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LIFE CYCLE ASSESSMENT OF PREFABRICATED BUILDINGS TOWARDS A BUILDING STOCK APPROACH

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supervised by Professor Fausto Miguel Cereja Seixas Freire, presented to the
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Abstract

Buildings are big consumers of energy and materials and significant producers of waste and emissions. Buildings are increasingly more energy efficient, but the rising number of buildings balances the impact reduction of single buildings; therefore, building stock life cycle impacts are a growing problem. Moreover, energy efficiency is sometimes achieved through increased embodied impacts, offsetting the impact reduction during the use phase. To achieve global and European Union (EU-27) targets, the impacts of buildings should be reduced towards a more sustainable construction sector while increasing the competitiveness of the construction sector. Prefabricated buildings may be a way to accomplish the construction sector's dual challenge: reducing buildings' impacts and costs.

This thesis has two main goals: First, to assess life cycle environmental impacts and costs of prefabricated buildings and compare them with conventional buildings. A life cycle assessment (LCA) model was developed to assess prefabricated and conventional single-family houses, mapping the main differences between both construction approaches and disclosing tradeoffs, e.g., between construction and use phases. The LCA focused on two single-family houses built in Portugal and alternatives including different house sizes, structural materials, final house locations, and insulation levels. A "*cradle-to-site*" assessment of a prefabricated house was performed focusing on embodied impacts; a "*cradle-to-use*" LCA balanced embodied and operational impacts to disclose tradeoffs between both phases; and a "*cradle-to-grave*" LCA assessed the environmental impacts, costs, waste, and production time of different prefabricated and conventional buildings using different structural materials.

Second, a building stock approach was developed and implemented to assess the influence of prefabrication wide adoption on EU-27 building stock. This goal also aims to contribute methodologically to the assessment of the introduction of disruptive technology– in this case, prefabrication – in a large set of products in use – the building stock. The building stock model (BSM) developed included the definition of archetypes representing EU-27 building stock, modular life cycle inventory (LCI) to calculate impacts, building information modeling (BIM) to forecast energy needs and extracted quantities, and statistics to estimate results at a country and EU-27 building stock levels. BIM integration allows the streamlined LCI and energy simulation. The proposed modular LCI calculates impacts of a large set of buildings using proxies such as building elements area, number of components, workdays, distance to the site. The developed building stock approach creates a large dataset of results combining alternatives: e.g., construction approaches, typologies, structural materials, insulation levels, and final location; while addressing regional variability with different climates, costs, electricity mixes.

The results from the life cycle model developed to show that compared with conventional, during construction, prefabricated single-family houses can use one-fourth of materials, produce the same fraction of waste, reduce 20% of costs, and take one-third of the time to be built. During the use stage, prefabricated buildings have similar energy performance (or better if insulation is adjusted to local climate) and produce one-fourth of the waste. At the end of life, prefabricated buildings produce one-fourth of the waste, being this waste 40% more recyclable, thus balancing up to 20% of the embodied impacts.

The novel buildings stock approach showed that combining archetypes, modular LCI, and a BIM-LCA approach is a streamlined approach to assess a vast set of buildings in a wide territory. Results at the country or the EU-27 building stock level can support decision-making at different scales, addressing regional variability. Prefabrication can reduce EU-27 building stock impacts and costs, thus contributing to achieving the EU environmental targets while increasing the construction sector competitivity.

Keywords: building stock model, construction and demolition waste, environmental targets, European Union, life cycle assessment, life cycle costs, prefabricated buildings.

Resumo

Os edifícios são grandes consumidores de energia e materiais, e importantes produtores de resíduos e emissões. Os edifícios são cada vez mais eficientes no consumo de energia, mas o número crescente de edifícios contrabalança a redução dos impactos dos edifícios individuais; sendo os impactos do ciclo de vida do parque edificado[1] um problema crescente. Além disso, a eficiência energética é por vezes alcançada com o aumento dos impactos incorporados, compensando a redução durante a fase de utilização. Para atingir os objetivos ambientais globais e os da União Europeia (UE-27), o impacto dos edifícios deve ser reduzido ao encontro de um setor da construção mais sustentável e simultaneamente aumentando a sua competitividade. Os edifícios pré-fabricados podem ser uma forma de alcançar o duplo desafio do setor da construção: reduzir os impactos e os custos dos edifícios.

Esta tese tem dois objetivos principais: Primeiro, avaliar impactos e custos do ciclo de vida de edifícios pré-fabricados e compará-los com edifícios convencionais. Uma avaliação de ciclo de vida (ACV) foi desenvolvida para avaliar edifícios pré-fabricados e convencionais, mapeando as principais diferenças entre as duas abordagens construtivas e revelando compensações, por exemplo, entre as fases de construção e de utilização. Diferentes alternativas foram incluídas no modelo: tamanho e *layout* das casas, material estrutural, localização final e nível de isolamento. Uma avaliação "*do berço ao estaleiro*" de uma casa pré-fabricada foi realizada focando nos impactos incorporados; uma avaliação "*do berço até à utilização*" calculou os impactos incorporados e os operacionais revelando compensações que possam ocorrer entre ambas as fases; e um ACV "*do berço ao túmulo*" avaliou os impactos ambientais, custos, resíduos e tempo de produção de diferentes edifícios pré-fabricados e convencionais, desde a extração dos materiais até a gestão de resíduos, considerando diferentes materiais estruturais.

Em segundo lugar, uma abordagem de avaliação do parque edificado[1] foi desenvolvida e implementada para analisar o efeito da adoção da pré-fabricação à escala da UE-27. Este objetivo visa também contribuir metodologicamente na avaliação da introdução de uma tecnologia disruptiva – neste caso a pré-fabricação – num alargado conjunto de produtos em uso o parque edificado. O modelo desenvolvido incluiu a definição de arquétipos que procuram representar o conjunto de edifícios na UE-27, o

[1] O termo "*parque edificado*" é a tradução livre do termo inglês "*building stock"* e refere-se ao conjunto dos edifícios habitacionais e comerciais.

inventário de ciclo de vida modular para calcular impactos, a modelação da informação de construção[2] (BIM) para calcular as necessidades de energia e extraindo as quantidades do modelo e, por último, a utilização de dados estatísticos para estimar os resultados para cada país e os resultados globais para o parque edificado da UE-27. A integração da metodologia BIM permite a construção do inventário e o cálculo das necessidades energéticas de uma forma simplificada. O inventário modular proposto calcula os impactos de um grande conjunto de edifícios usando fórmulas de cálculo baseadas, por exemplo, na área dos elementos construtivos, número de componentes, dias de trabalho, distância até o local. A abordagem de avaliação do parque edificado desenvolvida originou uma vasta base de dados com os impactos das diversas alternativas que resultam da combinação de soluções construtivas, tipologias, materiais estruturais, níveis de isolamento e localização final; e, simultaneamente, respondem à variabilidade regional, diferentes climas, custos, matrizes energéticas.

Os resultados da avaliação de ciclo de vida mostram que comparado com as convencionais durante a construção as casas unifamiliares prefabricadas usam até um quarto dos materiais, produzindo a mesma fração de resíduos, reduzindo 20% dos custos e até um terço o tempo de construção. Durante a fase de uso, as casas pré-fabricadas têm um desempenho energético semelhante (ou melhor se o isolamento for ajustado ao clima local) e produzem um quarto dos resíduos. No final da vida útil, as casas pré-fabricadas produzem um quarto dos resíduos de demolição, sendo estes resíduos 40% mais recicláveis, podendo compensar até 20% dos impactos incorporados.

A nova metodologia desenvolvida mostrou que uma abordagem de avaliação do parque edificado usando arquétipos, inventário modular e integrando a metodologia BIM com a ACV pode ser uma abordagem simplificada para avaliar um vasto conjunto de edifícios num amplo território. Além disso, os resultados por país ou de forma agregada à UE-27 podem apoiar a tomada de decisão a diferentes escalas, abordando a variabilidade regional. A pré-fabricação pode reduzir os impactos e os custos do parque edificado da EU27 contribuindo assim para atingir os objetivos ambientais da União Europeia e aumentar a competitividade do setor da construção.

Palavras chave: avaliação de ciclo de vida, custos de ciclo de vida, edifícios pré-fabricados, metas ambientais, modelo de parque edificado, resíduos de construção e demolição, União Europeia.

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[2] O termo "*modelação da informação da construção*" é a tradução livre do termo inglês "*building information modeling"* cuja sigla BIM é utilizada correntemente em português.

Acronyms

AC – acidification

AD – abiotic resource depletion

ADF – abiotic depletion of fossil fuels

BAU – business as usual

BIM – buildings information modeling

BS – building stock

BSM – building stock model

CDW – construction and demolition waste

ENTRANZE – (policies to) enforce the transition to nearly zero energy buildings in the EU-27

EPD – Environmental Product Declarations

EPISCOPE – energy performance indicator tracking schemes for the continuous optimization of refurbishment processes in European housing stocks

EU – eutrophication

EU-27 – 27 countries of the European Union

GW – global warming

HR – high-rise residential

HO – high-rise office

IMPRO – buildings environmental improvement potentials of residential buildings

LCA – life cycle assessment

LCI – life cycle inventory

LCC – life cycle costing

LEVEL(s) – a common EU framework of core sustainability indicators for office and residential buildings.

LSF – light steel framing

MR – medium-rise residential

MO – medium-rise office

NRE – non-renewable energy

OD – ozone layer depletion

PO – photochemical oxidation

RC – reinforced concrete

RC1 – reinforced concrete with single-layer concrete block exterior wall

RC2 – reinforced concrete double-layer brick exterior wall

SF – single-family house

TABULA – typology approach for building stock energy assessment

WF – wood framing

Z1 – zone 1, warm weather countries

Z2 – zone 2, moderate weather countries

Z3 – zone 3, cold weather countries

EU-27 Countries

AT – Austria

BE – Belgium

BG – Bulgaria

CY – Cyprus

CZ – Czechia

DE – Germany

DK – Denmark

EE – Estonia

ES – Spain

FI – Finland

FR – France

GR – Greece

HR – Croatia

HU – Hungary

IE – Ireland

IT – Italy

LT – Lithuania

LU – Luxembourg

LV – Latvia

MT – Malta

NL – Netherlands

PO – Poland

PT – Portugal

RO – Romania

SE – Sweden

SI – Slovenia

SK – Slovakia

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CHAPTER 1 INTRODUCTION

"The construction sector is the single largest energy consumer in the EU (40%), the largest raw materials user (50% of extracted materials), and thus one of the largest greenhouse gas emitters (36% of energy-related direct and indirect emissions)" (European Commission, 2020a). Moreover, construction and demolition waste (CDW) accounts for around one-third of Europe's waste, one of the most critical waste streams (European Commission, 2008). These are overwhelming figures, a threat (if ignored), or a significant opportunity (in a circular economy perspective).

1.1 Context

By 2050 the United Nations (UN) estimates that two-thirds of the world population will be living in urban areas with new megacities located in fast-developing countries. These cities need to lodge a large number of people quickly, safely, and comfortably. In some countries, the construction industry cannot build at the speed and scale required, so prefabricated buildings (mainly houses) are imported to respond to this urgent need. The fast growth of these megacities was identified as a global challenge, as the UN set the goal to "*make cities and human settlements inclusive, safe, resilient and sustainable*" by 2030 (Sustainable Development Goals of the UN, 2015).

The construction sector responds to the basic human need of shelter. Despite having a growing demand (increasing population with updated needs), the construction sector has lost competitiveness. In the global economy, the average real gross value added per hour worked by a person rose from 25$ to 37$ (1995-2014); in manufacturing grew to 39$, and in the construction sector, it remained stable (McKinsey Global Institute, 2017). The construction sector share in Portuguese gross domestic product (GDP) decreased (from 7% in 2000 to 4% in 2015), while minimum wage workers increased (from 2,7% in 2001 to 22,7% in 2015) (INE, 2018). These figures demonstrate the lack of productivity in the construction sector compared with other sectors. Roughly during the same period, the export intensity of the construction sector in Portugal rose (from 4% in 2000 of the total export intensity to 16% in 2015) due to the internalization efforts of construction companies triggered by the economic crises and a shrinking internal market. Some of these efforts relied on implementing prefabrication processes, a growing niche market. Buildings and components were designed and prefabricated in Portugal and after shipped overseas mainly to Portuguese-speaking countries (e.g., Angola, Brazil, and Mozambique), to the Mercosur market (e.g., Venezuela with the "*Petrohouses*"), or some European countries (e.g., France). Prefabrication responds to some of the Portuguese construction sector challenges: to expand the market beyond frontiers, reduce costs, and deal with local difficulties (e.g., lack of local workforce, extra taxes, lack of materials).

In Europe (EU-27), the construction sector represented 1.4 x 10^6 million euros (almost 10 % of GDP) and is mainly composed of micro and small enterprises (European Commission, 2012), while in Portugal represents 19 x 10^3 million euros and 313 thousand workers (Pordata, 2017). The foreseen reindustrialization of the construction sector will lead to the widespread use of prefabrication, expected to improve the efficiency of the construction process and buildings' performance. However, the consequences of prefabrication implementation are yet unknown, so environmental performance and the economic impact of the prefabricated process should be mapped and assessed.

1.2 Problem statement and research gaps

The construction sector faces two main problems: i) buildings are big consumers of resources and responsible for a large share of emissions, ii) the construction sector has lost competitiveness, is unspecialized, and workers are underpaid. Prefabrication aims to make buildings and the construction industry less energy- and resource-intensive, reduce burdens and waste, and increase the construction sector's productivity.

Buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in Europe. Moreover, 35% of building stock is over 50 years old, and 75% energy inefficient (European Comission, 2017). Together with food and mobility, buildings are one of the most critical key sectors to achieve resource efficiency (European Comission, 2011), and a Life Cycle Assessment (LCA) approach has been recommended to assess buildings' life cycle (LC) environmental impacts (European Commission, 2011a). Previous research has focused mainly on buildings' use phase and energy efficiency (Anand and Amor, 2017), often achieved by increasing the embodied impacts of buildings. Furthermore, energy efficiency and the consequential reduction of the operational impact of buildings will reach a limit when meeting low energy buildings standards and, in that context, embodied impacts have rising importance.

Results presented in the literature showed that both buildings and the construction sector could reduce impacts and costs through prefabrication (Kamali and Hewage, 2016). However, prefabrication benefits can be balanced by prefabrication extra activities and materials or by a less efficient use phase. So, before its wide adoption, prefabricated buildings must be assessed in a life cycle approach, and prefabrication analyzed at a building stock level. Different measures have been assessed, and others implemented to reduce the impacts of buildings and the building stock, e.g., refurbishment, energy efficiency, and renewable energy adoption. Prefabricated buildings have been previously assessed in literature through particular case studies, focusing on a specific material, building typology, or final location. No previous study has analyzed prefabrication adoption at a building stock level, mapping the differences within prefabricated buildings and processes and addressing regional variability. Moreover, the comparison of alternative prefabrication technologies with alternative conventional constructions has rarely been made before.

With the industrialization of the construction sector and the digitalization of the building process – from digital design all through automation in construction and maintenance – prefabrication seems to be the future of construction. However, partial LCAs (focusing on a specific phase), specific case studies, and limited research boundaries can hide buildings hotspots and cause burdens shifting. Impacts and costs of prefabricated and conventional approaches need to be holistically accounted for and balanced using a comprehensive life-cycle approach. The following four research gaps were identified, following the literature review presented in chapter 2:

I. The use phase and energy efficiency have been the main focus of previous research, but as neat or nearly zero energy buildings (nZEBs) will be a mandatory standard for all new buildings (regardless of the construction approach or materials used), operational impacts will be similar. Moreover, end-of-life (EoL) is usually excluded from the LCA of buildings due to its low share in total impacts, but the recycling potential of construction and demolition waste (CDW) of prefabricated buildings is significantly higher than conventional. Therefore, reducing the embodied and EoL impacts will be two crucial stages to decrease buildings impacts. A "cradle-to-grave" assessment (from materials extraction through disposal) allows to identify hotspots and unveil possible problem shifting in the life cycle of buildings (e.g., decreasing operational impacts at the expense of increasing embodied impacts) but has rarely focused on prefabricated buildings.

II. Few studies assessing prefabricated buildings have compared them with alternative conventional, considering different structural materials, insulation levels, sizes, layouts, or final locations. Moreover, tradeoffs between embodied and operational impacts and costs of prefabricated lightweight and conventional heavyweight buildings in different climates have not been previously assessed;

III. The building stock models (BSM) presented in the literature have assessed refurbishment measures and renewable energy sources adoption, but none has assessed prefabrication wide adoption. No BSM has been applied to prefabricated buildings assessing prefabrication potential contribution to achieving the EU-27 environmental targets;

IV. Combining BIM with LCA enables to streamline LCI and energy simulation of a vast set of alternatives. Some studies have previously combined BIM with LCA, but none of the previous building stock approaches combined a BIM-based energy assessment with a modular LCI and a statistical aggregation approach. Allocating costs and impacts to material use, waste generated, and construction time enables a streamlined assessment of the building processes and was not found in the literature.

1.3 Research goal

The main goal of this thesis is twofold: First, to assess life cycle environmental impacts and costs of prefabricated buildings and compare them with conventional buildings. A life cycle assessment (LCA) was developed to assess prefabricated and conventional buildings, mapping the main differences between both construction approaches and disclosing tradeoffs. Different alternatives were included: house sizes and layouts, structural materials, final house locations, and insulation levels. A "*cradle-to-site*" assessment of a modular single-family prefabricated house focused on the embodied impacts of prefabricated houses and the comparison with conventional. Different house sizes (from one to four bedrooms), final locations (Aveiro, Lisbon, Faro, Paris, Casablanca, Luanda, and Rio de Janeiro), and structural materials (steel, wood, and concrete) were considered. A "*cradle-to-use*" LCA accounted for the embodied and operational impacts of prefabricated buildings in different climatic regions – continental with cold weather, Mediterranean with moderate weather, and tropical with warm weather – and disclosed tradeoffs between both phases. A "*cradle-to-grave*" assessment of the life cycle environmental impacts, materials, costs, waste, and production time compared the most typically used prefabricated (light steel framing and wooden structure) with the most typically used conventional construction in the Mediterranean region (reinforced concrete structure with brick or concrete masonry).

Second, a building stock approach was developed and implemented to assess the contribution of prefabrication wide adoption to reduce the environmental impacts of the EU-27 building stock. A building stock model (BSM) was developed, aiming at a methodological contribution how to assess a disruptive technology adoption (in this case, prefabrication) in a large set of products in use (the building sector). The BSM included: i) the definition of archetypes to represent the EU-27 building stock, including single-family, medium-rise multifamily, high rise multifamily, medium-rise office, and high-rise office buildings; ii) a novel modular life cycle inventory (LCI) to calculate impacts with impacts allocated per building element or activity; iii) the integration of building information modeling (BIM) to forecast energy needs in different locations, and with different materials and insulation levels; and extract quantities from a BIM model to build the life cycle inventory; iv) the use of statistical data to estimate results at a country and EU-27 building stock levels, including regional variability. BIM integration allows a streamlined LCI and energy simulation. The novel modular LCI calculates impacts of a large set of buildings using proxies such as building elements area, number of components, work days, distance to the site. The developed building stock approach creates a large dataset of results combining alternatives: construction approaches (prefabricated and conventional), typologies (residential and office; single-family, medium- and high-rise), structural materials (steel, wood, and concrete), insulation levels (low, medium, and high), and final location (Lisbon, representing warm-weather countries; Berlim, moderate weather; and Stockholm, cold weather); while addressing regional variability (inherent to different climates, costs, electricity mixes). Assessing buildings impacts in each location is essential to reduce overall building stock impacts and contribute to achieving EU-27 environmental targets.

1.3.1 Research questions and specific objectives

The first goal of this thesis is to assess life cycle environmental impacts and costs of prefabricated buildings and compare them with conventional buildings. The following research questions were formulated based on the research goals defined to respond to the identified research:

- *What are the embodied impacts of prefabricated buildings?*
- *What is the balance of embodied and operation impacts of a prefabricated building?*
- *What are the main differences between prefabricated and conventional buildings?*

The second goal is to develop and implement a building stock approach to assess the contribution of prefabrication wide adoption to reduce the environmental impacts of the EU-27 building stock. The research question is:

- *What is the potential for prefabrication buildings to decrease the environmental impacts and costs of the EU building stock?*

Moreover, the main methodological research question is:

- *Can a building stock model approach, combining LCA, BIM, modular LCI, and statistical aggregation, be a streamlined approach to assess a large set of buildings in a wide area?*

The five research questions and specific objectives are presented in Table 1.

Table 1 Research questions and specific objectives

Research question	Specific objectives	Chapter or section
What are the embodied impacts of prefabricated buildings?	i) Perform an LCA to account for embodied energy and carbon of a house, assessing different alternatives (house sizes, structural materials, final house locations); ii) Assess transport-related impacts in modular prefabricated buildings; iii) Sensitivity analysis of the functional unit.	Section 4.1
What is the balance of embodied and operation impacts of a prefabricated building?	i) Asses the embodied and operational impacts of the prefabricated lightweight single-family house and conventional heavyweight one, using different structural materials and insulation levels, in different final locations (different electricity mixes, climates, transport); ii) Identify the tradeoffs.	Section 4.2
What are the main differences between prefabricated and conventional buildings?	i) Perform an integrated cost and environmental life cycle assessment of alternative structural materials for a single-family house; ii) Compare alternative prefabricated buildings with alternative conventional buildings; iii) Assess waste treatment in each alternative and the potential to reduce burdens at the EoL; iv) The model addresses costs, waste, material use, and production time, besides environmental impacts.	Section 4.3
What is the potential for prefabrication buildings to decrease the environmental impacts and costs of the EU building stock?	i) Assess the environmental and cost performance of various archetypes in different locations; ii) Sensitivity analysis to assess the influence of location, size, and use, construction system, insulation levels; iii) Introduce regional variability and assess how final location can influence results; iv) Identify key drivers and challenges in the construction sector.	Chapter 5
Can a building stock model approach be a streamlined approach to assess a large set of buildings in a wide area?	i) Develop and apply a building stock approach integrating LCA, BIM, modular LCI, and statistical aggregation; ii) Investigate how the streamlined BIM-LCA approach could be used to support decisions at the design stage; iii) Explore the potential to use the building stock approach in assessing disruptive technologies in the buildings sector before its wide adoption.	Chapter 5

1.4 Thesis outline

This thesis comprises six chapters and follows the research questions and specific objectives (presented in Table 1), as follows:

- **Chapter 1** presents the introduction with the context; problem statement; research gaps, goals and questions; specific objectives; and, finally, thesis outline;
- **Chapter 2** maps state-of-the-art with the literature review about buildings and prefabricated buildings with buildings types, impacts, modular prefabrication, transport-related impacts, lightweight vs. heavyweight, life cycle cost, and CDW. Environmental targets, building stock, and building information modeling (BIM) are also presented;
- **Chapter 3** presents research methodology describing life cycle assessment (LCA), the novel modular life cycle inventory (LCI), proposed BIM-LCA integration, and developed stock-based approach;
- **Chapter 4** presents the LCAs of prefabricated houses responding to the three first research questions (presented in Table 1) implementing a *cradle-to-site*, a *cradle-to-use*, and a *cradle-to-grave* assessment of two single-family prefabricated houses and alternatives;
- **Chapter 5** presents the stock-based approach developed to respond to the two last research questions (presented in Table 1), developing and implementing a building stock model;
- Finally, **Chapter 6** concludes with research contributions, key findings, and future work.

Figure 1 presents the thesis overview. Five appendices provide further information on the prefabricated building market (appendix I), environmental targets (appendix II), building stock (appendix III), and publications (appendix IV).

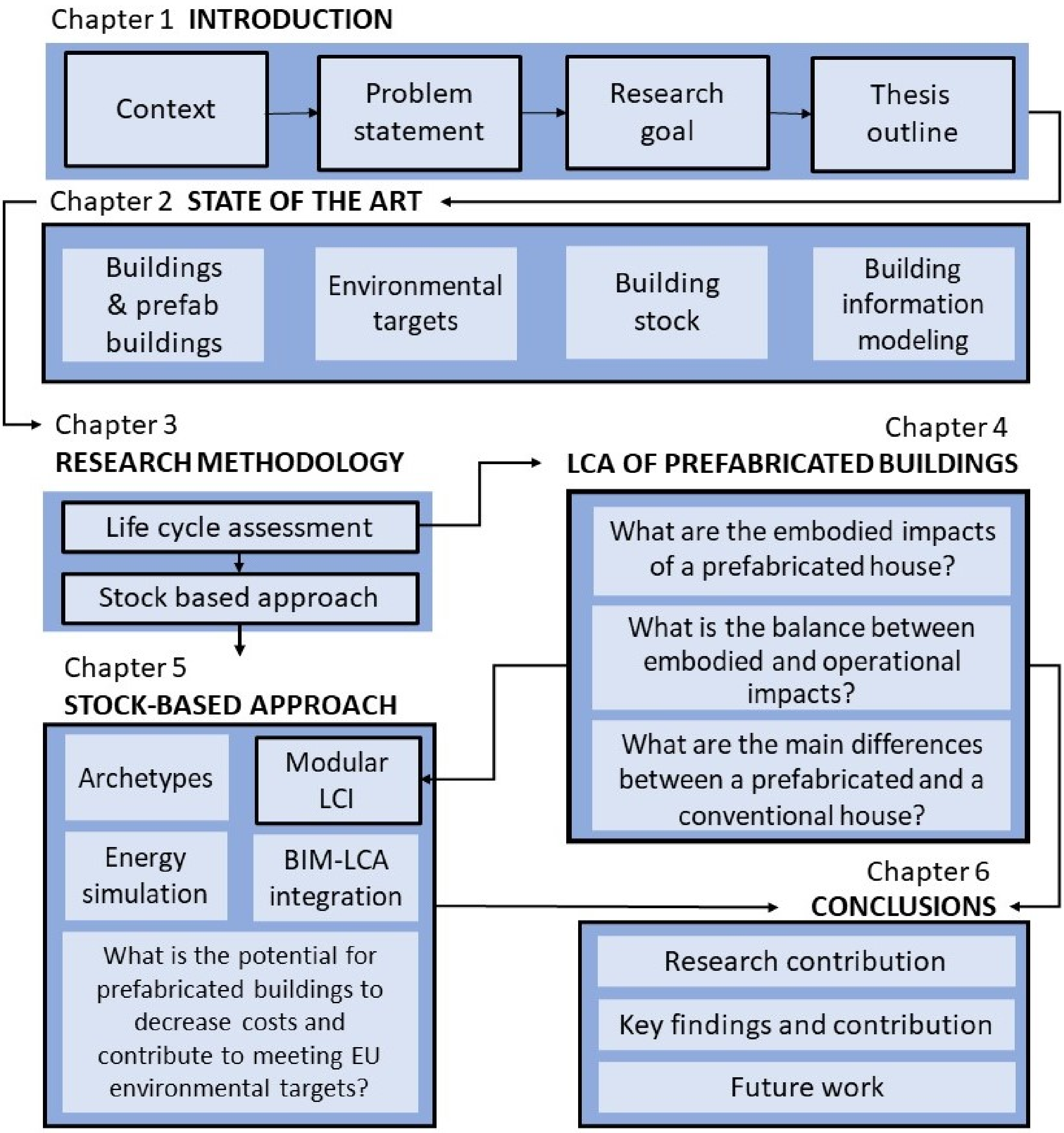

Figure 1 Thesis overview

1.5 Thesis main publications

Most of this thesis is based on the following articles (three published and one under review) in ISI-indexed journals (the abstracts of the articles are presented in Appendix IV):

Tavares, V., Gregory, J., Kirchain, R., Freire, F. (2021). What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? Journal of Building and Environment. Vol.206, 108382 (presented in chapter 5).

https://doi.org/10.1016/j.buildenv.2021.108382 JCR® impact factor (2021): 6.456

Tavares, V., Soares, N., Raposo, N., Marques, P., Freire, F. (2021). Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. Journal of Building Engineering, Vol.41, 102705 (presented in section 4.3).

https://doi.org/10.1016/j.jobe.2021.102705 JCR® impact factor (2021): 5.318

Tavares, V., Freire, F. (2021). Life cycle assessment of a prefabricated house for seven final locations and three insulation levels, under review (presented in section 4.2).

Tavares, V., Lacerda, N., Freire, F. (2019). Embodied Energy and Greenhouse Gas Emissions Analysis of a Prefabricated Modular House: the "Moby" case study. Journal of Cleaner Production vol. 212, pp. 1044-105 (presented in section 4.1).

https://doi.org/10.1016/j.jclepro.2018.12.028 JCR® impact factor (2021): 9.297

CHAPTER 2 STATE-OF-THE-ART

This chapter maps and discusses the literature on prefabricated buildings, addressing buildings types, impacts, modular prefabrication, transport impacts, lightweight and heavyweight construction, cost, and construction and demolition waste. Global and EU-27 environmental targets are discussed, and literature on construction and demolition waste (CDW) and building information modeling (BIM) is presented. Research on building stock models (BSM) was summarized, and EU building stock was briefly characterized.

2.1 Buildings and prefabricated buildings

Buildings are not a well-defined static entity, neither use a straightforward repetitive manufacturing process. Buildings are complex structures composed of different parts and systems, partially prefabricated and partially done onsite, produced by multiple stakeholders, using diverse materials, built in different locations, and hardly ever repeating. Buildings overlap and intersect different systems responding to different needs, e.g., structural, insulation, waterproofing, and mechanical, electrical, and plumbing (MEP) systems; and have long life spans with multiple users and unpredictable uses, changing function over time (sometimes even during a single day).

Building prefabrication refers to the process of manufacturing building parts, elements, or modules at a plant and then transporting them to the building site to be installed and assembled (Kamali and Hewage, 2016). In literature, different terms are used referring to prefabricated buildings: "*offsite construction*" (Goulding et al., 2012; Harvey, 2014; Salama et al., 2018; Sharma et al., 2017), "*modern methods of construction (MMC)*" (Goulding et al., 2012; Kozlovská et al., 2015; Monahan and Powell, 2011), "*modular buildings*" (Isaac et al., 2014; Kamali et al., 2019; Salama et al., 2018), among others. Moreover, different types of prefabrication were found in the literature: component manufacture and sub-assembly (such as windows, doors, or equipment), non-volumetric pre-assembly (panelized wall or timber trusts), volumetric pre-assembly (toilets or bathroom pods), and modular building (complete built units or modules that compose the whole building) (Kamali and Hewage, 2016). Different degrees of prefabrication can be employed, from prefabricated elements (façade, form, slab, balcony, staircase, and panel) to modules (such as hotel bedrooms) or entirely prefabricated buildings (mainly houses). Some structural materials used are also used in conventional building processes such as wood (Adalberth, 1997a; Monahan and Powell, 2011), steel (Tavares et al., 2019; Teng and Pan, 2019), and concrete (Bonamente et al., 2014; Hong et al., 2016); but others are more innovative such as plastics (Tumminia et al., 2018), or shipping containers (Dara et al., 2019; Islam et al., 2016). Table 2 sums up some of the terminology used in literature about prefabrication.

Table 2 Prefabrication terminology in the literature

	Terminology	Reference (up to three)
Designations	Prefabricated	(Aye et al., 2012; Pons and Wadel, 2011; Tumminia et al., 2018)
	Offsite	(Goulding et al., 2012; Harvey, 2014; Nihar et al., 2017)
	Modern Methods of Construction	(Goulding et al., 2012; Monahan and Powell, 2011; Waste & Resources Action Programme, 2007)
	Modular	(Isaac et al., 2014; Kamali et al., 2019; Steinhardt and Manley, 2016)
	Pre-assembly	(Olson, 2010; Why and Works, 2007)
	Pre-cast	(Ding et al., 2020; Pan and Sidwell, 2011)
Type	By elements or components	(Ahmed and Tsavdaridis, 2018; Hong et al., 2016; Jaillon and Poon, 2009)
	Panelized	(Boscato et al., 2018; Gasparri and Aitchison, 2019; Lopez and Froese, 2016)
	Modular	(Isaac et al., 2014; Olson, 2010; Smith and Rice, 2017)
Prefabrication level	Whole buildings	(Atmaca and Atmaca, 2016; Dara et al., 2019; Islam et al., 2016)
	Building parts *(e.g., bedrooms, classroom, laboratories)*	(Aye et al., 2012; Kamali and Hewage, 2016; Salama et al., 2018)
	Building components *(e.g., walls, windows, doors, stairs)*	(Ahmed and Tsavdaridis, 2018; Hong et al., 2016; Isaac et al., 2014)
Structural materials	Wood	(Achenbach et al., 2018; Adalberth, 1997a; Boscato et al., 2018)
	Steel	(Aye et al., 2012; Pons and Wadel, 2011)
	Concrete	(Li et al., 2021; Navarro-Rubio et al., 2019; Zhang et al., 2021)
	Light Steel Framed	(Gorgolewski, 2007; Mortazavi et al., 2020; Soares et al., 2017)
	Plastic	(Honic et al., 2019; Moreno-Sierra et al., 2020)
	Container	(Atmaca and Atmaca, 2016; Dara et al., 2019; Islam et al., 2016)
Uses	Residential	(Adalberth, 1997a; Chiang et al., 2006; Luo and Chen, 2020)
	Educational	(Gamarra et al., 2018; Pons and Wadel, 2011; Scheuer et al., 2003)
	Commercial	(Bahramian and Yetilmezsoy, 2020; Means and Guggemos, 2015; Scheuer et al., 2003)

Figure 2 presents the life cycle (LC) of conventional (on the top) and prefabricated buildings (on the bottom). Conventional buildings' LC includes materials extraction and transformation, transport to site, on-site construction, use phase, and demolition. Prefabricated buildings´ LC also includes the offsite fabrication stage and transport from the plant to the site (of materials, prefabricated elements, and workers). Prefabricated buildings are based on dry construction systems that are more likely to be disassembled with higher waste reuse and recycling potential and that are more likely to close the loop in a more circular economy.

