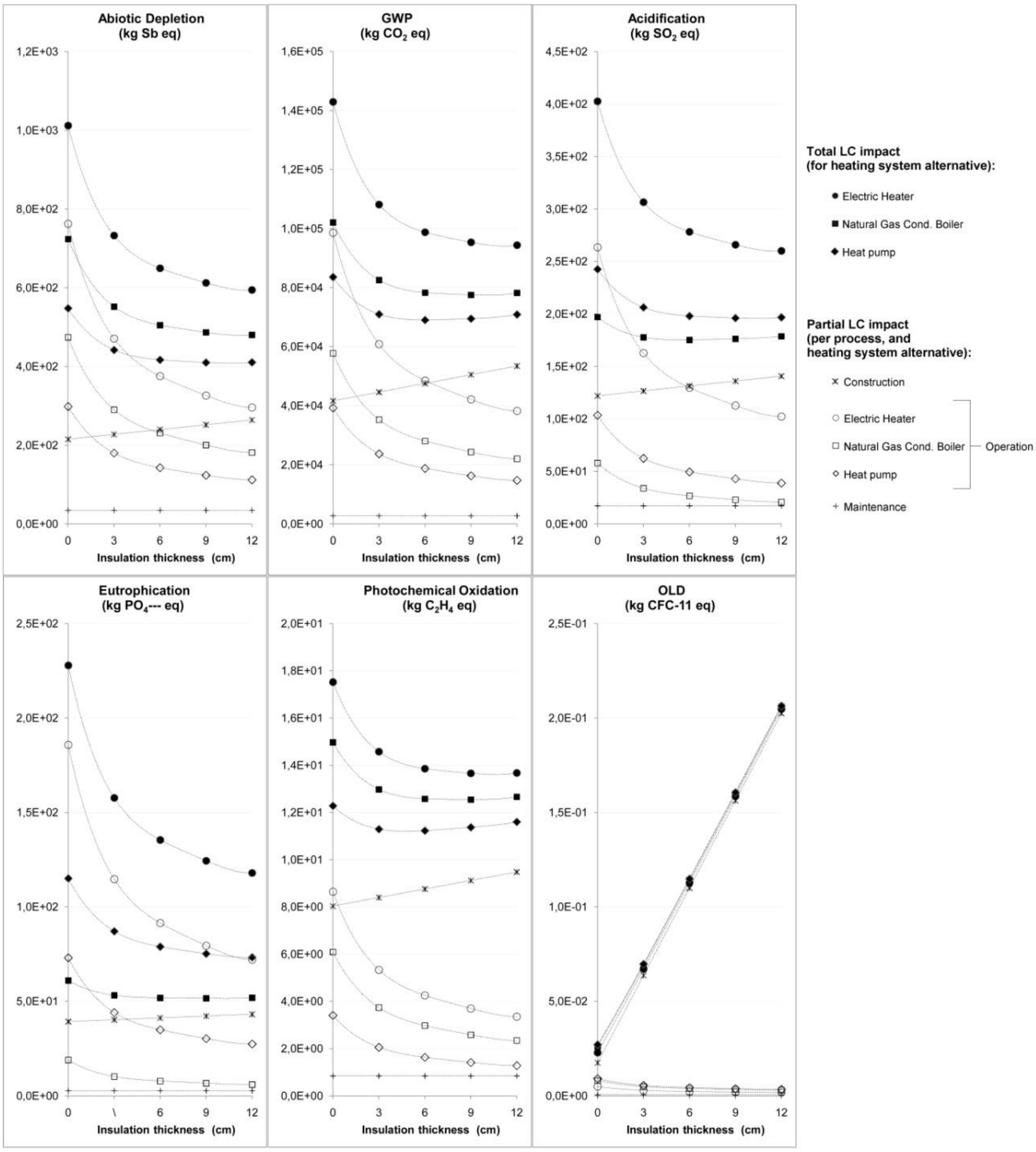


Figure 16. LCIA results for the base case house (brick house with 0.6 ac/h ventilation level) for OP50: heating systems *vs*. insulation level (0-12 cm)

4.2. Building design options

In this subsection the influence of three building design options – building orientation, window placement and sizing (window-to-wall ratio)), and building shape – are assessed in terms of operational and LCIA results of the house, located in Coimbra. The base case building envelope construction was used: double hollow brick walls; 6 cm insulation level; 0.6 ac/h ventilation level; double glazing window with thermal break aluminum frame.

4.2.1. Building orientation and window placement

Eight building orientations were assessed for the base case house for two window placement alternatives: H1W1 (the base case, which has openings placed in two opposite façades with 45% and 55% of the glazing area each) and H1W1-b (with similar window sizing but with windows placed in three facades) as presented in section 3.5.1, in page 69, and Figure 5.

- **Operational final energy**

Figure 17 presents the annual final energy for heating and cooling the house with window placements H1W1 and H1W1-b, using a heat pump system under OP100, for eight building orientations. Schematic axonometric drawings of each building have been included in Figure 17 to more easily recall each building characteristics. Polynomial trend lines were added in to show how operational energy varies with the varying orientation and window placement. The results show that heating needs represent 80-87% of the annual final energy for both H1W1 and H1W1-b under Coimbra climate.

Operational results show a maximum variation of 8% among H1W1 orientations, but a much higher variation, around 22%, for H1W1-b orientations. The base case window placement (H1W1) oriented W-E had the highest final energy, whereas oriented N-S had the lowest heating and cooling needs. In the N-S orientation, the back façade facing South allowed higher solar passive gains than in other orientations, which reduced heating needs (by 6%, when compared to W-E) and, at the same time, the cooling needs were also reduced (by 16%, compared to W-E) because there was less overheating through the front façade facing north.

The alternative H1W1-b had the lowest final energy when oriented W-E, and the highest operational energy oriented E-W. As this window placement has higher glazing area (64%) placed in the lateral façade, the minimum and maximum heating needs occurred when this façade was facing South (maximum solar passive gains) and North (minimum passive gains), respectively. Although the house oriented W-E had increased cooling needs, heating needs (which represents the majority of operational energy) were reduced by 29%, resulting in a total operational energy reduction of 22% when compared to E-W orientation.

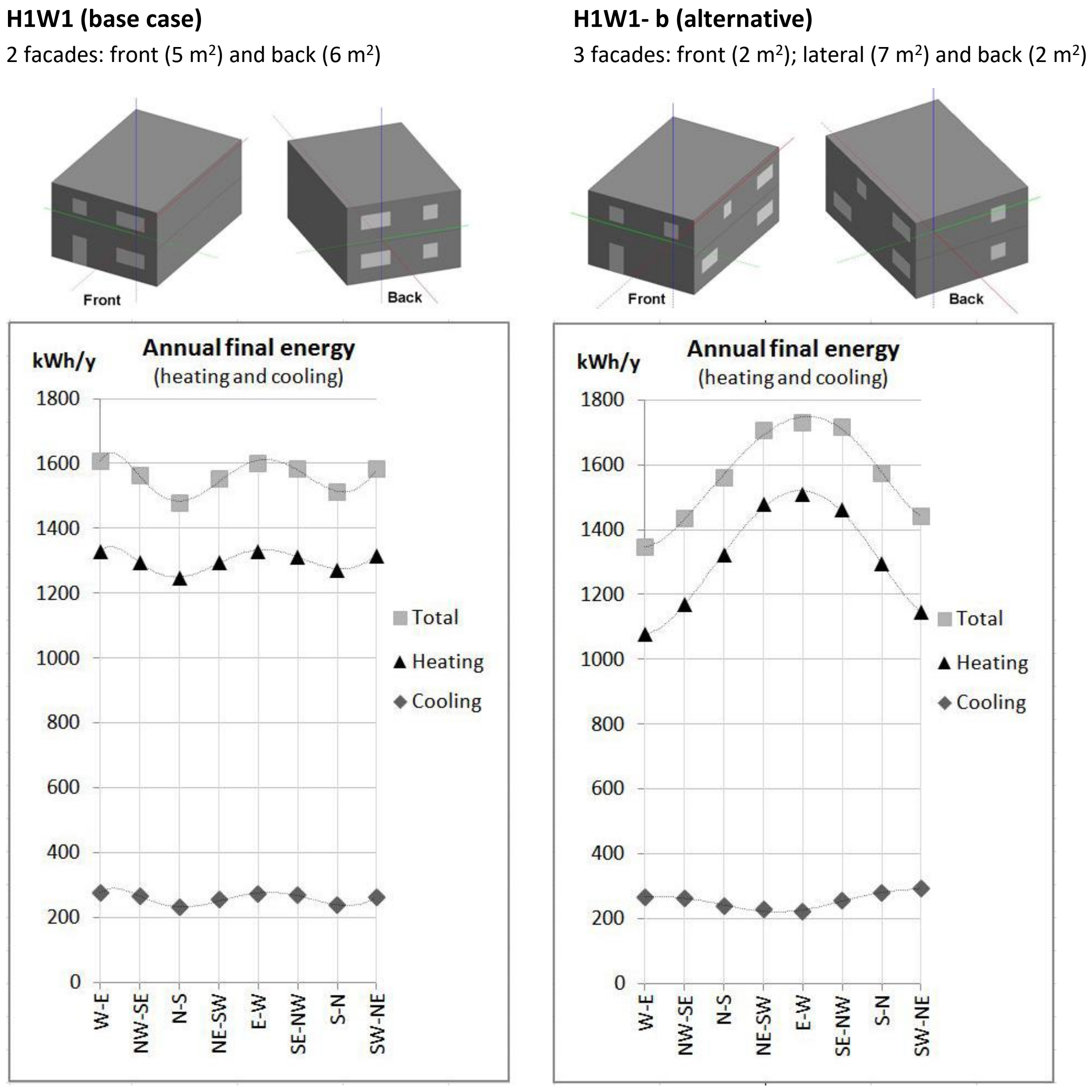


Figure 17. Annual final energy of the base case (H1W1) and alternative window placement (H1W1-b) for 8 building orientations for OP100 using a heat pump system.

- ## LC primary energy

Building construction elements are identical for H1W1 and H1W1-b, thus when assessing different orientations, maintenance and construction impacts are constant and only operational energy changes. However, building orientation may affect other passive measures influence, namely the window-size tipping points both in terms of operational and LC results (assessed in subsection 4.2.2).

In this subsection the LC results are only presented for NRPE. The other LC environmental categories are presented in the next sub-section for two orientations for each house (the orientations with maximum and the minimum operational values).

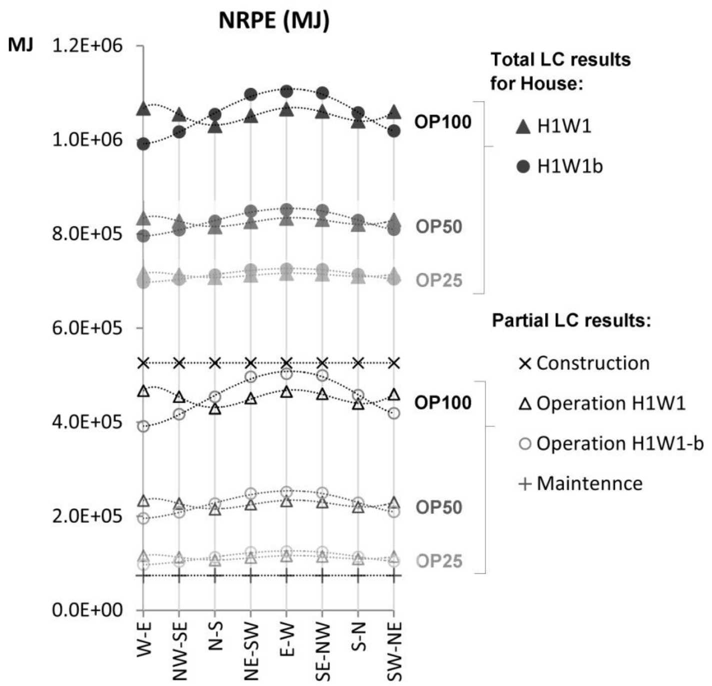


Figure 18. NRPE of the H1W1 and H1W1-b for 8 building orientations and three operational patterns (OP100, OP50, and OP25) using a heat pump.

Figure 18 presents the NRPE of house H1W1 and H1W1-b with varying orientation, for three operational patterns (OP100, OP50 and OP25). LC NRPE show that even under OP100, operational energy for heating and cooling the house is lower than the house embodied energy (in construction). For moderate operational patterns, construction energy became very significant representing 61-75% of NRPE (under OP50-OP25). Operational energy represents 46-39% of NRPE in OP100, but only represents 25-29% in OP50 and 14-17% in OP25%. Therefore, the influence of orientation is lower in LC NRPE compared to operational final energy, particularly for lower operations patterns (OP50 or OP25). In OP100, H1W1 presents a 3% LC variation among W-E and N-S orientations while H1W1-b presents a 10% LC variation among W-E and W-E orientations. The LC variation due to different orientations is: 2% for H1W1 and 7% for H1W1-b, in OP50; 1% for H1W1 and 4% for H1W1-b, in OP25.