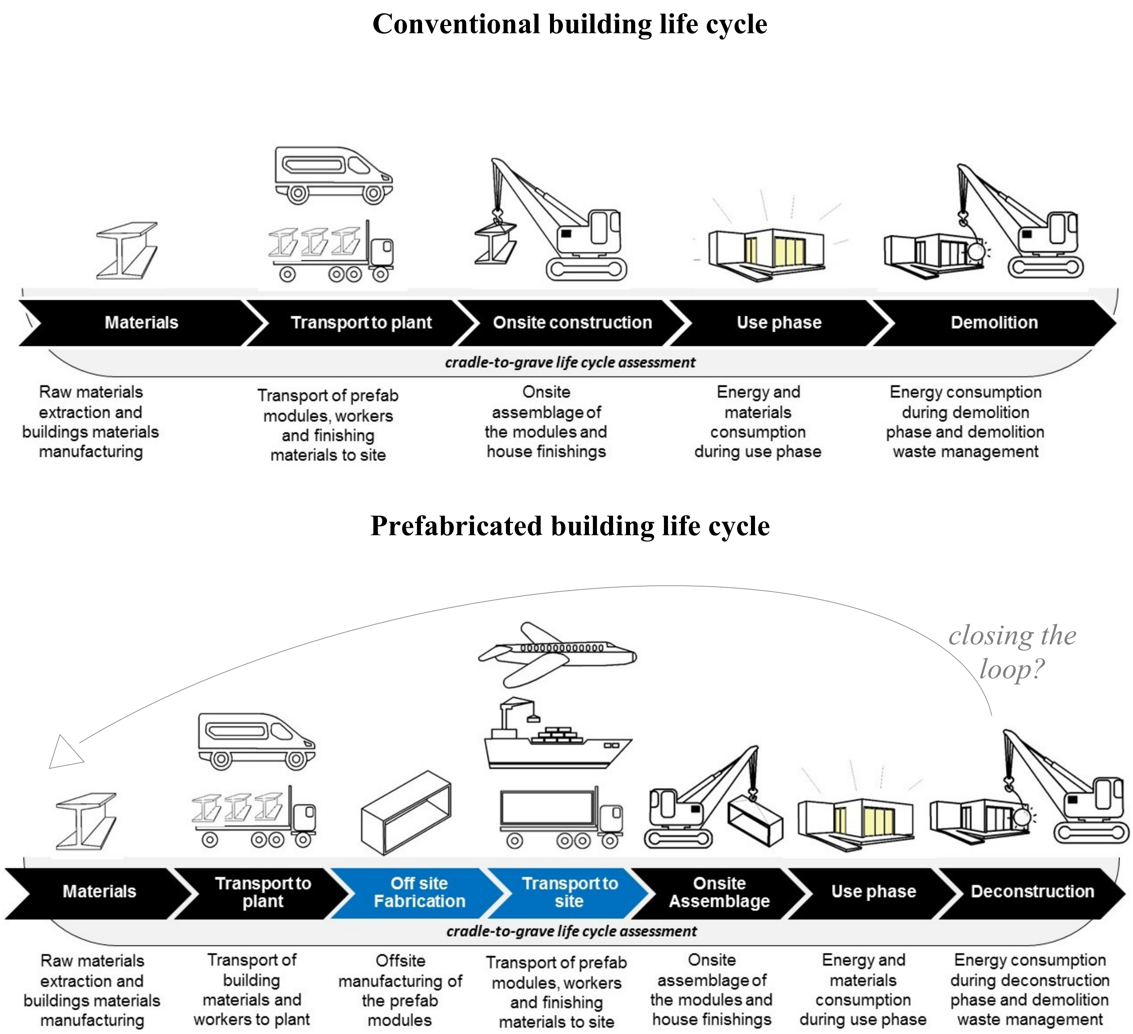

Figure 2 Life-cycle of conventional buildings (top) and prefabricated buildings (bottom)

Prefabrication can drive the construction process and buildings to become more efficient, less energy-intensive, and resource-dependent. However, having one extra phase (prefabrication at a plant), transportation stage (from plant to site), and different energy performance (being based on lightweight construction), prefabrication impacts and costs need to be carefully balanced when compared with conventional construction.

Production-related impacts of prefabricated buildings are more controlled and can be better accounted. However, once the building leaves the gate, impacts are influenced by numerous factors: distance to the site, local weather, users' profile, HVAC system, among other issues. Impacts beyond the gate cannot be fully controlled (and are beyond the companies' accountability) but can be forecasted and optimized. Prefabricated buildings can be adapted to local weather (reducing heating and cooling needs), transport optimized, end-of-life foreseen, and demolition waste impacts reduced. To effectively reduce buildings burdens using prefabrication, impacts of both building processes (prefabricated and conventional) must be carefully identified.

The benefits of prefabrication are cost control and cost reduction, reduced construction time, increase in safety and product quality, growth of productivity, improved buildings performance, and increased on-site safety (Kamali and Hewage, 2016). Some studies concluded that as the level of prefabrication increases, the use of materials, energy, and greenhouse gas (GHG) emissions decreases (Hong et al., 2016; Mao et al., 2013; Pons and Wadel, 2011). However, the prefabrication process also poses some challenges, such as more complex project planning, transport restraints and extra burdens (in transport, prefabrication, and packaging), high initial cost, among other factors (Chen et al., 2010; Dave et al., 2017; Tam et al., 2007). The decrease of energy and material consumption and emission due to prefabrication may be balanced by prefabricated specific processes, such as extra production phase (with related consumptions and facilities) and transport (especially in modular prefabricated buildings), redundant materials (due to modularity or to allow the transport), and increase in consumption during use phase (due to low thermal mass). Therefore, studies comparing prefabricated building processes with standard processes must be developed to fully understand the prefabrication processes (benefits and disadvantages) quantitatively accounting and balancing the benefits and challenges of prefabricated processes (Kamali and Hewage, 2016).

Table 3 presents the main characteristics of conventional and prefabricated buildings, highlighting the differences. In the materials extraction phase, conventional buildings use heavyweight materials and weights four more than a prefabricated one. However, some mass-related impacts in prefabricated buildings (such as steel) are much higher than in conventional. Nevertheless, part of the embodied impacts can be balanced at EoL due to higher recovery and recyclability rate.

At the construction stage, the conventional building process is less accurate, with more man-related errors, waste generated, and water used, being highly dependent on the local weather. Opposingly, prefabricated elements or modules are produced in a more controlled plant, with reduced waste production (and well-organized waste streams) regardless of the weather. However, plant-related impacts (such as the required gross floor area and plant energy consumption) can increase burdens.

Operational energy needs can be forecasted for both constructions and designs adapted to different final locations to reduce use-phase impacts. The conventional building process is less controlled and more error-prone, resulting in more construction defects and possibly in less energy-efficient buildings. The increased control over the prefabricated process may reduce those risks. Finally, maintenance interventions in conventional construction are more complicated than in prefabricated buildings that being dry construction systems can be partially dismounted for inspection or replacement. However, buildings inertia (usually low in prefabricated buildings and high in conventional) needs to be assessed in different climate zones as both constructions will have different needs.

The end-of-life phase presents significant differences: conventional buildings demolition waste is hardly selected and redirected to waste treatment facilities, having low economic value. Opposing prefabricated buildings can be dismantled, with some waste reused or recycled and higher economic value.

Transportation occurs during different stages of the LC and can jeopardize the impact reduction achieved by the prefabrication. Prefabricated housing plants are scarce and serve broad distribution areas, including overseas transportation to other countries. That means a longer traveled distance for workers (if specialized and not hired locally) and prefabricated parts. Transport-related burdens are mainly influenced by distance from the plant to site, weight, and volume. Prefabricated buildings have one extra transport stage (from and to the plant), and modules transportation impacts (in modular prefabricated buildings) are significant as volume (not weight) is transported.

Table 3 Life cycle of conventional and prefabricated buildings: characterization and main differences

Conventional	Prefabricated
Materials extraction & transformation phase	
Heavyweight materials *- increased embodied impacts* *- increased transport-related impacts* *- materials with lower mass related burdens*	Lightweight materials *- decreased embodied impacts* *- decreased transport-related impacts* *- materials with higher mass related burdens* Extra material *- extra material for transport & assemblage*
Prefabrication & construction phase(s)	
Conventional construction system *- less controlled building process* *- more waste generated* *- more water used* *- higher dependency on weather conditions*	Dry construction system *- more controlled building process* *- less waste generated* *- decrease in water used* *- independence to weather conditions (due to reduced time on site)* *- extra plant-related impacts (such as the building itself)*
Use phase	
Less predicted use phase *- increase in operational energy (due to design and building failures)* *- unpredictable maintenance activities, more challenging to perform (increased lifespan)* *- damage due to catastrophe challenging to solve* High inertia *- (possible) decrease in operational heating needs* *- (possible) increase in operational cooling needs*	More predicted use phase *- decrease in operational energy (due to improved design and building)* *- predictable maintenance activities, easier to perform (variable lifespan)* *- damage due to catastrophe easy to solve (due to customization)* Low inertia *- (possible) increase in operational heating needs* *- (possible) decrease in operational cooling needs*
End-of-life phase	
Complete demolition *- more waste generated (due to materials used in construction)* *- difficult to separate different wastes*	Selective decommissioning *- less waste generated (due to materials (re)used in construction)* *- easier to reuse and recycle materials*
Transport phases	
Local construction enterprise *- small local companies* *- short travel distance*	Regional, national or international construction enterprise *- larger companies serving a wider area* *- long travel distance* Extra phase, extra transport *- increase in travel distance due to transport to and from plant* *- extra transport in modular prefabrication (due to volume transported, not weight)*

2.1.1 Building types

Previous works have focused on different building types: lightweight and heavyweight buildings (Hacker et al., 2008); non-prefabricated with three prefabricated (concrete, timber, and steel) (Pons and Wadel, 2011); traditional masonry and modern method of construction with two timbre framing types (Monahan and Powell, 2011); a modular average with a modular conventional (Quale et al., 2012); and a conventional concrete, prefabricated steel and a wood building (Aye et al., 2012). Others focused on prefabricated elements or building parts such as prefabricated façades, staircase, and slabs (Mao et al., 2013); or precast façade, slab, balcony, staircase, and panel (Hong et al., 2016). Most of the studies conclude that prefabricated buildings or building elements can decrease buildings´ burdens through reducing materials weight (Hacker et al., 2008) and waste (Pons and Wadel, 2011) and increasing the reuse and recyclability of materials (Hong et al., 2016); thus decreasing the embodied carbon and energy (Mao et al., 2013). Some studies have compared partially prefabricated buildings with non-prefabricated (Cao et al., 2014; Hong et al., 2016; Mao et al., 2013) and proved that even with a small degree of prefabrication, some benefits could be achieved (Cao et al., 2014). Two conclusions about the prefabricated market are pointed out: when prefabrication is only partially applied, the environmental benefits from a scale effect are difficult to be evaluated (Cao et al., 2014), and the maturity of the prefabricated market should increase to avoid additional impacts (Hong et al., 2016).

2.1.2 Life cycle assessment of prefabricated buildings

Life Cycle Assessment (LCA) quantifies the environmental impacts and identifies improvement opportunities during the life-cycle of products: from the early beginning (the *cradle*) all through the end-of-life (the *grave*) (ISO, 2006a). LCA has been applied since the 1970s (Rebitzer et al., 2004), although the first papers focusing on buildings were only published in the 1990s (Khasreen et al., 2009). The importance of LCA as a supporting decision tool is extensively confirmed in literature (Erlandsson and Borg, 2003).

The complexity of buildings and the uncertainty due to their long life span makes it difficult to perform a comprehensive study, assessing the building as a whole and including the complete life cycle: from materials extraction to demolition. Therefore, some researchers limit the research boundary to a specific process stage (mainly focusing on construction or use phase) or focusing on elements or parts (e.g., walls, structure, windows). Holistic and comprehensive LCA of buildings, including end-of-life (EoL), are rarely performed.

Prefabrication is not a brand-new approach, but it is a promising and emergent construction approach reaffirmed by the increasing number of papers in literature. One of the first studies over prefabricated buildings was published over 20 years ago in two different papers (Adalberth, 1997b, 1997a). Since then, a growing number of LCA studies have been published focusing on prefabricated buildings (a small fraction of total studies focusing on buildings). Studies in literature concluded that prefabrication could reduce costs and impacts. (Aye et al., 2012; Chen et al., 2010; Hong et al., 2015; Quale et al., 2012). However, most papers present incomplete assessments (e.g., excluding EoL), mainly focusing on reducing use phase impacts (Szalay, 2007) even though prefabrication presents an opportunity to further reduce buildings burdens by reducing embodied and end-of-life impacts (Li et al., 2014). Moreover, previous works fail to capture the differences between prefabrication and conventional construction regarding production time, materials used, and waste generated. Studies based on detailed and reliable data comparing prefabricated building processes with conventional must be developed to understand better the advantages and disadvantages between both approaches (Aye et al., 2012; Chen et al., 2010).

2.1.2.1 Embodied, operational, and end-of-life impacts

The impacts of buildings are usually divided into embodied, operational, and (rarely included in the LCA) end-of-life (EoL) impacts. According to CEN European Committee for Standardization (2013) and ISO and Technical Committee (2006), embodied impacts are associated with the product stage, including material extraction and transformation (A1), transport to plant (A2), manufacturing (A3); and construction product stage, including transport to the site (A4) and site construction and materials installation (A5). Operational impacts include the use of installed products (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and water use (B7). Finally, EoL impacts include deconstruction and demolition (C1), transport of waste (C2), waste processing (C3) and disposal (C4), and reuse, recovery, and recycling potential (D) (not a mandatory stage).

Most of the LCA of buildings focus on the use phase (e.g., Adalberth, 1997; Atmaca and Atmaca, 2016; Bonamente et al., 2014), which represents around 60-80% of total impacts (Sajn, 2016). However, embodied impacts become more significant as buildings become energy-efficient and may reach 40% of total LC impacts for a low energy consumption building (Thormark, 2002). The new political agenda proposes a more holistic approach to buildings’ assessment, including an LCA approach to disclose burdens shifting (e.g., increasing embodied impacts to decrease operational impacts). Moreover, as new buildings must meet the EU energy efficiency directive (European Commission, 2002), the energy performance and consequential operational impacts of new prefabricated or conventional buildings will be roughly similar.

2.1.2.2 Embodied impacts of prefabricated buildings

Table 4 shows an overview of studies that assessed the embodied impacts of prefabricated and conventional buildings and lists embodied energy (EE) and GHG per living area. Results show that the embodied impacts (EE/m^2 and GHG/m^2) for prefabricated buildings are generally lower than for conventional buildings (Aye et al., 2012; Cao et al., 2014; Hong et al., 2016; Monahan and Powell, 2011; Pons and Wadel, 2011; Quale et al., 2012; Vitale at al., 2018). An exception occurs for prefabricated steel buildings that show similar or even higher impacts of the conventional (Aye et al., 2012; Pons and Wadel, 2011), stressing the need to assess and compare prefabricated buildings with alternative structural materials.

The impacts range from 1.75 to 14.4 GJ/m^2 for energy and 211 to 1000 kg CO_2eq/m^2 for GHG. Timber and concrete buildings and container houses have the lowest impacts, and steel the highest. The lowest impacts are reported for timber houses (Adalberth, 1997a); and for container houses (Atmaca and Atmaca, 2016; Islam et al., 2016). Lower impacts can also be seen in papers focusing only on building parts, such as structural frame (Heravi et al., 2016), or only on the differences between modular and conventional buildings (Quale et al., 2012). The highest impacts are for prefabricated steel (Aye et al., 2012; Bonamente et al., 2014) and non-prefabricated buildings (Monahan and Powell, 2011; Pons and Wadel, 2011). Moreover, Bonamente et al. (2014) and Adalberth (1997) showed that buildings with bigger areas have lower impacts per m^2.

Table 4 Embodied impacts of prefabricated buildings

Reference	Construction type	Location	Distance plant to site (km)	Building type	Structural material/ Alternatives	Embodied energy (GJ/m²)	Embodied GHG (kgCO_2eq/m²)
Adalberth 1997	Prefabricated	Sweden	-	Residential	Timber house 1 (1-floor 130m²)	3.7	-
					Timber house 2 (1-floor 129 m²)	3.5	-
					Timber house 3 (2-floor 138m²)	2.9	-
Pons and Wadel, 2011	Prefab and conventional	Catalonia, Spain	100-300	Educational	Non-prefabricated	-	752
					Concrete	-	692
					Timber	-	526
					Steel	-	852
Monahan and Powell, 2011	Panelized Modular and conventional	Norfolk United Kingdom	213 (9372 tkm)	Residential	Timber frame larch cladding	5.7	405
					Timber frame brick cladding	7.7	535
					Conventional masonry	8.2	612
Quale et al., 2012	Modular and conventional	USA	483 (300 mi)	Residential	Timber modular	-	73*
					Timber conventional	-	105*
Aye et al., 2012	Prefab and conventional	Australia	-	Residential	Concrete (convent.)	9.6	578
					Steel (prefab)	14 .4	864
					Timber(prefab)	10.5	630
Mao et al., 2013	Partially prefab and conventional	Shenzhen, China	45-95	Residential	Concrete semi-prefabrication	-	336
					Concrete conventional	-	368
Bonamente et al., 2014	Prefab	Perugia, Italy	-	Industrial	Steel 1 000 m²	14	895
					Steel 2 500 m²	12.8	821
					Steel 5 000 m²	12.2	783
					Steel 10 000 m²	11.8	757
					Steel 20 000 m²	11.5	738
Cao et al., 2014	Partially prefab and conventional	Beijing, China	-	Residential	Concrete precast	-	-
					Concrete traditional		
Hong et al., 2016	Partially prefab and conventional	China	100	Residential	Concrete & steel precast facade	-	-
					Concrete & steel Precast form		
					Concrete slab		
					Concrete Balcony		
					Concrete Staircase		
					Concrete Panel		
Atmaca et Atmaca, 2016	Prefabricated and container	Turkey	100	Residential	Concrete and aluminum sheet prefabricated	4.1	-
					Concrete and steel sheet container	3.2	-
Islam et al., 2016	Container	Melbourne, Australia	100	Residential	Steel container base case	3.24	211
					Steel container 100 y lifespan	3.24	211
					Steel container 100 km transportation	3.31	215
					Steel container low maintenance	3.24	211
Heravi et al., 2016	Prefabricated	Tehran, Iran	100	Residential	Concrete frame	1.75 - 3.01**	-
					Steel frame	2.36 - 4.16**	-
Vitale et al., 2018	Prefab and conventional	Campania, Italy	15-900	Residential	Prefab LSF	9.9	923
					Traditional concrete	8.5	1000

* Took into account only the building materials whose amounts differed between construction methods
** Only considered the concrete and steel frame of 4 to 10-story buildings

Pons and Wadel (2011) compared prefabricated schools (concrete, steel, and timber) with non-prefabricated ones and concluded that prefabricated schools had slightly fewer impacts, which can be further reduced with a higher industrialization level of the prefabricated companies. The steel and concrete schools have higher impacts during the extraction and fabrication phase, and timber and steel schools during transport and maintenance. Monahan and Powell (2011) analyzed the embodied energy and carbon of two prefabricated houses (timber frame with larch cladding and timber frame with brick cladding) and one conventional (in masonry), concluding that materials are responsible for around 80% of embodied impacts, mainly related to the substructure, foundations and ground floor. Aye et al. (2012) compared a conventional concrete house with two prefabricated houses (steel and timber) and, contrary to most studies, concluded that conventional concrete has the lowest embodied impacts while the prefabricated steel house has the highest. Figure 3 presents the embodied energy (EE) and greenhouse gasses (GHG) of prefabricated buildings divided per structural material for the studies presented in Table 5.

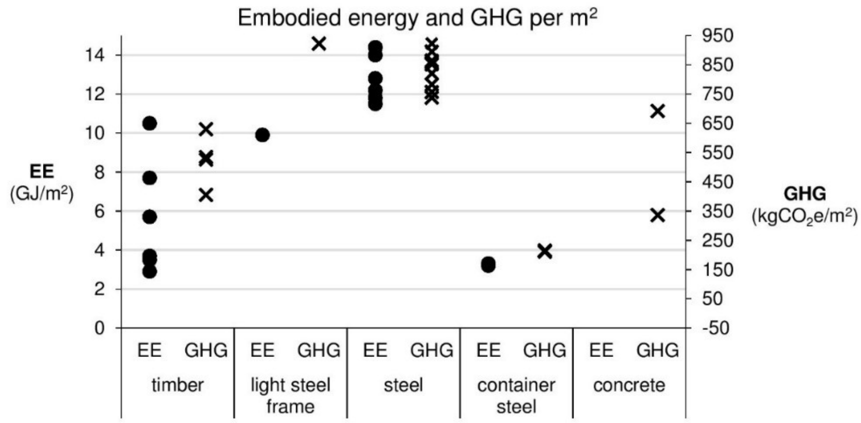

Figure 3 Embodied energy and GHG of prefabricated buildings

2.1.2.3 Balancing embodied impacts and operational impacts of prefabricated buildings

Table 5 presents an overview of embodied and operational impacts of prefabricated buildings. The embodied phase is the most assessed phase, followed by the operational phase. Energy and GW are the most commonly assessed categories, with the following values range (per m^2): for embodied phase 3-15.6 GJ and 27-949 kgCO_2eq; and operational phase 9.5-193 GJ and 661-15 054 kgCO_2eq. Results comparison is challenging due to differences in the case studies (e.g., building form and type, users' profile, location) and assumptions (e.g., boundary, functional unit, life span, impact categories). Moreover, some impact categories are included in only a small number of papers, thus lacking representativeness.

Table 5 Embodied and operational impacts of prefabricated buildings (per m^2)

Reference	Location	Structural material	Life-span (years)	Life cycle phase	AD (g Sbeq)	NRE (GJ)	GW (kg CO_2eq)	OD (mg CFC-11eq)	AC (kg SO_2eq)	EU (kg PO_4)
(Leskovar et al., 2019)	Slovenia	Cross-laminated timber	-	embodied	-	5.5 - 8.4	27 - 163	-	2.1- 2.8	-
			50	operational	-	9.5 - 12.2	661 - 857	-	1.3 - 1.7	-
(Iuorio et al., 2019)	Italy	LSF	-	embodied	-	9	601	0.1	3.79	1.27
(Dara et al., 2019)	Canada	Steel	-	embodied	-	3.1 - 3.8	222 - 286	1.2- 1.6	1.2 - 1.5	-
			50	operational	-	67 - 187	5 256-14 610	0.3 - 0.5	0.1 - 29.3	-
		Wood	-	embodied	-	3.0 - 3.6	185 - 248	1.0 - 1.5	1.4 - 1.6	-
			50	operational	-	69 - 193	5 391-15 054	0.3 - 0.5	0.1 - 30.0	-
(Sandanayake et al., 2019)	China	Concrete	-	embodied	-	-	-	-	0.5-0.7	-
(Tumminia et al., 2018)	Italy	Pultruded fiber reinforced	-	embodied	20.3	15.6	949	1.5	4.2	1.6
			25	operational	0.6	12.4	435	0.0	2.2	0.5
(Islam et al., 2016)	Australia	Steel container	-	embodied	-	3.24	211	-	1.21	0.13
			50	operational	-	10.98	667	-	3.31	0.66
(Cao et al., 2014)	China	Concrete	-	embodied	-	-	193	-	1	-
(Quale et al., 2012)	USA	Wood	-	embodied	-	-	73	1.2	-	0.29

2.1.2.4 Life cycle impacts of prefabricated buildings

Table 6 presents an overview of LCA studies for prefabricated buildings with different structural materials, showing the energy and carbon life cycle impacts divided into embodied, operational, and end-of-life. A few studies comparing conventional buildings are also included (Cao et al., 2014; Mao et al., 2013; Pons and Wadel, 2011; Quale et al., 2012; Sandanayake et al., 2019). Most of the studies have been performed for prefabricated buildings with steel structures followed by wood, with prefabricated concrete buildings being the least frequent. Most of the case studies are single-family houses at a specific location (Adalberth, 1997b; Atmaca and Atmaca, 2016; Aye et al., 2012; Islam et al., 2016; Iuorio et al., 2019; Monahan and Powell, 2011), though educational (Pons and Wadel, 2011), industrial (Bonamente et al., 2014), and commercial buildings (Sandanayake et al., 2019) can also be found. Some studies consider only materials and activities that differ from conventional ones (Quale et al., 2012) or that are used during the transformation of a shipping container into a house (excluding the container itself) (Heravi et al., 2016; Vitale et al., 2017); while others have a more comprehensive approach.

The few studies comparing prefabricated with conventional buildings show that prefabrication reduces 5–40% of impacts, which is more relevant in the embodied phase. Compared with conventional, prefabricated buildings reduce GHG emissions (Ding et al., 2020; Quale et al., 2012), energy use, resource depletion, and health and ecosystem damage (Cao et al., 2014). While reducing embodied and operational carbon (Ding et al., 2020; Teng et al., 2018), prefabrication can cost roughly 30% less than conventional construction (Atmaca and Atmaca, 2016). Prefabricated concrete and wood schools have less CO_2 emissions than conventional schools, and prefabricated steel schools slightly more (due to transport-related impacts, the remote factory, and the transport of finished modules) (Pons and Wadel, 2011). In a study comparing LSF construction with reinforced concrete (Pierluca, et al., 2018), LSF showed a reduction in respiratory inorganics, global warming, and non-renewable energy. At the end-of-life, prefabricated steel and wood buildings present higher recyclability rates than prefabricated concrete and non-prefabricated buildings (Pons and Wadel, 2011).

Differences in case studies, boundaries, and assumptions have led to a wide range of results. For prefabricated buildings, embodied carbon range between 193–852 $kgCO_2eq/m^2$; operational carbon 10.8–20.5 $kgCO_2eq/m^2$ per year, and end-of-life carbon -228– (-0.17) $kgCO_2eq/m^2$; embodied energy range 1.74–10.38 GJ/m^2, operational energy 0.38–1.37 GJ/m^2 per year, and end-of-life energy -1.7–0.14 GJ/m^2.

Table 6 Embodied, operational, and EoL impacts of prefabricated and conventional buildings

				Prefabricated		Conventional	
	Ref.	**Location**	**Typology**	**Energy**	**Carbon**	**Energy**	**Carbon**
a) Embodied energy and carbon emissions				GJ/m^2	$kgCO_2eq/m^2$	GJ/m^2	$kgCO_2eq/m^2$
STEEL	(Pons and Wadel, 2011)	Spain	Educational	-	852	-	-
	(Aye et al., 2012)	Australia	Residential	14.4	864	-	-
	(Bonamente and Cotana, 2015)	Italy	Industrial	3.5–6.8	246–459	-	-
	(Atmaca and Atmaca, 2016)	Turkey	Residential	3.2–4.1	-	-	-
	(Islam et al., 2016)	Australia	Residential	3–3.3	212–217	-	-
	(Heravi et al., 2016)	Iran	Containers	2.4–4.2	-	-	-
	(Pierluca at al. 2018)	Italy	Containers	1.0*	63*	-	-
	(Vanessa Tavares et al., 2019)	Various	Residential	7.5–10.4	454–647	-	-
	(Dara et al., 2019)	Canada	Containers	3.1-3.8	222-286	-	-
	(Iuorio et al., 2019)	Italy	Residential	5.5*	371*	-	-
WOOD	(Adalberth, 1997a)	Sweden	Residential	2.9–3.7	-	-	-
	(Pons and Wadel, 2011)	Spain	Educational	-	526	-	-
	(Monahan and Powell, 2011)	UK	Residential	5.7–7.7	405–535	-	-
	(Quale et al., 2012)	USA	Residential	-	62–89**	-	65–156**
	(Aye et al., 2012)	Australia	Residential	10.5	630	-	-
	(Achenbach et al., 2018)	Germany	Residential	2.1	207	-	-
	(Dara et al., 2019)	Canada	Residential	3.0-3.6	185-248	-	-
	(Leskovar et al., 2019)	Slovenia	Residential	5.5-8.4	26-162	-	-
	(Pierobon et al., 2019)	USA	Residential	3.4	327-333	-	-
CONCRETE	(Pons and Wadel, 2011)	Spain	Educational	-	692	-	752
	(Aye et al., 2012)	Australia	Residential	9.6	578	-	-
	(Mao et al., 2013)	China	Residential	-	337	-	348
	(Cao et al., 2014)	China	Residential	-	193	-	215
	(Heravi et al., 2016)	Iran	Containers	1.8–3.0	-	-	-
	(Pierluca et al., 2018)	Italy	Containers	-	-	0.76	47
	(Teng and Pan, 2019)	China	Residential	-	418-480	-	-
	(Sandanayake et al., 2019)	China	Commercial	-	406-448	-	447-489
	(Pierobon et al., 2019)	USA	Residential	3.7	450	-	-
b) Operational energy and carbon emissions (in Southern Europe)				GJ/ m^2*y	$kgCO_2eq/$ m^2*y	GJ/ m^2*y	$kgCO_2eq/$ m^2*y
STEEL	(Pons and Wadel, 2011)	Spain	Educational	-	12.2	-	-
	(Gervásio et al., 2014)	Portugal	Residential	-	-	0.03-0.04	
	(Atmaca and Atmaca, 2016)	Turkey	Residential	1-1.4	-	-	-
	(Pierluca et al., 2018)	Italy	Containers	0.4	20.5	-	-
WOOD	(Peuportier, 2001)	France	Residential	-	-	0.12	-
	(Pons and Wadel, 2011)	Spain	Educational	-	11.6	-	-
	(Peuportier et al., 2013)	France	Residential	-	-	0.1-0.58	-
	(Leskovar et al., 2019)	Slovenia	Residential	0.88-0.91	43.2-45.8	-	-
CONCRETE	(Pons and Wadel, 2011)	Spain	Educational	-	10.8	-	12.2
	(Vitale et al. 2018)	Italy	Residential	-	-	0.43	23.07
c) End-of-life energy and carbon emissions				GJ/m^2	$kgCO_2eq/m^2$	GJ/m^2	$kgCO_2eq/m^2$
STEEL	(Aye et al., 2012)	Australia	Residential	-11.70		-	-
	(Bonamente and Cotana, 2015)	Italy	Industrial	-0.02–(-0.017)	-0.26–(-0.17)	-	-
	(Islam et al., 2016)	Australia	Residential	-0.07–(-0.14)	-52.90–(-25.61)	-	-
	(Pierluca et al., 2018)	Italy	Containers	-1.65*	-227.69*	-1.72	-193.08
	(Dara et al., 2019)	Canada	Containers	0.13-0.20	8.4-12.6		
	(Iuorio et al., 2019)	Italy	Residential	-0.85*	-114.6*	-	-
WOOD	(Adalberth, 1997a)	Sweden	Residential	0.10–0.14	-	-	-
	(Aye et al., 2012)	Australia	Residential	-7.20	-	-	-
	(Achenbach et al., 2018)	Germany	Residential	-0.02	-1.30	-	-
	(Dara et al., 2019)	Canada	Residential	0.13-0.20	2.97-3.60	-	-
	(Leskovar et al., 2019)	Slovenia	Residential	0.20-0.45	51.1-105.4	-	-
CONCRETE	(Aye et al., 2012)	Australia	Residential	-3.10	-	-	-

* Light steel frame

** Only considered the building materials whose amounts differed between construction methods.

2.1.3 Modular prefabrication

Modular prefabrication presents a higher level of prefabrication even though some manual processes are still performed (Pons and Wadel, 2011). The few studies focusing on modular prefabricated buildings have concluded that modular construction has 20-70% fewer impacts than conventional (Quale et al., 2012) and produces 40% of the solid waste (Kim, 2008). However, a significant impact variation exists within different modular and conventional types (Pons and Wadel, 2011), stressing the need to develop further studies that quantitatively account for and balance the benefits and challenges of modular construction (Kamali et al., 2019).

A particular but emergent type of modular prefabricated building is based on the adaptation of shipping containers to houses. Focusing on temporary post-disaster buildings, one study showed that a prefabricated light steel framing (LSF) house has 25% fewer impacts and 30% lower costs than a container house (Atmaca and Atmaca, 2016). Another study assessing container-based houses excluded the impact of the shipping container since it was assumed as an 'upcycled material' (i.e., reused with minimal modification for another purpose) and concluded container houses had fewer impacts (Islam et al., 2016).

2.1.4 Transport-related impacts

Transport-related impacts are influenced by the distance from the plant to the site and the prefabrication type. Particularly for modular construction, transport is a critical issue limiting the dimension and weight of the modules, distance, transport mode, and routes (Kamali and Hewage, 2016). Modular buildings can have significant transport-related impacts due to the high volume of the finished modules (requiring one truck for each module) (Pons and Wadel, 2011), and transport to the site of modules and workers may represent around 20% of embodied GHG (Quale et al., 2012).

In prefabricated construction, impacts associated with transportation can be significant as prefabrication requires an additional transportation phase (from plant to site), extra load and unload processes (from the factory into the site), and extra material and clamps (for handling and transport) (Hong et al., 2016). However, most studies calculated relatively low transport-related impacts, assuming short (typically from 50 to 100 km) or no distance from the plant to the site is declared (Adalberth, 1997a; Aye et al., 2012; Bonamente et al., 2014; Cao et al., 2014). Others highlight that transportation impacts cannot be neglected, as they can represent up to 20% of total embodied impacts (Achenbach et al., 2018). A comprehensive assessment of transport-related impacts in prefabricated construction was not found in literature.

2.1.5 Lightweight vs. heavyweight

Prefabricated buildings are generally lightweight buildings composed of wood or a steel structural frame with lightweight panels (weighing around 100 kg/m^2). Conventional buildings in the Mediterranean climate are usually heavyweight buildings with concrete or masonry structural frames and ceramic or concrete brick walls (weighing around 500 kg/m^2) (Hoes and Hensen, 2016). When compared with heavyweight, lightweight buildings use fewer materials and have lower embodied impacts. However, lightweight buildings can have higher operational needs, thus balancing the initial benefit of reduced embodied burdens (Hacker et al., 2008).

The thermal transmittance of a lightweight and heavyweight building envelope can be equivalent (increasing the thickness of the insulation layer of the lightweight buildings) even though an equivalent thermal mass may not be achieved. Commonly referred to as "*inertia*," the thermal mass describes the materials' capacity to store energy. Heavyweight buildings have higher inertia, with a slow response to temperature fluctuation that flattens the daily temperature curve. However, in a non-continuous use of space, the lightweight buildings have a faster response to the HVAC system, reducing energy needs and accordingly use phase impacts (Hoes and Hensen, 2016). Contrary, heavyweight buildings require more energy (and time) to heat and cool the inner space. So, compared to heavyweight, the lightweight buildings in some specific settings may reduce the energy needs.

2.1.6 Life cycle cost

As repetition lowers the costs, prefabrication has been pointed out as a way to reduce the costs of building (Benros and Duarte, 2009). Moreover, prefabricated buildings use fewer materials and energy and produce less waste (Kamali et al., 2019), reducing construction costs. However, the costs of prefabrication may be higher than for conventional due to component production, transportation, and the need for skilled labor (designers and workers) (Mao et al., 2016). To lower costs, prefabrication has to be developed in countries with high prefabrication skills and low production costs (Baldwin et al., 2009). Previous research pointed out the need to include waste management costs as the economic value of prefabricated CDW may be higher than conventional CDW (Cao et al., 2014). Costs are highly dependent on time and location, so costs are challenging to account for and compare (among different alternatives). Cost criteria have been integrated into the BIM models to assess the LCC of buildings early in the design process, with some cost estimating tools being under development (Kamel and Memari, 2019).

2.1.7 Construction and demolition waste

Construction and demolition waste (CDW) account for around 1 billion tonnes per year in EU-27 (Commission and Environment, 2012) and can be divided into four different types i) Production Waste (PW) produced at the product stage; ii) Construction Waste (CW) during construction; iii) Use Waste (UW) at the service stage due to maintenance operations, and iv) Demolition Waste (DW) at the end of life (Silvestre et al., 2014). The main waste management strategies identified are (from the most to the least applied): i) recycling off-site combined with landfilling; ii) incineration, energy from the wood; iii) re-use or recycling on-site.

Waste sorting is essential to achieve high levels of recycling or recovery, as mixed wastes are unable to be recovered. Even though it is a considerable amount of waste (and unused resources), most studies neglect or underestimate construction and demolition waste (CDW), thus excluding end-of-life (EoL) impacts (Khasreen et al., 2009). In conventional buildings, selective demolition is hardly ever realized due to mixed materials (challenging to be separated by waste type, e.g., reinforced concrete), unskilled labor or machinery, lack of space in the shipyard (to segregate waste types), low waste, recycled materials, and disposal taxes value. In prefabrication, 25% to 80% of waste reduction is reported due to: better quality control, more accurate estimation of material, higher reuse, and recycling (better sorting facilities and waste management procedures) (Cao et al., 2014). The change from a linear "*production, consumption and disposal*" approach to a circular economy approach (reuse or recycling of all waste) will depend on the design for deconstruction designing buildings to be more assembly than constructed, and at EoL more disassemble than demolish. Table 7 presents some waste rates per material in a conventional construction process and using prefabrication.

Table 7 Waste rate during construction per building materials and approach presented in the literature

	Conventional				**Prefabricated**
	(Blengini, 2009)	(Pons and Wadel, 2011)	(Tam et al., 2007)	(Adalberth, 1997b)	Hong et al. (2016b)
concrete	7%	3-5%	4-7%	10-20%	0,5-3,5%
steel bar	7%	1-8%	3-8%	5%	0,2-0,4%
timber	7%	5-15%	4-23%	7-10%	0,6-12%
block/brick	10%	4-8%	5-8%	-	0,6-4%

2.2 Environmental targets

Sustainability was first defined in 1987 by the World Commission for Environment and Development of the United Nations (UN) as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*." To achieve that goal, global and regional targets were defined.

2.2.1 Global targets

In 2015 all the UN Member States adopted the 2030 agenda for sustainable development as a "*shared blueprint for peace and prosperity for people and the planet, now and into the future*," and seventeen sustainable development goals (SDG) were defined:

1- No Poverty,
2- Zero Hunger,
3- Good Health and Well-being,
4- Quality Education,
5- Gender Equality,
6- Clean Water and Sanitation,
7- Affordable and Clean Energy,
8- Decent Work and Economic Growth,
9- Industry, Innovation, and Infrastructure,
10- Reducing Inequality,
11- Sustainable Cities and Communities,
12- Responsible Consumption and Production,
13- Climate Action,
14- Life Below Water,
15- Life On Land,
16- Peace, Justice, and Strong Institutions
17- Partnerships for the Goals.

These goals summarize the shared commitment resulting from the work started over 30 years ago at the Earth Summit in Rio de Janeiro in 1992. Prefabrication can contribute to achieving six of these goals: creating better work conditions and economic growth (SDG8), boosting innovation in the construction industry (SDG9), creating more sustainable cities and communities (SDG11), the responsible consumption of resources, and efficient production (SDG12), fighting climate change (SDG13) and, finally, end poverty enabling to fulfill the fundamental human right to housing (SDG1).

2.2.2 European Union targets

In Europe, buildings are responsible for 40% of total primary energy consumption, 36% of total GHG emissions, and 25%-30% of the waste generated. Even though buildings are increasingly more efficient, the population rise and the growing cities have increased building stock total impacts. To tackle climate change, the EU has set some challenging environmental targets for the building sector. By 2020, 70% of construction and demolition waste (CDW) should deviate from landfills; energy efficiency must increase by 20%, and GHG emissions will be reduced by 20%. Furthermore, by 2050 the emission from buildings should be reduced by 80%. Some of these targets are expressed in the Eu-27 initiatives and regulatory framework: the New European Bauhaus initiative, The European Climate Pact, the Renovation Wave, the Energy efficiency directive, the New Circular Economy Action Plan, and the New Industrial Strategy (introduced in appendix II). Table 8 sums up the main EU environmental targets related to buildings or the construction sector.

Table 8 EU-27 environmental targets related to buildings or the construction sector

Year	Targets
By 2020	– 20% cut in greenhouse gas emissions (compared with 1990) (Energy Efficiency Directive 2012) – 20% of EU energy from renewables (Energy Efficiency Directive 2012) – 20% improvement in energy efficiency (Energy Efficiency Directive 2012) – 70% of CDW deviated from landfill
By 2030	– 55% GHG emissions reduction (compared with 1990) (European Green Deal) – 60% GHG emissions reduction from buildings (compared to 2015) (Renovation Wave) – 14% final energy consumption reduction (compared to 2015) (Climate Pact) – 18% energy consumption for heating and cooling reduction (compared to 2015) (Climate Pact) – 2% annual renovation rate (double of the current rate) (Renovation Wave) – 32.5% energy efficiency target (compared to projections 2030) ((Energy Efficiency Directive 2018) – 32% share for renewable energy
By 2050	– climate-neutral continent (European Green Deal) – 80% GHG emissions reduction from buildings – the zero-emission building stock in the EU

2.3 Building stock

"*Building stock*" is a term used to describe all the buildings included within a temporal and spatial boundary. A holistic assessment of the building stock is required to support sustainable planning, decreasing energy and resource demand (Mastrucci et al., 2020), and recognizing building stock as a materials bank and resource supplier (Lavagna et al., 2018). The building stock can be characterized by archetypes representing building cohorts grouped by size, typology, construction technologies, and construction date (Lavagna et al., 2018; Nemry et al., 2010). Previous studies have modeled current and future stock, aiming to predict its dynamics (Lavagna et al., 2018; Vásquez et al., 2016) and impacts (Nemry et al., 2010; Sandberg et al., 2016; Vásquez et al., 2016). Dynamic models considered variation in population and area per person and buildings' construction, retrofit, and replacement. Fixed rates or functions have been used to forecast future building stock (Nägeli et al., 2020; Sandberg et al., 2016; Vásquez et al., 2016). Building stock models have mainly focused on use-phase energy consumption (D'Alonzo et al., 2020; Mastrucci et al., 2017; Ürge-Vorsatz et al., 2015), refurbishment measures (Nemry et al., 2010), or Net Zero Energy Building (nZEB) implementation (Serghides et al., 2015). None of the BSM has focused on prefabricated buildings. To analyze the influence of prefabrication wide adoption, a large group of buildings should be assessed (ideally the whole building stock) accounting impacts and costs, thus comparing the building stock (BS) with and without prefabrication adoption.

2.3.1 Building stock models

LCA is a methodological approach to assess the impacts of products and services first applied to the chemical and food industry and later to buildings. However, as buildings are complex systems with long life, different uses (and users), and multiple stakeholders, the LCA is complex and time-consuming. So, the LCA of buildings at a large scale or applied at the building stock level has rarely been done before. Most LCA studies focus on a single product, which does not capture the transient effects of new technologies within a class of products over time (Field et al., 2007; Garcia and Freire, 2017). To tackle this limitation, a fleet-based life-cycle (LC) approach was proposed by Field et al. (2000), combining the LCA methodology with fleet models by describing the stocks and flows and unveiling the dynamics of a set of products at use. When applied to the building stock, the fleet based is named a stock-based approach and grounds on building stock models (BSM). Different BSMs have been developed and implemented in the literature, most of them in the last couple of years (D’Alonzo et al., 2020; Lavagna et al., 2018; Marinova et al., 2020), but no BSM has been previously implemented to assess prefabrication.

Two main approaches have been previously applied in the literature: a top-down approach (stock-level) and a bottom-up approach (building-level) (Geraldi and Ghisi, 2020). The top-down models use statistical data (e.g., average country energy consumption), failing to capture the variety of typologies or construction technologies and rendering a “flat” average assessment. The bottom-up approach has a higher resolution based on more complex models with limited spatial coverage (Lavagna et al., 2018).

Table 9 sums up the different approaches in the building stock research field. The main research streams are to evaluate stock performance, compare current and future scenarios, or model stock evolution over time (Mastrucci et al., 2020). Moreover, the primary purposes are benchmarking, assessing climate change mitigation strategies, or building a legal framework (Geraldi and Ghisi, 2020). Different temporal (short, medium, and long) and spatial dimensions were used (regional, national or transnational), assessing (past, present, and future) stocks; and different time dependency approaches: accounting, describing stock size and composition, and related materials and energy flow; static, focusing on the model on a precise moment in time, e.g., one year; or dynamic, capturing the evolution of building stock being input- or activity-driven, or stock-driven based. The technologies previously assessed were: building refurbishment (Nemry et al., 2010; Sandberg et al., 2016); low energy or nZEB buildings (Serghides et al., 2015); and no technology implementation with business as usual scenario (Lavagna et al., 2018).

Table 9 Building stock modeling research in literature

Building stock modeling *			
Streams of investigation [1]	Evaluating the environmental performance of the building stock	Comparing the current situation with a hypothetical future scenario (s)	Modeling the evolution of the building stock over time
Proposes of investigation [2]	Benchmarking	Climate change mitigation strategies	Building a legal framework
Technology implementation	None (business as usual)	Low energy buildings or nZEB	Renovation
Temporal dimension	Short temporal horizon	Medium temporal horizon	Long temporal horizon
Spatial dimension	Regional / urban	National	Transnational
Scenario analysis	Past	Present	Future
Stock type	Residential	Services and commercial	Industrial
Grouping approaches[3]	**Supervised approach** *Successive division of the dataset in a hierarchical structure of groups and subgroups defined manually*	**Unsupervised approach** *Clustering by applying an algorithm that groups buildings according to multidimensional features (e.g., location, size)*	**Semi-supervised** *Labeled and unlabeled data are combined to improve grouping*
Time dependency	**Accounting** *Describes stock size and composition; and related materials and energy flows*	**Static** *Focus on the model at a precise moment in time (e.g., one year)*	**Dynamic** *Captures the evolution of building stock. Input- or activity-driven (construction or demolition rates). Stock-driven (service demand-provision concept based on population, size and type preferences, and mass balance eq)*

* Vertical reading per column does not apply
1) Based on (Mastrucci et al., 2020)
2) Based on (Geraldi and Ghisi, 2020)
3) Based on (Goy et al., 2021)

Table 10 presents the building stock model composition: a) the energy demand model, b) the LCA model, and c) the stock aggregation model. The a) energy demand model assesses present and future operational energy needs of the building stock using dynamic (engineering-based), statistical, or hybrid approaches; by a top-down (statistical-based), bottom-up (inferring from a group of pre-assessed buildings), or a combined approach. The b) LCA models can use multiple approaches: attributional when accounting for impacts; or consequential when analyzing technologies implementation; process-based, input-output, or a hybrid LCA. The models have different system boundaries (most of them focusing on operational impacts) and functional units (FU) (e.g., total, per area, per inhabitant). Finally, the c) stock aggregation model combines and scales up results from LCA and energy models, using archetypes (modeled buildings, e.g., Lavagna et al., 2018), building samples (actual building) that represent cohorts (e.g., Aelenei et al., 2016; Nemry et al., 2010), or a building-by-building approach based on GIS technologies (e.g., García-Pérez et al., 2018; Mastrucci et al., 2017). Each aggregation approach presents different constraints being the more detailed models, such as the building-by-building approach, generally applied to considerably narrower areas.

Table 10 Building stock model composition:
A) Energy demand model + B) LCA model + C) Stock aggregation model *

A) ENERGY DEMAND MODEL			
Energy model	**Engineering-based approach** Based on dynamic energy simulation (limited-range and able to account for impacts of new technologies)	**Statistical approaches** Based on statistical data (wide-range but unable to render differences within the stock)	**Hybrid approach** Combining both approaches
Energy data	**Bottom-up** Extrapolated from buildings or group of buildings	**Top-down** Energy consumption statistics correlated with socio-economic-technical drivers	
B) LCA MODEL			
Functional unit	**Absolute** Total	**Space-related** Gross floor or living area	**Per capita** Inhabitant or dwelling
LCA approaches	**Attributional**	**Consequential**	
System boundaries	**Embodied** Including: *- Materials extraction and transformation* *- (Pre)fabrication* *- Assemblage and construction*	**Operational** Including: *- Buildings' use* *- Maintenance*	**End-of-life** Including: *- Demolition/disassembling* *- Waste treatment*
Data collection approaches	**Process-based LCA**	**Input-output LCA**	**Hybrid LCA**
Data resolution and scope	**High resolution** Detailed data typically in small scale studies (a narrower scope, e.g., neighborhood)	**Low resolution** More aggregated data typically in large scale studies (a broader scope, e.g., country level)	
C) STOCK AGGREGATION MODEL			
Building stock aggregation model	**Archetypes** Model representative buildings for each cluster at a specific region or type	**Sample** Pick a representative sample of actual buildings	**Building-by-building** Represents the entire population usually using GIS
Model characterization	**Building related** - Size and shape - Building envelope - Systems - Location and orientation	**User related** - Operation and maintenance - Users' profile - Indoor air quality	

* Vertical reading per column does not apply

2.3.2 EU-27 Building stock

Europe is the "*old continent*," with an aged but growing population. From 2020-2050, the EU-27 population is expected to increase in some countries (e.g., Malta and Ireland) and decrease in others (e.g., Latvia and Lithuania), varying from -23% to +32% (European Commission, 2020a). The built area will roughly accompany this tendency though the area per capita rate is expected to increase (not considered in this work). In 2011 it was estimated that over 25 billion m^2 of useful floor space existed in the EU (including Switzerland and Norway), half of it in the North & West countries (AT, BE, CH, DE, DK, FI, FR, IE, LU, NL, NO, SE, UK with 281 million people), one-third in the South (CY, GR, ES, IT, MT, PT with 102 million people), and the rest in the Central & East (BG, CZ, EE, HU, LT, LV, PL, RO, SI, SK with 129 million people). Three-quarters of the total stock is residential and varies between 21 m^2/capita (in Malta) and 54 m^2/capita (in Denmark). Average floor space per capita varies within each region: 20-26 m^2 in Central & East, 31-41 m^2 for North and West, and 36-50 m^2 for South (the top of the range for single families and the bottom for apartment floors). Service area per capita varies between 3 m^2/capita (in Romania) and 22 m^2/capita (in Denmark). All these figures highlight the great variability within EU-27 countries.

Residential buildings are 75% of the total m^2 of the European building stock, being this segment divided between single-family houses (64%) and apartment blocks (36%). The non-residential building stock is divided into wholesale and retail (28%), offices (23%), educational (17%), hotels and restaurants (11%), hospitals (7%), sports facilities (4%), and others (11%) (Nolte and Strong, 2011). In Portugal (INE), the share of m^2 occupied by residential is 86% (in 2011) (90% when assessed by the number of buildings). The average floor area of permanently occupied dwellings in Europe has risen from 88 m^2 (in 2011) to 90 m^2 (in 2014), while in Portugal has risen from 109 m^2 to 111 m^2. Almost half of the buildings in Europe are at least 60-year-old (49%), followed by 30-years-old (42%). Concluding, residential buildings are the most predominant in the building stock, mostly single-family houses, followed by multi-family. Half of the buildings have more than 60 years, and around 25% have more than 75 years. Moreover, dwelling size is growing around 0,5 m^2 per year. Table 11 presents residential and non-residential buildings distribution in Europe and Portugal per number and total floor area.

Table 11 Residential and non-residential buildings in Europe and Portugal

Per number	PT			EU		
	2011	2012	2013	2011	2012	2013
TOTAL (in thousands)	6522	6525	6536			
Non residential	643	618	610	12485	15538	12589
Residential	5879	5907	5926	245059	245978	247368
Multi family	1624	1636	1644	100280	101602	102645
Single family	3470	3487	3498	125751	125780	125230

Per total floor area	PT			EU		
	2011	2012	2013	2011	2012	2013
TOTAL (in Mm^2)	748	748	751	30579	30834	31294
Non residential	107	104	104	6828	6950	7013
Residential	641	644	646	21741	21905	22300
Multi-family	160	160	160			
Single-family	276	276	277			

2.4 Building information modeling

BIM is a collaborative methodology based on a shared object-oriented model representing the geometry and the attributes of a building and its components. The BIM model can follow the building through its life cycle (Ghaffarianhoseini et al., 2017), aggregating data inside the virtual model (or externally linked to it): thermal performance of materials, costs, environmental data, construction sequence, use and maintenance data (Vitiello et al., 2018). Future LCA tools must be integrated into the designer’s workflow to be fully adopted and widely used (Means and Guggemos, 2015).

New technologies (e.g., CNC machines and robots) and methodologies (such as Building Information Modelling) are enablers of the industrialization of sector by linking digital models to production. The automated link between computer-aided design (CAD) and computer-aided manufacturing (CAM) has already been established in some of the construction subsectors, such as heavy metal structures, but it is not mainstream. In the last decades, computer models are used to predict buildings' performance, enabling the energy simulation of buildings and alternatives before construction, during design. During use phase, digital models have supported buildings management and maintenance, controlling HVAC, lighting, cleaning and gardening of big buildings (such as hospitals, hotels, airports). Even though all these technologies are available and have been used in some stages of the LC and in some specific building (complex and large private and public buildings), the digitalization and industrialization of the construction sector are still in its early stage, being one of the least competitive sectors in the global economy.

2.4.1 BIM-LCA approach

The integration of BIM with LCA can streamline data inventory construction and enable tools to assess buildings performance (Soust-verdaguer et al., 2017). Several approaches have been developed to link BIM methodology with the LCA approach: i) BIM as a tool to extract a list of materials and quantities ii) perform the energy simulation to forecast energy consumption; iii) incorporate environmental data using "green templates" (Lee et al., 2015); iv) combining multiple software and databases, to automate processes (Antón and Díaz, 2014; Soust-verdaguer et al., 2017). Other researchers have developed novel approaches such as including the Environmental Product Declarations (EPD) data in the BIM models (Shadram et al., 2016) and linking costs (Guo and Wei, 2016). Several limitations are pointed out in the BIM-LCA integration approaches such as a considerable amount of data required; the environmental data existing in different platforms with no interoperability with LCA software; the "black-box" effect without any control over the environmental data and different modeling approaches, measure criteria and units used (Shin and Cho, 2015).

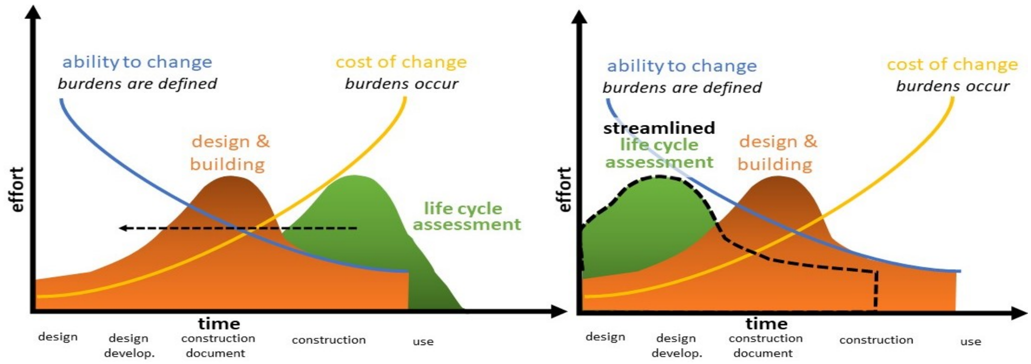

Figure 4 Time vs. effort during design and construction (based on MacLeamy curve): current approach (left) and using a BIM-LCA approach (right).

Figure 4 represents efforts (y-axes) through time (x-axis) during design and building (being one reinterpretation of MacLeamy curve about BIM). At the beginning of a design process, the ability to change the building (e.g., its form, material, orientation, openings, area) is high, and the costs of changes are low. As time passes, the costs of changes increase, and the ability to change decreases. A similar tendency can be seen with building-related impacts. Most of the LC impacts of buildings (embodied, operational, and EoL) are defined in an early moment during the design stage, while most impacts will later occur during construction, use, and demolition. The LCA of buildings is typically performed after buildings are constructed when LCA results cannot influence design choices and impacts. A streamlined approach can make the LCA simpler and faster. Furthermore, the integration of BIM with LCA can embed the LCA in the current design process. A BIM-LCA approach can bring LCA from a post-construction phase to the design stage when impacts and costs are defined and when LCA results can make a difference.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter presents the research methodology with the LCA implemented to assess the case studies and alternatives; and the developed BSM combining modular LCI, the BIM-LCA integration, and the statistic aggregation model. A model representing the current EU-27 stock and future scenarios was developed and implemented, including costs, waste, and production time.

3.1 Life cycle assessment

LCA is a methodological approach to assessing the impacts of products and services, later established in the ISO 14044 (ISO, 2006b), that specifies requirements and provides guidelines for life cycle assessment (LCA). Figure 5 presents the LCA framework with four sequential and interactive phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

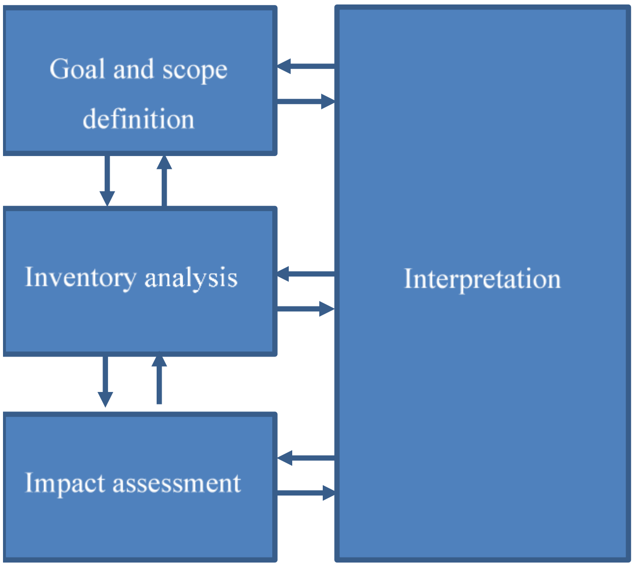

Figure 5 LCA framework, based on (ISO, 2006b)

3.1.1 Goal and scope

Goal and scope definition is the starting point of any LCA study in which it identifies the context and application of the study, drivers and motivations, possible limitations, and target audience. The goal and scope of this work is to implement life cycle environmental impacts and costs assessments of prefabricated buildings, compare them with conventional buildings, and assess the contribution of prefabrication wide adoption to reduce the environmental impacts of the EU-27 building stock. Different functional unit and system boundaries (including geographical and temporal boundaries) were defined per study.

3.1.2 Inventory analysis

Inventory analysis collects information about the flows in the system, including inputs of resources, materials, water, and products, as well as outputs as emissions, waste, and sub-products. The flows are allocated to the product, and the functional unit determines the reference flow. Primary data was collected with the collaboration of prefabricated building companies, designers, and experts to define the foreground processes (mainly prefabrication and assemblage phases) and secondary data used to define background processes (market data) and calculate emissions (using ICE and Ecoinvent 3 databases). Table 11 defines the primary and secondary data sources, and Table 12 the tools used.

Table 12 Data sources

Source	Reference	Aim
IMPRO study	(Uihlein and Eder, 2009)	Define materials for the conventional building and the baseline
Building observatory	(European Commission, 2016)	Define the existing stock
Eurostat	(European Commission, 2020a)	Define the stock and feed future scenarios model
Gerador de preços *("Price generator")*	(CYPE Ingenieros, 2020)	Define construction costs for Portugal
Parametric model	–	Calculates inventory quantities and energy consumption during use
EcoInvent v3	(Weidema et al., 2013)	Impacts
Prefabricated companies and designers	–	Quantities, materials, process, transport

Table 13 Tools used

Tool	Reference	Use
Excel	–	Combine data, calculate results from different sources, present data
SimaPro	(PRé Sustainability, 2021)	Combine and extract the environmental data from different sources
Revit	(Autodesk, 2021)	Builds the BIM model, extract data to build the inventory, link the model with the energy simulation software
EnergyPlus	(U.S. Department of Energy's (DOE) Building Technologies Office (BTO), 2021)	Perform the dynamic energy simulation

3.1.3 Impact assessment

The Life Cycle Impact Assessment (LCIA) translates the inputs and outputs, previously compiled in the inventory, into impact indicator results related to human health, natural environment, and resource depletion. Following the calculation method of the environmental performance of buildings standard (EN 15978:2011) and Level(s) (Dodd et al., 2017), the present work selected the following mid-point categories: Carbon and Energy (in section 4.1); abiotic resource depletion (AD), abiotic depletion of fossil fuels (ADF), global warming (GW), ozone layer depletion (OD), photochemical oxidation (PO), acidification (AC), and eutrophication (EU) categories of CML method and non-renewable energy (NRE) of CED method (in sections 4.2 and 4.3); and global warming (CML method) and non-renewable energy (CED method) (in chapter 5).

Table 14 Impact categories

Acronym	Category	Unit	Description
AD	**Abiotic Resource Depletion** [1]	Antimony equivalents (Sb eq)	Depletion of scarce metal resources, determined by the extraction based on concentration reserves and rate of de-accumulation.
ADF	**Abiotic Depletion of Fossil Fuels** [1]	Joule (J)	Depletion of energy carriers determined by extraction based on concentration reserves and rate of de-accumulation.
GW	**Global Warming** [1]	Carbon dioxide equivalents (CO_2 eq)	Contribution of a substance to the greenhouse effect, calculated for several substances over 100 years (the most common choice).
OD	**Ozone Layer Depletion** [1]	Chlorofluorocarbon equivalents (CFC^{-11} eq)	Accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone-depleting substances (mainly for hydrocarbons containing combined bromine, fluorine, and chlorine, or CFCs).
PO	**Photochemical Oxidation** [1]	Ethylene equivalents (C_2H_4 eq)	Estimating the ozone formation in low NOx.
AC	**Acidification** [1]	Sulfur dioxide equivalents (SO_2 eq)	Acidifying effect of SO_2, including other known acidifying substances like nitrogen oxides and ammonia.
EU	**Eutrophication** [1]	Phosphate equivalents (PO_4 eq)	Includes impacts due to excessive macronutrients in the environment caused by emissions of nutrients to air, water, and soil (also referred to as nutrification).
NRE	**Non-Renewable Energy** [2]	Joule (J)	Calculation of the non-renewable, fossil impact category

1) Considered in CML impact assessment method. Description based on (Pré, 2014)
2) Considered in Cumulative Energy Demand (CED), a single issue impact assessment method. Description based on (Pré, 2014)

3.1.4 Interpretation

The interpretation stage is when significant issues are identified (hotspots), results are evaluated, completeness of the inventory checked, sensitivity or consistency checked, conclusions are drawn, limitation recognized, and recommendations developed. Consistency of results must be confirmed according to goal and scope definition, the study purpose, and target audience. As represented in Figure 5, this is an interactive phase and may lead to goal and scope, inventory, and impact assessment redefinition. The interpretation stage was presented in the results and discussion sections of chapter 4 and 5.

3.2 Modular LCI

The developed Modular LCI enables a streamlined assessment of numerous alternatives based on some common elements, building parts, and stages. The modular LCI is based on the allocation of impacts and costs per building element and activities. Some proxies were considered and impacts allocated using different metrics: e.g., impacts of building compositions such as wall, roofs, and floor allocated per area (m^2), of elements such as windows and doors per unit (un), of transport per transported weight per distance (tkm), of energy per time (days). The structure of the modular LCI is presented in Table 15.

Table 15 Modular LCI: proxies, unit and stages/elements

Proxies	Unit	Stages / elements
Notes:		A1-A3 Raw material
Area of EXT WALL	m^2	Exterior wall
Area of ROOF	m^2	Roof
Area of FLOOR	m^2	Floor
Area of PARTITION WALL	m^2	Partition walls
Area of STAIRS	unit	Stairs
Area of WINDOW	unit	Window
Area of DOORS	unit	Doors
Distance to PLANT x weight	tkm	A4-Transport to the plant of materials
Distance to PLANT x nr of workers x 2 trips x nr of days	pkm	A4-Transport to the plant of workers
Nr of days working ON PLANT x nr hours day x nr workers	days	A5-Pre-construction stage on plant
	kWh	Electricity
	MJ	Gas
	m^3	Water
	days	Machinery
	hour	Labor
Distance to SITE x weight	tkm	A4-Transport to the site of prefabricated elements or materials
Distance to SITE x nr of workers x 2 trips x nr of days / sharing car	pkm	A4-Transport to the site of workers
Nr of days working ON SITE	days	A5-Construction/Assemblage stage
	kWh	Electricity
	MJ	Gas
	m^3	Water
	days	Machinery
	hour	Labor
Nr of days working ON SITE	days	B2-B5 - Maintenance, Repair, Replacement, Refurbishment
	kWh	Electricity
	MJ	Gas
	m^3	Water
	days	Machinery
	hour	Labor
Material replacement	%	B2-B5 - Maintenance, Repair, Replacement, Refurbishment
Life span	years	B6-7 - Operational Energy and Water Use
	kWh	Electricity
	MJ	Gas
	m^3	Water
Nr of days working ON DEMOLITION SITE	days	C1 Deconstruction/demolition
	MJ	Electricity
	MJ	Gas
	m^3	Water
	days	Machinery
	hour	Labor
Distance to WASTE FACILITY x weight	tkm	C2 Transport of materials (waste)
	%	C3 Waste processing
	%	C4 Waste disposal
	%	D Benefits and loads

3.3 BIM-LCA model

Building Information Modelling (BIM) can reduce the complexity of buildings' assessment streamlining the LCA during the design, construct, and maintenance stage. The developed BIM-LCA approach enabled the streamlined construction of the LCI (extracting quantities from the BIM model) and assessing the energy needs (linking the BIM model to energy simulation software) of the case study and alternatives in different locations. The BIM-LCA approach was used in the implemented LCAs and included in the developed building stock approach.

3.4 Stock-based approach

A stock-based approach was developed and implemented to assess the influence of prefabrication wide adoption at the EU-27 building stock level (presented in chapter 5). The developed and implemented building stock model (BSM) is represented in Figure 6. The building stock model developed includes:

- the **energy demand model,** using an engineering-based approach linked to the BIM model (a bottom-up approach based on simulated archetypes), and a top-down statistical model (to estimate energy demand of non-simulated archetypes);
- the **attributional LCA model** based on the developed modular LCI including embodied, operational, and end-of-life impacts and costs, using high-resolution data (e.g., materials impacts and costs) and low-resolution national data (e.g., for labor and energy cost, transport and energy);
- the **stock aggregation model** is based on archetypes, buildings types, and statistical country-level information.