4.2.2. Window sizing and placement

To frame the range of variation due to different orientations, the building orientations with the maximum and minimum operational results have been assessed for the house alternatives H1 (house with openings almost evenly placed in two opposite facades) and H1-b (house with openings placed in 3 façades but with the majority in the lateral façade, following the H1W1-b window placement): W-E and N-S for house H1; W-E and E-W for house H1-b. To study the influence of window sizing (or window to wall ratio) in the operational results, four alternative window sizes were assessed for each house. The scenarios presented in this section are detailed in Table 10.

Figure 19 presents the final energy of the house with window placement H1 and H1-b with varying window sizes or window wall ratios (WWR) and orientations, for operational pattern OP100 using a heat pump system. The WWR tipping point, for which operational final energy is reduced, varies with the building orientation. Results show that houses with bigger WWR (and glazing areas) are generally more sensitive to orientation influence due to higher solar passive gains and summer overheating.

- **Operational final energy**

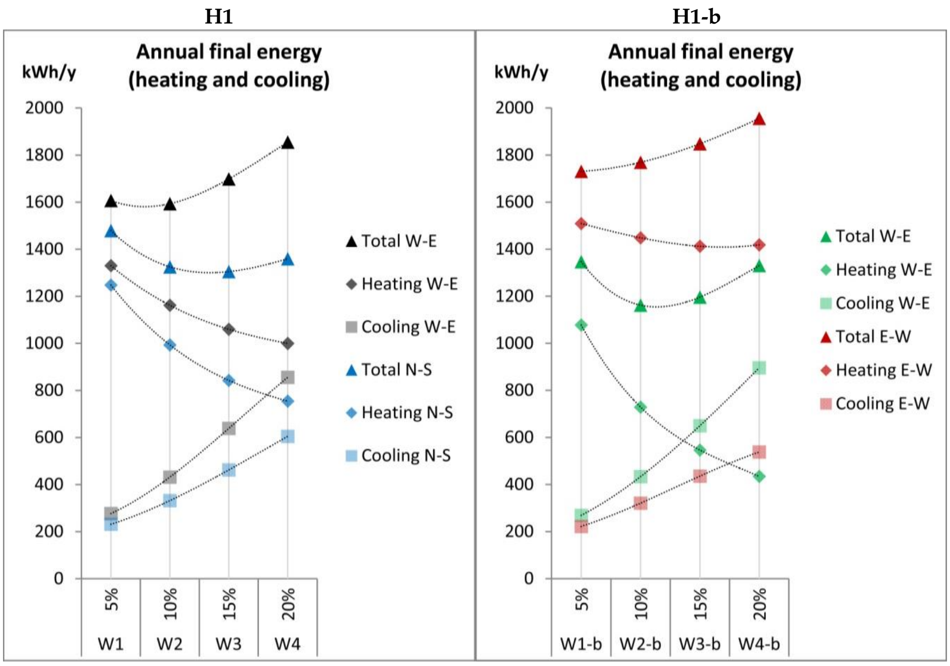


Figure 19. Annual final energy of the house with window placement H1 and H1-b, different window sizing (window wall ratio (%)) and orientation, for OP100 using a heat pump.

For alternatives H1 (houses with openings placed almost evenly in two opposite facades), an increase in window area (and WWR) gradually reduces heating needs for both orientations (due to greater solar passive gains), however, it increases cooling needs. The balance between heating and cooling needs determinates the tipping point, for which the operational energy is reduced. To minimize operational needs (tipping point), a 15% WWR (or window area around 33 m^2) is suggested for a N-S oriented house (in blue), whereas half that window sizing or WWR (8%) is preferred for a W-E oriented house (in black). The N-S oriented house with 15% WWR (W3) has 12% lower operational energy than the same house with 5% WWR (W1), and 18% lower operational energy than an W-E oriented house with 10% WWR (W2).

For alternatives H1-b, the tipping point is below 5% WWR for an E-W oriented house (in red), whereas it is between 10-13% for the same house oriented W-E (in green) achieving the lowest operational energy for the same house construction (34% lower than the house oriented E-W). The W-E oriented house has most glazing area facing south and therefore the increase in WWR greatly reduces heating needs but highly increases cooling needs. For example in a W3-b alternative, cooling may represent more than heating.

These results show that decisions regarding architectural window sizing and placement should be related to specific building orientation (in order to improve operational performance of the house). Houses with identical construction elements perform differently due their orientations and window sizing or WWR. However, as different WWR influence the embodied impacts (resulting in different window and exterior wall inventory quantities), it matters to assess whether the identified tipping points change under a LC perspective.

- **LC primary energy**

Figure 20 presents the NRPE of the house H1 and H1-b with varying window sizing and orientations considering three operational patterns (OP100, OP50 and OP25). NRPE results show that a house with a higher window sizing (or WWR) has higher embodied energy, because windows (aluminum framed with thermal break and double glazing) have a higher embodied energy per m² of facade than exterior walls (double hollow brick exterior walls). The LC NRPE tipping point is given by the balance between embodied and operational NRPE. The most adequate window sizing (WWR tipping point) depend on building orientation and on the operational pattern assumed.

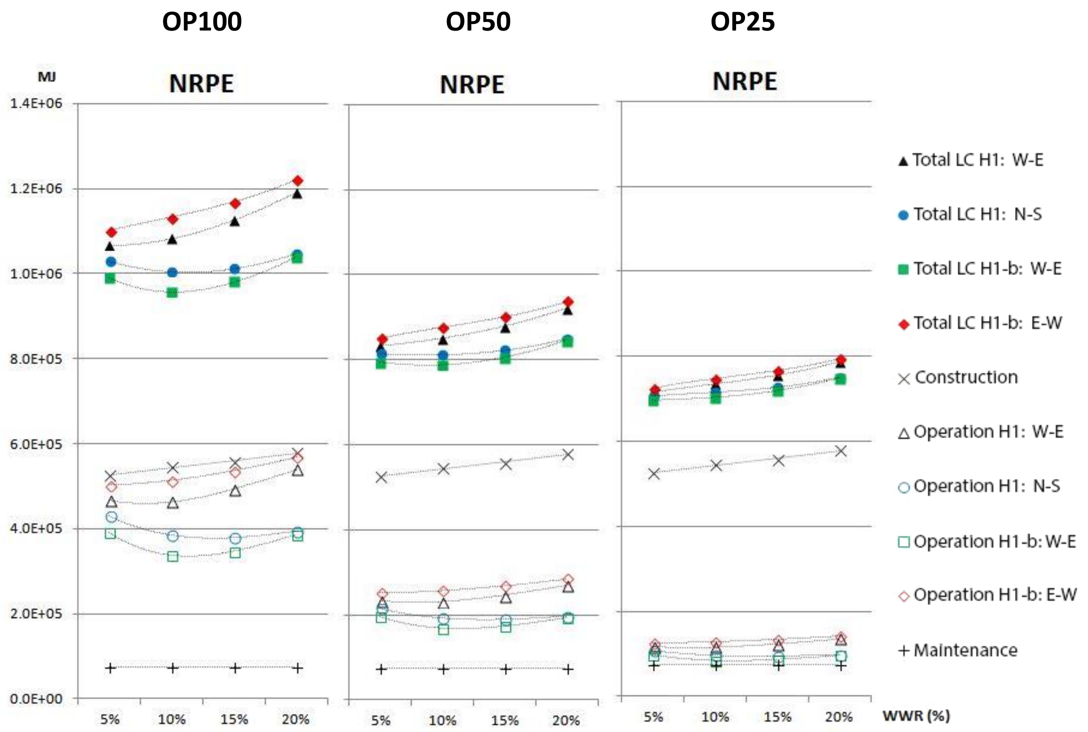


Figure 20. NRPE of the house with window placement H1 and H1-b, different window sizing (window wall ratio, %) and orientation, for three operational patterns (OP100, OP50, OP25) using a heat pump.

In OP100, the WWR tipping point is around 10% for both house H1-b oriented W-E (in green) and house H1 oriented N-S (in blue), whereas it is below 5% for house H1-b oriented E-W (in red) and house H1 oriented W-E (in black). In OP50, the WWR tipping point is below 5% for H1-b oriented E-W (red) and for H1 (black and blue). In OP25, the WWR tipping point is below 5% WWR for all house scenarios. This shows how operational patterns (user behavior) can influence the LC primary energy of the house over 50 years and how different window sizing can change the house LC performance. Furthermore, depending on the expected operational patterns, different window sizes can be recommended based on life cycle NRPE results, and those recommendations differ from recommendations based on the operational assessment.

- **Environmental impact assessment**

In this subsection the LCIA results are presented only for OP50, assuming that new houses are likely to have a higher operational pattern than the one reflected by national statistics (INE-I.P./DGEG, 2011; INE, 2015), due to a lower *prebound effect* (Sunikka-blank & Galvin, 2012). It should be noted that compared to OP50 results, the two other operations patterns results (OP100 and OP25) will remain proportional to the NRPE results presented before.

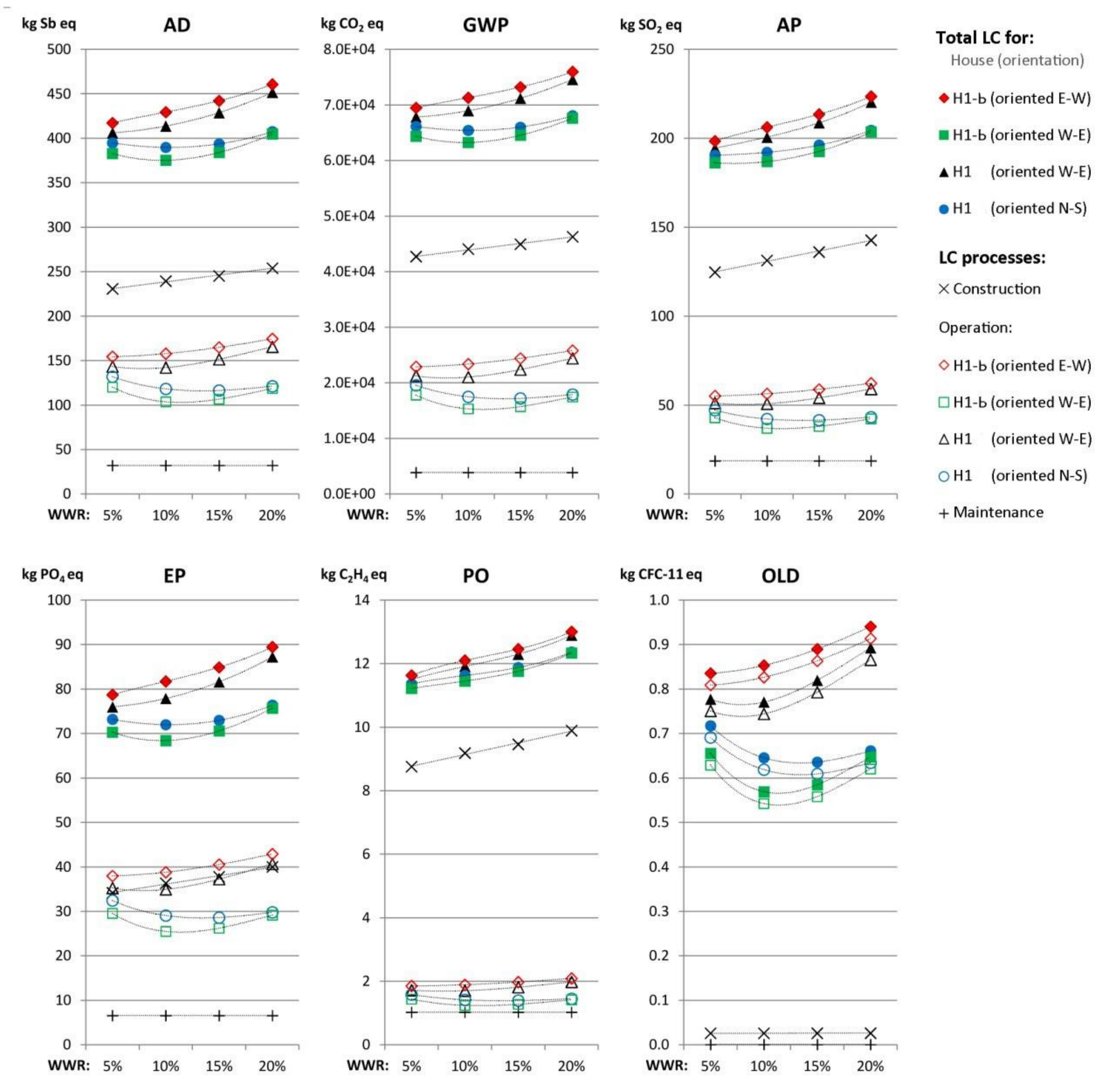


Figure 21. LCIA results of the house with window placement H1 and H1-b, different window sizing (window wall ratio, %) and orientation, for operational pattern OP50 using a heat pump.

Figure 21 presents the LCIA results of the house H1 and H1-b with varying window sizing for the operational pattern OP50. The WWR tipping points depend on orientation and on environmental category considered. LCIA results show that a house with a higher window sizing (or WWR) has higher embodied impact (windows have a higher embodied impact per m^2 of facade than exterior walls) for all categories except for OLD.

The WWR with lowest acidification potential (AP) and photochemical oxidation (PO) is below 5% (W1) for both house window placements (H1 and H1-b). Considering Abiotic depletion (AD), GWP and Eutrophication (EP), the WWR that has lowest impact is below 5% (W1) for H1 oriented W-E (in black) and H1-b oriented E-W (in red) but it is around 10% (W2) for the H1-b oriented W-E (in green) and for the H1 oriented N-S (in blue).

The OLD impacts are mostly due to the heat pump operational energy since this system uses a refrigerant fluid (R134a) with a high OLD impact. It should be noted that the XPS house thermal insulation has a much lower impact in OLD than in the results presented in section 4.1, since the production inventory was updated to an environmentally improved production process that uses CO_2 as blowing agent[1] (instead of HFC-123). The WWR level that minimizes OLD for each house is coincident to the results presented in operational final energy assessment. The H1-b oriented E-W has lower burdens with a WWR lower than 5%, whereas if oriented W-E it has lower burdens with a 10% WWR. The later has a total OLD 30% lower that the former. Whereas, the H1 lowest OLD is achieved with a 10% WWR when the house is oriented W-E, and with a 15% WWR when oriented N-S.

Based on LCIA results, the window size that reduces the overall LC impacts of the house is generally 5-10% WWR depending on the building orientation and window placement.

[1] The XPS production assumed was based on ecoinvent v3.2 process: polystyrene, extruded (XPS) CO_2 blown, at plant process. Blowing agent is CO_2 (50.7% w/w). Co-blowing agent is aceton (49.3% w/w). Process emissions are 25% (w/w) for aceton.

4.2.3. Building shape

This subsection assesses the influence of different building shapes in the LCA of a house to further understand how building design can affect the environmental impacts. The joint influence of building shape and window sizing was assessed in terms of operational and total LCA results of the house for 12 scenarios, presented in Table 11 and Figure 6. Three building shapes with the same living area and interior volume were considered (the compact base case shape (H1), a one-floor-terraced house (H2), and a two floor less compact house (H3)) jointly with four window sizes (W1, W2, W3, W4). The base case building construction was used: double hollow brick walls; 6 cm insulation level; 0.6 ac/h ventilation level; double glazing window with thermal break aluminum frame. The base case window placement was assumed (the windows are almost evenly placed in two opposite facades). In order to account for different orientation influence, the results for the building orientations with the maximum (W-E) and the minimum operational results (N-S) are presented.

- **Operational final energy**

Figure 22 presents the final energy of three shaped houses (H1; H2 and H3) with varying window sizes (W1 to W4) and orientations, for operational pattern OP100 using a heat pump system. Comparing the building shapes, H3 has 20-40% higher operational results than H1, and 24-58% higher operational energy than H2 for the same window size and orientation. The terraced house shape (H2) is less sensitive to building orientation, having closer operational results for the two orientations than the other two shapes. If the base case window size W1 is assumed, H1 and H2 houses have close total operational energy (if N-S orientation is assumed, H2 has slightly higher operational energy). H2 has lower cooling needs, but higher heating needs than H1. H3 has 34-38% higher operational energy needs than H1, due to higher heating needs, but it has similar cooling to H1.

Window sizing influence generates different operational results on the three shaped houses. The three shapes have a different window size tipping point (for which the operational energy is reduced). H1 window size tipping point is around 17 m^2 (W1-W2) if oriented W-E, and 33 m^2 (W3) if oriented N-S. H2 window size tipping point is around 44 m^2 (W4) if oriented W-E, and 28 m^2 (W2-W3) if oriented N-S. H3 window size tipping point is around 28 m^2 (W2-W3) if oriented W-E, and 40 m^2 (W3-W4) if oriented N-S. Additionally, if the house is oriented W-E, the house with the lowest operational energy is H2 with W4 window size. If the N-S orientation is adopted, the lowest operational result is achieved by H1 with W3 window size.

For heating purposes the bigger window sizing is preferred (around 44 m^2, W4) for the three building shapes. However, bigger openings cause higher summertime overheating, and therefore increase cooling loads. If W4 window size is considered instead of W1, cooling loads are particularly increased in H1, and H3. The terraced ground floor house (H2) can more easily cool itself during the night period, due to its higher area of roof and ground floor (non-insulated). The same happens with the less compact house (H3).

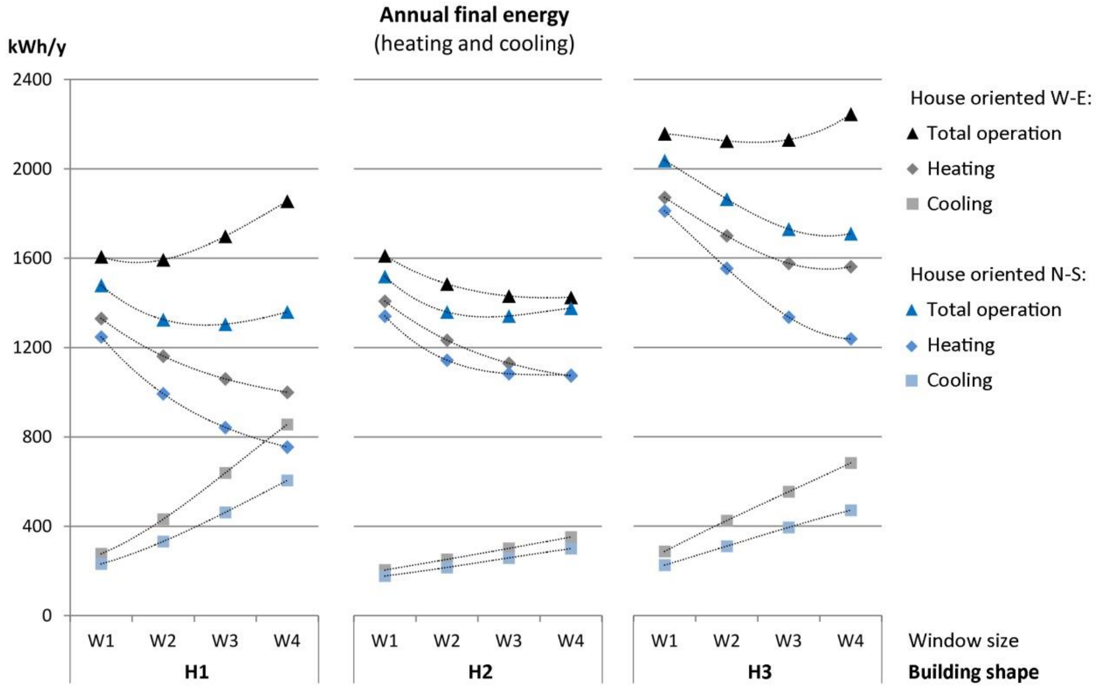


Figure 22. Annual final energy of the house with three building shapes(H1;H2; H3) and varying window size (W1; W2; W3; W4) and orientation (W-E; N-S), for OP100 using a heat pump

The operational results reinforces the idea that building shape can be used as a passive strategy to deal with high heating needs (using more compact building shapes) or high cooling needs (using less compact or ground floor houses). Building shape influence heating and cooling operational results; window sizing and orientation affect those results differently depending on the building shape. Thus, these design options should be studied together in new buildings design. In this research to further assess these passive options a LC perspective is adopted and in the subsequent paragraphs the NRPE results are presented followed by LCIA results.

- **LC Primary energy**

Figure 23 presents the NRPE for the house shapes with varying window sizing and orientation for three alternative operational patterns (OP100, OP50 and Op25). Results show that embodied energy is higher than the operational energy for almost all house scenarios assessed even if OP100 is considered; the only exception is shape H3 with W1 windows oriented W-E (under OP100). Comparing the embodied energy in the three alternative shapes, H1 has the lowest NRPE and H3 has the highest NRPE (15-17% higher embodied energy than H1); H2 has 8-9% higher embodied energy that H1. Maintenance follows the same trend: H1 has the lowest NRPE followed by H2 (5% higher the H1), and H3 has the highest maintenance NRPE (14% higher than H1). As shown in section 4.2.2, higher window sizes account for higher embodied energy because windows have higher embodied energy than exterior walls per surface area (m^2).

Regarding the total NRPE, H3 has the highest LC NRPE (18-25% higher than H1 and 19-26% higher than H2). Shape H2 is less sensitive to building orientation than the other two shapes as showed by the operational results. The window sizing tipping points for which the LC primary energy is reduced vary with the building shape, orientation and operational pattern assumed. Moreover, they are diverse from the operational energy tipping points identified previously.

From LC primary energy assessment for OP100, H1 window size tipping point is around 11 m^2 (W1) if oriented W-E, and 22 m^2 (W3) if oriented N-S. H2 window size tipping point is around 33 m^2 (W3) if oriented W-E, and 22 m^2 (W2) if oriented N-S. H3 window size tipping point is below 11 m^2 (W1) if oriented W-E, and 33 m^2 (W3) if oriented N-S. Additionally, if the house is oriented W-E, the house with the lowest operational energy is H1 with W1 window-size. If the N-S orientation is adopted, the lowest operational results are achieved by H1 with W2 window-size.

Assuming operational pattern OP50, the influence of operational on total LC results is reduced (when compared to OP100). The scenario with lowest NRPE is H1 with W1 both for W-E and N-S orientations. For house shape H2, the window size tipping point is lower than in OP100, being around W1 (W-E oriented) and W2 (N-S oriented). For house shape H3 the recommended window-sizes remain the same as in OP100. Considering a low operational pattern, as OP25, the window size that has the lowest LC primary energy for the three shapes is below or near 11 m^2 (W1).

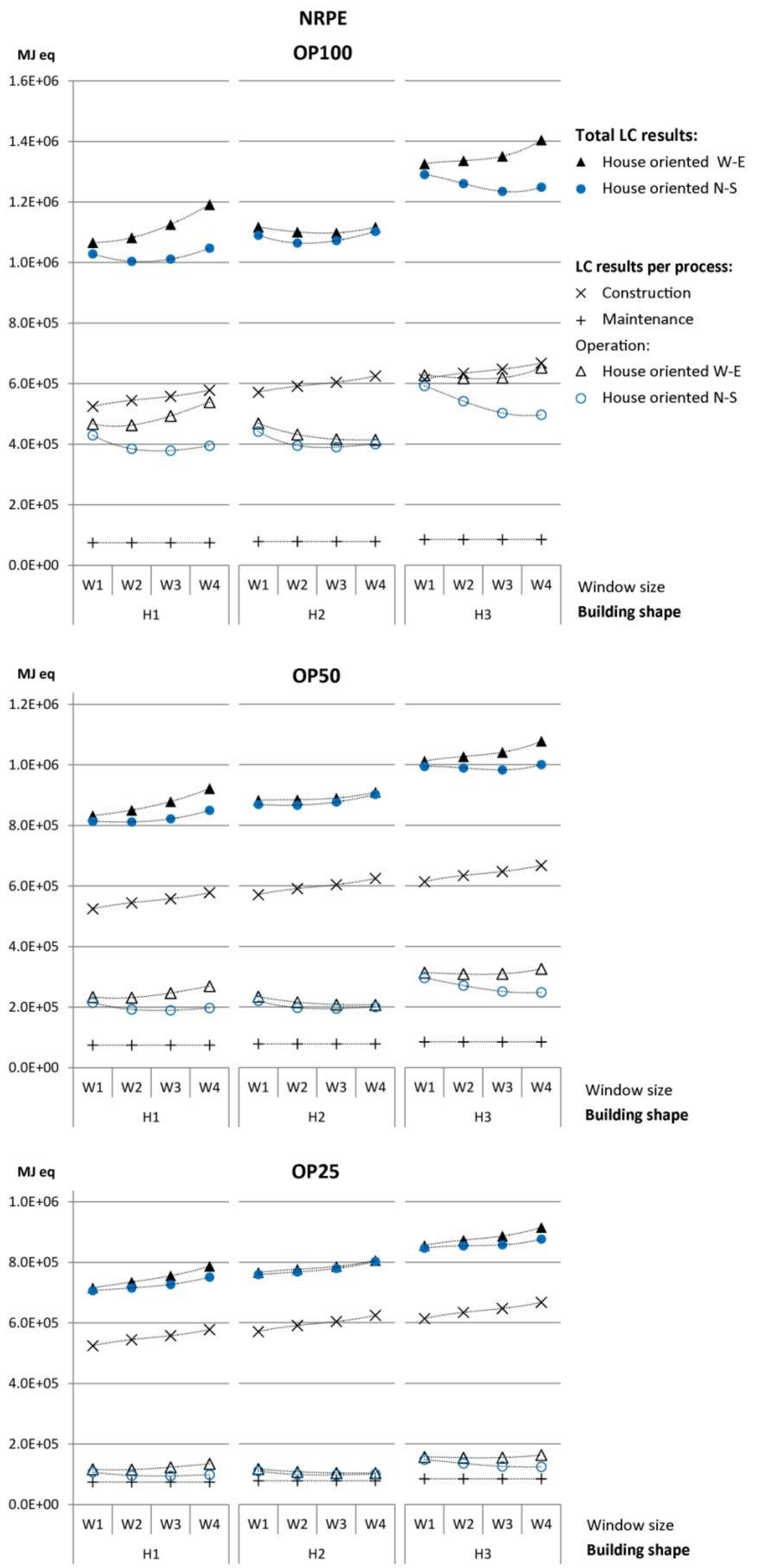


Figure 23. NRPE of the house with three building shapes (H1; H2; H3), varying window size (W1; W2; W3; W4) and orientation (W-E; N-S), for three operational pattern (OP100; OP50; OP25), using a heat pump