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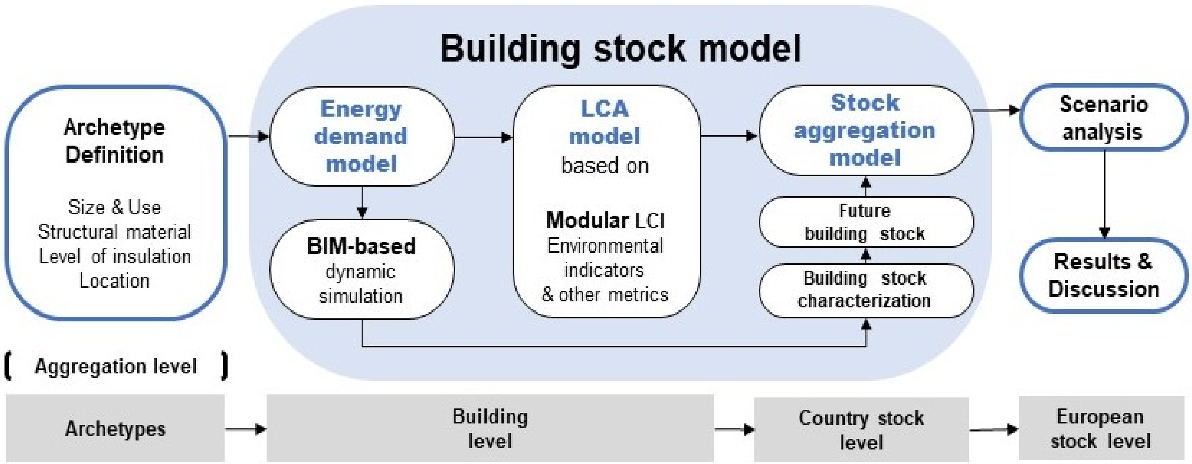

Figure 6 Building stock model framework

The BSM developed uses BIM to collect building data (geometry, location, orientation, material, and quantities), extract data to build the LCI, and perform the energy assessment enabling the fast simulation of a large set of archetypes in different locations. The modular LCI enables the vast assessment of alternatives. This BSM combining BIM-based energy model, modular LCI, and stock aggregation is a novel approach.

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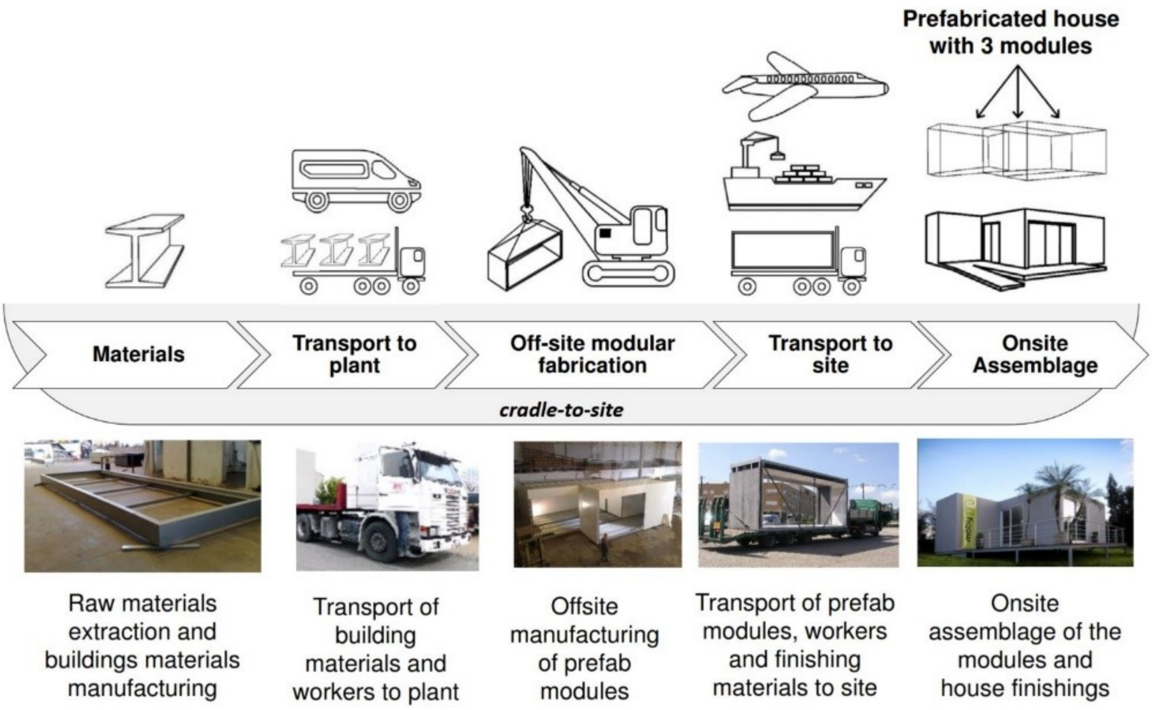
CHAPTER 4 LCA OF PREFABRICATED HOUSES

In this chapter, three case studies are presented to respond to different research questions: *What are the embodied impacts of prefabricated buildings?; What is the balance of embodied and operation impacts of a prefabricated building?;* and *What are the main differences between prefabricated and conventional buildings?* In section 4.1, a *cradle-to-site* focus on the embodied impacts of a modular prefabricated single-family house with alternative sizes, materials, final locations; on section 4.2, *cradle-to-use* balances embodied and operational impacts of a prefabricated single-family house, with alternative insulation levels and final locations; and on section 4.3, a *cradle-to-grave* compares two prefabricated single-family houses and two conventional, with different insulation levels, and includes costs, material, waste, and production time. These three sections are based on papers 1, 2, and 3 presented in appendix IV.

4.1 What are the embodied impacts of a prefabricated house?

Based on: Tavares, V., Lacerda, N., Freire, F. (2019). Embodied Energy and Greenhouse Gas Emissions Analysis of a Prefabricated Modular House: the "Moby" case study. Journal of Cleaner Production vol. 212, pp. 1044-105. https://doi.org/10.1016/j.jclepro.2018.12.028



Abstract: This section intends to answer the research question: *What are the embodied impacts of prefabricated buildings?* A *cradle-to-site* energy and GHG assessment of a prefabricated modular house was performed, including materials production, transport to plant, modules production, transport to site, and final assemblage on site. Seven house final locations (three in Portugal, one in Europe, and three overseas) were considered to assess transport-related impacts. Scenarios for alternative structural materials and house sizes (bedroom number) were also analyzed to understand its influence on results and represent other prefabricated modular houses currently produced in Europe.

4.1.1. Introduction

Buildings are big consumers of energy and materials and important producers of waste and emissions. Prefabrication is foreseen as one possible way to reduce the environmental impacts in the building sector, but transport can jeopardize the benefits achieved through prefabrication. Most studies assessing prefabricated buildings discuss the importance of the use phase (e.g., Adalberth, 1997; Atmaca and Atmaca, 2016; Bonamente et al., 2014); however, embodied impacts become more relevant as buildings become more energy efficient. Embodied energy can represent as much as 40% of total energy (Thormark, 2002, for a low energy consumption building). Therefore, there is a need to reduce the embodied impacts of buildings and of the construction sector, and prefabrication presents an opportunity to reduce the energy and resource-intensive building process.

This section presents energy and carbon analysis of a prefabricated house named "Moby," which is based on a modular system to enable different layouts (area and inhabitants). A "cradle-to-site" analysis was performed, including materials production, transport to plant, modules production, transport to site, and final assemblage on site. Several house final locations (in Portugal and overseas) were addressed to assess transport-related impacts. Scenarios for alternative building structural materials and house sizes (bedroom number) were also analyzed to understand the influence of these aspects in the results and represent other prefabricated modular houses currently produced in Europe. The main goal is to quantify the embodied primary energy requirements and GHG intensity of the Moby prefabricated modular house, assessing the contribution to each phase and the influence of distance from the plant to the site.

4.1.2. Model and inventory

In response to the research question, a case study was selected aiming at assessing a representative modular house manufactured in Europe with a high degree of prefabrication, for which primary data was collected for fabrication, including alternative structural materials, house sizes, and final house locations. Therefore, using scenario analysis, the assessment of the Moby house has been generalized with additional production options and for broader applicability to be representative of prefabricated modular houses currently produced in Europe.

A cradle-to-site model of a prefabricated modular house was implemented to the following phases: i) materials production, ii) transport of materials and workers to plant, iii) module production on the plant, iv) transport of modules, workers, and material to the construction site and v) on-site modules assemblage and finishes. Figure 7 illustrates the system boundary of the assessment.

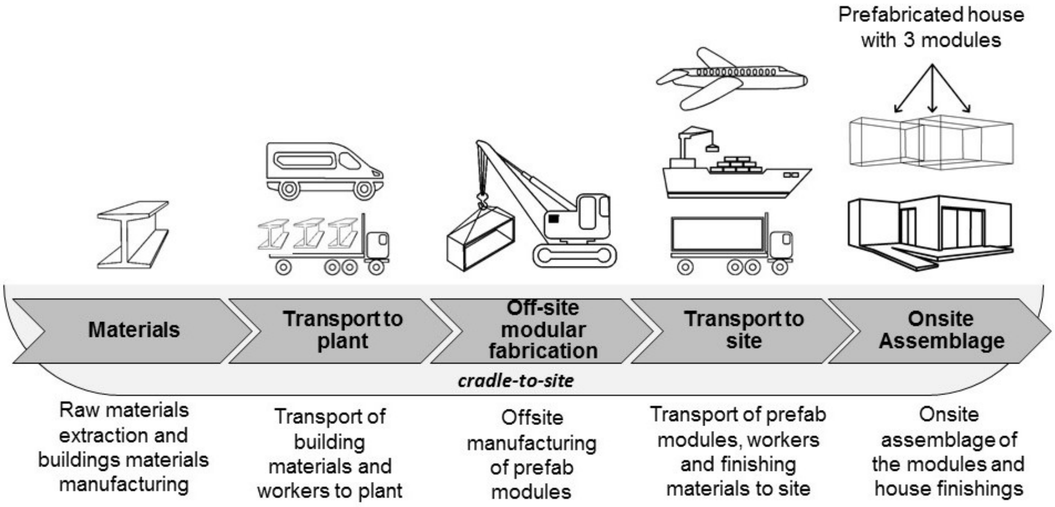


Figure 7 System boundary: Moby house “cradle-to-site” assessment

The prefabricated house – named Moby – is a detached, one-store, modular house developed by a Portuguese company (CNLL Ltd). It is based on the production concept of prefab industrialized modules (referred to as “core”) and an onsite personalized assemblage and finishing (referred to as “shell”). It is built in two phases: first, 2.5 x 7.5 x 3.6 m modules are produced in the plant; second, the modules are transported to the site, assembled, and finished. The modules can be combined into different house sizes, typically from one-bedroom to four-bedroom, as shown in Figure 8.

Figure 8 Floor plan, elevations and a picture of the one-bedroom Moby house

4.1.2.1 Embodied Energy and GHG

Embodied energy (EE) is the energy required to extract, produce and transport building materials (in a "cradle-to-site" assessment); operation energy refers to the energy used during the use phase (Bastos et al., 2013; Thormark, 2002). Similarly, embodied GHG estimates the GHG intensity from the extraction of raw materials to the building site, and operation GHG accounts for GHGs released into the atmosphere during to use phase. The EE measures the non-renewable primary energy, as it is not so relevant to account for renewable energy (Malça and Freire, 2006), and there is no consensus on how to estimate primary energy values (Molenbroek et al., 2011).

In this section, the embodied energy (EE in MJ/kg) and GHG emissions (in kg CO_{2eq}/kg) of the Moby prefabricated house were calculated from cradle-to-site, using the Inventory of Carbon and Energy (ICE) Version 2.0. (Hammond and Jones, 2006), for construction materials, together with data for electricity in Portugal (Garcia et al., 2014) and fuels for the transportation of materials and the final house (Spielmann et al., 2007). GHG emissions were based on the Intergovernmental Panel on Climate Change (IPCC) method v1.02, with a 100-year time horizon (IPCC, 2007).

4.1.2.2 One-bedroom Moby

A one-bedroom Moby with three modules and a total floor area of 56 m^2 was assessed as the base-case house. The floor plan, elevations, and one picture are presented in figure 10. Four house sizes (from the 1-bedroom to the 4-bedroom house) will be presented in subsection 4.1.3.4. Table 16 presents the inventory of producing the one-bedroom Moby, including the EE and GHG of materials and electricity. Primary data for the foreground processes (transport, manufacturing, and assemblage phases) was collected by the authors, with interviews with the manufacturing team and from the design project (detailed implementation drafts, shop drawings, and bill of quantities). The electricity input for the prefabrication of a Moby module at the plant was calculated based on the plant electricity bill and the number of modules being produced.

The inventory of the modular house is organized into two main parts:

- the core includes foundations, the primary structure of the modules, exterior wall, floor, roof, and infrastructures for water, gas, electricity, and rain drainage systems.
- the shell includes exterior wall and floor finishes, interior walls, doors, windows, and other elements (baseboard and cornices, sanitary equipment, wardrobe, kitchen, and bathroom cabinet).

Table 16 Inventory of the production of one-bedroom Moby: a) materials; b) modules production

	a) materials	**weight**	**embodied energy**[3]	**embodied GHG**[3]
		kg	MJ kg^{-1}	$kgCO_2eq\ kg^{-1}$
CORE		8 325		
Foundation	Steel	1 692	25.3	1.95
Structure	Steel	642	25.3	1.95
Exterior wall	Steel	713	25.3	1.95
	Plasterboard	704	6.8	0.39
	Polyurethane rigid	217	101.5	4.26
	Polyvinyl chloride (PVC)	404	77.2	3.10
	Rockwool	67	16.8	1.12
	Stainless steel	14	56.7	6.15
Floor	Aluminum	256	155.0	9.18
	Bitumen	215	51.0	0.49
	Steel	713	25.3	1.95
	Medium-density fiberboard (MDF)	576	11.0	0.39
	Rockwool	92	16.8	1.12
Celling	Steel	578	25.3	1.95
	Plasterboard	863	6.8	0.39
	Polyurethane rigid	118	101.5	4.26
	Polyvinyl chloride (PVC)	270	77.2	3.10
	Rockwool	92	16.8	1.12
Infrastructure	Bronze	1	69.0	4.00
Water supply	Copper	4	42.0	2.71
Gas supply	Polyethylene (LDPE)	4	83.1	2.54
Electricity	Polyvinyl chloride (PVC)	79	67.5	3.23
Rain sewage	Zinc	10	53.1	3.09
SHELL		4 126		
Exterior wall finishing	Cement	466	4.5	0.74
	Expanded polystyrene	124	88.6	3.29
	Fiberglass	17	28.0	1.35
	Paint	150	70.0	2.91
	Plaster	466	1.8	0.13
Interior wall	Steel	12	25.3	1.95
	Paint	45	70.0	2.91
	Plasterboard	317	6.8	0.39
	Rockwool	124	16.8	1.12
Floor finishing	Wood laminated flooring	308	12.0	0.42
	Polyethylene	27	83.1	2.54
	Timber	45	10.0	0.31
	Varnish	3	50.0	5.35
Doors	Brass	1	44.0	2.64
	Laminated veneer lumber	19	9.5	0.33
	Plywood	4	15.0	0.45
	Veneer	6	9.5	0.33
Windows	Extruded aluminum	147	154.0	9.08
	Glass	858	15.0	0.91
Other element	Brass	15	44.0	2.64
Baseboard and cornice	Ceramic	137	29.0	1.61
	Aluminum	68	155.0	9.16
Bathroom equipment	Resin	34	11.0	0.70
	Medium-density fiberboard (MDF)	708	11.0	0.39
Kitchen cabinet	Nickel	3	164.0	12.40
Countertop	Stainless steel	11	56.7	6.15
Lighting	Timber	12	10.0	0.31

[3] (Hammond and Jones, 2006)

	b) modules production	kWh	MJ kWh^{-1}	$kgCO_2eq\ kWh^{-1}$
Electricity [4]		12 000	4.4	0.36

[4] (Garcia et al., 2014)

4.1.2.3 Moby structure, size, and location

Four alternative structural materials, four house sizes, and seven final locations were comparatively assessed as described below.

4.1.2.4 Structural materials

Four alternative structural materials were analyzed: steel (base-case), concrete, timber, and light steel framing (LSF). Table 17 details the weight (total and only the structure) of the one-bedroom Moby and the embodied energy and GHG of the four structural materials.

Table 17 One-bedroom Moby with alternative structural materials

	total weight	**structure weight**		**embodied energy**	**embodied GHG**
	kg	kg	%	MJ/kg	kgCO2eq/kg
Steel (Base case)	12 450	2 647	21%	25.3	1.95
Concrete	52 377	42 573	81%	2.3	0.24
Timber	13 077	3 273	25%	10.0	0.31
LSF	11 196	1 393	12%	13.1	0.72

4.1.2.5 Moby house size

Four house sizes (bedroom number) were analyzed to assess the influence of house size in impacts. The one-bedroom Moby has three modules and 56 m^2 of gross floor area, which can be expanded (as needed) by adding further modules. Table 18 presents the inventory and Figure 9 the floorplan and modules schemes for four layouts (different rooms, areas, and inhabitants).

Table 18 Inventory of Moby houses (1- to 4-bedrooms)

	1-bedroom		**2-bedroom**		**3-bedroom**		**4-bedroom**	
	weight		weight		weight		weight	
	kg	%	kg	%	kg	%	kg	%
Foundations	1 692	14%	2 256	13%	2 820	13%	3 384	13%
Structure	642	5%	856	5%	1 070	5%	1 284	5%
Exterior wall	2 119	17%	2 435	14%	2 653	13%	2 900	12%
Floor	1 852	15%	2 469	14%	3 086	15%	3 703	15%
Celling	1 921	15%	2 561	15%	3 202	15%	3 842	15%
Infrastructure	99	1%	132	1%	165	1%	198	1%
Exterior wall finishing	1 222	10%	1 405	8%	1 531	7%	1 673	7%
Interior wall	499	4%	1 773	10%	2 609	12%	3 259	13%
Floor finishing	383	3%	511	3%	638	3%	766	3%
Doors	78	1%	156	1%	234	1%	234	1%
Windows	1 004	8%	1 358	8%	1 535	7%	1 863	7%
Other elements	988	8%	1 317	8%	1 647	8%	1 976	8%
TOTAL	**12 499**		**17 229**		**21 190**		**25 081**	

Figure 9 Floor plans of the 1- to 4-bedroom houses

4.1.2.6 Final house location

Seven alternative final locations were analyzed to understand the influence of distance from the plant to the site. Three national locations: north of Portugal (city of Aveiro, base-case), center (Lisbon), and south (Faro), as well as four international locations: Paris, Casablanca, Luanda, and Rio de Janeiro, represent potential markets for modular houses.

Transport has two main stages: transport to plant (of workers and materials) and transport from plant to site (of modules, workers, and finishing materials). The transport of materials to the plant requires one trip of a 3.5-16t lorry, fleet average (Spielmann et al., 2007), and a 50 km distance. The transport of six workers to the plant was done in three passenger cars at a 10 km distance. Regarding transport from plant to site, modules were transported individually in a lorry with a load capacity over 28t, fleet average, with an empty return (Spielmann et al., 2007). When overseas locations were considered, the transport was considered between ports in transoceanic vessels. Modules were individually transported to the port and from the port in a 28t lorry fleet average (Spielmann et al., 2007). Finally, finishing materials were considered to be locally acquired, and a single trip in a 3.5-16t lorry (fleet average at a generic 50 km distance) was considered (Spielmann et al., 2007). The transport of six workers from the plant to the domestic sites was done in a passenger van (Spielmann et al., 2007). For overseas locations and Paris city, two workers (supervisors) were transported by plane, and a team of four was hired locally.

4.1.3 Results

The main results are presented in this section: for the base case scenario (one-bedroom Moby) and scenario analysis: alternative structural materials, different house sizes, and final house location.

4.1.3.1 One-bedroom Moby

Figure 10 shows EE and GHG for the one-bedroom Moby. Materials production impacts were calculated by multiplying quantities of materials with the corresponding embodied energy and GHG data. Materials production is the most critical phase in a cradle-to-site assessment (80% of EE and GHG), followed by modules production (12% of EE, 16% of GHG). Modules production shows an inversion in the relation between GHG and EE relatively to materials production, due to the relatively low EE of modules production (mainly electricity generation: 4.4 MJ kWh^{-1}).

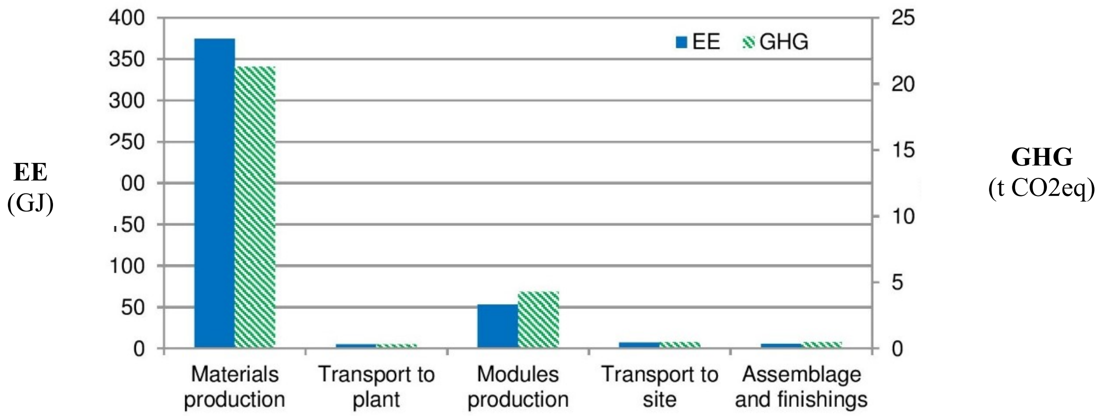


Figure 10 Cradle-to-site energy and GHG of the one-bedroom Moby

Results for the materials production phase are presented in Figure 10 and a breakdown in Table 19. Most of the impacts are associated with the core (more than 70% of EE and GHG). Floor composition and exterior wall composition have similar impacts (around 20%), followed by foundations and roof composition (both around 15%). The sum of transport to plant, transport to the site (city of Aveiro), and assemblage and finishing phases accounts for less than 5% of total impacts.

Table 19 Materials production phase: contribution to impacts

	Embodied Energy (EE)		Greenhouse Gases (GHG)	
	MJ	% of total	kgCO_2eq	% of total
CORE	**274 852**	**73%**	**15 948**	**75%**
Foundations	42 802	11%	3 299	15%
Primary structure	16 244	4%	1 252	6%
Ext. wall composition	77 948	21%	4 005	19%
Floor composition	76 521	20%	4 171	20%
Roof composition	54 833	15%	2 907	14%
Infrastructure	6 505	2%	314	1%
SHELL	**99 516**	**27%**	**5 339**	**25%**
Exterior wall finishing	24 907	7%	1 273	6%
Interior wall	7 681	2%	417	2%
Floor finishing	6 546	2%	229	1%
Doors	328	0%	12	0%
Windows	35 462	9%	2 113	10%
Other elements	24 592	7%	1 295	6%
TOTAL	**374 368**	**100%**	**21 288**	**100%**

4.1.3.2 Scenario analysis

The results for the alternative scenarios for structural materials (steel, timber, LSF, and concrete), house size (from 1- to 4-bedroom house), and final locations (Aveiro, Lisbon, Faro, Casablanca, Paris, Luanda, and Rio de Janeiro) are discussed in this section.

4.1.3.3 Structural materials

Figure 11 compares the impacts of the materials production phase of the one-bedroom Moby with different materials for the structure. The structures with light steel framing (LSF) or timber have the lowest GHG and EE impacts, a reduction of about 20% GHG and 10% EE, relatively to the steel structure (base-case). The concrete structure has the highest impacts: more 24% GHG and 9% EE relatively to the steel structure. Similar findings were presented by Cabeza et al. (2014) (in a revision paper about LCA of buildings) that concluded that concrete and steel were responsible for most of the buildings' impacts. It can also be seen in Figure 12 that the concrete house shows an inversion in GHG/EE relatively to the other three structural materials due to a higher GHG/EE ratio for concrete: GHG/EE (gCO_2eq/MJ) is 100 for concrete, 80 for steel; 50 for LSF; and 30 for timber.

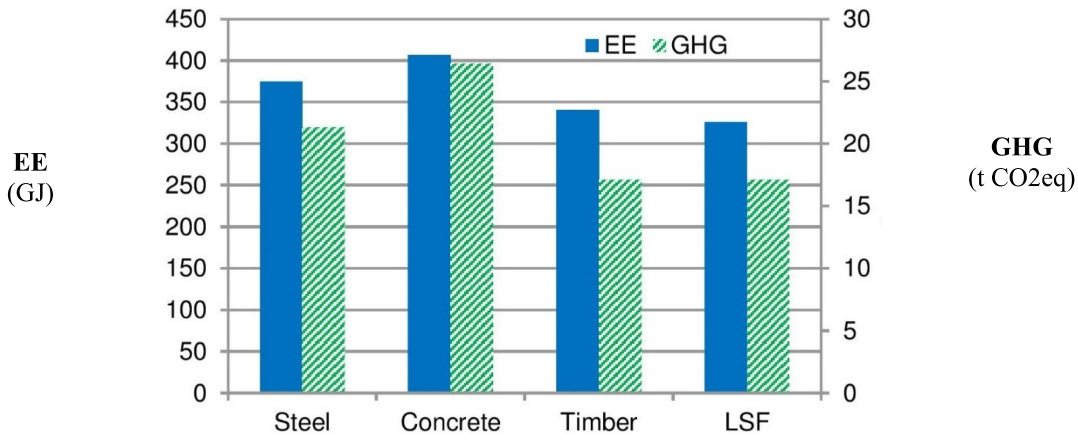


Figure 11 Materials production phase impacts for the one-bedroom Moby

4.1.3.4 House size (number of bedrooms)

Figure 12 compares the EE and GHG impacts of four house sizes (different number of bedrooms and inhabitants). Fig. 13.a) reports total values while Fig. 13.b) relative values for two alternative functional units: one inhabitant (hab); and one m^2 of gross floor area. The house embodied impacts per inhabitant reduce significantly with the area increase (and inhabitants in the house), but not the impacts per m^2. This is because the impact increase is related to area increase, but the number of inhabitants rises more sharply than the area. Thus, a larger house leads to lower impacts per inhabitant but similar impacts per m^2.

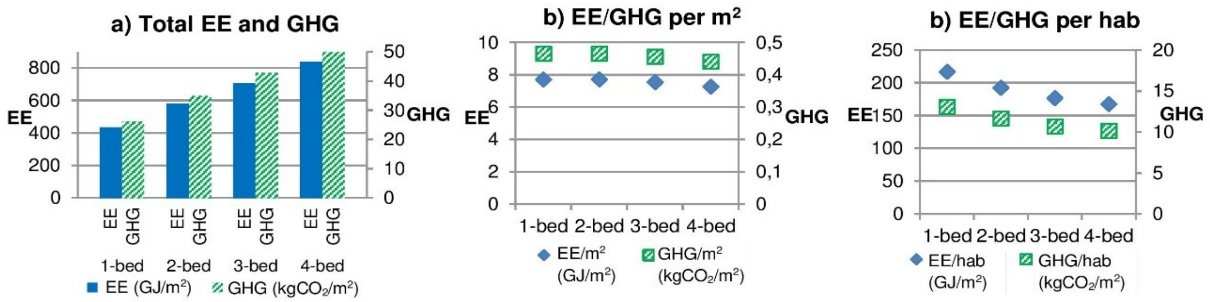


Figure 12 a) Embodied energy and GHG intensity for the four houses and b) The influence of house size on impacts for two alternative functional units

4.1.3.5 Final house location

Figure 13 shows the impacts of transportation of modules, workers, and finishes of the "one-bedroom Moby" for seven final locations (four national and three international). In the base-case scenario (steel structure, one-bedroom house located in Aveiro), transport to the site represents 2% of total impacts. However, figure 14 shows that transport to final location can represent a significant share of total impacts for other cases, being as much as 25% of EE and 27% of GHG for Rio de Janeiro. The transportation impacts to the final house location do not rise linearly with distance but are also dependent on transport mode. For example, transport to Faro (500 km distance, by land) represents 8-9% of total impacts, while to Casablanca (1000 km distance, by water) only 6-7%.

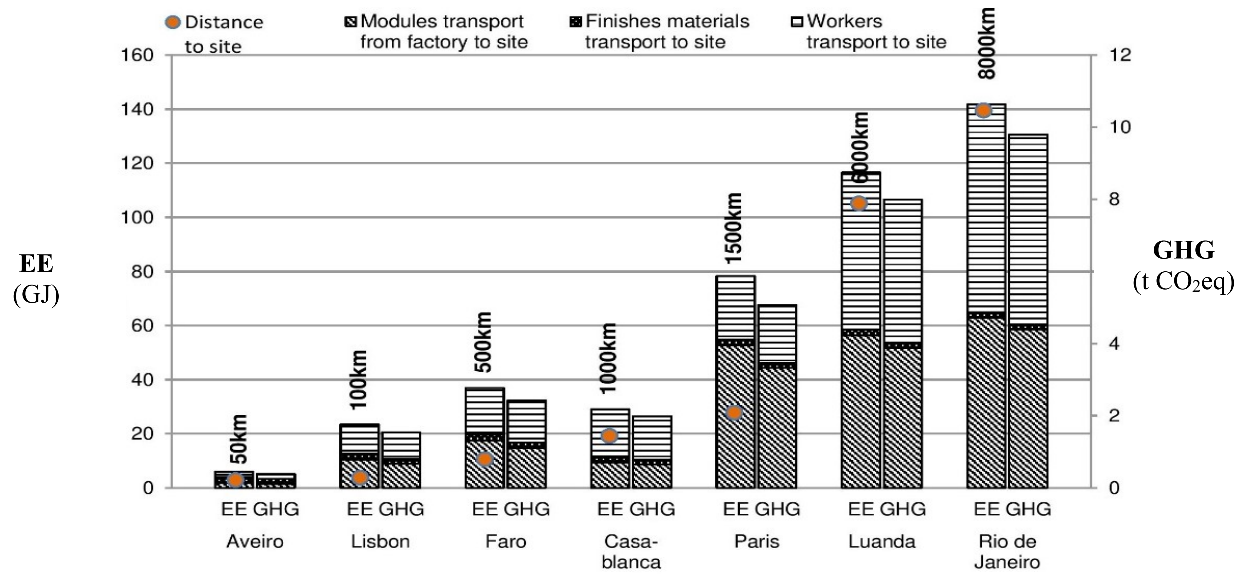


Figure 13 Embodied energy and GHG for the transport for final house location

4.1.4 Conclusions

This study has assessed the embodied energy and GHG of a modular prefabricated house named Moby, addressing alternative structural materials (steel, concrete, timber, and LSF) and alternative house sizes (number of bedrooms and inhabitants). Alternative house final locations have also been assessed to analyze transport-related impacts, which have been much neglected in previous studies of prefabricated buildings.

The embodied impacts calculated (cradle-to-site) for the Moby house show that materials production is the most important contributor (64-90% of EE and 59-87% of GHG). For the base-case scenario (1-bedroom, steel structure, located in Aveiro), materials production represents about 80% of total impacts (around 3/4 from the Moby "core"). The second most crucial phase is modules production, but the low level of industrialization of prefabricated companies should be noted, as discussed by others (Pons and Wadel, 2011).

The impacts of transportation (of modules, workers, and finishes) vary significantly for the various house final locations assessed: from 2% (for Aveiro, the base case) to around 26% (for Rio de Janeiro) of total embodied impacts. Transport-related impacts can be critical as they may balance the potential benefits of prefabrication, particularly for modular prefabrication due to the high volume of the finished modules. The electrification of the transport and rail transport was not considered and may lead to different results. The embodied impacts increase with the house size (number of bedrooms and inhabitants); however, a larger house leads to lower impacts per inhabitant, but similar impacts per m^2 (of gross floor area), since the number of inhabitants rises more sharply than the area).

The results presented in this article for the various alternatives and scenarios assessed show some variation but fit the ranges presented in the literature: embodied energy (EE) varies from 7 489 MJ/m^2 to 10 378 MJ/m^2 (from Aveiro to Rio de Janeiro); and GHG from 454 kgCO_2eq/m^2 to 647 kgCO_2eq/m^2, while EE in the literature varies between 1 750 MJ /m^2 (Heravi et al., 2016) and 14 400 MJ/m^2 (Aye et al., 2012); and GHG varies between 211 kgCO_2eq/m^2 (Islam et al., 2016) and 1000 kgCO_2eq/m^2 (Vitale et al., 2018). A comparison with other modular prefabricated buildings is limited since only Monahan and Powell (2011), and Quale et al. (2012) addressed modular, and the latter performed a partial assessment of the building (considering only the materials that were different between prefab and conventional). Monahan and Powell (2011) calculated embodied impacts for a modular timber frame house in the USA ranging from 5700 to 7700 MJ/m^2 and from 405 to 535 kgCO_2eq/m^2, likewise to those calculated for the Moby house with timber structure (7642 MJ/m^2 and 425 kgCO_2eq) for similar plant-to-site distances (around 200 km). The impact for Moby built in Aveiro (with alternative structural materials) range from 7100 to 8500 MJ/m^2 and from 405 to 571 kgCO_2eq/m^2, which is a lower range of impacts than those for non-prefabricated houses (presented in table 1: 8200-9600 MJ/m^2 and 578-752 kgCO_2eq/m^2).

As discussed by Bastos et al., (2015), any LCA study for buildings involve a number of assumptions and simplifications. We have assumed our study is static and technological progress (hardly predictable) was not considered. Evolving production technology and increasing the scale production might lead to gains in efficiency and reduction of embodied impacts, but this was not addressed due to lack of information. We have implemented a detailed building construction model using primary data collected from actual processes, but secondary data (for materials) comes from the ICE Version 2.0 database (assumptions discussed in section 4.1.2). Assumptions for the transport stages were discussed in sub-section 4.1.3.4, but it should be added that future efficiency or electrification of the transport fleet could decrease related burdens.

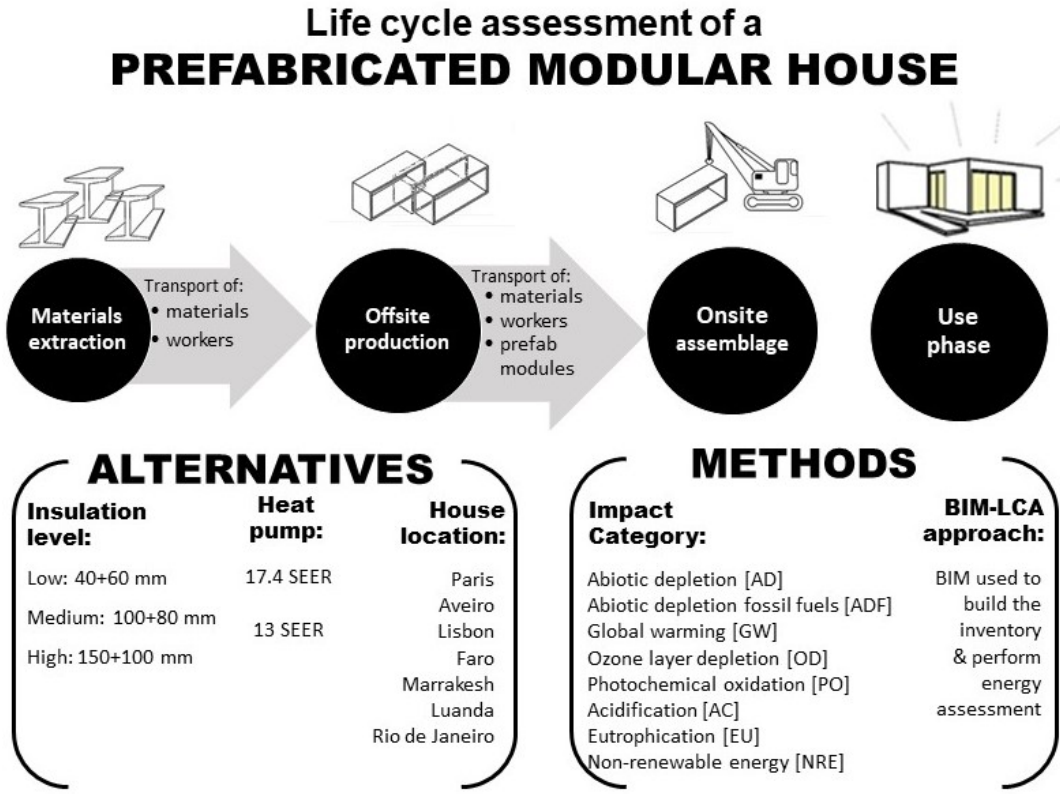
Our study is cradle-to-site, and processes occurring during use and end-of-life phases are beyond the boundary. However, issues related to concrete (an alternative structure material in the scenario analysis) during the use and demolition phase need further discussion. Concrete carbonation – a reaction occurring under natural conditions to cement – naturally reabsorbs CO_2 (Lee et al., 2013, García-Segura et al., 2014, Yang et al., 2014), reducing the overall GHG intensity of concrete house. However, the carbonation process is highly dependent on the type and quality of the cement, the service life, and environmental alternatives (García-Segura et al., 2014); thus, it is difficult to be accounted for. Despite these assumptions and simplifications, the analysis provides a comprehensive assessment of a modular prefabricated building and the importance of transportation in a cradle-to-site assessment. Lastly, further studies are needed to assess the entire life-cycle of prefabricated modular houses (for different climatic regions), and a comparison with conventional buildings should be performed.

To improve the environmental performance of prefabricated houses, we recommend focusing on selecting less energy and carbon-intensive materials and reducing the impacts of transportation of modules and workers by:

1. reducing the distance from the plant to the site;
2. choosing less energy-intensive transport modes;
3. transport prefabricated panels instead of modules; and
4. selecting local materials and workers to complete the onsite assemblage stage.

4.2 What is the balance between embodied and operational impacts of a prefabricated house?

Based on: Tavares, V., Freire, F. (2021). Life cycle assessment of a prefabricated house for seven final locations and three insulation levels, under review in the Journal of Building Engineering.



Abstract: This section presents a *cradle-to-use* assessment to answer the following research question: *What is the balance of embodied and operation impacts of a prefabricated building?* A BIM-LCA approach was implemented to i) assess the energy needs of the prefabricated house; ii) analyze the influence of final house location (with differences in transport, climate, and electricity mix), HVAC system, and insulation level; and finally, iii) understand the tradeoffs between embodied and operation impacts for all the alternatives.

4.2.1 Introduction

Prefabrication is increasingly being applied in the construction sector (Kamali and Hewage, 2016) with the offsite production and pre-assembly of components (elements, panels, or modules) before final onsite assembly. The prefabrication of buildings can have different degrees: from prefab elements (Cao et al., 2014; Hong et al., 2016); to completely prefabricated buildings (Heravi et al., 2016; Islam et al., 2016). Prefabricated buildings are typically lightweight, with fewer materials and reduced weight compared to conventional heavyweight buildings, thus reducing embodied impacts. However, lower embodied impacts of lightweight buildings can be jeopardized by higher operational energy needs (Hacker et al., 2008).

This section presents a life cycle assessment (LCA) of a prefabricated house to analyze the influence of house location (addressing different climate, transport, and electricity mix), insulation level, and heat pump efficiency ratio. A BIM-LCA approach was implemented to assess a prefabricated one-bedroom house with a steel structure and unveil the tradeoffs between embodied and operation impacts for all the alternatives.

4.2.2. Material and methods

A life-cycle (LC) model was developed for a prefabricated one-bedroom house with a steel structure composed of three offsite prefabricated modules. The house is built in two phases: first, modules are produced in the plant; second, the modules are transported to the site, assembled, and finished. Figure 14 presents the floorplan, a picture, an axonometric view of the BIM model, and the energy model of the lightweight prefabricated house built in Aveiro, Portugal. The functional unit is one prefabricated house with 56 m^2 of gross floor area over 50 years. The system boundary includes materials, transport to plant, modules prefabrication, transport to site, and use phase. End-of-life was excluded as it is insignificant (1-6% of impacts according to Khasreen et al., 2009; Morales et al., 2019) and might be even less significant for prefabricated buildings easier to disassemble and with higher waste recovery rates (Pierluca et al., 2018).

Figure 14 Prefabricated house picture and axonometric view of the BIM model, floorplan, and axonometric view of the energy model.

The LC model was implemented to assess seven house locations (addressing transport, climate, and electricity mix), three insulation levels (low: 40+60 mm; medium: 100+80 mm; high: 150+100 mm), and two heat pumps (17.4 and 13 SEER, seasonal energy efficiency ratio). Seven locations were selected, representing potential markets for prefabricated houses in three different climates: Mediterranean temperate climate (Aveiro, Lisbon, Faro, and Casablanca); continental climate (Paris); and tropical climate (Rio de Janeiro and Luanda). Three insulation levels and two heat pump systems were modeled in the seven final locations, which resulted in 42 combined alternatives. Figure 15 presents external wall and roof sections for the three insulation levels.

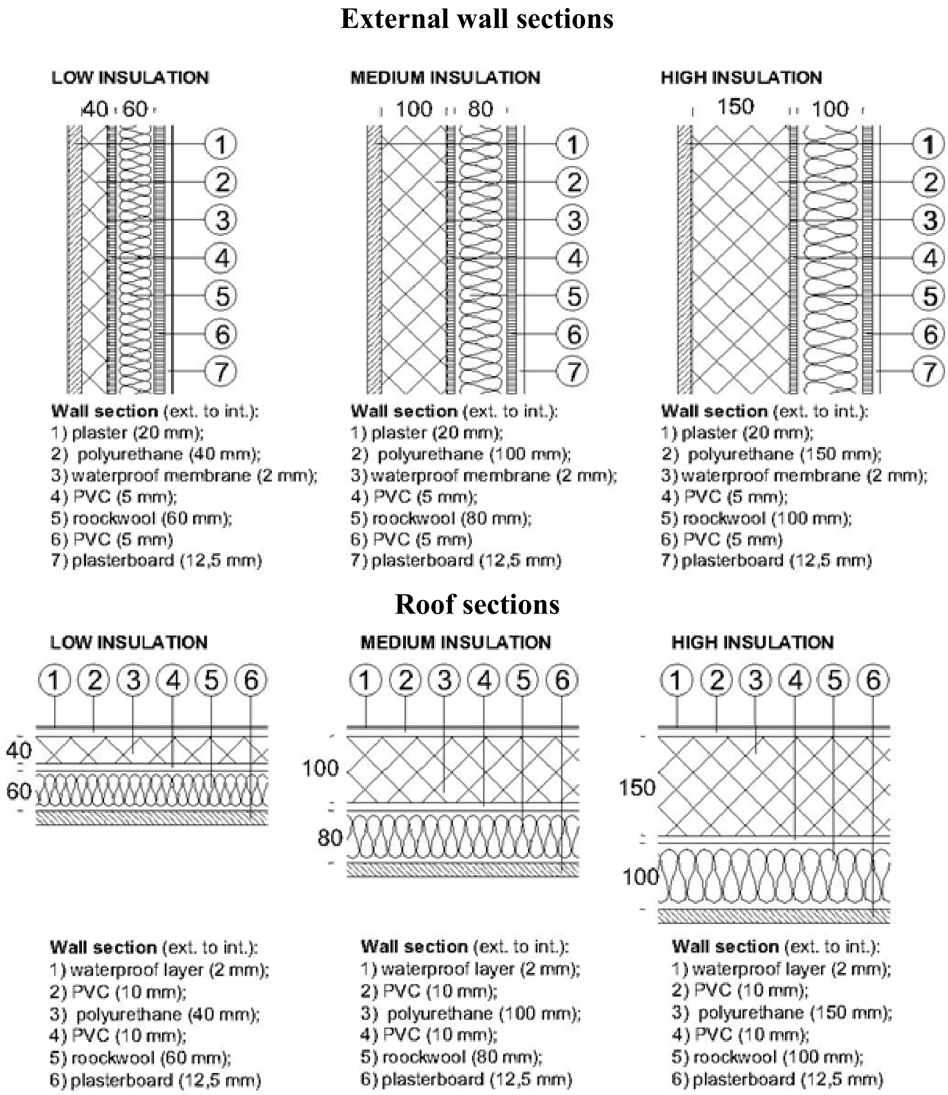


Figure 15 Sections of the external wall and roof with low, medium, and high insulation levels

A BIM model was used to extract the bill of quantities (to build the life cycle inventory) and perform the dynamic energy simulation (to predict energy needs in each location). EnergyPlus (US Department of Energy's (DOE) Building Technologies Office (BTO), 2021) was linked to the BIM model to assess energy needs during the use phase. A life cycle model was implemented in Simapro 8.1 software (PRé Sustainability, 2021), combining primary data collected with the prefabricated construction company and designers and secondary data using Ecoinvent 3 database (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2021). Following the European framework for sustainable buildings Level(s) (European Commission, 2017) and EN 15978 standard (European Committee for Standardization, 2011) recommendations, eight impact categories were calculated: abiotic resource depletion, abiotic depletion of fossil fuels, global warming, ozone layer depletion, photochemical oxidation, acidification, and eutrophication (using the CML method); and non-renewable energy (using the Cumulative Energy Demand method).

4.2.3 Life cycle inventory

Life cycle inventory (LCI) is divided into embodied phase (presented in section 4.2.3.1), including materials, transport to plant, prefabrication, transport to site and assemblage; and operational phase (presented in section 4.2.3.2), including heating, cooling and ventilation, materials replacement, and hot water supply and other appliances.

4.2.3.1 Embodied phase

Table 20 presents the LCI for embodied phase, including 1) materials; 2) Transport to plant of materials and workers; 3) prefabrication of Modules; 4) Transport to the site of materials, workers, and prefabricated modules; and 5) Assemblage and finishing. Seven house locations with low, medium and high levels of insulation have been assessed.

Table 20 Life cycle inventory for embodied phase for the seven house final locations

LC Stage	Description		Alternatives
	Insulation level		**Low | Medium | high**
1) Materials	Building materials (ton)		13.3 | 13.9 | 14.6
2) Transport to plant	Materials to plant (tkm)		885 | 946 | 1 021
	Workers to plant (tkm)		1 056
3) Modules' prefabrication	Electricity (kWh)		12 000
	Water (L)		200
4) Transport	**House locations**		
	Materials to site		441
	Workers to plant (km)		1 000
	Workers from plant to site (km)		9 000 | 1 000 | 1 200 | 2 000 | 6 000 | 48 000 | 36 000
	Modules from plant to site (tkm)	Low	13 277 | 443 | 2 655 | 4 426 | 9 737 | 71 696 | 53 993
		Medium	14 410 | 473 | 2 839 | 4 732 | 10 410 | 76 656 | 57 729
		High	15 318 | 511 | 3 064 | 5 106 | 11 233 | 82 719 | 62 294
5) Assemblage and finishing	Electricity (kWh)		1 364
	Diesel (MJ)		1.2

4.2.3.2 Operational phase

The operational phase includes energy consumption for the heat pump, hot water, and other appliances; and materials and refrigerant replacement. Energy consumption was calculated through dynamic energy simulation considering three insulation levels and two heat pumps (with different efficiency ratios) for seven house locations.

Figure 16 shows the operational energy of the prefabricated house with medium insulation for seven locations considering two heat pumps with different energy efficiency ratios (represented by the variation bar). Houses located in the tropical region (Rio de Janeiro and Luanda) have the lowest energy needs, followed by houses in a temperate Mediterranean region (Casablanca, Faro, Lisbon, and Aveiro). The house in the continental region (Paris) has the highest energy needs. The heating influences houses located in continental and Mediterranean regions. Cooling influences the house in Rio de Janeiro with no heating needs. In Paris, energy demand is dominated by heating needs even though cooling is also required. Hot water and appliances' energy demand are similar in all locations.

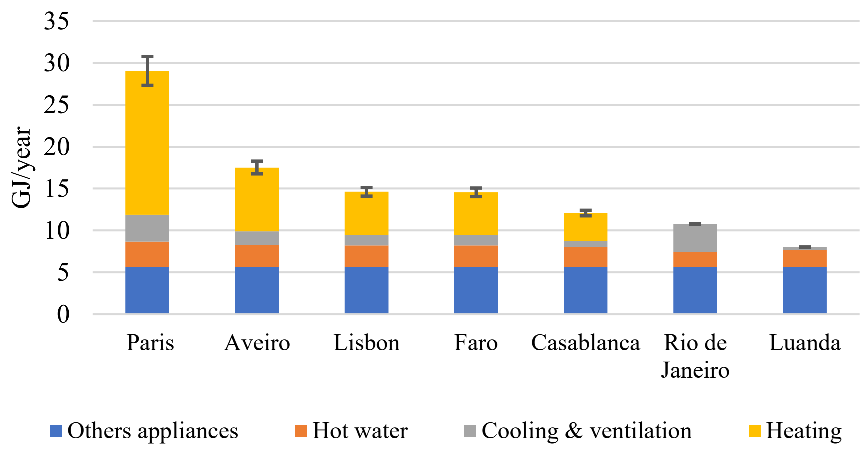


Figure 16 Operational energy for the seven house locations with medium insulation levels. Contribution of use type: cooling & ventilation, heating, hot water, and other appliances (error bar represents the efficiency variation of the heat pump).

Figure 17 presents the yearly operational energy for the house located in the following regions: Paris, Aveiro, Lisbon, Faro, Casablanca, Rio de Janeiro, and Luanda; and considering low, medium, and high insulation levels. The influence of insulation level on operational energy is more significant for the Paris region (with higher energy needs) and can be reduced by 10% by increasing insulation level from low to medium and by 3% from medium to high. For the Mediterranean region (Aveiro, Lisbon, Faro, and Casablanca), a slight decrease in energy use can be achieved by increasing the insulation level from low to medium; but no decrease (or even a slight increase) when increasing it from medium to high. The insulation level has a minor influence on the prefabricated house energy needs in the tropical region (Rio de Janeiro and Luanda). For comparison purposes, a conventional concrete house (heavyweight) with medium insulation was assessed for the seven house locations, and results are also shown in Figure 17 (black marks). The conventional house presents similar operational energy of prefabricated high insulated houses in Paris (+4%) and the Mediterranean region (±2%), and higher needs in the tropical region (+15%).

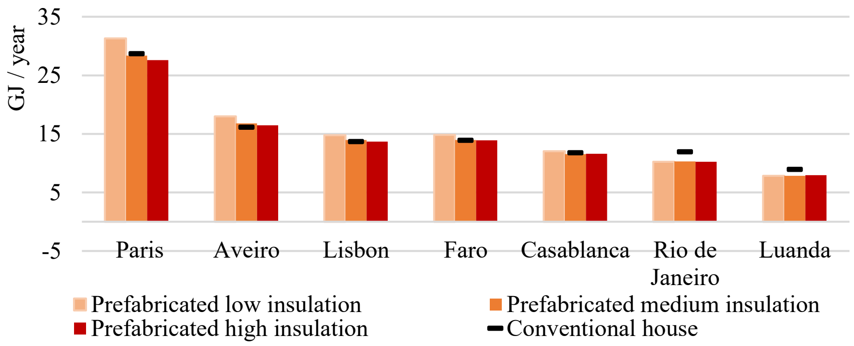


Figure 17 Operational energy for the seven house locations and three insulation levels
Black mark represents operational energy for a conventional house with medium insulation

4.2.4 Results and discussion

This section presents embodied, operational and total impacts for each house location and insulation level (section 4.2.4.1). Contribution analysis of each LC phase is presented in section 4.2.4.2, followed by the use phase (section 4.2.4.3) and embodied impacts of materials (section 4.2.4.4). A sensitivity analysis of impacts for the different insulation levels for the seven house locations is presented in section 4.2.4.5. and section 4.2.4.6 presents the comparison of results with impacts previously presented in the literature.

4.2.4.1 Life cycle impacts

Figure 18 presents operational, embodied, and total impacts of the house for the seven alternative locations with low, medium, and high insulation levels. Operational impacts represent 40-90% of total impacts, which vary significantly for continental (Paris) and Mediterranean regions (Aveiro, Lisbon, Faro, and Casablanca) when increasing the insulation level (mainly from low to medium). Embodied impacts are similar for all locations, with a slight increase for increasing insulation levels or distances to the site. When increasing insulation levels, operational impacts present a decreasing tendency in the continental and the Mediterranean region but stay constant or suffer a minor increase in the tropical region (Rio de Janeiro and Luanda) due to increased cooling.

Operational impacts roughly reflect energy consumption, presenting a similar trend within the same climatic zone. However, even though having higher operational energy, the house in Paris presents lower impacts than houses in the Mediterranean region in ADF, GW, PO, and AP categories, due to the lower impact of the French electricity mix. Total impacts are highly dependent on operational impacts except for AD in some of the Mediterranean and tropical regions, EP in the tropical region, and ADF, GW, AP, and NRE for Rio de Janeiro. The influence of embodied impacts is significant in houses with lower operational energy.

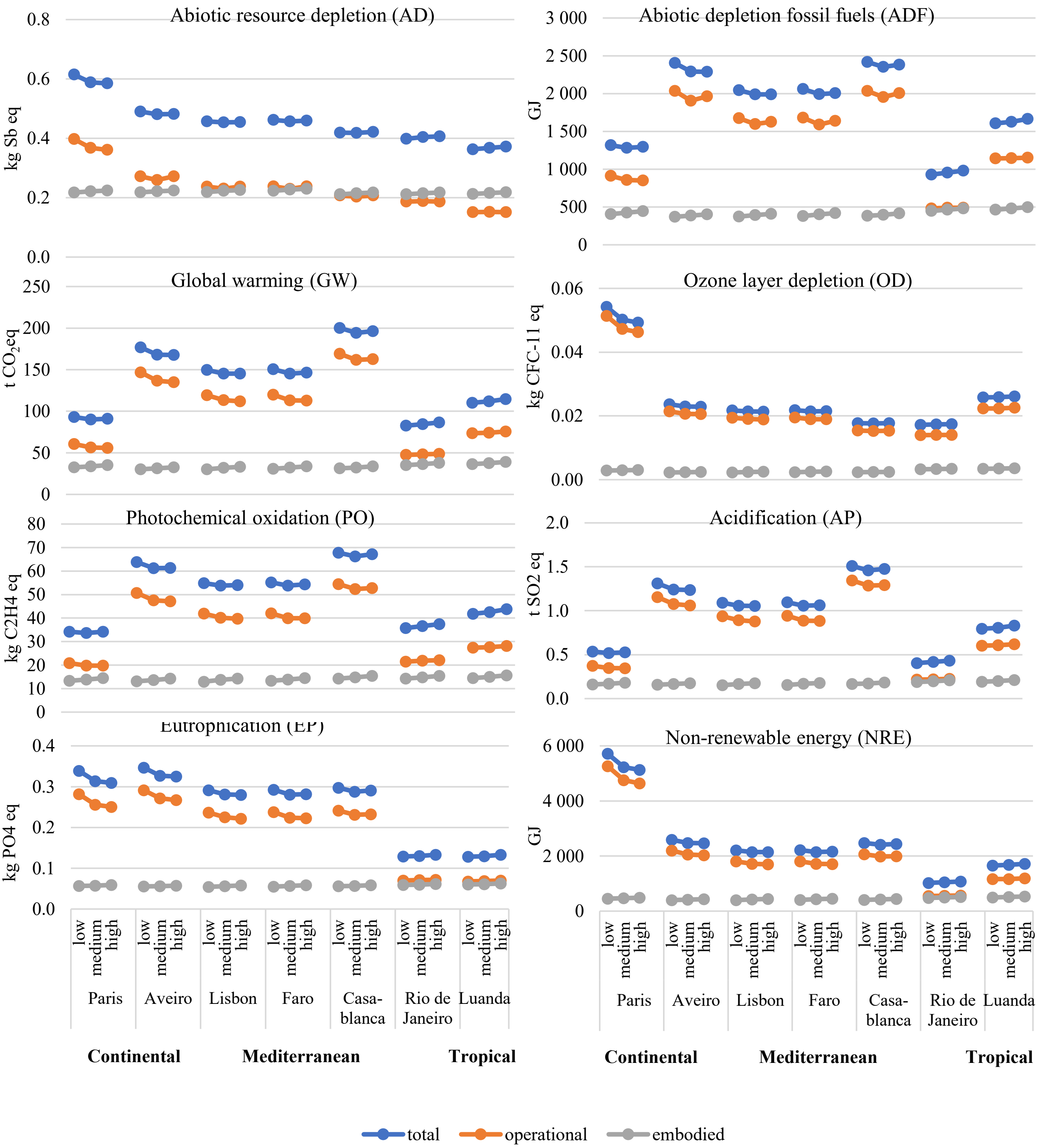


Figure 18 Operational, embodied, and total environmental impacts and non-renewable energy of the house for the seven locations with three insulation levels

4.2.4.2 Contribution analysis of each LC phase

Figure 19 presents the contribution of each phase to the life cycle: materials, transport to plant, on plant production, transport to site, onsite assemblage, and use phase. The use phase is most significant (40-90%), followed by materials (10-50%). Transport to the site has a small contribution in overseas locations (up to 10% for Rio de Janeiro) and is insignificant to all the other locations. Transport to plant, plant production, and onsite assemblage have negligible impacts. Use phase impacts are lower for the tropical region (due to lower operational energy) or for countries with an electricity mix with lower impacts (as Paris and except for AD, OD, and NRE). Materials are significant for AD (35-55%) and OD (25-55%). The variation bar represents the difference in operational energy during the use phase due to alternative heat pump systems (± 1% in EU and OD, and ± 6% in the other categories).

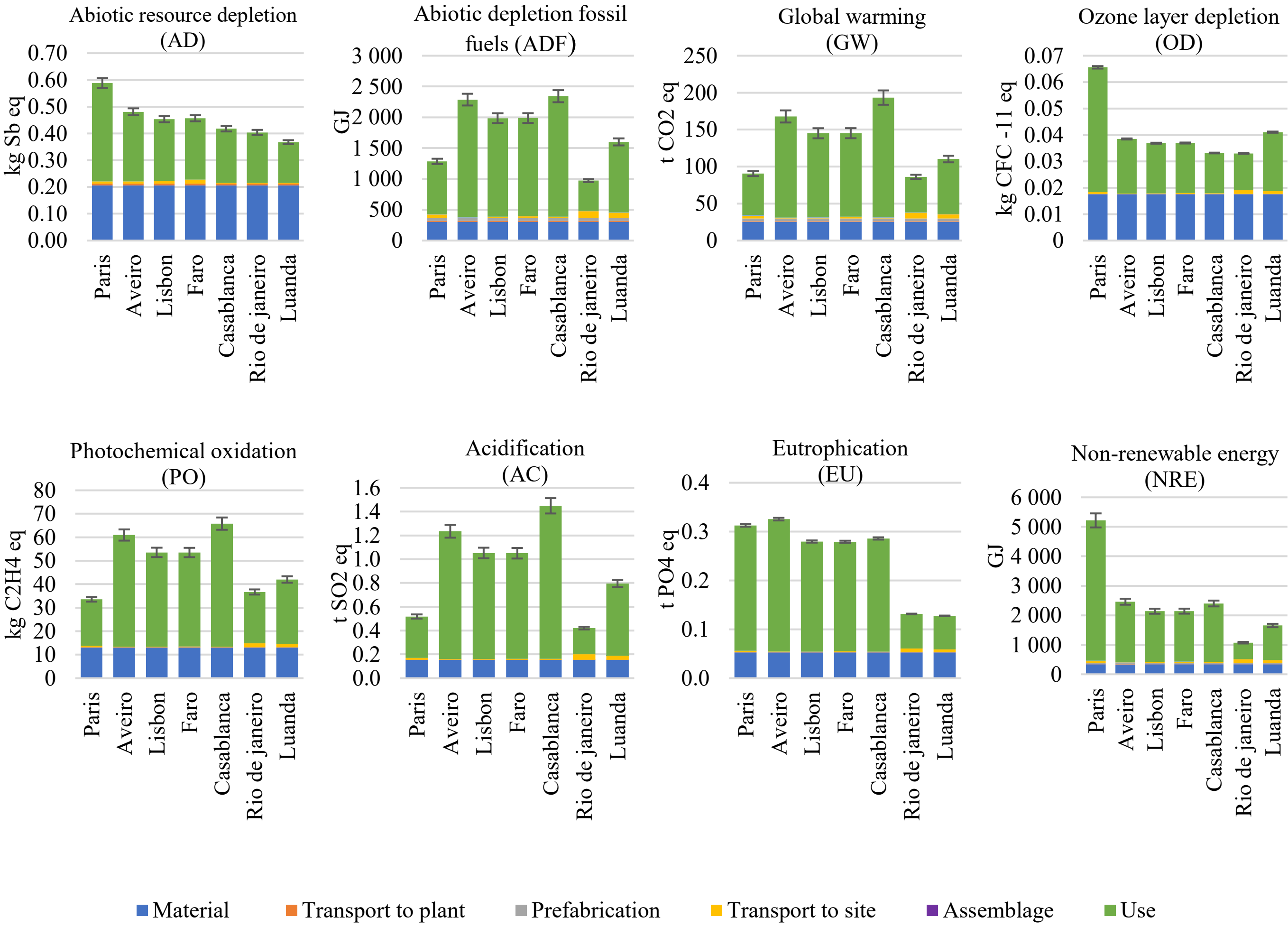


Figure 19 Life cycle environmental impacts for the seven house locations per phase: materials, transport to plant, on plant prefabrication, transport to site, onsite assemblage, and use phase.

4.2.4.3 Use phase

Figure 20 presents impacts of the use phase, divided by materials replacement, heat pump refrigerant, hot water, heat pump system, and other appliances. Heat pump systems and other appliances is the most significant and variable part (35-90% except OD) being influenced by climate and electricity mix, followed by materials replacement with similar impacts for all locations. For the Mediterranean and tropical regions, materials replacement can represent up to 70% of AD due to the reduced need for the HVAC system. Refrigerant represents 30-65% of OD and hot water up to 20% of ADF and

NRE. The efficiency ratio variation of the heat pump system is represented by the variation bar.

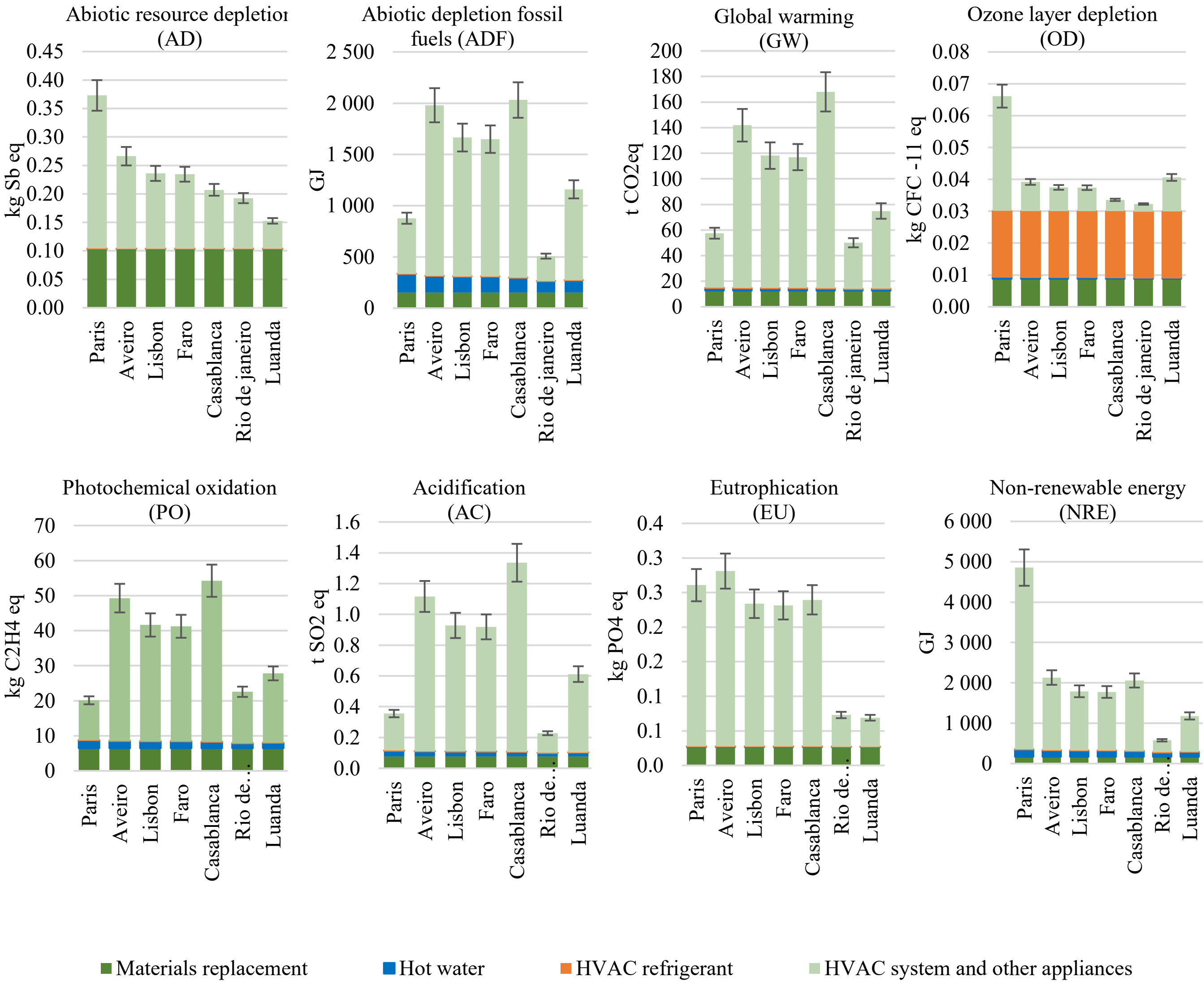


Figure 20 Use phase impacts of the house at the seven locations divided by maintenance works, refrigerant, hot water, heat pump system, and other appliances.

4.2.4.4 Materials

Figure 21 presents impacts of materials divided into foundation, structure, exterior wall, floor, MEP system, exterior wall finishes, interior wall, floor finishes, doors and windows, other elements, and heat pump refrigerant. Results show that for most categories, the floor and exterior wall are the most significant (20-30%), followed by foundations and roof (15-25%); except for OD (dominated by heat pump refrigerant standing for 90%) and AD (with MEP system representing around 40%). Most of the impacts are mass related (materials with higher volume or weight represent a higher share of impacts), except for AD – due to the use of metals such as zinc, brass, and aluminum in the MEP system and other elements – and OD – due to the heat pump refrigerant.