- **Environmental impact assessment**

This subsection presents the LCIA results for operational pattern OP50 aiming to highlight the main differences between LC primary energy and other environmental results. Figure 24 presents the LCIA results for the three house shapes with varying window sizing and orientation for OP50. The house shape H1 has the lowest LC impact for all environmental categories, except for OLD when the house is oriented W-E. Assuming W-E orientation, house shape H2 with window-size W4 has lowest OLD burdens. Four categories present similar results to NRPE: abiotic depletion, GWP, acidification, and eutrophication. Photochemical oxidation and OLD categories present dissimilar results. For photochemical oxidation, embodied impact in construction present the majority of the LC impact and therefore the smaller window size (W1) has the lowest impact for the three shaped houses. Contrasting, OLD burdens are mostly due to operational phase impact, thus window sizing tipping points are similar to the ones presented on the operational final energy assessment, being very dependent on orientation for house shapes H1 and H3.

As design alternatives have identical (base case) construction materials and building envelope assemblies, embodied environmental impact only differs due to differences in the amount of materials used, whereas their operational impact depends on the thermal performance of the building and operational conditions assumed. LCIA results can reveal impacts due to processes whose impact are mostly independent from energy consumption, and therefore that would not be revealed by the LC NRPE results. Therefore LCIA results are more significant when different construction techniques, building assemblies, or energy systems are being addressed.

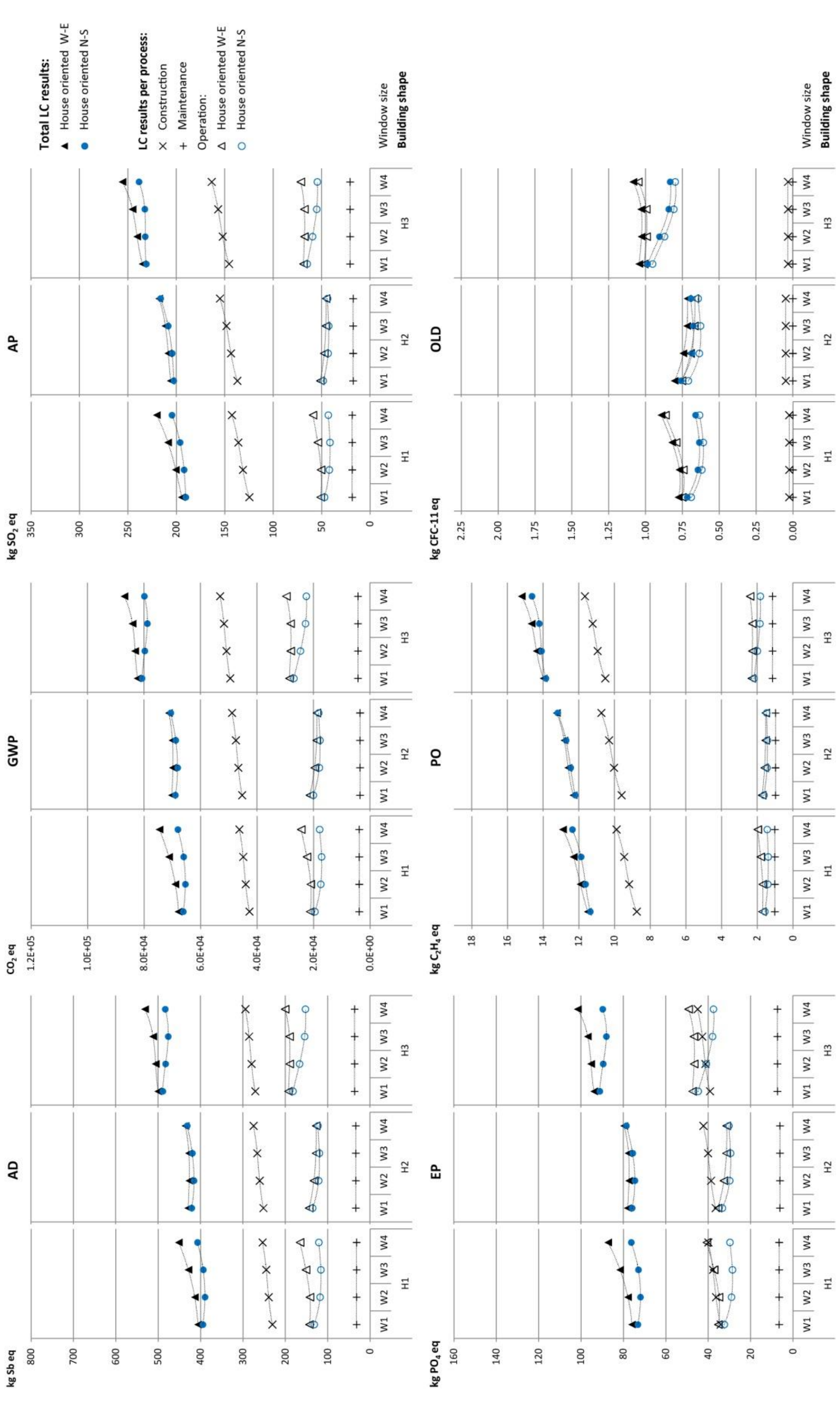


Figure 24. LCIA of the house with three building shapes (H1; H2; H3), varying window size (W1; W2; W3; W4) and orientation (W-E; N-S), for operational pattern OP50 using a heat pump

4.3. Building location

This section assesses the influence of six alternative Portuguese building locations: Coimbra, Porto, Lisboa, Faro, Bragança and Évora. The aim is twofold. Firstly, to assess how operational and total LC results of a Portuguese house vary for different climate in Portugal and to understand how the previous findings for Coimbra can be extended to other locations. Secondly, to identify the house insulation thickness tipping point for each location from an operational assessment and from an LCA, assuming alternative operational patterns.

The base case house with the base case construction was assumed (double hollow brick walls; XPS[2] insulation; 0.6 ac/h ventilation level; double glazing window with thermal break aluminum frame, oriented West-East) and four insulation thickness were considered (3, 6, 9, and 12 cm of XPS). The main differences among scenarios are given by the distinct thermal performance and by the operational impact. In this section, the LC results are presented only for the NPRE, because the proportion between NRPE and other environmental LCIA results has already been explored in the previous sub-chapters for the base case house. To better assess climate influence and frame possible user behaviors, alternative operational patterns were considered. OP100 (continuous comfort operational pattern) and OPx (scheduled intermittent operational pattern) were simulated and NRPE results are presented for four operational patterns: OP100; OP50; OP25 and OPx.

- ## Operational final energy

Figure 25 presents the annual operational final energy (for heating and cooling) of the base case house (H1W1) with varying insulation thickness, using the heat pump system under OP100 and under OPx for six Portuguese locations. Figure 25 shows that different local climates in Portugal had a great influence on operational energy. The house in Bragança required more than twice the heating energy of the house in Coimbra, and three to four times more heating than the house in Faro. Cooling represented more than 50% of the thermal operational energy of the house in Faro, and around 25-30% of the house in Lisbon and in Évora, whereas for the remaining locations it was less significant. A highly insulated house (12 cm) in Bragança had higher 35 to 40% thermal operational energy than a low-insulated house (3 cm) in Coimbra.

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[2] The XPS production assumed was based on ecoinvent v3.2 process: polystyrene, extruded (XPS) CO_2 blown, at plant process.

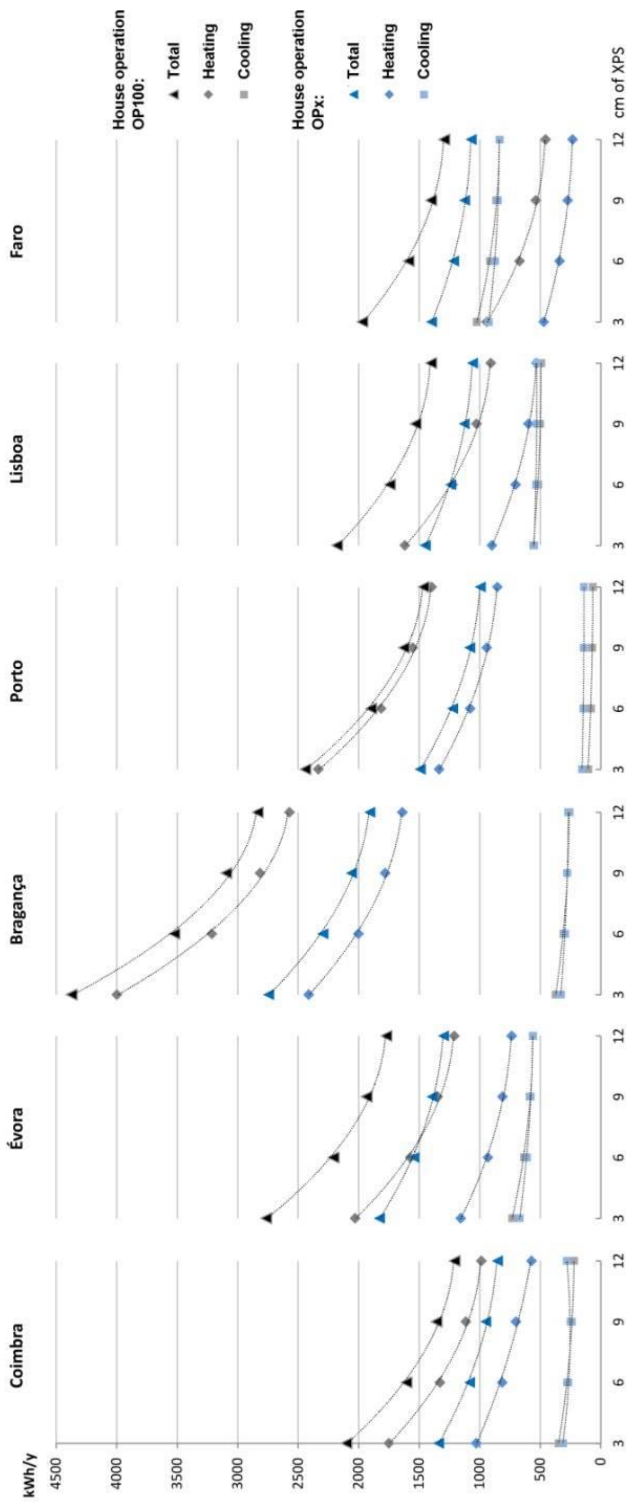


Figure 25. Annual final energy of the house H1W1 with varying insulation level for two operational scenarios (OP100 and OPx) and six alternative locations

Despite the variation among different local climates and the two operational patterns (OP100 and OPx), the operational results pointed to an insulation thickness tipping point near or above 12 cm for all locations assessed. This is higher XPS thickness than the one usually used in new Portuguese houses, especially in locations such as Coimbra, Porto, Lisboa, and Faro.