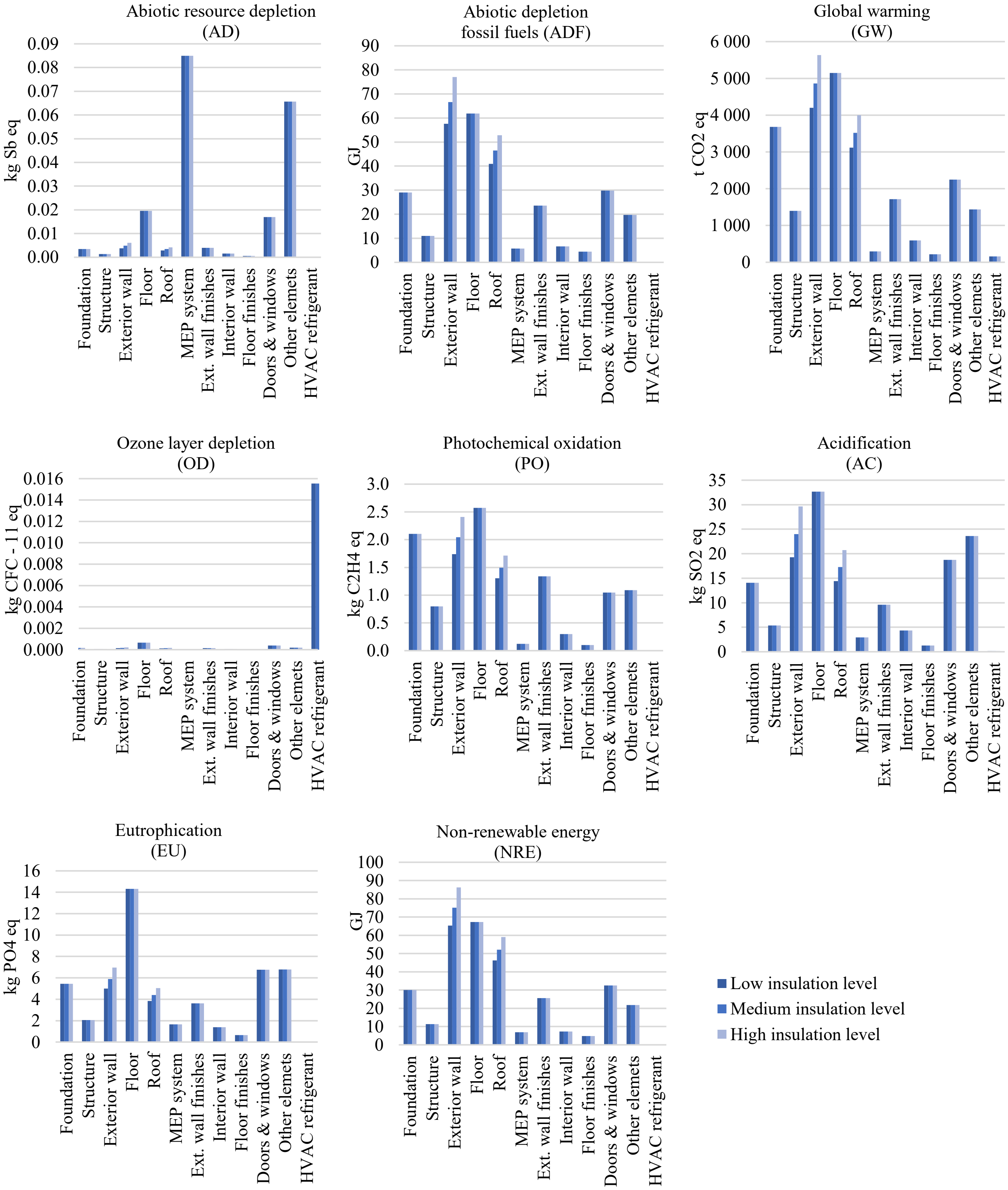


Figure 21 Impacts of materials divided in foundation, structure, exterior wall, floor, MEP system, exterior wall finishes, interior wall, floor finishes, doors and windows, other elements, and heat pump refrigerant.

4.2.4.5 Insulation level

Figure 22 shows results variation while increasing insulation levels from low to medium and from medium to high for the seven house locations. Similar results can be observed for locations within the same climatic regions: dark blue for continental, yellow to orange for the Mediterranean, and green for tropical regions. Results show that the increase of insulation level from low to medium can reduce impacts for continental and Mediterranean regions, reducing the impacts of the house in Paris up to -9% and in the Mediterranean region up to -5%. The increasing of insulation from medium to high presents a smaller decrease or even an increase of impacts for both regions. For the tropical region, increasing the insulation leads to increased impacts in all the categories (up to +3%).

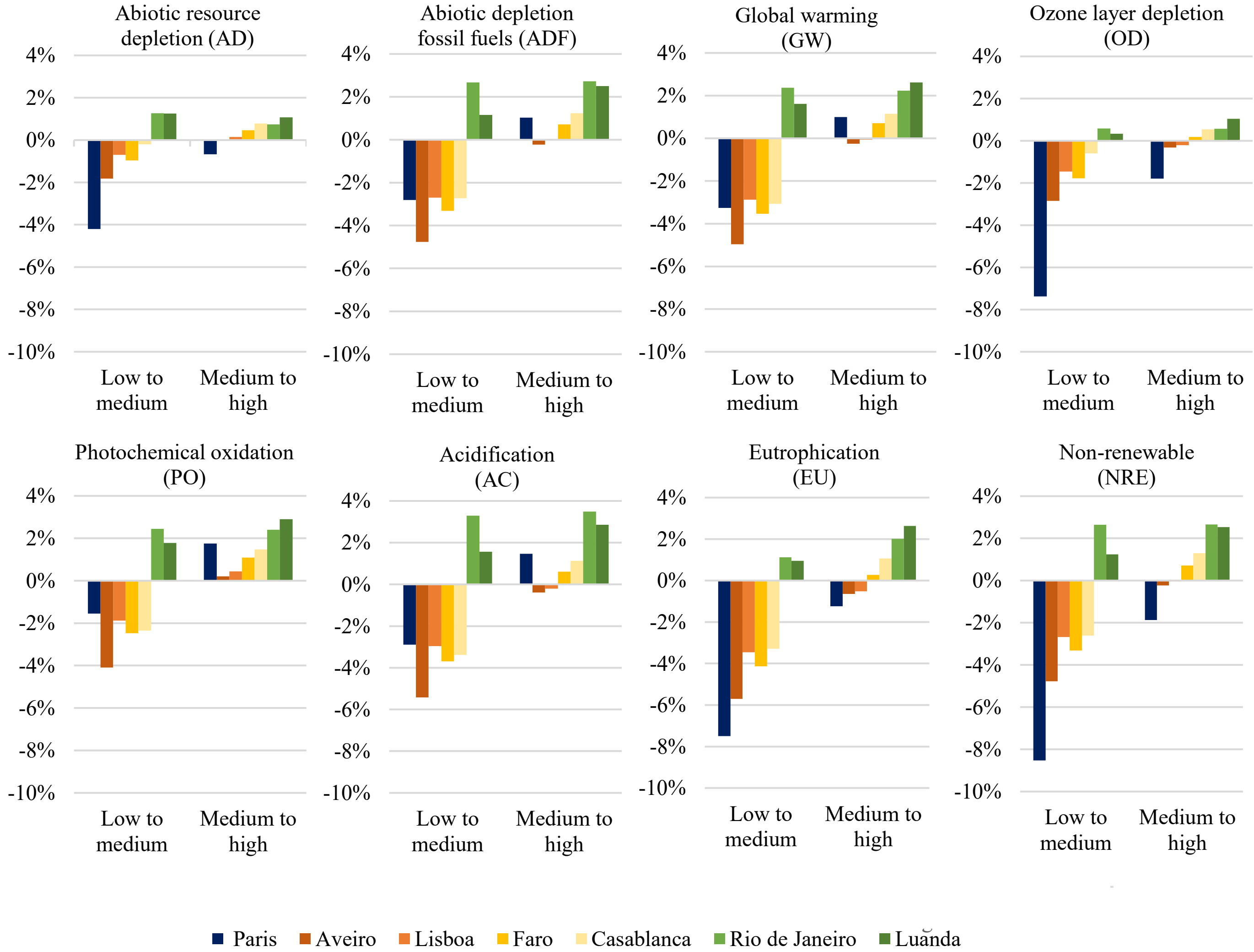


Figure 22 Variation of impacts while increasing insulation levels for the seven house locations

4.2.4.6 Results comparison with literature

The results comparison with previous studies results (presented in section 2.1.2.2, table 5) shows that GW, NRE, and AC are within the range of values presented in the literature, namely (per m^2):

- Embodied: GW 560-672 kg CO_2 eq (in literature 27-949), NRE 7.1 – 8.6 GJ (in literature 3.1 – 15.6); and AC 2.9 – 3.6 kg SO_2 eq (in literature 0.5 – 4.2);
- Operational: GW 860 – 2 890 kg CO_2 eq (in literature 435 – 15 054), NRE 8.8– 35 GJ (in literature 9.5 – 193); and AC 3.9 – 19.2 in kg SO_2 eq (in literature 0.1 – 29.3).

The operational impacts of some categories (EU, OD, PO, and AD) are higher than the results presented in the literature (Table 5) due to differences in the system boundaries and assumptions. In this article, the use phase includes heating and cooling, materials replacement, hot water, and heat pump refrigerant, and considers a 50 years life span, whereas, e.g., Tumminia et al., 2018 considers 25 years of life span.

4. 2.5 Conclusions

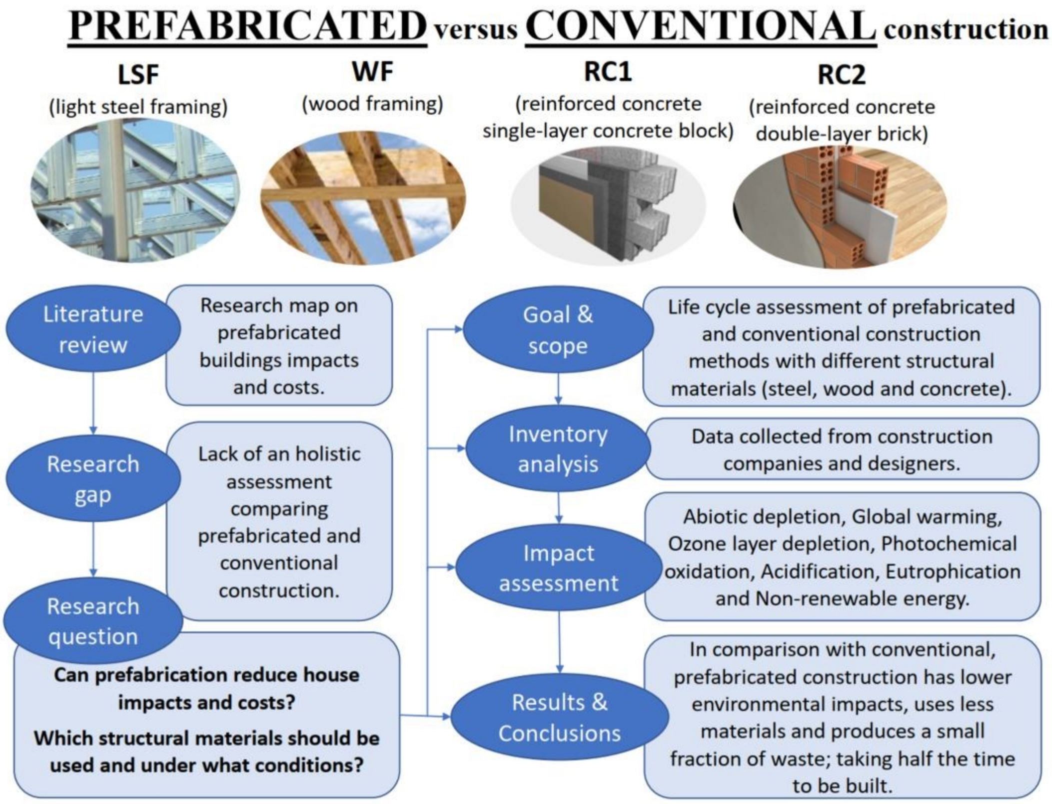
A lightweight one-bedroom prefabricated house with a steel structure was assessed for seven house locations (addressing transport, climate, and electricity mix), three insulation levels, and two heat pumps. A life cycle model was developed addressing materials, modular prefabrication, transport to site, onsite assemblage, and use phase.

Results show that lightweight prefabrication can have lower embodied impacts (due to fewer materials) and have similar operational impacts than conventional heavyweight construction (or lower, if insulation level is adapted to local climate). Operational impacts are the most significant (40-90%), but embodied impacts can reach more than half of total LC impacts for some categories in houses in warm and moderate climates (with lower operational energy needs). Operational impacts are significantly influenced by the house's final location, namely climate, electricity mix, and transport to the site. LC impacts of the house in Paris can be up to 8 times the value of the house in the tropical region. The heat pump system with a higher seasonal energy efficiency ratio (SEER 17.4) uses 10% less operational energy than a heat pump with a lower efficiency ratio (SEER 13), leading to 5% decrease in LC impacts. Increasing the insulation level from low to medium can decrease LC impacts up to less 12% of the house in the cold-climate region and less 8% in the Mediterranean region. Increasing the insulation level from medium to high will reduce the impacts in Paris but may increase the impacts in the Mediterranean (and will increase impacts in the Tropical region).

To reduce operational impacts, buildings should adapt the insulation level to the local climate, as highly insulated lightweight buildings (similarly to heavyweight conventional) may increase operational energy (mainly due to cooling). To reduce embodied impacts, materials with high embodied should be avoided. In a future warmer planet, cooling needs in temperate climate regions (such as the Mediterranean) will increase and may surpass heating, and lightweight prefabricated buildings may better adapt to that future trend.

4.3 What are the main differences between a prefabricated and a conventional house?

Based on: Tavares, V., Soares, N., Raposo, N., Marques, P., Freire, F. (2021). Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. Journal of Building Engineering, Vol.41, 102705. https://doi.org/10.1016/j.jobe.2021.102705 .



Abstract: This section presents a cradle-to-grave of a prefabricated single-family house and alternatives aiming to answer the research question: *What are the main differences between prefabricated and conventional buildings?* And the specific questions: *"Can prefabrication reduce house impacts and costs? Which structural materials should be used and under what conditions?"* This work aims to assess the life cycle environmental impacts, costs, waste, and production time of two constructive systems (prefabrication and conventional) and different structural materials (steel, wood, and concrete) for a single-family house.

4.3.1 Introduction

This work responds to the following research gaps: 1) comprehensive assessments and the comparison between prefabrication and conventional construction are scarce and fail to capture the differences between both approaches (not only in the environmental impacts but also in costs, production time, materials used, and waste generated); 2) most LCA exclude end-of-life, referring to it as an insignificant phase and missing the opportunity (or the challenge) in waste management; 3) most studies focus solely on environmental impacts or costs ignoring that, to be fully implemented, both costs and impacts have to be minimized. This paper presents a comprehensive life cycle and costs assessment that unveils the environmental impacts and costs trade-offs by performing a complete life cycle (LC) comparing conventional and prefabrication, an innovative production approach, using fewer materials, and producing less waste.

4.3.2 Material and methods

The research framework implemented for this article is based on the LCA ISO 14040 standards (ISO, 2006b) which is organized into four phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation, extended to address costs and production time to respond to the research questions (summarized in Figure 23).

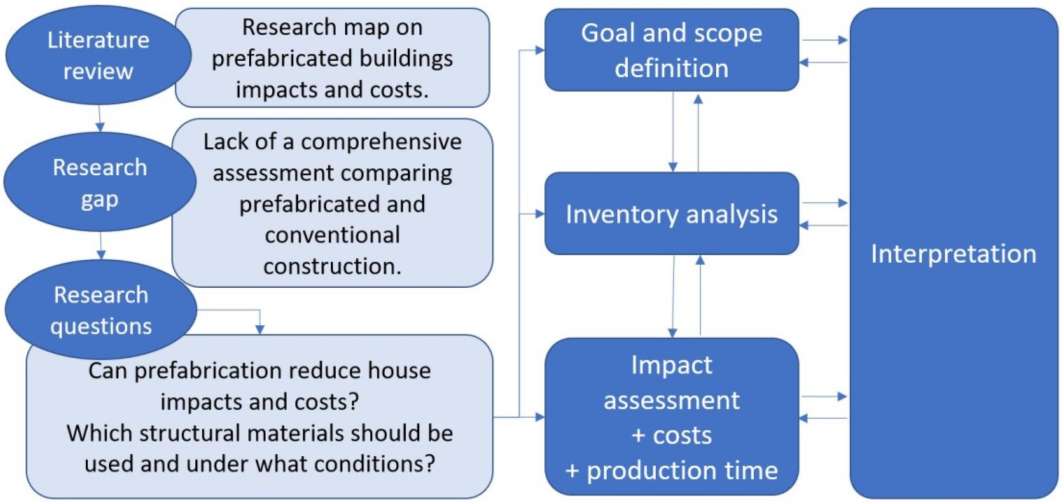


Figure 23 Research framework

4.3.2.1 Goal and scope

A life cycle model and inventory were developed and implemented for alternative construction systems of a single-family house. The main goal is to assess the embodied and end-of-life phases of the two construction methods (prefabricated and conventional) with different structural materials (steel, wood, and concrete).

Figure 24 shows the system boundary. The foreground includes prefabrication and construction and disassembly and demolition. Primary data was collected directly from building companies or experts. The background includes raw materials extraction and transformation, use phase, and end-of-life waste treatment, mainly based on market data and the Ecoinvent 3. The use phase is part of the background, with similar energy consumption assumed for the construction alternatives. An appropriate design of the alternatives (thermal transmittance, users' profile, and HVAC system) was performed to assure a similar use performance, not dependent on the construction method.

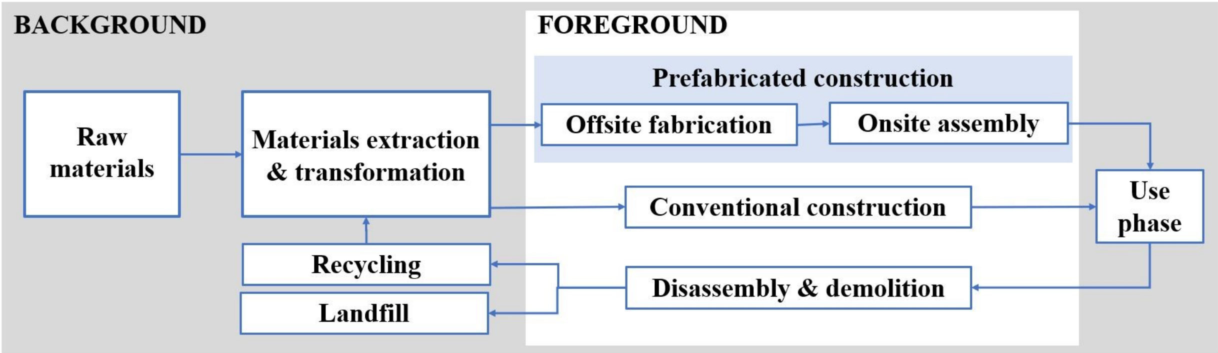


Figure 24 System boundary of prefabricated and conventional construction.

Bill of materials, time, waste rates, and production costs were directly collected from the company producing prefabricated houses and designers to construct the inventory. Current costs were considered to assess the end-of-life stage. Two Life Cycle Impact Assessment (LCIA) methods, CML and Cumulative Energy Demand (CED) have been used to calculate the following impacts: Abiotic depletion (AD), Abiotic depletion (fossil fuels) (ADFF), Global warming (GW), Ozone layer depletion (OD), Photochemical oxidation (PO), Acidification (AC), Eutrophication (EU) (from CML 2001 baseline), and Non-renewable energy (NRE) (from CED). These categories were commonly used in previous studies and are used in the environmental product declaration (EPD) of building materials. The environmental impacts calculations were performed using the SimaPro V8.0 software and Ecoinvent database version 3. The system model approach considered was Allocation at the Point of Substitution (APOS), "the attributional approach in which burdens are attributed proportionally to specific processes, including the treatment of waste allocated by aggregated activity" (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2021).

Figure 25 presents the house, a one-story house built in Portugal (warm-summer Mediterranean climate) with a 125 m^2 living area (3.2 m story height). It includes three bedrooms, two bathrooms, a kitchen, a dining and a living room, a pantry, a corridor, and an entry. The 11 m^2 storage area includes the laundry and a storeroom. The gross floor area is 249 m^2 (including porches, storage, utility spaces, and carports), and 50 years lifespan was considered.

Figure 25 Picture, 3D views, floor plan, and elevations of the single-story house.

4.3.2.1 Life cycle inventory: four construction systems

Four construction systems were modeled: prefabricated light steel framing (LSF) and wooden frame (WF); and conventional reinforced concrete with a single layer concrete block (RC1) and with a double-layer brick external wall (RC2). The LSF and WF structures are lighter and very suitable for dry prefabricated construction being commonly used in prefabrication; RC is a heavyweight structure used in the vast majority of conventional Southern European construction. Balthazar Aroso Arquitectos Lda designed LSF construction. (www.balthazar-aroso.com), manufactured and assembled in the North of Portugal using the prefabricated LSF System B(A)ª (www.urbimagem.com) as presented in Figure 26. Further details about the LSF System B(A)ª can be found in Rodrigues et al. (2018) and Soares et al. (2017). A detailed execution project for the other three construction systems was developed by designers, including the activities and bill of quantities that allowed to construct the inventory.

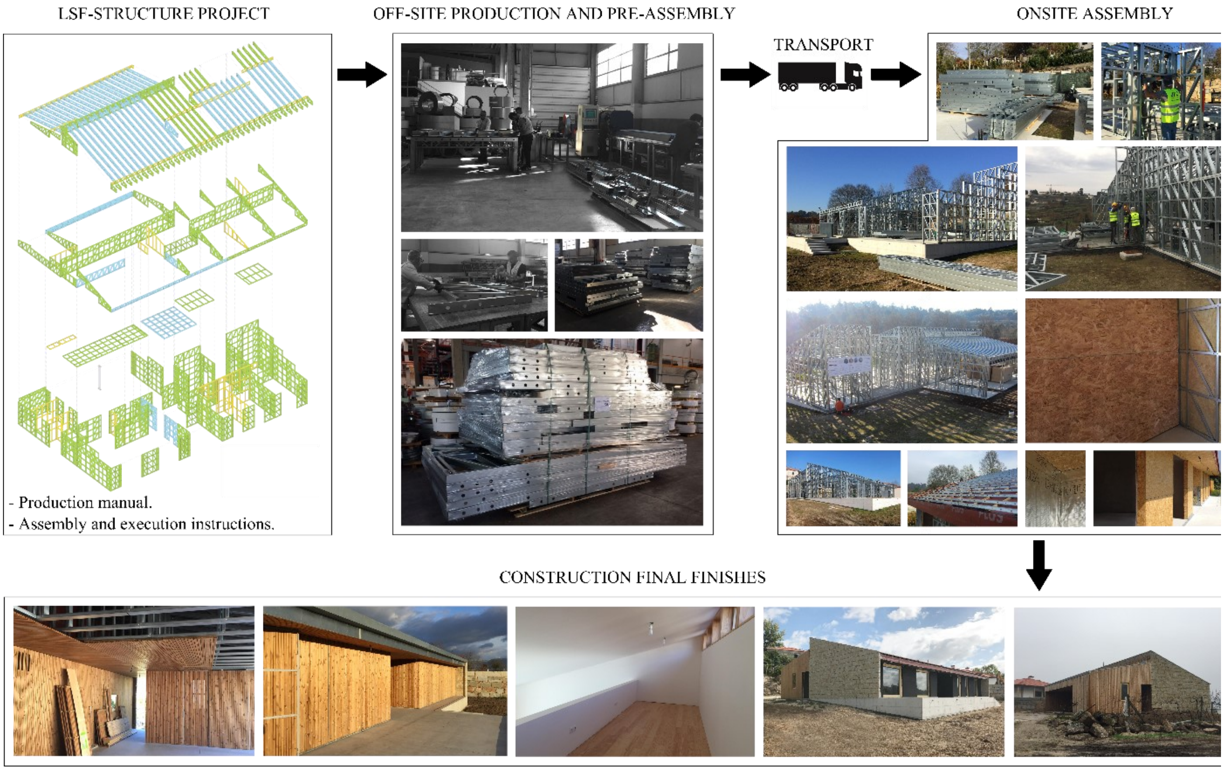


Figure 26 The single-family house building process with the LSF construction.

Materials and activities inherent to each construction alternative were included in the assessment, and the common ones were considered out of the scope (e.g., windows, doors, HVAC system, water, and wastewater collection systems, lighting, electricity, home automation systems, furniture, landscaping activities and finishes, etc.). The building envelopes associated with each construction system have similar thermal transmittance (*U*-value) to guarantee similar heating and cooling energy demand. Different insulation layer thicknesses were considered at the external walls and roofs of the four alternative scenarios to achieve the same *U*-value. The effect of thermal mass was neglected.

The following assumptions were considered for all the alternatives: internal surface resistances of 0.13m^{2}K/W (horizontal heat flux) and 0.10 m^{2}K/W (heat flow upwards); for the ventilated air gaps, the thermal resistance of the air equals zero, and the surface resistances are equal to the previous values. The thermal resistance of the vapor permeable and water control layers was neglected in the calculation of the *U*-values. In the LSF, a simplified method was used to account for the effect of thermal bridging caused by steel framing components in the calculation of the *U*-value of the hybrid-framed LSF walls (Doran and Gorgolewski, 2002; Gorgolewski, 2007) and was used (p = 0.5). The method is similar to the one presented in the ISO 6946:2007 (2017) and was used in previous studies (Rodrigues et al., 2018; Soares et al., 2014).

Figure 27 shows the cross-section and the *U*-value of the building envelope (external wall and roof) of each alternative. The LSF system uses a single cold-formed shape profile (C100×45×1.2 mm), and for the walls were considered: stud and nogging spacing of 625 mm, flange width of 45 mm, and studs of 100 mm deep made of 1.2 mm thick steel. The wood-framed structural system is composed of Glulam GL24H beams and columns secured by aluminum alloy connectors, and the bracing against horizontal loads consists of steel tie rods connecting adjacent columns. The RC structural system consists of a space frame made with C30/37 concrete and A500 reinforcing bars, and the roof is made of prestressed T beams and infills hollow concrete blocks.

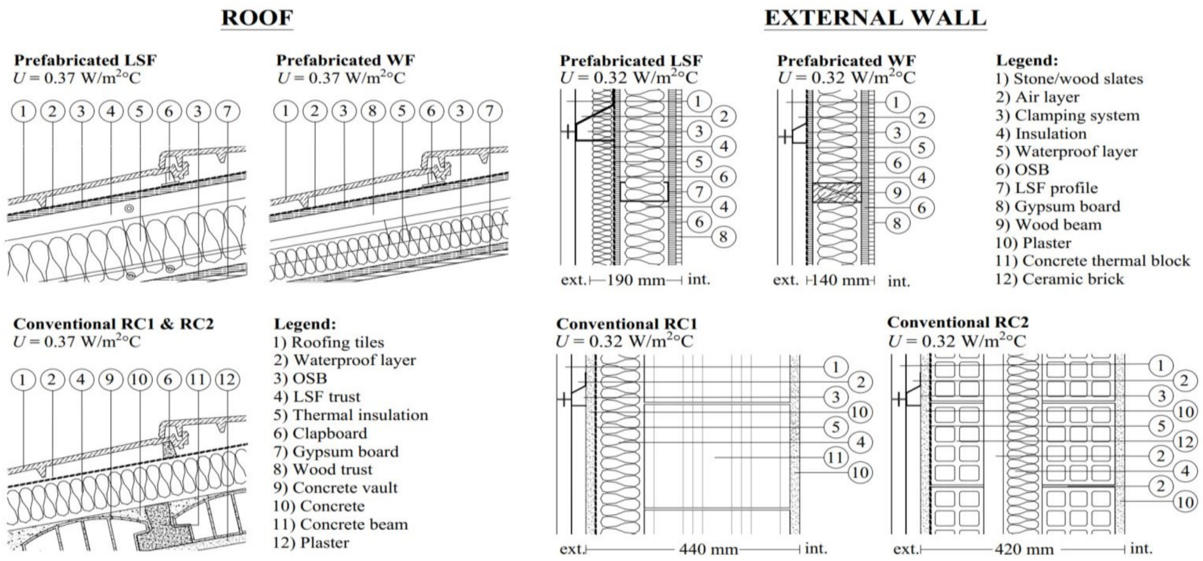


Figure 27 Cross-section of the roof and the external wall of the prefabricated (LSF and WF) and conventional (RC1 and RC2) construction (not to scale).

Table 21 presents the inventory of the four construction alternatives per life cycle phases: (1) materials divided by element: foundation and ground floor, floor, external wall, internal wall, and roof; (2) off-site prefabrication includes transport (to and from the plant), labor, electricity, water, and production waste; (3) onsite assembly and construction include transport (to and from the construction site), labor, electricity, water, and construction waste; (4) use phase includes space heating and cooling, energy, and water use; (5) disassembly and demolition includes (transport to and from demolition site), labor, electricity, water, and demolition waste; (6) waste treatment includes transport (to waste treatment facilities) and waste recycling, landfilling and incinerating activities. The inventory includes the gross amount of materials required and waste from production, construction, and demolition. For the use phase, 40-80 kWh/m^2 of electricity consumption per year was considered for heating and cooling needs, and no electricity consumption for other appliances was considered. For the LSF structure, it is assumed that 85% of the steel will be sent for recycling at the EoL, while the RC structure will be 43%.

Table 21 Life cycle inventory for the prefabricated (LSF and WF) and conventional (RC1 and RC2) alternatives.

Life cycle phase	LSF	WF	RC1/ RC2
1. MATERIALS (kg)	51231	46602	260575[1] /260247[2]
Foundations (kg)			
Concrete	12480	12480	17885
Reinforcing steel	385	385	577
Formwork wood	244	244	412
Polyethylene	9	9	9
Floor (kg)			
Cold-formed Steel	308	-	-
Structural wood	-	435	-
Concrete	-	-	4570
Reinforcing steel	-	-	343
Oriented strand board	364	364	-
Formwork wood	-	-	429
Concrete vaults	-	-	2138
Concrete beams	-	-	6942
Aluminum	-	48	-
Internal wall (kg)			
Cold-formed steel	1129	-	-
Structural wood	-	205	-
Concrete	-	-	2990
Reinforcing steel	-	-	312
Formwork wood	-	-	411
Gypsum board	1920	1920	-
Ceramic bricks	-	-	22500
Plaster	-	-	3900
Steel connectors	-	49	-
Roof (kg)			
Cold-formed steel	4058	-	-
Structural wood	-	4450	-
Concrete	-	-	33528
Reinforcing steel	-	-	2231
Formwork wood	-	-	2157
Concrete vaults	-	-	16980
Concrete beams	-	-	53716
Oriented strand board	3120	3120	-
Ceramic tiles	4000	4000	4000
Polyester	30	30	30
Polyethylene foam	30	30	-
Mineral wool	1800	960	1200
Gypsum board	4000	4000	4000
Aluminum	-	97	-
External wall (kg)			
Thermal concrete block	-	-	61850[1]
Bricks	-	-	61750[2]
Gypsum board	1824	1824	-
Granite	4900	4900	4900
Plaster	-	-	2470
Mineral wool	1710	1140	1140[1]/ 912[2]
Cold-formed steel	4056	-	-
Structural wood	-	863	-
Concrete	-	-	6101
Reinforcing steel	-	-	636
Oriented strand board	3458	3458	-
Formwork wood	-	-	839
Wooden slaters	1350	1350	1350
Polyester	29	29	29
Polyethylene foam	29	29	-
Steel connectors	-	185	-

Life cycle phase	LSF	WF	RC1/ RC2
2. OFFSITE PREFABRICATION			
Transport			
Materials (tkm)	40287	26008	-
Workers (pkm)	2800	2800	-
Waste (tkm)	13	14	-
Prefabrication			
Labor (h)	672	672	-
Electricity (kWh)	240	240	-
Water (l)	65	65	-
Production waste (kg)	265	289	-
3. ONSITE ASSEMBLY/ CONSTRUCTION			
Transport			
Modules to site (tkm)	825	664	-
Materials (tkm)	3893	3822	240655[1]/240639[2]
Workers to site (pkm)	8067	12833	20167
Waste (tkm)	65	67	482[1]/ 406[2]
Assemblage / construction			
Labor (h)	2112	2816	7040
Electricity (kWh)	3000	3000	6000
Water (l)	150	150	300
Construction waste (kg)	2590	2697	18496[1]/ 17893[2]
4. USE PHASE (50 years)			
Electricity (MWh)	340-680	340-680	340-680
Water (ton)	10950	10950	10950
5. DISASSEMBLY/ DEMOLITION			
Transport			
Workers (pkm)	133	133	67
Deconstruction / demolition			
Labor (h)	1232	1232	616
Electricity (kWh)	1000	1000	500
Water (l)	50	50	50
Demolition waste (kg)			
Insulation materials	3454	2115	2287[1]/ 2071[2]
Mixture concrete & bricks	-	-	97942[1]/ 41386[2]
Bricks	-	-	20925[1]/ 82073[2]
Concrete	11856	11856	72079
Tiles & ceramics	3800	3800	3800
Wood	7794	13390	1148
Aluminum	-	145	-
Iron and steel	9725	588	53893
Gypsum-based	7357	7357	9852
Mixed CDW	4655	4655	4655
6. WASTE TREATMENT			
Transport (tkm)			
Demolition waste	1216	1098	5422[1]/ 5531[2]
Waste treatment (kg)			
Recycled	17348	13142	74572[1]/ 103286[2]
Landfilled	23499	23899	165485[1]/ 136844[2]
Incinerated	7794	6865	1148

[1] Referring to RC1
[2] Referring to RC2

4.3.3 Results

This section presents LC results divided into embodied and end-of-life impacts, costs, production time, and waste. Use phase impacts vary between 45-90% of total impacts (depending on the construction system and impact category) and are identical for the four construction systems.

4.3.3.1 Embodied and end-of-life impacts

Figure 28 presents the life cycle impacts, excluding the use phase. The impacts are divided into (i) embodied impacts, including materials extraction and transformation, transport to plant, off-site prefabrication, transport to site, onsite assembly, and construction, and (ii) end-of-life impacts, including disassembly or demolition, transport to waste facilities, and waste treatment.