Houses placed in locations with colder winters (higher heating needs) were more influenced by insulation. Operational heating was significantly reduced with the insulation thickness, whereas cooling did not vary significantly. Compared to a 3 cm insulation level, a house with 6 cm achieved a 17 to 29% annual heating reduction; a house with 9 cm achieved a 26 to 43% reduction (9-14% for the additional 3 cm); and a house with 12 cm achieved a 32-52% reduction (6-9 % for the additional 3 cm). Additionally, a higher insulation level might be counterproductive in summertime, since it makes nighttime conductive passive cooling harder.

Another important finding was that the intermittent scheduled operational pattern (OPx) had generally similar cooling energy to a continuous operational pattern (OP100). Whereas intermittent heating (OPx) had significantly lower heating energy (36 to 50% lower depending on the house location and insulation level) than continuous heating (OP100).

- **LC primary energy**

Figure 26 presents the NRPE results for the base case house with varying insulation thickness, using the heat pump system under four operational patterns (OP100, OPx, OP50, and OP25) for six Portuguese locations. From a LC perspective the influence of local weather is reduced when compared to the operational assessment. A highly insulated house (12 cm) in Bragança had only a 20% higher NRPE than a low-insulated house (3 cm) in Coimbra. LC results show that even under Bragança weather, the embodied energy may surpass the thermal operational energy if OPx or a lower operational pattern is considered, which is highly likely in the Portuguese context.

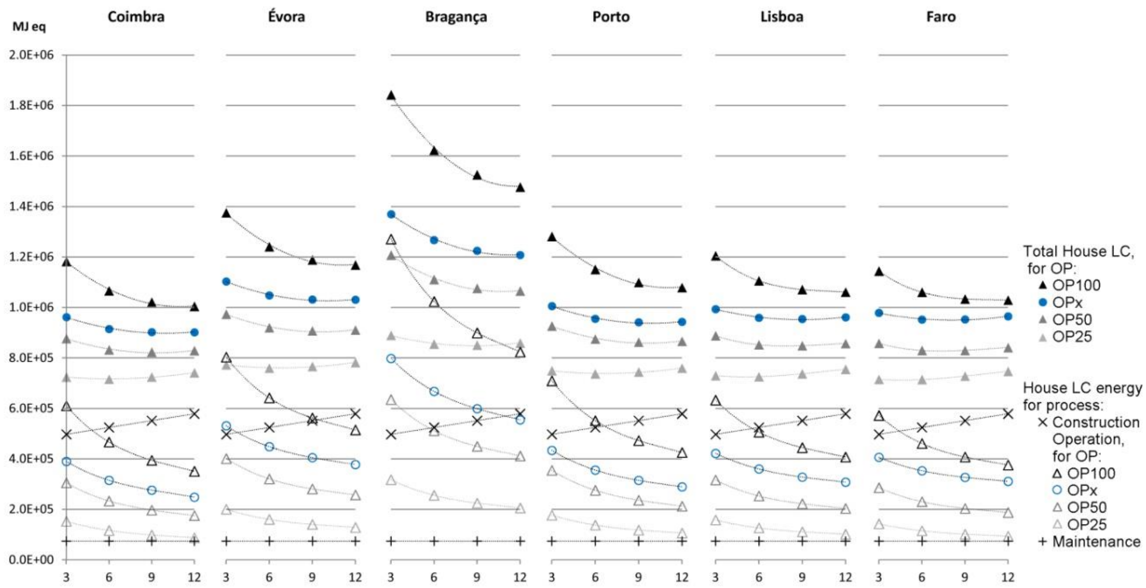


Figure 26. Life cycle NRPE of the house H1W1 with varying insulation levels for 4 operational scenarios (OP100, OPx, OP50, and OP25) and 6 alternative locations

User behavior (operational patterns) can significantly shorten or expand the local climate influence. The NRPE difference between the same house in Coimbra and in Bragança is lower than 34% assuming OP100, and it is lower than 17% assuming OP25. But, if OP100 is assumed in Coimbra and OP25 in Bragança, the NRPE of the house in Coimbra surpasses the NPRE of the house in Bragança. Operational patterns, have higher influence (may generate greater operational variation) in low-insulated houses than in high-insulated houses, and in high-demanding climates (Bragança). At the same time, the thermal insulation level has higher influence in houses with high-demanding user behavior (OP100) and/or cold local climate conditions.

The insulation thickness tipping point varied with the operational pattern and with the building location (climate). However, if assumed OP50, the XPS tipping point thickness would be between 6-9 cm for any location assessed, whereas the operational assessment suggested an insulation thickness tipping point near or above 12 cm. The embodied NRPE (construction and maintenance) of the base case house (with 6 cm XPS insulation) is higher than the operational energy of the house (heating and cooling) in any of the following locations – Coimbra, Porto, Lisboa and Faro – for all operational patterns studied.

4.4. Operational conditions: new house *vs*. existing house

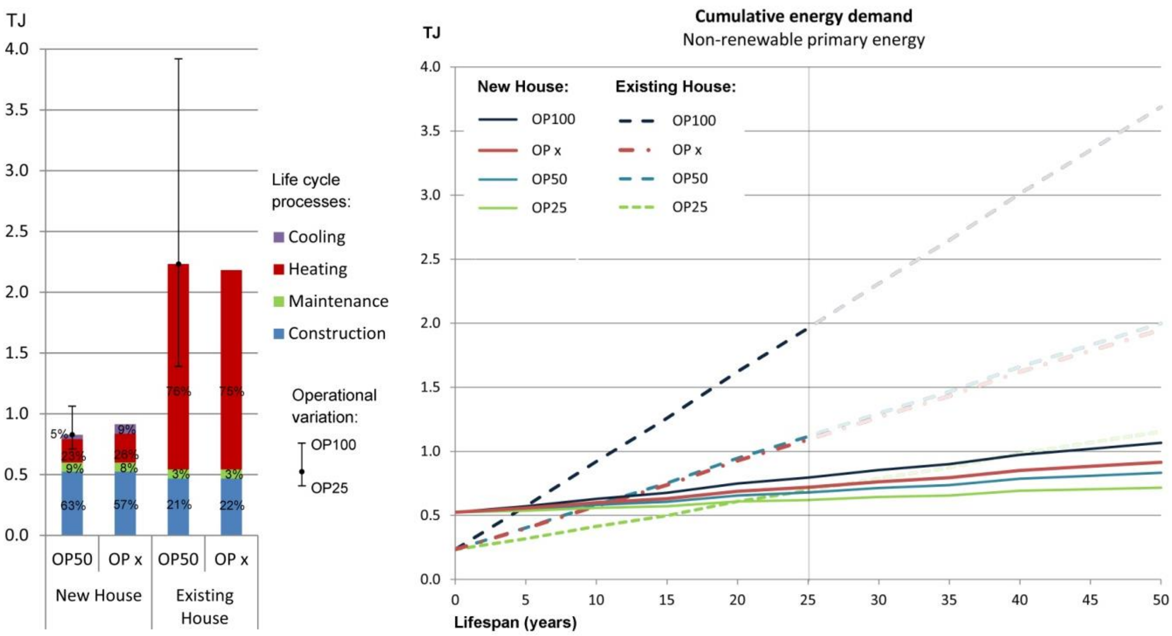
As showed in the previous results sections, the specific operational conditions or assumptions of a study may influence the results, especially in comparative studies identifying constructive elements tipping points and the most significant processes (or stages) on which additional research efforts should be focused. Although this thesis primary focus was on building envelope and design options, construction phase relative relevance is intrinsically associated with operational phase, and therefore dependent on operational assumptions. This section aims to assess the influence of alternative operational conditions (user behavior, HVAC systems, and electricity supply chain) on the LC results of the base case new house and of an equivalent 25-year old existing house. Simultaneously it aims to compare the base case new house with a 25-year equivalent existing house (non-insulated, single-glazing, high ventilated), to unveil how better is a new house from a LC perspective depending on the operational conditions.

In section 4.4.1, the influence of alternative operational patterns (user behavior) is assessed for the new and the existing house. The jointly influence of the operational pattern, the HVAC system and the electricity generation mix is considered for both houses in section 4.4.2. In section 4.4.3, the magnitude of operational and embodied energy is analyzed considering the process-based and a simplified IO-hybrid LCI approach and accounting for all household energy needs. The base case house (building shape and window size H1W1) with the base case construction was used to present the variability of the LC results for the operational assumptions under study. To simplify the assessment this section only presents the life cycle NRPE results.

4.4.1. Operational patterns

The NRPE for the new and the existing house are presented in Figure 27, showing the influence of the operational patterns: (a) per LC processes and (b) over time for the lifespan. The 25-year-old existing house has only half its lifespan ahead, so only half its embodied energy was accounted at year 0 in Figure 27 (b). NRPE results show that the new house construction energy was more significant than other LC processes (heating, cooling and maintenance) for any operational pattern, representing 50% (OP100) to 73% (OP25) of total primary energy over 50 years. Regarding the existing house, heating was the most significant process representing 61% (OP25) to 86% (OP100) of total LC energy. These results suggest that building components, construction, and material selection should be further studied to support primary energy reduction, whereas operational heating primary energy reduction should be studied for existing houses.

The new house had lower primary energy than the existing house for any operational pattern over the 50 years: the additional embodied energy (428 MJ/m²) was offset by 90% lower operational primary energy when compared to the existing house with the same operational pattern. Though, the offset period of time was highly dependent on the operational pattern assumed: for OP100, it was less than 5 years; while for OP50, it was 10 years; for OPx, it was 11 years; and for OP25 it was around 20 years. According to Portuguese statistical data and research studies on the *prebound* effect (Galvin & Sunikka-Blank, 2013; Sunikka-blank & Galvin, 2012), dwellers living in thermally inefficient buildings usually use lower operational patterns than dwellers living in thermally efficient buildings. Assuming the existing house with OP25 (comparable to (INE-I.P./DGEG, 2011)) and the new house with OP50 or OPx, the offset period increased to 24-28 years (OP50-OPx). Moreover, although unusual, if the new house had continuous interior thermal comfort (OP100), it would require higher primary energy than the existing house with OP25. These results indicate that new houses can effectively reduce LC primary energy of residential buildings, but careful attention should be paid to the LC operational assumptions to represent actual end-users habits since they affect LC results.



(a) b)

Figure 27. New and existing house NRPE. Alternative operational patterns: a) per LC processes; b) along the lifespan

Comparing the intermittent and continuous based operational patterns, OPx required a higher heat-up power (to achieve comfort conditions rapidly) than OP100 (to keep continuous set points), and more energy was consumed during short periods. OPx, although working only 32% of the time, accounted for more heating than OP50 (50% of OP100) but similar cooling to OP100. This is also justified by internal heat gains being modeled as coincident (in time and space) with the shorter occupation period, when cooling was needed. Therefore, in cases where cooling needs are significant it is important to dynamically access the effect of intermittent HVAC patterns. Whereas when cooling needs are not predominant it is reasonable to assume a range of energy consumption based on continuous comfort condition (as OP50). In this specific case, cooling did not hold a large share of LC energy.

The results showed that intermittent heating during short periods can significantly reduce the operational energy of new and existing houses when compared to continuous heating. A standard new house can meet the passive house level due to user behavior. In contrast, other studies showed that for very-low-energy houses, intermittent heating leads to marginal savings when compared to continuous heating (Pineau, Rivière, Stabat, Hoang, & Archambault, 2013) and that continuous heating based on low-temperature systems operating more than 14h a day can have lower costs than intermittent heating at higher temperatures (Badran, Jaradat, & Bahbouh, 2013).

4.4.2. Heating systems and electricity mix

Four alternative HVAC scenarios presented in Table 17 (heating systems: electric resistance, heat pump, natural gas condensing boiler, and wood pellets boiler) were considered for each house. The only system that satisfies heating and cooling needs is the heat pump. For systems using electricity, two Portuguese electricity generation mix scenarios (based on data presented on Table 18) were addressed: 2012-year and 5-year-average (2008-2012) and variation. Figure 28 presents the annual operational NRPE ($MJ/m^2 \cdot year$) for both houses under these scenarios for the four operational patterns. Wood pellets had the lowest NRPE, about 19% of the electrical heating, 24% of the natural gas boiler, 44% of the heat pump (2012 mix). The heat pump had 58% lower NRPE than the electric heating. Due to the electricity mix variation, a significant variation of operational NRPE (+16% to -21%) occurred for heat pump and electric heating. Despite that variation, wood pellets boilers or heat pump significantly reduce NRPE when compared to the other systems. But, depending on the electric mix, a natural gas condensing boiler (considered a high efficient system) may have similar impact to resistance heating because the electric mix has been decreasing its impacts (displacing coal and fuel oil and incorporating higher shares of renewable).

Including electricity generation mix trends in LC studies is, therefore, significant to compare systems relying on different supply chains.