Prefabricated construction has significantly fewer impacts than conventional construction for most impact categories (less 20–63% for ADFF, GW, OD, AC, and NRE). WF has the lowest impacts in all categories, having half the impacts of RC1 and RC2 (except for AD and OD) and 10–50% less than LSF (except for AD). Results show that prefabricated LSF presents an increase in AD (more 26-32%) and smaller reduction (less 7-19%) for PO and AC, compared with conventional construction. Regarding the two prefabricated construction, LSF has significantly more impacts than WF (more 17-78%), while for conventional construction methods, RC1 has more impacts than RC2 for GW, PO, AC, and EU (more 18-42%).

Embodied impacts vary 7-54 % of total life cycle impacts and are mainly influenced by materials that represent *ca.* 60–90% of embodied impacts. The second most significant phase for prefabricated construction is off-site prefabrication (5–22%), while the in the conventional construction is the construction phase (13–27%). Figure 28 shows an important reduction in the total impacts of the LSF structure due to the recycling of the steel at the end-of-life (less 15-35% in NRE, EU, PO, GW, and ADFF).

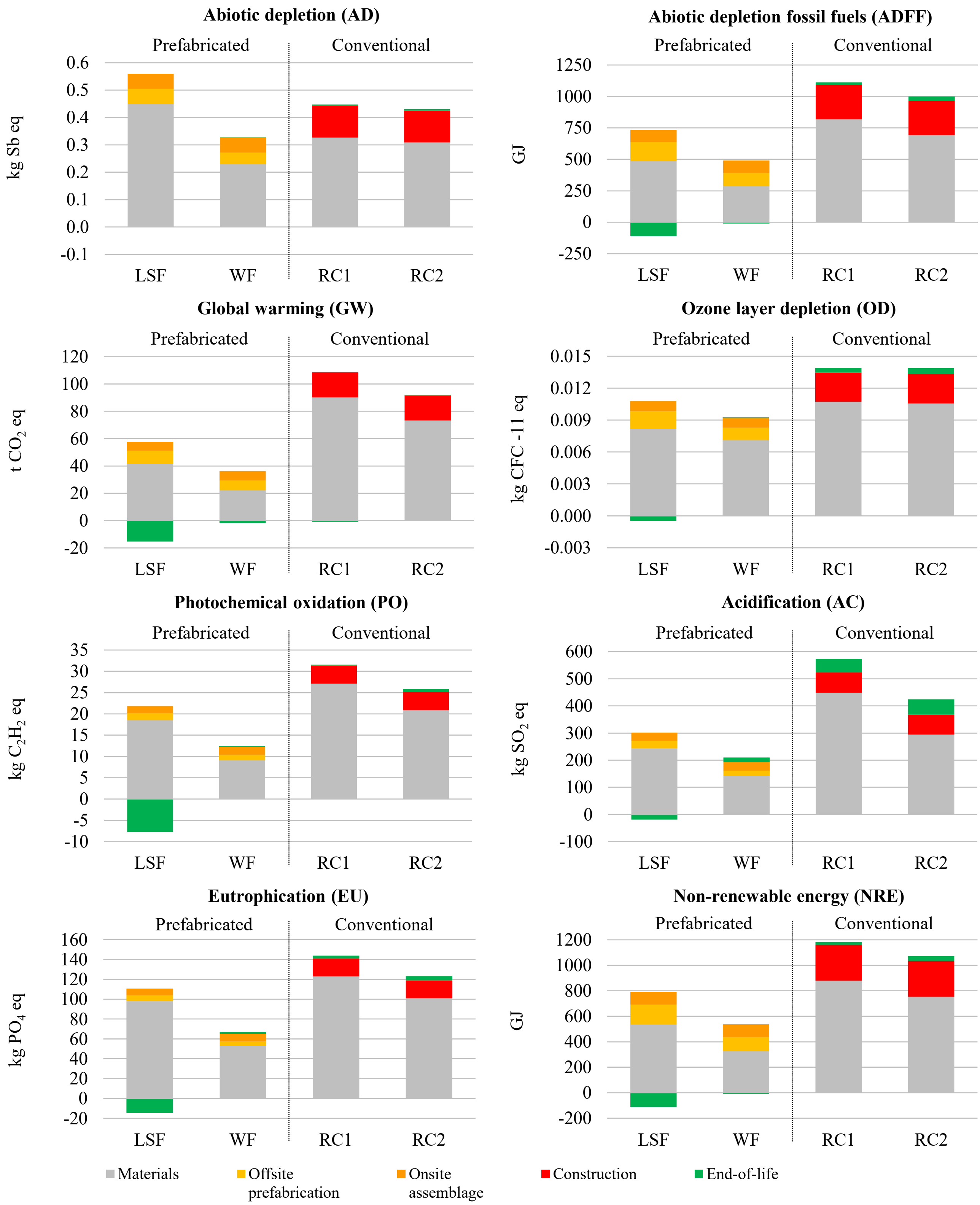


Figure 28 Embodied (materials, off-site prefabrication, onsite assemblage, and construction) and end-of-life energy and environmental impacts for the prefabricated (LSF and WF) and conventional (RC1 and RC2) construction.

Figure 29 shows the life cycle impacts of materials per building element (foundations, floor, external walls, internal walls, and roof). The external wall and the roof are the most critical elements summing up 75–95% of materials, followed by foundations and internal wall. The roof has an important contribution to all impacts (30-95%) except for OD (representing 10-20%). The external wall represents 30-80% of impacts (except for AD, representing 10-25%). However, architectural design deeply influences building elements as another layout (e.g., a different external wall to gross floor area ratio) would change the relative weight of elements in the global impacts.

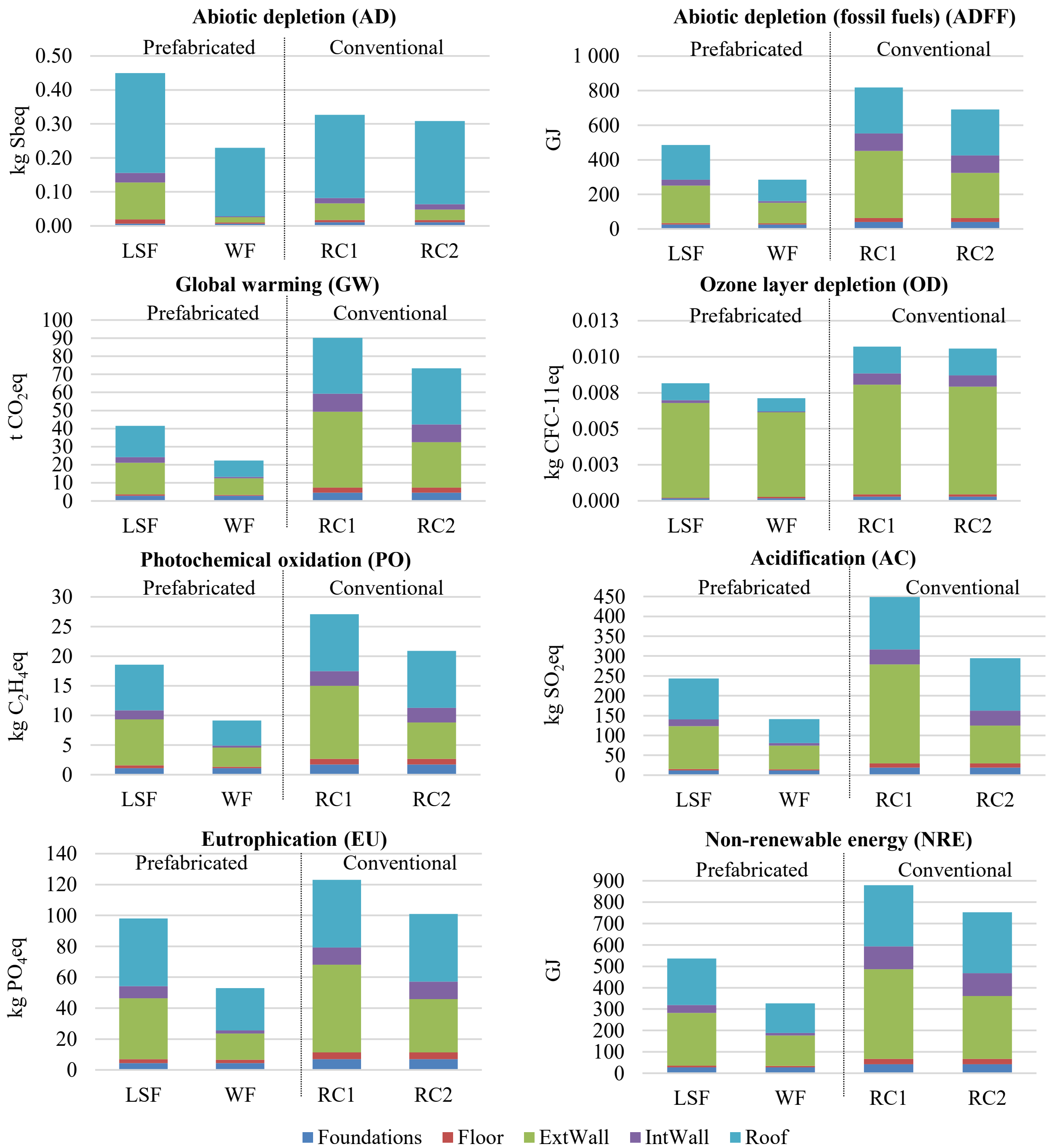


Figure 29 Life cycle impacts of materials, per building element, for the prefabricated (LSF and WF) and conventional (RC1 and RC2) construction.

4.3.3.2 Costs

Figure 30 shows the embodied and end-of-life costs for prefabricated and conventional construction methods. Use phase costs have not been included because they are similar for all four alternatives and are highly dependent on the users' profiles. LSF has the lowest total cost due to low onsite assemblage costs, and WF has the highest costs due to materials and onsite assemblage. However, the variation in the total costs of the four alternatives is lower than 20%.

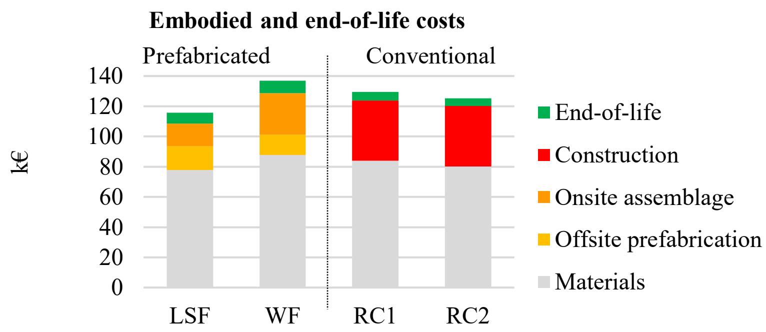


Figure 30 Embodied and end-of-life costs for the prefabricated (LSF and WF) and conventional (RC1 and RC2) construction.

4.3.3.3 Production time

Figure 31 presents the time associated with prefabrication, onsite assembly or construction, and end-of-life disassembly or demolition of the four alternatives, considering the sequential performance of works (a) or that the off-site prefabrication is done simultaneously to site works (b). In comparison with conventional, prefabricated construction takes around 2/3 of the time to build or almost half of the time if the prefabricated stage is simultaneously done with site works.

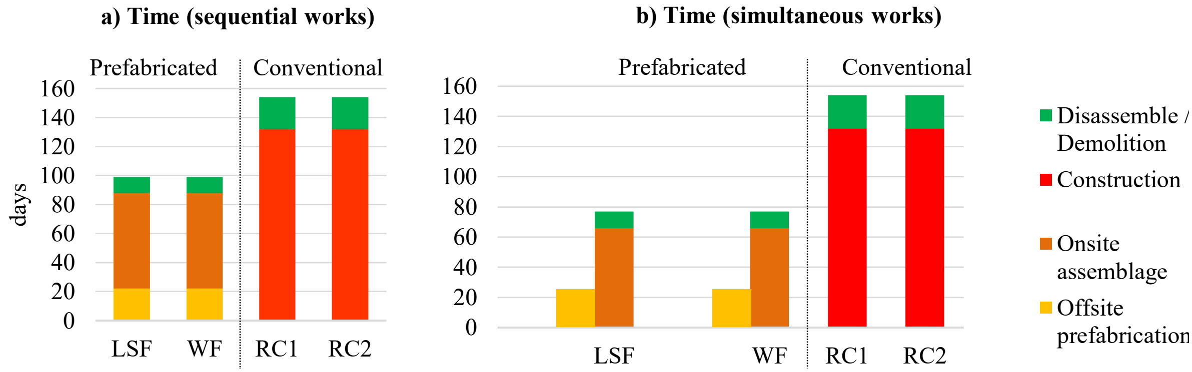


Figure 31 Time for prefabrication and disassembly (LSF and WF) and construction and demolition (RC1 and RC2) considering sequential (a) or simultaneous works (b).

4.3.3.4 Waste

Figure 32 shows construction (a) and demolition waste (b) for the four construction systems. The total waste associated with prefabricated construction (LSF and WF) is around 20% of the RC1 and RC2. In addition, prefabricated construction has a lower rate of landfill waste (43% for LSF and 49% for WF) compared to RC (62-76%), with half of the waste being recycled or incinerated. Waste recycling is higher in prefabricated buildings not only because of the type of materials used but also because it is a dry assembly system enabling the complete separation of materials.

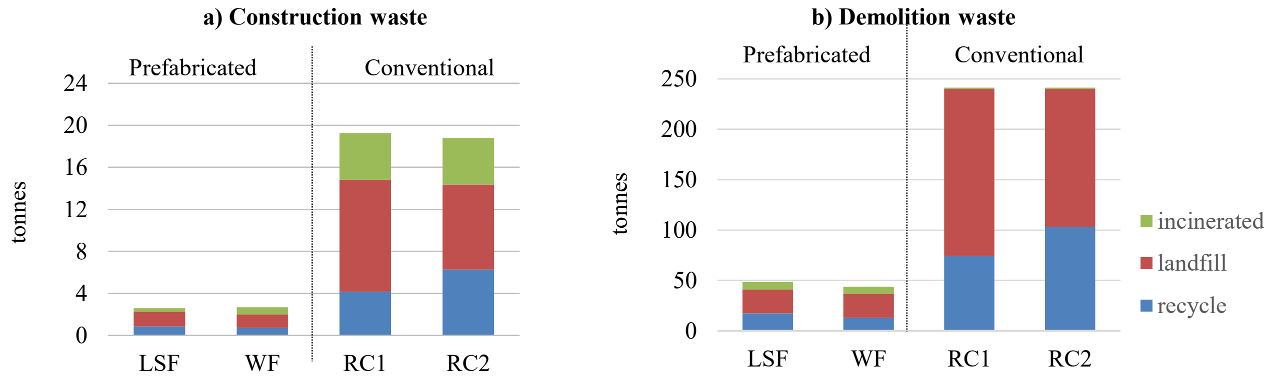


Figure 32 a) Construction and b) demolition waste for the prefabricated (LSF and WF)

4.3.4 Discussion

Embodied impacts can represent more than half of total life cycle impacts, demonstrating the importance of the embodied phase. In comparison with conventional construction, prefabricated houses have up to 65% less embodied impacts. Prefabricated houses fit the low edge of the values presented in Table 6 (section 2.1.2.4) for previous studies. The embodied impacts of the prefabricated LSF house are c.a. 167kgCO_2eq/m^2 and 2.2 GJ/m^2 (in literature, the values are typically in the 63-864 CO_2eq/m^2 and 1.0-14.4 GJ/m^2 ranges for steel structure houses); while for the WF house these values are about 145 CO_2eq/m^2 and 2.2 GJ/m^2 (in literature, these values are about 26-630 CO_2eq/m^2 and 2.1-10.5 GJ/m^2 for WF houses). The embodied costs are about 436 €/m^{2}for LSF, 516 €/m^2 for WF, 497 €/m^2 for RC1 and 482 €/m^2 for RC2. In literature, the embodied costs typically range from 400 €/m^2 to 1400 €/m^2 [24,33]. Therefore, the results are in accordance with the values provided in the literature. In addition, steel recycling contributes to reducing impacts at the end-of-life (EoL). The prefabricated LSF house has -61 kg CO_2eq/m^2 and -0.5 GJ/m^2 of EoL impacts, fitting the literature range (-227.7-(-0.17) CO_2eq/m^2 and -11.7-(+0.20) GJ/m^2). Moreover, considering a circular economy perspective, prefabricated buildings use less materials (weighting roughly ¼ of conventional construction) and produce less waste (with a higher recycling rate).

The total costs variation between prefabricated and conventional construction is below 20%, and materials are responsible for more than 50% of the total cost. Even though prefabricated construction weights five times less than conventional, costs are roughly similar because the costs of conventional materials (concrete and bricks) is much lower than prefabricated materials (steel or wood). Moreover, some prefabricated-related costs reductions might be underestimated, as costs reduction due to large scale production is envisaged but has not been accounted for. Finally, shorten production time should be viewed as an added value, but as it is highly dependent on market fluctuation, it has been disregarded.

Within both prefabricated houses, the light steel house (LSF) has up to 50% more burdens than the prefabricated wood house (WF), showing the influence of the structural material. Within both conventional, single layer concrete block wall house (RC1) has up to 40% more burdens than a double layer brick wall house (RC2), showing the influence of external wall composition. Besides all these variations, we can affirm that prefabricated buildings have lower environmental impacts and costs the same (or even less) than conventional buildings while having a similar performance, using less materials, and producing less waste.

Some of the simplifications and assumptions of this work led to limitations and potential uncertainties. The LC model adopted for background processes average European data for materials, similarly for all alternatives and system boundaries. Background data homogenously represents the group of suppliers. Use phase impacts were statistically calculated considering a ± 33% variation; however, results are expected to hold as the four houses have similar energy performances. End-of-life is expected to be different 50 years from now with higher recycling rates and material recycled contents, but changes are difficult to forecast. Different house designs could lead to different results. This study has focused on a specific house and location, and results may not represent different building sizes. This was previously discussed in Tavares et al. 2019 (Vanessa Tavares et al., 2019), concluding that impacts per m^2 are similar among different size prefabricated houses.

4.3.5 Conclusions

This section presents a life cycle assessment (LCA) comparing two constructive systems (prefabrication and conventional) and different structural materials (steel, wood, and concrete) for a single-family house, considering impacts, waste, costs, and production time.

In comparison with conventional construction, prefabricated construction has lower environmental impacts (with the exception of abiotic depletion for LSF), uses less materials, and produces a small fraction of waste, taking half the time to build. WF has the lowest environmental impacts for all the categories but slightly higher cost. LSF has the lowest life cycle cost. Differences exist within the same building process: for prefabricated alternatives, WF has fewer impacts and lower costs than LSF; and for conventional, RC2 has fewer impacts (except for OD) and a similar cost than RC1. Including the end-of-life presents a more holistic insight over buildings' assessment showing that prefabrication can present an opportunity to decrease buildings' impacts, not only during production but also at the end-of-life.

The difference in the total cost of the four alternatives is lower than 20% of the total cost. Construction costs are variable and highly sensitive to local costs (e.g., labor and materials), so the ability to relocate part of the building process might present a significant economic advantage for prefabricated buildings, reducing prefabrication (and buildings) costs, although transport cost ought to be considered.

This section presented a comprehensive assessment comparing prefabricated with conventional construction, balancing embodied, operational, and end-of-life impacts and costs, unveiling the importance of embodied and end-of-life phases. Hotspots and improvement opportunities have been identified for a single-family house. Prefabrication can reduce impacts, material use, waste, and production time for a similar operational performance, leading the way towards a more circular construction sector.

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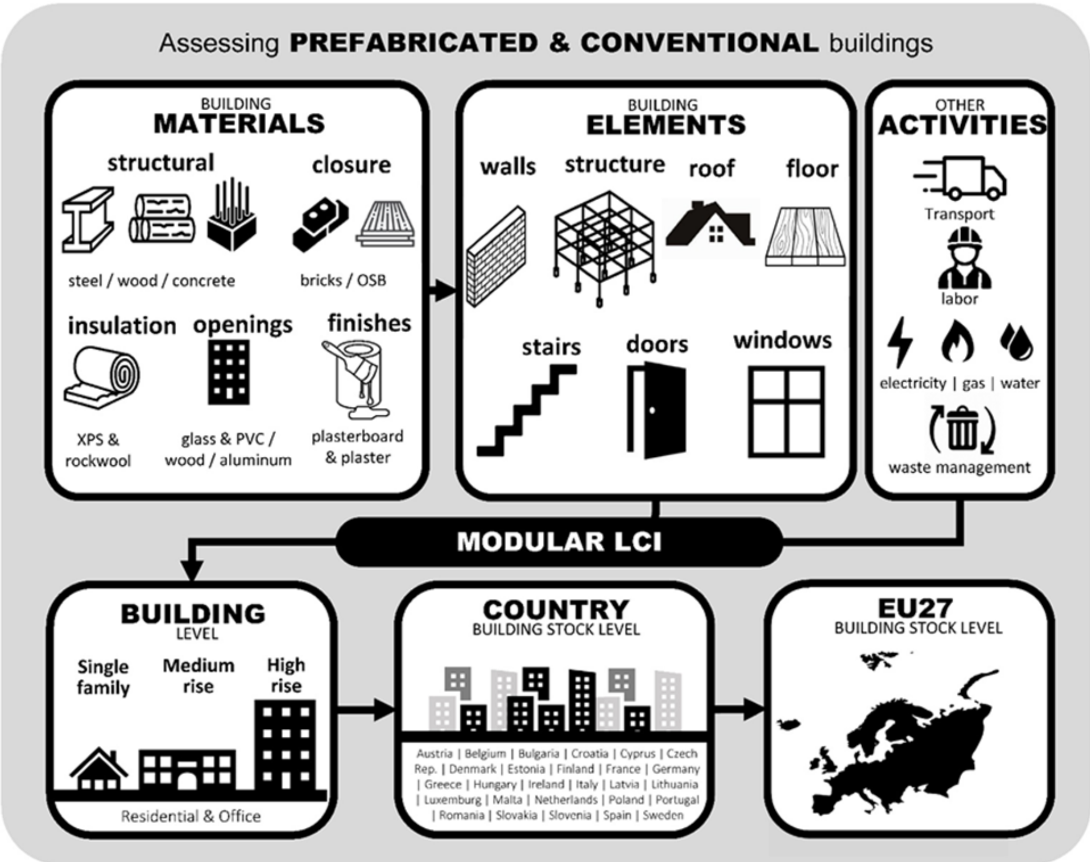
CHAPTER 5 STOCK-BASED APPROACH FOR THE EU-27

This chapter presents the developed building stock model (BSM) aiming to answer the following research question: *What is the potential for prefabrication buildings to decrease the environmental impacts and costs of the EU building stock?* And the methodological question: *Can a building stock model approach developed combining LCA, BIM, modular LCI, and statistical aggregation is a streamlined approach to assess a large set of alternatives in a wide area?* The developed BSM includes archetypes definition, energy demand model, modular LCI, and stock aggregation. Results are presented at the building stock level, country level, and building level, and the contribution to the EU-27 targets discussed.

5.1 What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?

Based on: Tavares, V., Gregory, J., Kirchain, R., Freire, F. (2021). What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? Journal of Building and Environment. Vol.206, 108382 https://doi.org/10.1016/j.buildenv.2021.108382.



Abstract: A stock-based approach was developed and implemented to assess prefabrication wide adoption at the EU-27 building stock level. The stock-based approach responds to the need to assess a wide range of buildings at different places. A modular life-cycle inventory was constructed to calculate non-renewable energy (NRE), global warming (GW), and the costs of each archetype in each city. After, results were aggregated at the stock level using country-specific typology distribution (typologies and structural materials) defining the baseline. Future stocks were forecasted using stock dynamics (growth and replacement rates) and future hypothetic scenarios (considering prefabrication adoption) and then compared with baseline, thus identifying the impacts reduction potential. Results are presented at the building, the country, and the EU-27 stock level.

5.1.1. Introduction

The main goal of this research is to analyze building prefabrication adoption's potential contribution to the EU's twin challenges of sustainability and affordability in the construction sector (European Commission, 2020b). The main research question is stated in the title of the manuscript: *what is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?* Present work compares equivalent buildings with similar energy performance: new prefabricated buildings with new conventional buildings. A stock-based approach combining archetypes, dynamic energy simulation, modular life cycle inventory (LCI), and a statistic-based stock aggregation was developed to measure the influence of wide adoption of building prefabrication in the EU-27 building stock impacts and costs from 2020 to 2050.

5.1.2. Building stock model

One-third of buildings in the European Union (EU) are over 50 years old, and most of the building stock is energy inefficient. Buildings are responsible for more than one-third of energy consumption and CO_2 emissions in the EU (European Commission, 2019a). Several research projects have been conducted to evaluate the environmental impacts of the building stock and identify improvement opportunities: i) IMPRO Buildings project (2006-2008) assessed the potential to decrease the EU-15 stock impacts by implementing refurbishment measures (Nemry and Uihlein, 2008a; Uihlein and Eder, 2009); ii) TABULA (2009-2012) mapped residential building technologies and the following (Loga et al., 2016); iii) EPISCOPE (2012-2014) aimed to assess refurbishment processes and forecast energy consumption in the future building stock models (Serghides et al., 2015; Stein, B.; Loga, T.; Diefenbach, 2016), and iv) ENTRANZE (2012-2014) sought to support nearly zero energy buildings (nZEB) and renewable energy sources for heating and cooling implementation (Kranzl et al., 2014; Zangheri et al., 2014). Some studies forecasted future stock size (Lavagna et al., 2018); others focus on impacts (Sartori et al., 2016). Some evaluated a business as usual (BAU) scenario (Nägeli et al., 2020) and others alternative scenarios (Nemry et al., 2010; Vásquez et al., 2016). Previous research assessed energy efficiency measures and refurbishment scenarios, but none analyzed the influence of wide adoption of building prefabrication at the EU-27 building stock scale (previously discussed in section 2.5)

A stock-based approach of combining BIM-LCA integration and statistical distributions was developed and implemented to better understand the cradle-to-grave impacts and costs of buildings (individually) and the building stock (as a whole) in each country and EU-27, from 2020-2050. This building stock approach aims to assess the influence of wide adoption of prefabrication to help decision-makers define future measures to achieve EU environmental targets.

Figure 33 presents the stock-based approach developed to quantify the impacts and costs of the EU building stock over time and assess different scenarios considering the adoption of building prefabrication. Five buildings were modeled to represent the EU-27 building stock: single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO), and high-rise office (HO), representing the building stock in Europe (EU building stock characterized in appendix III, table III.1, table III.2 and table III.3). Three different structural materials (steel, wood, and concrete) and three insulation levels were considered, summing up 45 archetypes. The distribution of the three structural materials across the EU-27 countries is described in table III.5. The operational energy use of these archetypes was calculated for three cities: Lisbon representing warm countries in zone 1 (Z1), Berlin representing moderate countries in zone 2 (Z2), and Stockholm representing cold countries in zone 3 (Z3). Climatic zones are based on climatic data (see table III.1), IMPRO study (Uihlein and Eder, 2009), and EU buildings observatory (European Commission, 2016).

A modular life-cycle inventory was constructed to calculate the indicators of non-renewable energy (NRE), global warming (GW), and the costs of each archetype in each city. After, indicators were aggregated at the stock level using country-specific typology distribution (of typologies and structural materials) defining baseline. Future stocks were forecasted using stock dynamics (growth and replacement rates) and future hypothetic scenarios (considering prefabrication adoption) and then compared with baseline, thus identifying the improvement potential. Results are presented at the building, the country, and the EU-27 stock level.

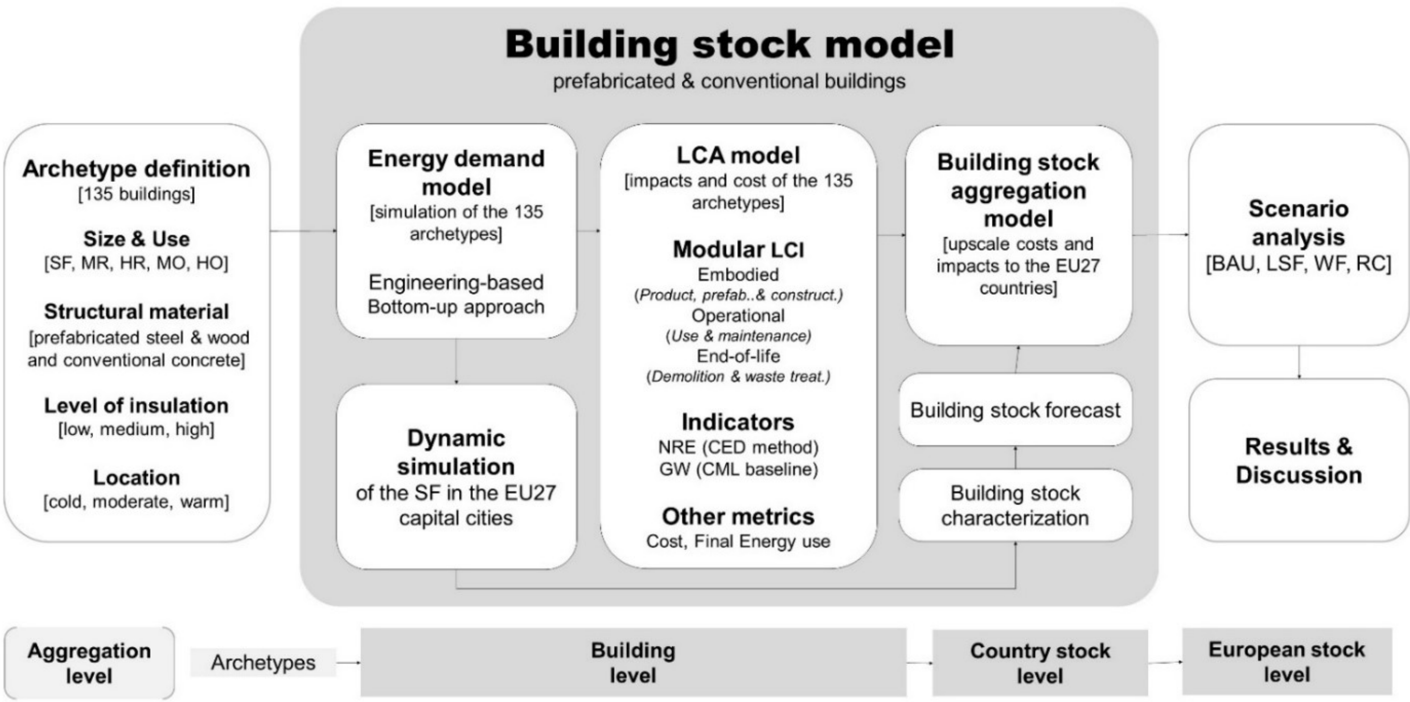


Figure 33 Stock-based methodological approach

5.1.2.1 Archetype definition

The archetypes in this study represented the main typologies in the EU-27 building stock and were based on previous work (Lavagna et al., 2018; Nemry et al., 2010). Details are presented in Table 22.

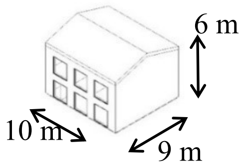
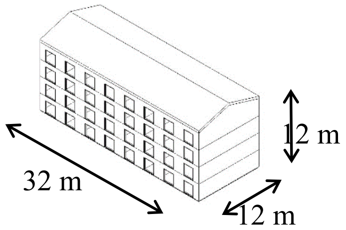
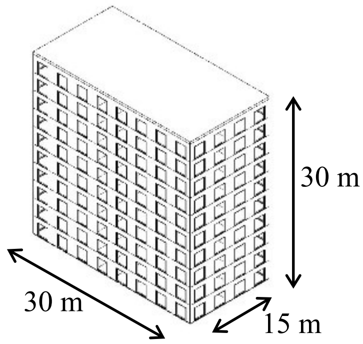
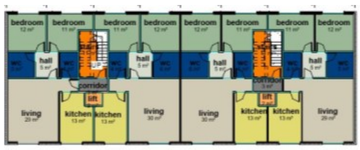
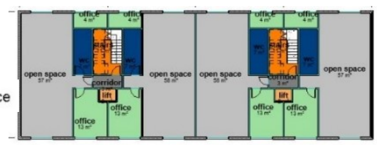
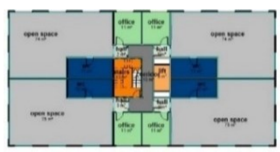
Table 22 Construction and site alternatives

Building location	**Warm**	**Moderate**	**Cold**
City	Lisbon	Berlin	Stockholm
Heating degree days (HDD)	1109*	2801*	5120*
Cooling degrees days (CDD)	167*	46*	1*
Exterior wall insulation thickness	**Low**	**Medium**	**High**
Prefabricated (prefab_LSF & prefab_WF)	30+60 mm	60+80 mm	100+100 mm
Conventional (conv_RC)	30 mm	60 mm	100 mm
Roof insulation thickness	**Low**	**Medium**	**High**
Prefabricated (prefab_LSF & prefab_WF) roof	50+60 mm	80+80 mm	100+100 mm
Conventional (conv_RC) roof	50 mm	80 mm	100 mm

* Data from the 2019 year.

The three construction systems selected are usually used in the EU-27 construction sector: prefabricated light steel framing (prefab_LSF) and wood framing (prefab_WF), and conventional reinforced concrete (conv_RC). Structural material distribution per climatic zone is presented in table III.5 and was used to build the business as usual (BAU) scenario. Table 23 presents archetypes' main characteristics: floorplan, main dimensions, and an axonometric view.