Due to an improved thermal envelope, the new house had 60% to 68% (OP100) lower operational NRPE than the existing house for the same OP and heating system. Depending on operational conditions, the new house embodied energy (construction and maintenance) may be two to three times higher than the thermal operational energy (heat pump and OP50) or even seven times higher (wood pellet boiler and OP50). The *Passive House* standard (PH) final energy limit (15 kWh/m^2·year for cooling and for heating) is shown in Figure 28. The new house with a heat pump met the PH in any operational pattern studied; but, with a natural gas or wood pellets boiler, the PH is only met using an operational pattern lower or equal than OP50. The non-insulated existing house can achieve a lower NRPE than the PH, using a heat pump with an operational pattern lower or equal than OP50, while with a wood pellets boiler, which had the lowest NRPE, the PH is not met.

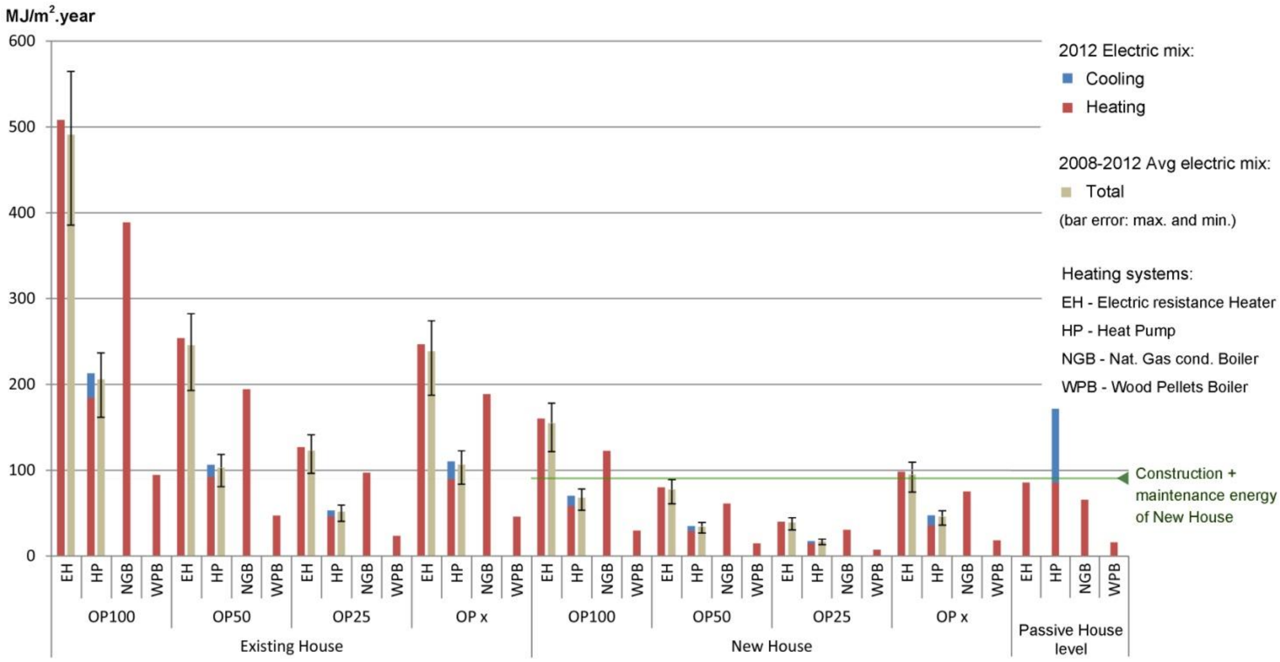


Figure 28. Annual operational NRPE (MJ/m^2·year) for the existing and the new house, considering alternative operational scenarios (four heating systems, two electricity generation mixes, and four operational patterns)

4.4.3. Embodied vs. operational energy

Figure 29 shows the magnitude of embodied and operational energy (NRPE) of both houses for two LCI approaches: a simplified IO-hybrid, obtained using an IO-hybrid coefficient (1.94) from Swedish data (Nässén et al., 2007) presented in section 3.2.1, and the process-based followed in this thesis. The operational energy addresses heating and cooling, as well as the energy needs described in Table 20. NRPE was calculated based on the 2012 year electricity mix. In the IO-hybrid calculation, the new house embodied energy represented 54% of total NRPE; construction was higher than the other LC processes, being as significant as all operational energy. Regarding the existing house, heating remained the most significant process, representing 41% of total LC energy. In the process-based approach, operation energy represented the majority of NRPE (57% for new house; 86% for existing house). The other operational energy uses (domestic hot water production, kitchen and electrical appliances) represented a significant share of total LC energy for both houses: 34-35% in IO-hybrid; 38-42% in process-based. Regarding building related impacts, an IO-approach reinforces the importance of embodied energy in comparison to heating and cooling: construction energy of the new house represented more than four times the heating and cooling energy (OP50). Therefore, IO-results highlight that embodied energy must not be neglected and that building materials and construction need to be assessed in order to identify new houses improvement options.

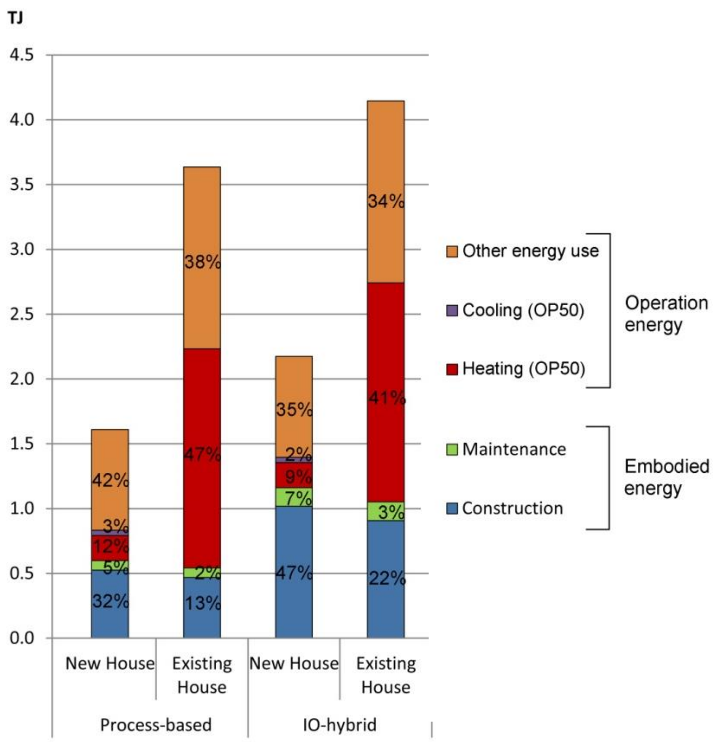


Figure 29. NRPE of the new and the existing house (OP50) with two LCI approaches: process based; input-output hybrid

4.5. Discussion

This section discusses the relevance of the building envelope, design, and operational conditions in the life cycle impact of new Portuguese houses. Firstly, the NRPE variations among each set of alternatives studied along this chapter are compared to assess which parameters have most influence in the LC NRPE of the base case house. Secondly, the base case new house embodied energy is presented per building component to clarify how significant the assumed building components are in terms of initial and recurrent embodied impact.

- **Joint influence of building envelope, design and operational conditions**

Figure 30 synthesizes the NRPE LC variation achieved among the studied construction, design and operational options for the base case house (presented along chapter 4). Variations are presented in three colors: in black, as a result of both embodied and operational variation; in red, mainly due to operational variation; in blue, mainly due to embodied variation. Based on Figure 30, the main findings of this thesis are discussed and compared to the existing knowledge from the literature.

As presented in the beginning of section 4.1, simulated heating final energy results to achieve continuous comfort condition (OP100) are far from real Portuguese household energy consumption data. Due to Portuguese dwellers, who are used to adapt to wider interior thermal conditions than north European dwellers, in the Portuguese context the operational loads may be around 25% to 50% of the simulated loads for OP100, which can significantly reduce the impact of operational stage (heating and cooling) without changing the house embodied burdens.

Alternative construction options that affect mainly the thermal performance of houses have been assessed. Thermal insulation is thought to be one of the main strategies to reduce heating energy consumption and LC impacts. However, assuming the base case new house (0.6 ac/h and 6 cm XPS insulation), a lower ventilation level (air-tight building: 0.3 ac/h), especially during winter, has more influence than a higher insulation thickness to reduce to operational NRPE. High ventilation levels (for instance due to users) can easily undo the thermal insulation benefit. Moreover, the NRPE savings achieved with a variation of the insulation thickness (e.g., from 3 cm to 9 cm) are lower than the embodied energy reduction of using alternative building construction components (for instance a wooden wall house instead of the base case brick wall house).

Influence of the building options considered

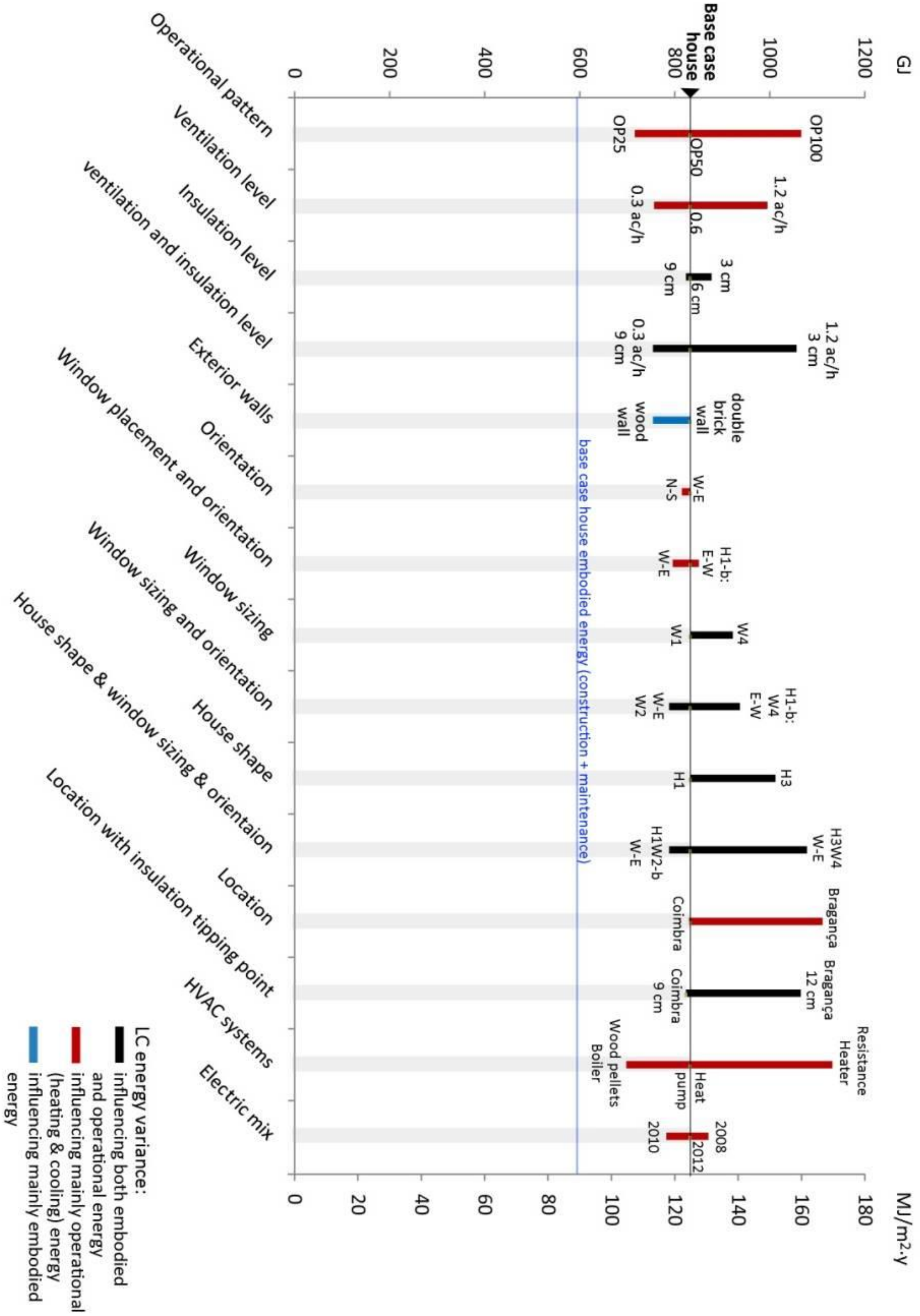


Figure 30. NRPE variation of the base case house for the building envelope, design and operational options assessed

These results emphasize the importance of assessing the embodied energy in new houses. This has been also suggested by other LC studies; however, many studies (due to its climatic nature or because do not consider user behavior influence) still identify operational phase as the most significant phase (Citherlet & Defaux, 2007; Sartori & Hestnes, 2007). In contrast, this research highlights that the thermal operational needs directly influenced by the new house characteristics can be much lower than the building embodied energy. So, at building design stage, great attention should be paid to the building components, since the embodied energy (initial and recurring) can represent three to seven times the operational heating and cooling energy (OP50 with a heat pump or a wood pellets heater, respectively). Based on the potentially small contribution of thermal energy requirements, current building regulations miss significant LC impacts when focusing only on operational energy, especially in new Portuguese houses.

The influence of simple building design options were assessed (building orientation, window placement, window sizing and building shape). Figure 30 shows that these options can be accountable for a significant LC NRPE variation that surpasses the influence of a thermal insulation variation (from 3 to 9 cm). If such simple design options are not considered from a LC perspective, a careless design may overshadow the operational savings of using the appropriate thermal insulation and air-tightness for a building. The results suggest that these design options are as significant as the envelope construction options and therefore should be simultaneously addressed.

This thesis also shows that LC studies outcomes are very sensitive to operational conditions: different forms to inhabit a house (operational patterns), energy systems, and their supply chain. In countries with mild climatic conditions and culturally low operational patterns, it is important to plan for plausible operational scenarios addressing the user behavior variability. As shown in section 4.4.2, assuming the same operational pattern, a new house (with electric heating or even with a natural gas condensing boiler) can have higher NRPE than an equivalent (non-insulated) existing house (with a wood pellets boiler), regardless of the new house's lower final energy.

Previous studies have also revealed that passive houses can have close or higher LC impact than standard buildings depending on the heating systems (Brunklaus et al., 2010; Dahlstrøm et al., 2012; Gustavsson & Joelsson, 2010; Stephan et al., 2013a). Some argued that heating energy supply system had a greater effect on primary energy than energy efficient construction measures (Dodoo et al., 2010; Gustavsson & Joelsson, 2010). This thesis findings are in agreement with previous research, extending their validity for a different climatic and operational reality.

Typically, the cold climate passive houses previously assessed have very thick insulation layers, triple-glazing windows, ventilation systems with heat recovery and assume continuous interior thermal comfort conditions. In contrast, this study base case house is a standard Portuguese new house, which meets the passive house standard, due to mild South European climatic conditions and typical Portuguese dweller behavior (intermittent HVAC operation).

Assuming a heat pump system, a 37% variation of use phase NRPE can be attributed to the Portuguese electrical generation mix variation over 5 years. This variation did not influence the choice of the HVAC system with the lowest NRPE (wood pellets boiler), but the lower impact of the electric mix placed the natural gas system impact very close to the resistance heating impact. Other authors (Blom et al., 2011; Brunklaus et al., 2010; Citherlet & Defaux, 2007; Ortiz, Castells, et al., 2010a; Stephan et al., 2013a) studied the effect of the energy supply chain and electricity production mix in operational results; they highlighted that besides heating needs, other household energy needs can highly influence total operational impact, since these represent a significant share of new houses operation, as also shown in section 4.4.3. Lowering the LC impact of these needs can be achieved with user behavior and supply-chain improvements as mentioned by Brunklaus et al. (2010).

- **New house embodied energy**

Figure 31 presents the base case new house embodied energy (from construction and maintenance) per building component. NRPE results are presented for the whole house over the 50 year, and per m²·year. The new house process-based embodied energy was around 4.51 GJ/m², with 3.95 GJ/m² embodied in construction and 0.56 GJ/m² in maintenance. Although embodied energy varied with the two calculation approaches presented in section 4.4.3, the embodied energy results fit within a large range of existing process-based literature results: 3.1-7.6 GJ/m² (Bastos et al., 2015; Ramesh et al., 2010; Sartori & Hestnes, 2007). In the Portuguese context, due to cultural and economic constraints, maintenance activities of dwelling are mainly corrective, instead of preventive. The low maintenance to initial embodied energy ratio (15%) presented in this thesis is in accordance with other Mediterranean process-based studies (Ortiz, Bonnet, et al., 2009; Rodrigues & Freire, 2017) but it is much lower than values presented by IO-hybrid LCA studies (Crawford, 2013; Rauf & Crawford, 2015).

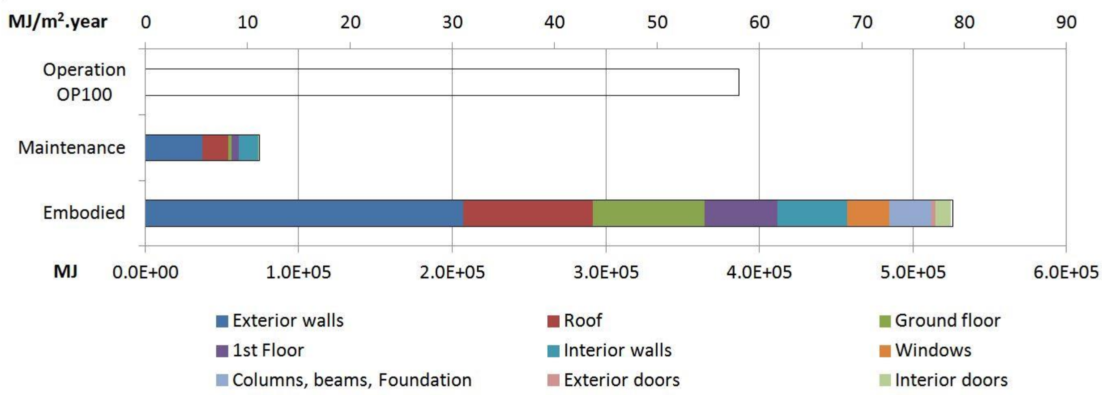


Figure 31. NRPE of the new house (whole building) per building component

Exterior walls (double hollow brick) were the most significant building component holding around 40% of the house construction energy and 50% of maintenance energy. Exterior wall embodied energy was higher than the thermal operational energy of the house with OP50, in Coimbra climate. The other building components with a significant amount of embodied energy were the floors (23%), the roof (16%), and the interior walls (9%). These results are close to previous research results for Mediterranean single-family houses, that found that exterior walls were accountable for more than 40% of embodied energy, and that floors, roof and basement structure were responsible for another 40% (Nemry et al., 2008). As the embodied impact of a new house is likely to surpass the thermal operation NRPE, and the house heavy-construction elements (brick walls, concrete slabs and roof) hold most of embodied NRPE, further research should focus on improving these building assemblies to reduce Portuguese houses LC impact.

5. CONCLUSIONS

In this thesis, a LCA framework was developed and implemented to assess the influence of alternative building envelope, design, and operational options on the environmental impact of Portuguese single-family houses. New south European houses on a mild Mediterranean climate, as Portuguese ones, have seldom been addressed from a LC perspective, and the few existing LC studies fail to consider that in such climatic conditions the thermal operational patterns (for heating and cooling) are highly dependent on user behavior, rather than following a fixed operational pattern (continuous or intermittent). Thus, in this context, operational energy levels may vary but usually are much lower than in North and Central European countries. Therefore, assessing the influence of different options from a LC perspective is even more important to ensure overall LC impact reduction of new houses in mild Mediterranean climate. Additionally, published LC studies of new houses did not account the relevance that building design may have on LC results. To address this particular context and gaps, the framework developed combines LCA and building dynamic simulation to account for the embodied and operational (heating and cooling) impacts of new Portuguese houses under alternative operational patterns that frame possible user behavior. Aiming to expand the existing knowledge, create awareness, and support decision making, the LC influence of options at different levels – building envelope construction, design, and operation – was assessed, unveiling what can be missed if the development of new houses focuses only on reducing thermal operational energy requirements. The major findings of this PhD thesis are summarized in the next paragraphs in response to the research questions presented in section 1.2.

- **1. How alternative building envelope construction options (building thermal performance and building components) influence the LC impact of a Portuguese house?**

In order to frame alternative building thermal performance, both the thermal insulation thickness and the total ventilation level of the house were parametrically assessed. The results for the base case house located in Coimbra and using a heat pump system showed that combining two simple passive construction measures – a good envelope insulation level and an air-tight envelope (6 cm of XPS (0.035 W/m.K) and a 0.6 ac/h ventilation level) – leads to very significant operational savings (65% lower operational energy) when compared to no insulation and a total ventilation rate of 1.2 ac/h. However, from a LC perspective due to the significance of the house embodied energy, the NRPE reduction of those measures is lower and dependent on the operational pattern (17% for OP25, and 30% for OP50). Aiming to improve the base case house, an operational assessment suggests that a higher insulation level is desired; however, the LCA performed showed that a XPS insulation higher than 6 cm (exterior wall and roof U-value lower than 0.36 $W/m^2 \cdot K$ and 0.39 $W/m^2 \cdot K$, respectively) does not achieve a significant LC impact reduction for the house in Coimbra, and a thickness higher than 9 cm (exterior wall and roof U-value about 0.28 $W/m^2 \cdot K$ and 0.29 $W/m^2 \cdot K$, respectively) can result in an increased overall impact for OP50 and lower operational patterns.

A lower total ventilation level (0.3 ac/h), especially during the heating season, has a higher influence on reducing operational heating and the overall LC impact of the house than an increase in thermal insulation thickness form 6 cm to 9 cm. A lower ventilation level is possible assuming an air-tight construction and careful user behavior, which has no significantly higher embodied impacts than the base case. Whereas a higher envelope thermal resistance is achieved through an increase in the insulation material which results in an increase in embodied impacts. From a LC perspective, when an incremental increase of the insulation material thickness has lower embodied impact than the energy saved on operation (heating and cooling), the overall LC balance is positive. This balance depends not only on the specific insulation material (and its LCI data considered), but it is also highly influenced by the user behavior operational pattern, as shown throughout results. Therefore, LC studies including different ways of inhabiting a house are recommended to identify adequate insulation levels. Insulation thickness tipping points also varied with the impact category considered, but generally the base case house XPS tipping point was between 3-6 cm for OP25, and 6-9 cm for OP50.

The assessment performed also shows that considering different impact categories in the LCA of buildings is important because each building material performs differently in alternative environmental impact categories. While NRPE provides results close to other environmental impact categories, it still is important to check if problem–shifting from one environmental problem to another is not occurring. For instance, the XPS impact on OLD category changed dramatically depending on the production process considered, as detailed in section 4.4.1 and in the LCA literature addressing insulation materials (Pargana et al., 2014).

Regarding the influence of alternative building components, three exteriors walls with alternative construction materials were considered (double brick, concrete block, and wooden framed wall). Assuming the same insulation thickness, the house with alternative exterior walls (similar envelope U-values) showed similar operational impacts. Since the heavyweight core of the house was kept constant (high thermal inertia), the operational impact was mainly influenced by the exterior envelope insulation level. Regarding the total LC results, the wood wall house has the lowest LC impacts for six impact categories, presenting a LC reduction of 7-20 % (amongst those categories) when compared to the double brick wall alternative. Assuming the base case house (brick wall; 6 cm insulation; 0.6 ac/h ventilation), the adoption of an alternative building component with lower embodied impact as the wooden framed wall allowed to achieve a lower LC impact than improving the house thermal performance (e.g., an increased insulation to 9 cm or an increased air-tightness to 0.3 ac/h). The finding that wooden components have generally lower impacts than concrete and brick components is in agreement with other literature studies (Dodoo et al., 2012; Petersen & Solberg, 2005; Salazar & Meil, 2009; Upton et al., 2008). However, most previous studies performed for cold climate houses did not reveal that the influence of a lower embodied energy may surpass the influence of a thermal improved envelope; which happened for this case study under the Portuguese operational context.

The exterior wall assessment shows that the selection of alternative building construction materials hold the potential to significantly lower the embodied impact of new Portuguese dwellings. In houses where the embodied impact represents more than the thermal operational impact (for heating and cooling), breakthroughs can be achieved at material producers level towards lowering impacts of the materials used and at design stage by shifting to alternative building components or construction practices with lower incorporated impacts (as the wooden frame wall when compared to the double brick wall). Therefore, other building components are worth of further studies especially the heavy-construction elements (roofs, concrete slabs); more on this on section 5.2.

- **2. How design options (window sizing, orientation and building shape) influence the house LC results?**

Another key finding is that building design should be considered an important part of the strategy to reduce the LC impact of new houses. Remarkably, simple building design options such as building orientation, window placement and sizing, and building shape have a large influence on overall results affecting both embodied and operational impacts of houses. Despite, building design options have generally been disregarded in LC studies, their influence may surpass the influence of thermal insulation options in new houses: window orientation and placement may have as much influence as increasing thermal insulation (from 3 to 9 cm), and window orientation, placement and sizing may have two to three times higher influence. Jointly, building shape, window sizing and orientation may have five times more influence than an insulation thickness increase (from 3 to 9 cm), and as much impact as varying insulation and ventilation levels from 1.2 ac/h with 3 cm insulation to 0.3 ac/h with 9 cm insulation, in Coimbra climate. Design options, as window sizing, placement and building shape, should be carefully thought as a way to reduce new houses LC impact. For instance, due to design options, the house H3W4 (two floor less compact house with 20% window to wall ratio) has 30% higher LC impact than the base case house (H1W1: two floor compact house with 5% window to wall ratio) having the same living area and volume. Additionally, alternative design options may reduce (or amplify) the influence of different Portuguese weather condition on the overall LC impact. For example, the house H3W4 in Coimbra has similar LC NRPE than the house H1W1 located in Bragança.

- **3. How location influences LC impacts and building recommendations?**

The sensitivity analysis performed showed that the base case house (H1W1) located in Bragança has more than twice the heating loads than in Coimbra, Faro or Lisboa. But although the weather conditions vary significantly with the location, results showed that in Portugal, if operational pattern OP50 is considered, a new house is likely to have higher embodied impacts (from construction and maintenance) than operational impacts (from heating and cooling). Therefore, the importance of efforts to reduce or control the LC impacts of new houses through building design options and building material selection is transversal to the Portuguese context. The insulation thickness tipping point varies both with building location (different weather conditions) and with the operational pattern. Assuming OP50 for house H1W1 (base case, two floor compact house with 5% window to wall ratio), the results presented in section 4.3 show that the XPS tipping point thickness is within 6 to 9 cm for all locations assessed. However, if focusing only in operational thermal energy reduction the insulation thickness tipping point is near or above 12 cm for all locations.

- **4. How operational conditions influence the LC impact of a new house and of a 25-year equivalent existing house?**

Options and conditions that mainly affect the operational impact, such as the HVAC system selection, the user operational pattern, the total ventilation level and the building location were shown to be very significant from a LC perspective, since together, they can deeply change the operational impact of both new and existing houses. Results showed that operational heating and cooling represents less than 1/3 of the total LC impact of the base case new house (Coimbra location), but the operational impact can be highly increased or further decreased depending on these options and conditions. More importantly, the expected operational impact (of the assumed HVAC system and its supply chain) can influence decisions at design stage of new houses, such as, the more adequate insulation thickness level and window sizing for which the house LC impacts are minimized (tipping points).

The HVAC system selection was shown to be determinant to reduce operational impacts. Changing systems (e.g., from resistance heating to a wood pellets heater) had the higher LC influence from the parameters studied throughout this thesis. As shown in section 4.4.2, efforts should be given to incorporate efficient systems as wood pellets and heat pumps in any dwelling. This conclusion was not altered by the 5-year electricity generation mix variation, being therefore rather robust. Although the electric mix trend is not a building option, it affects the future operational impacts of buildings and therefore it should be considered in LC studies. The trend of low-carbon fuels displacing high-carbon fuels in the electricity generation sector (as the Portuguese one) may play an important role in reducing the operational impacts of electric systems (e.g., heat pumps) and possibly future building material production.

In order to reduce the overall LC impact of new houses in mild Mediterranean climate, the user behavior (through operational patterns) was shown to have a large influence. Dwellers used to accept more broad thermal comfort levels require less energy consumption for heating and cooling their homes. When compared to continuous interior comfort (OP100), an intermittent HVAC pattern (as OPx) results in a significant heating operational reduction and in a similar cooling load. Operational results showed that intermittent cooling (OPx) requires a higher cool down power than OP100 which results in OPx having similar cooling energy consumption to OP100. Even though, the results for six Portuguese locations showed that in Mediterranean climate, considering the user behavior (partial and intermittent heating and cooling) can avoid spending more energy upfront (e.g., in thermal insulation) than what it is needed. This finding may also be valid for south European houses under similar climate, operational and construction conditions.

Another key thermal aspect on total LC results is the total ventilation rate, which is determined not only by the building air-tightness level (construction, windows and openings) and the systems installed (e.g., extracting fans), but also by user behavior. Ventilation remove odors, and renew the interior air to achieve a good indoor air quality but is highly dependent on dwellers habits (i.e., opening windows and doors). User ventilation habits affect total ventilation level and therefore affect the interior thermal confront conditions. Natural night cooling (through opening windows at night) was not considered, but this is a common strategy in houses that do not have an active cooling system installed (the majority of Portuguese dwellings). Additionally, the windows shutter scheduled considered assumes a conscious user behavior that promote passive solar gains in winter (leaving shutters wide-open during the day) and control undesired solar gains in summertime (through shutters shadow during the day on workdays). Despite building construction and systems used, conscious or climate-adapted user behavior can help reducing impacts, but a careless behavior can easily increase the operational impact.

Regarding the comparison among a new house and 25 year (non-insulated) existing house, based on current building practices and on the systems assumed, new houses can effectively reduce LC primary energy of residential buildings, but careful attention should be paid to operational conditions. Compared to the existing building, the new house embodied energy offset-period of time is highly dependent on the operational pattern (user behavior). The new house thermal improved envelope achieved an annual operational primary energy reduction from 60-68% when compared to the existing house. However, a shift can occur if assuming the same operational pattern but different HVAC systems for both houses: a new house with electric heating or even with a natural gas condensing boiler can have higher NRPE than an equivalent non-insulated existing house with a wood pellets boiler, regardless of the new house's lower final energy. This finding is in alignment with previous research as discussed in section 4.5.

5.1. Contribution

This research expands the existing knowledge of LC studies of new houses in Portugal and in the mild Mediterranean south European context, highlighting that the environmental impact of new houses in Portugal is intrinsically dependent on the jointly effect of options at different levels. This thesis findings can be extended to other south European and Mediterranean locations with similar mild climatic conditions and close electric mix. To effectively reduce the overall environmental impact of new houses requires efforts and improvements from multidisciplinary fields, such as:

i) Construction options at design stage: this research shows that building materials embodied impact may have a higher influence on reducing the overall impacts than improvements in the thermal performance of the new houses. As exemplified by the wood walls, alternative materials or building components with significantly lower environmental impact may be selected. Additionally, material producers can also improve material production and reduce the environmental impacts per product. A regional electricity generation mix with lower impact may also contribute to reduce the building material impacts.

ii) Architectural building design at design phase: window sizing, orientation and building shape have a higher influence than thermal insulation and air-tightness. It is fundamental to acknowledge that architectural building design affects both the thermal performance and the embodied impact of buildings. Therefore, efforts to incorporate embodied impacts and thermal assessment of buildings along the design stage should be valued.

iii) User behaviors (operational patterns and total ventilation) significantly influence the operational phase. Additionally, in a LC study, the magnitude of operational phase may influence options at design stage for which the overall LC impact is reduced (tipping points). Plan for reasonable operational patterns instead of continuous comfort may also prevent the undesired "rebound effect" that has been observed in cold climate VLE houses, where users become careless about energy efficient behaviors due to the small significance of thermal energy consumption. Technology is needed to help lower overall LC impact reduction, but having informed and conscious users should be a goal of any developed society to effectively reduce building sector environmental impacts in the next decades. Houses should be planned to provide comfort conditions for people, but should not twist the natural human ability to adapt to climate. Addressing and incentivizing dwellers "sustainable" habits and behaviors trough information and education can have a significant impact especially in mild Mediterranean climates.

iv) System selection at design stage and along the life span. The operational phase environmental impact is deeply influenced by HVAC systems and their energy supply chains (e.g., electricity generation mix). The adoption of efficient and low impact systems available on market (e.g., heat pumps or wood pellets boilers) is recommended and should be promoted to reduce the environmental impacts of the residential building sector. Since the life-time of several active systems (HVAC and others) is lower than the building lifespan, changes in systems are likely to occur during the lifespan. More efficient systems may be available in the future. Policies and public incentives can also encourage the adoption of efficient systems and help overcome the investment cost barrier.

Another contribution of this thesis is the life cycle inventory framework developed for Portuguese residential buildings, which is based on common building components and therefore can be applied to houses with different design and size relying on the same construction techniques. Moreover, the framework developed can be updated, for instance to: i) model additional alternative building components or materials; ii) study alternative maintenance and/or transportations assumptions; iii) change the generic background data used (ecoinvent 2.2) by regional or local environmental data available (e.g., based on local producers).

5.2. Further research

The LC model boundary was limited to the building exterior envelope. The base case single-family house although representative in shape and size does not consider specific local conditions which may affect each house operational performance, such us: local shading from taller and neighboring buildings or trees. However, from the sensitivity assessment performed varying the building orientation, it is expected that the general conclusions of this research remain valid. Indirect embodied impacts from municipal infrastructure serving the house, land use changes, and the transport of the dwellers during the lifespan of the building were out of scope. A few studies performed at a broader scale (Bastos et al., 2015; Stephan & Crawford, 2014; Stephan, Crawford, & De Myttenaere, 2011; Stephan & Stephan, 2016), showed that the building location (urban or suburban), urban density, and different means of transport available (e.g., public transportation; private car) highly affect transportation energy, which, can represent a significant share of the LC impacts per person (up to 50%). Therefore, although out of the scope of this research those impacts might be significant and worth of assessment studies at a different scale, for instance in order to support urban planning decisions.

This thesis showed that reducing building components embodied impact is an important part of a strategy to reduce the overall environmental impact of residential buildings with low operational impact, such as new Portuguese houses. Thus, to further support embodied energy reduction it would be valuable to model a broader range of construction solutions and building components especially for heavy-construction elements such as roofs, floors, and slabs, as highlighted in subsection 4.5.1. The LCI framework developed along this research could be expanded to include additional building components on a common functional unit (e.g., surface area of building component) and allow other comparative assessments beyond the ones here presented.

In this research, building materials were inventoried based on European background data from Ecoinvent database, which presents an extensive environmental inventory based on unit processes for the construction sector, available in the beginning of this research. In order to better support embodied energy reduction for Portuguese context, it would be desirable to use regional data. However, regional LCI data for construction materials are yet not available systematically (with a few exceptions in recent research and EPD's). However, due to policy and efforts at individual producer's level, existing data is expected to increase in the next years (e.g., EPD's availability). Additionally, a recent literature study (Silvestre et al., 2015) suggested ways of adapting existing databases to a local reality, modifying the background data to include the regional electricity generation grid. Therefore besides extending the building components LCI database for new houses, the future efforts should adapt existing data to represent more approximately the regional context under study. That includes better accounting of insulation materials embodied impacts as suggested in Pargana et al. (2014).

Architectural building design jointly with material selection were shown to be very significant to the overall LC impact of new houses. Therefore, future efforts should focus in allowing architects and building designers to account the environmental impact (embodied and operational) along the design process. For instance to incorporate LCI environmental data in Building Information and Modeling (BIM) may allow more informed comparisons among different design alternatives.

This thesis results were based on a process-based LCA, which is known to suffer from a truncation error (section 2.2). As shown in section 4.5 by the simplified IO-hybrid results, the difference among new houses' embodied energy and related thermal operational energy is likely to be higher. Since currently an IO database for the Portuguese reality is not available, further investigation would be needed to allow a better overall embodied impact accounting (Monteiro et al., 2016). Studies relying on Australian IO-data (Crawford, 2011a; Crawford & Stephan, 2013; Stephan & Stephan, 2014) suggested a higher truncation error, presenting IO-hybrid results 3.78 to 4.36 times higher than process-based.

Like most literature studies, this research assumed an average lifespan of 50 years, and a constant performance of building materials over time. However, the lifespan of a building is highly dependent on maintenance activities and local climatic conditions. It is known that several building materials suffer degradation over time (their performance is not linear) and their service life prediction is dependent on local degradation agents and mechanisms. Alternative building material maintenance activities and service life prediction influences the overall LC results of a building and therefore it is one area of research that could be further studied from a LC perspective. A longer lifespan would lead to higher operational and maintenance impacts, and may decrease embodied energy relative magnitude. For instance, a lifespan increase from 50 to 150 years, may result in a 29% decrease of the annual embodied energy (Rauf & Crawford, 2015).

End-of-life was out of the scope of this study. However, as the embodied impacts were shown to be so relevant on new Portuguese houses, further research focusing on assessing end-of life scenario for building materials beyond the landfill scenario should be considered. Literature shows that planning dwellings end-of-life can potentially reduce embodied impacts of houses possibly through selective dismantling, and material recovery for reuse, recycling or energy recovery. Desirably, buildings and houses should be thought and planned as a part of a human eco-system, reducing wastes and feeding a circular economy. Non-renewable resources are limited. Research, awareness, and human creativity are renewable and can find multiple ways to approach and solve today's challenges for a better future.

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