Table 23 Building stock archetypes characterization

	Low rise	Medium rise	High rise
Axonometric view			
Dimensions (L*W*H)	10*9*6 m	32*12*12 m	30*15*30 m
Nr of floors	2- floors	4- floors	10- floors
Gross-floor area	180 m^2	1 536 m^2	4 500 m^2
Volume	540 m^3	4 608 m^3	13 500 m^3
Roof slope	30%	30%	0%
Window-to-wall ratio	30%	30%	30%
	single family (SF)	medium-rise residential (MR)	high-rise residential (HR)
Residential Floorplans			
		medium-rise office (MO)	high-rise office (HO)
Office Floorplans			

* Archetypes are based on IMPRO project (Nemry et al., 2010)

a) Building construction alternatives

Building prefabrication refers to the process of manufacturing building parts, elements, or modules at a plant and then transporting them to the final building site to be installed and assembled (Kamali and Hewage, 2016). Impacts and costs need to be carefully balanced when comparing prefabricated with conventional building construction, as prefabricated buildings with one extra phase (prefabrication at a plant), transportation stage (from plant to site), and a different performance (being based on lightweight construction). In this study, the two most commonly used prefabrication systems were analyzed: light steel framing (prefab_LSF), and wood framing (prefab_WF) structure with OSB panel walls, and a conventional reinforced concrete (conv_RC) structure with a brick siding.

Table 24 describes the main construction elements (external wall, roof, internal wall, and windows) for the three constructive systems: prefabricated LSF and WF, and conventional RC (further details are presented in B.1 of SI presents). Three code complying insulation levels are considered: low, medium, and high; and three cities selected to represent different climatic zones: Stockholm (cold weather countries), Berlin (moderate weather countries), and Lisbon (warm weather countries). Table 25 presents the construction details of the main elements (external wall, roof, internal wall, and windows) for the three constructive systems: prefabricated light steel framing (prefab_LSF) and wooden framing (prefab_WF); and conventional reinforcing concrete (conv_RC).

Table 24 Construction elements characterization

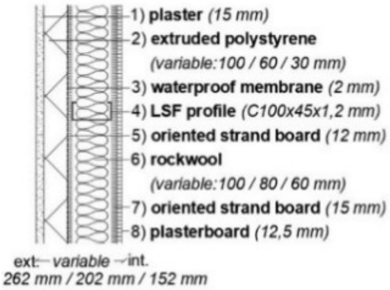
	PREFABRICATED		CONVENTIONAL
	Prefab_LSF	**Prefab_WF**	**Conv_RC**
Exterior wall*	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) LSF profile (C 100*45*1,2 mm) Oriented strand board (15 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) Wood beam profile (100*45 mm) Oriented strand board (15 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) Reinforced concrete column (150*300 mm) Concrete masonry (150 mm) Plaster (15 mm)
Roof*	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) LSF truss (1.8 mm) Waterproof membrane (2 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) Wooden truss (70*50 mm) Waterproof membrane (2 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) Concrete filling (60 mm) Vaulted concrete block Concrete beam Plaster (15 mm)
Interior wall	Plasterboard (12.5mm) Steel profile (48*70*0.55mm) Rockwool (70mm) Plasterboard (12.5 mm)	Plasterboard (12.5mm) Wooden profile (40*60mm) Rockwool (70mm) Plasterboard (12.5 mm)	Plaster (15 mm) Brick masonry (110mm) Plaster (15 mm)
Window	Double glazing Aluminum frame	Double glazing Wooden frame	Double glazing PVC frame

* Layers described from the exterior to the interior; and from high to low insulation level

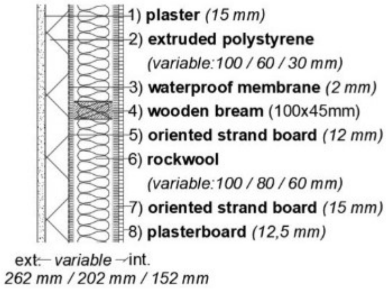
Table 25 Construction details of the main elements for the three constructive systems: prefabricated light steel framing and wooden framing; and conventional reinforcing concrete.

PREFABRICATED		CONVENTIONAL
Light steel framing (prefab_LSF)	**Wood framing (prefab_WF)**	**Reinforced concrete (conv_RC)**

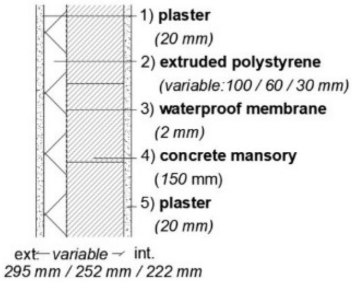
prefab_LSF Exterior wall



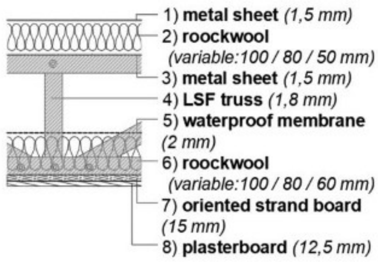
prefab_WF Exterior wall



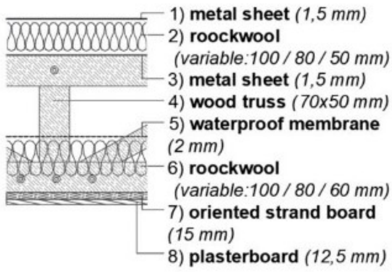
conv_RC Exterior wall



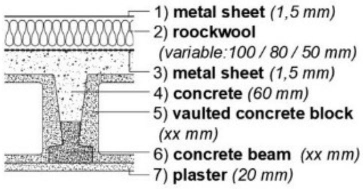
prefab_LSF Roof



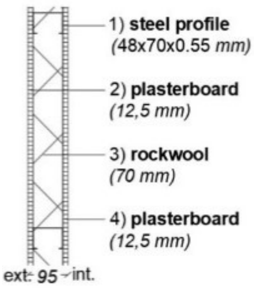
prefab_WF Roof



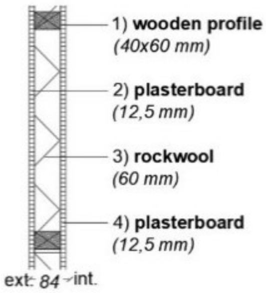
conv_RC Roof



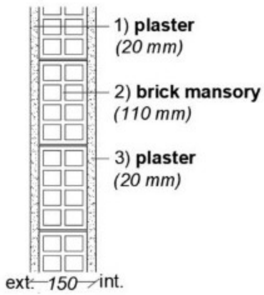
prefab_LSF Internal wall



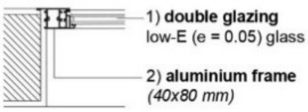
prefab_WF Internal wall



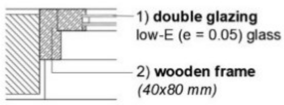
conv_RC Internal wall



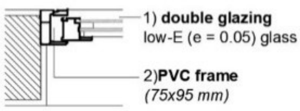
Aluminium Window



Wood Window



PVC Window



5.1.2.2 Energy demand model

Energy consumption was calculated through dynamic energy simulation of the archetypes (SF, MR, HR, MO, HO; prefab_LSF, prefab_WF, and conv_RC) in the three cities (Lisbon, Berlin, and Stockholm) considering low, medium, and high insulation levels. Energy needs were calculated using a dynamic energy simulation software (EnergyPlus) linked to BIM modeling software (Revit 2020) and considering a split system with mechanical ventilation to meet cooling and heating needs. Interior lighting and equipment energy needs were based on average consumption per area. The five archetypes, with the three structural materials and the three insulation levels, were simulated in the three cities, summing up 135 alternatives. In addition, operational energy for the single-family (SF) with medium insulation level was calculated for all the EU-27 capital cities. The energy needs of the archetypes in all the remaining 24 capital cities were statistically calculated using typical energy needs variation within each climatic zone (among typologies and within structural materials) and using the SF as model calibration. Random archetypes were simulated in each city, and the difference to the estimated value was calculated and below 10%. The energy needs of both prefabricated designs are similar since the prefabricated buildings are lightweight buildings with similar thermal mass and thermal transmittance of the building envelope.

5.1.2.3 Life cycle model

The life cycle model follows the ISO 14040 (ISO, 2006b) and CEN/TC 350 standards using the following phases: product stage (A1-A5); construction stage (A4-A5); use stage maintenance (B1-B5); use stage operation (B6-B7); end-of-life stage (C1-C4); and benefits and loads beyond system boundaries (D). Waste recycling by waste type was included in the LC model, but modules, parts, or materials reuse was not considered. Moreover, water use was excluded and energy use was calculated using dynamic energy simulation for all final locations. The selected indicators are non-renewable energy (NRE of CED impact assessment methods) and global warming (GW of CML baseline), as both are commonly used in building and building stocks assessments and are recommended by the environmental product declaration and JRC report (Gervasio and Dimova, 2018). Additionally, operational energy use and costs were also selected as both influence policy-making and individual owners' choices. Cost, GWP, and operational energy use are indicators proposed by Level(s) – the EU proposed framework to report buildings' sustainability using LCA (European Commission, 2017).

5.1.2.4 Modular life cycle inventory

A modular LCI was developed to enable the rapid construction of the inventory for the 45 archetypes (presented in Figure 34). Building materials are assembled into building elements that, in addition to other activities (performed during construction, use, maintenance, and demolition), build up the life cycle inventory. Indicators and costs are allocated to each building element and activity using different units: building elements are defined per area (m^2 of walls, floors, and roof) or unit (number of doors and windows) during construction and maintenance (replacement rates based on life span); transport of workers by traveled distance (km), and transport of materials and waste by mass traveled distance (tkm); for electricity, gas and water use the time of manufacture, assemblage, construction and demolition (number of hours); and for use phase annual operational energy needs (to meet the heating and cooling needs, electric equipment use and lightening). In medium-rise and high-rise, both prefabricated systems consider an additional RC structural core (comprising the stairs and the walls around the stairs) as of current practice. Lights, appliances, HVAC equipment, foundations, cabinets, kitchen, and bathroom equipment, were excluded from the present analysis as they were considered to be similar among all the three alternatives. A modular cradle-to-grave LCA assessment was completed for all the alternatives.

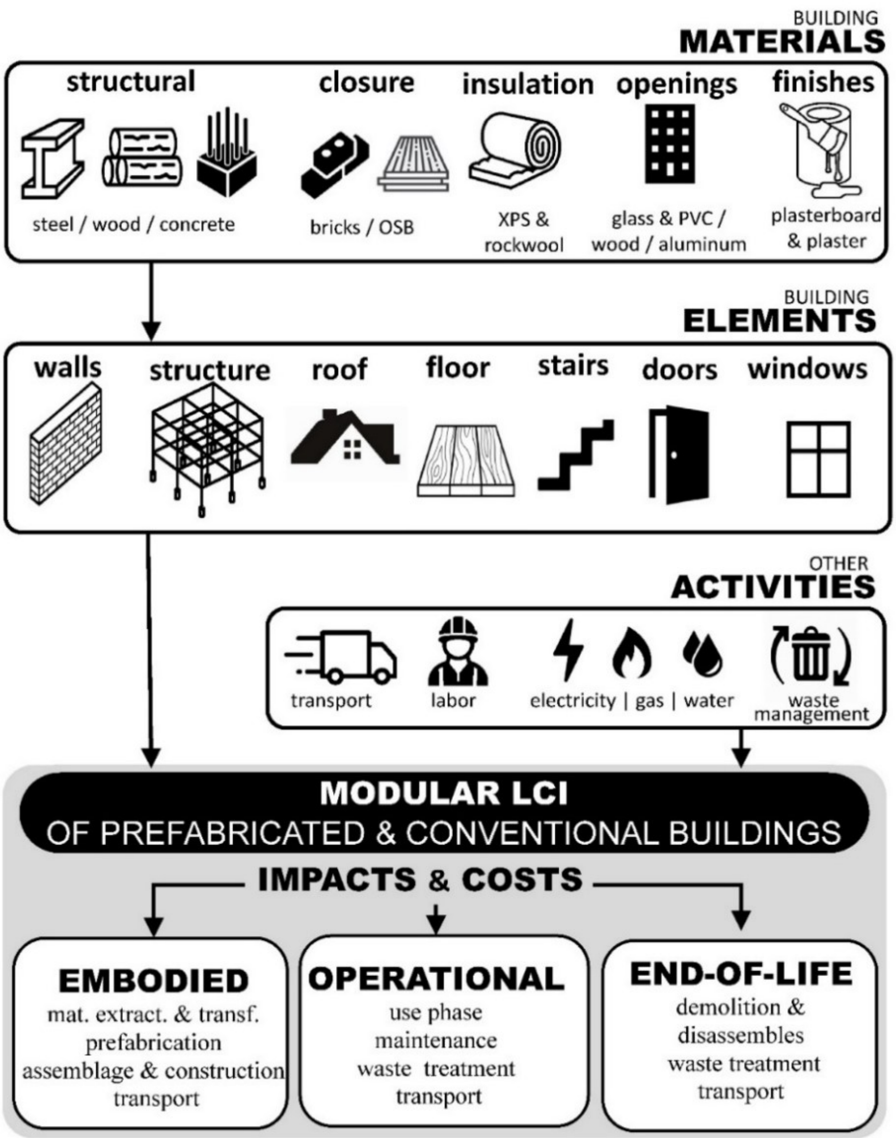


Figure 34 Modular life cycle inventory

The life cycle inventory is divided into three main stages: embodied, operational, and end-of-life phases. The embodied phase includes materials extraction and transformation, plant prefabrication, onsite assemblage and construction, and transport (of materials, prefab parts, and workers). The operational stage comprises the use phase needs; maintenance works, waste, and transport (of materials, waste, and workers). Finally, the end-of-life consists of demolition and disassembles works, waste treatment, and transport (of waste and workers). Waste is grouped according to the waste list (European Commission, 2008), and impacts are calculated accordingly to each waste stream treatment strategy.

Table 26 presents the life cycle inventory of archetypes with a medium insulation level. A detailed inventory is presented in appendix III. The inventory shows the similarity among both prefabricated buildings and more significant differences with the conventional. Conventional RC is roughly four times heavier than prefabricated buildings (around 3.7 times heavier than prefab_WF and 4.2 times the prefab_LSF) with similar differences in demolition waste and equivalent transport of materials and waste. Conventional buildings have no prefabrication stage with no transport-, labor-, utilities-related burdens. However, conv_RC needs extra time and a higher number of workers during the construction stage, balancing (and even surpassing) prefabrication stage labor and time.

Use stage differences between prefabricated and conventional buildings are less significant. Maintenance works of conventional buildings are slightly more complex (taking a little more time, labor, and materials) than both prefabricated. Operational energy tendency shows that prefabricated buildings with medium insulation levels use less energy with heating needs, and contrary, conventional RC uses less energy with cooling needs. This comes from the fact that conventional building is a heavyweight construction system, with higher inertia (less likely to overheat during the cooling season) and prefabricated buildings lightweight (easier to be heated during the heating season) and follows previous LR results (Zhu et al., 2018). Operational energy must be carefully analyzed in each location and using different insulation levels as buildings react differently to increased insulation levels, in each location and using different construction systems. Finally, at the EoL, the demolition of conventional and deconstructing prefabricated buildings was considered to take the same time and the number of workers, though benefits of prefabricated (mainly LSF reuse and recycling) will reduce buildings impacts and costs at EoL.

Table 26 Life cycle inventory of materials, waste and labor of the archetypes with medium insulation level

	A1-A5 PRODUCT & CONSTRUCTION STAGE *								
	Materials (ton)			Offsite work (hr)			On site work (hr)		
	LSF	**WF**	**RC**	**LSF**	**WF**	**RC**	**LSF**	**WF**	**RC**
SF	35	41	152	1 848	1 848	-	1 848	1 848	14 784
MR	404	428	1 223	2 772	2 772	-	7 392	7 392	59 136
HR	963	1 034	2 827	3 696	3 696	-	22 176	22 176	129 024
MO	387	414	939	2 772	2 772	-	7 392	7 392	59 136
HO	899	963	2 440	3 696	3 696	-	22 176	22 176	177 408

	B1-B5 USE STAGE *								
	Maintenance materials (ton)			Maintenance waste (ton)			Maintenance work (hr)		
	LSF	**WF**	**RC**	**LSF**	**WF**	**RC**	**LSF**	**WF**	**RC**
SF	22	22	31	22	22	31	385	385	578
MR	129	129	236	129	129	236	1 540	1 540	2 310
HR	289	289	507	289	289	507	3 465	3 465	5 198
MO	119	119	208	119	119	208	1 540	1 540	2 310
HO	244	244	358	244	244	358	3 465	3 465	5 198

	C1-C4 END OF LIFE STAGE & D BENEFITS & LOADS *					
	Demolition waste (ton)			Demolition work (hr)		
	LSF	**WF**	**RC**	**LSF**	**WF**	**RC**
SF	35	41	152	70	70	70
MR	404	428	1 223	280	280	280
HR	963	1 034	2 827	630	630	630
MO	387	414	939	280	280	280
HO	899	963	2 440	630	630	630

NB: LSF – prefabricated LSF, WF – prefabricated wood-framing, RC – conventional reinforced concrete, SF – single-family house, MR – medium-rise building, HR – high-rise building, MO – medium-rise office, HO – high rise office.
** Life cycle inventory is further detailed in Table III.6, III.7, and III.8 of appendix III*

Environmental impacts were calculated using the Ecoinvent 3 database using NRE (CED method) and GW (CML baseline method) categories. In the absence of data on material production sources and destinations and the associated transportation routes, impacts of materials and transport are considered identical for all the different countries. By contrast, the specific electricity mix was considered for each EU-27 because this information is readily available. Costs were first calculated for Lisbon (Portugal) for all the five typologies, with different materials and insulation levels. Materials costs were based on an open-access database (CYPE Ingenieros, 2020), and transport, labor, energy, and waste costs were based on technical or statistical databases. Materials costs were calculated for the other two cities (Berlin and Stockholm) using a conversion factor based on the construction costs index (European Commission, 2020b). Electricity, gas, water, and labor costs used were specific to each city and based on EU-27 country-specific statistics (European Commission, 2020c).

5.1.2.5 Stock aggregation model

Building stock dynamics comprise buildings construction, demolition, and refurbishment. New buildings will be constructed due to: i) stock size variation because of population fluctuation and; ii) buildings replacement as buildings are demolished at the end-of-life. Buildings' life span varies from 50 to 100 years, so the annual construction rate varies from 1.2-1.5%, as was previously considered in (Sartori et al., 2016) and (Sandberg et al., 2016). A fixed replacement rate of 1.2% was considered in the present work for the period 2020-2050, based on (Kellenberger et al., 2007) and (Sartori et al., 2016). No data was found on building stock size projection, so the stock area had to be calculated based on available statistical data was from the last Census in 2011 (European Commission, 2011b). A dynamic stock rate has been calculated by multiplying the population per building area per capita area in each EU-27 country; data were collected from Eurostat (European Commission, 2020a). Table III.1 presents EU-27 Building stock characterization in 2019 divided between residential (single-family, medium- and high-rise) and non-residential (medium and high rise). EU-27 Building stock forecast for 2050 and Table III.2 EU-27 New buildings forecast from 2020 to 2050.

Residential area per capita varies between 21 m^2/capita (in Malta) and 54 m^2/capita (in Denmark). Service area per capita varies between 3 m^2/capita (in Romania) and 22 m^2/capita (in Denmark). Population from 2020-2050 will vary between +32% and -23%, as some countries' population is expected to increase (such as Malta and Ireland) while others will decrease (such as Latvia and Lithuania). This stock forecast model is based on the following assumptions: i) population variation determine building stock size for residential and office areas buildings; ii) the ratio of built area per person stays constant even though some studies have pointed out that area per person may increase; iii) the fact that some buildings may last beyond considered life span (such as heritage builds) was not considered.

The operational energy of the single-family (SF) medium insulation house was calculated through dynamic energy simulation in the EU-27 capital cities. The operational energy of all the other archetypes in the EU-27 countries was calculated through a statistical correlation based on the calculated operational energy variation between each typology (from single-family to medium-rise residential, high-rise residential, medium-rise office, and high-rise office) and level of insulation (from medium to low or high level) within each climate zone (warm, moderate or cold weather.).. One hundred fifty-nine buildings were simulated (5 typologies, in 3 construction systems and 3 insulation levels, in 3 cities totalizing 135 plus 24 SF in each EU-27 capital), and the operational energy of the other 624 buildings was calculated based on statistics. The stock-based model considers operational impacts variation due to the electricity-mix impacts of each of the EU-27 countries.

The impacts and costs of the archetypes were calculated for each of the EU-27 countries based on statistics correlation (of construction, labor and electricity costs, and electricity mix impacts). Impacts at the country level were aggregated based on typology distribution and stock composition in terms of structural materials in each country. Typology distribution was based on statistical data, and stock composition in terms of structural materials was based on the new buildings defined in the IMPRO study (Nemry and Uihlein, 2008a) and assumed to represent the current construction practice in Europe.

5.1.3 Results

Results are presented at three different levels: at the EU-27 level (section 5.1.3.1), country-level (section 5.1.3.2), and building-level (section 5.1.3.3). Each aggregation level presents data with different resolutions that led to different conclusions, highlighting the importance of scope definition and aggregation level in building stock research.

5.1.3.1 Results at the building stock-level

EU-27 building stock was characterized by size (built area), composition (typologies), and construction systems (structural materials). Impacts are forecasted from 2020 to 2050 in future scenarios (considering prefabrication adoption) and the business-as-usual scenario.

<u>a) Size and composition</u>

Figure 35 presents the EU-27 stock composition and forecast of the new building area. Around 70% of buildings in Europe are residential, half of them single-family houses (~50%), followed by multi-family houses (~20%). High-rise buildings (residential and non-residential) represent a small fraction of the stock (less than 5%). Around 60% of the new building area will be located in moderate weather countries (mainly in Germany and France) followed by warm weather countries (around 35%, mainly in Italy and Spain). In warm weather countries, all new buildings use RC structure; in moderate weather countries, 1/3 of single-family use WF and all the others RC; and in cold weather countries, half of SF and 2/3 of MF use WF, and all the others RC. Structural materials considered per climatic region and typology are detailed in appendix III, table III.4 - Structural material share per region for each archetype.

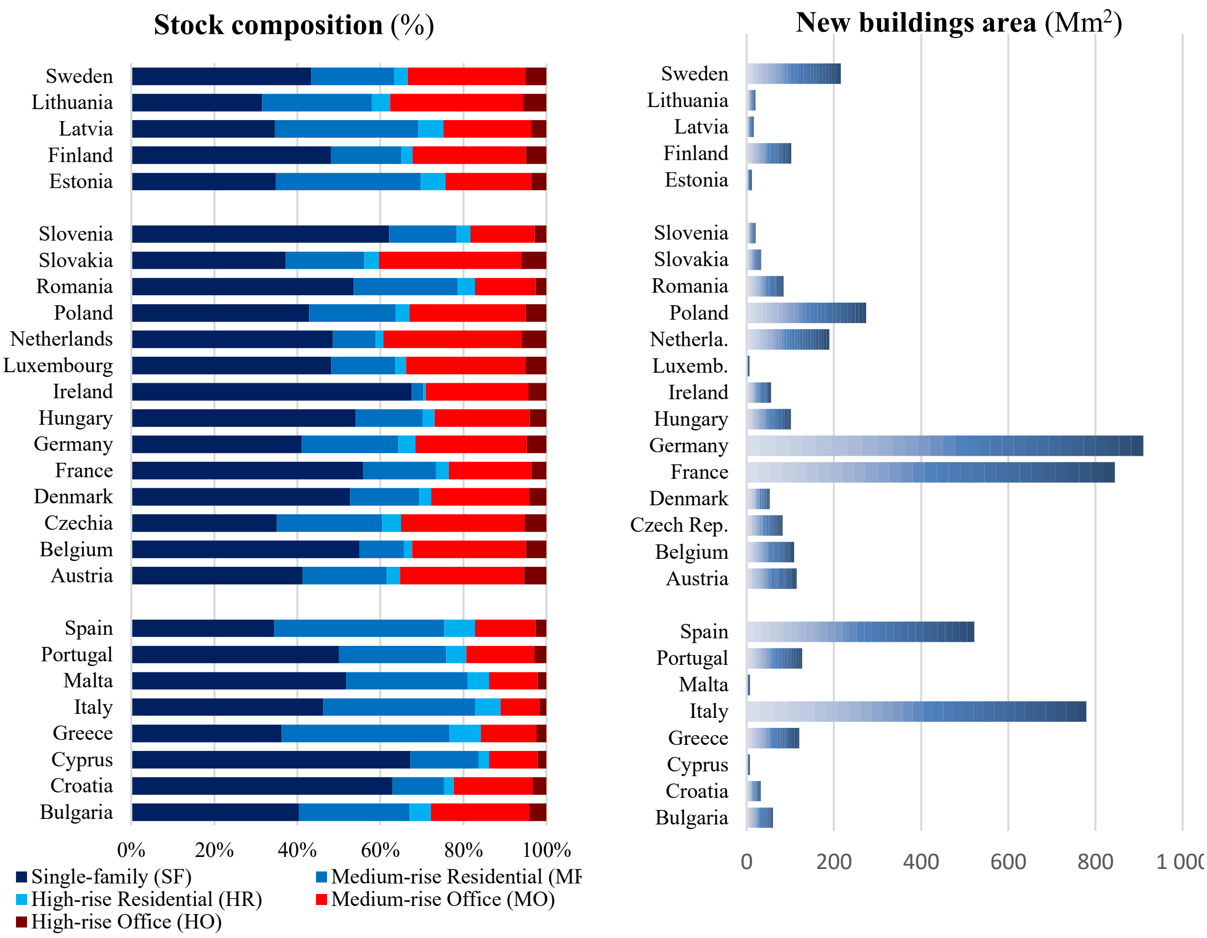


Figure 35 Stock composition (left) divided into single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO), and high-rise office (HO); and estimated new building area (right) per each EU-27 country from 2020 to 2050.

<u>b) Future scenarios</u>

Figure 36 presents EU-27 building stock total impacts, costs, and operational energy comparing the business as usual (BAU) scenarios with the alternative scenarios: hypothetical scenarios considering all new buildings are built in prefab_LSF, prefab_WF, or conv_RC. By 2050 prefabrication can decrease building stock GW by -6% (using prefab_LSF) or -4% (using prefab_WF) when compared to 2020, and NRE can be decreased by -4% (using prefab_LSF) or -3% (using prefab_WF). On the contrary, in the conv_RC scenario, impacts could increase by +1%. Buildings' costs can be decreased by -10% (using prefab_LSF) or -8% (using prefab_WF) compared with the BAU scenario. Operational energy use is identical for prefab_LSF and prefab_WF, and the reduction compared to BAU is insignificant (less than 1%).

Compared with the BAU, the variation in costs is the most significant since prefabricated buildings need less time and labor. By contrast, the variation in energy needs is the least significant as all the alternatives have roughly similar energy performance. The prefabricated building stock has similar reduction potential in GW and NRE categories. EU-27 building stock impacts, costs, and operational energy variation per m^2 of alternative scenarios compared with the business as usual (BAU) scenario are presented in figure E.1 of SI.

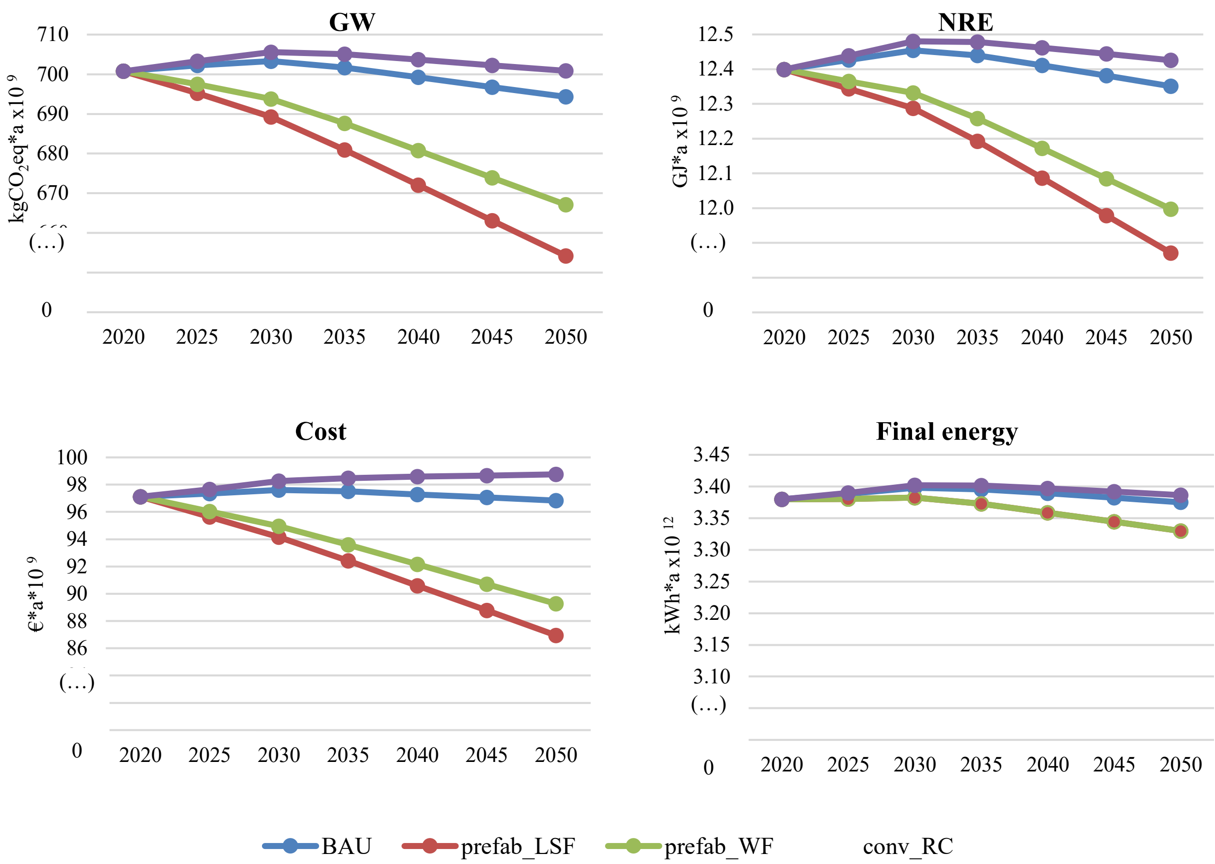


Figure 36 EU-27 building stock total impacts, costs, and operational energy in business as usual (BAU) and alternative scenarios: from 2020 to 2050
All new buildings are built in prefab_LSF, prefab_WF, or conv_RC. Note that the y-axes show a fraction of the total scale.

c) Business as usual

Figure 37 presents building stock area and costs (left) and GW and operational energy (right) at the business-as-usual scenario (BAU). Aggregated impacts and costs of EU-27 building stock follow the building area curve that will peak around 2030 and is expected to decrease after. Both figures show that the total area of the building stock is the most critical aspect. So even if buildings are more energy-efficient and have less embodied impacts, the building stock impacts will follow gross floor area growth because it is increasing at a significant rate. The built area will respond not only to the growing population but also to the increasing area-per-person ratio.

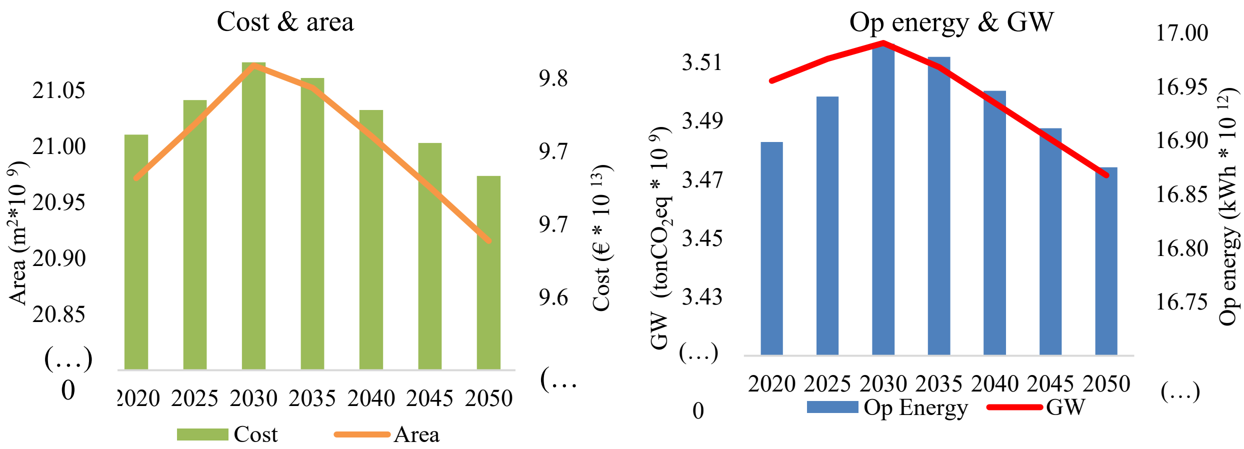


Figure 37 EU-27 total building stock costs and area (left); and operational energy and GW (right).

5.1.3.2 Results at the country-level

Results are presented for each archetype for each one of the 27 European countries grouped in three climatic zones: warm, moderate, and cold weather countries.

<u>a) Operational energy</u>

Figure 38 presents the operational energy per m^2 per year for prefabricated light steel framing (prefab_LSF), prefabricated wood framing (prefab_WF), and conventional reinforced concrete (conv_RC) buildings in EU-27 countries divided into single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO) and high-rise office (HO); with different insulation levels (low, medium, high). In the EU-27, the operational energy varies from 102-271 kWh/m^2*year (warm countries 118-237, moderate countries 102-231, and cold countries 134-271 kWh/m^2*year). In warm countries, insulation has a small influence on operational energy except for medium-rise residential (in prefab_LSF and prefab_WF) and high-rise office (in RC) that with lower insulation decreases the operational energy. The energy needs of conventional RC are more dependent on the insulation level, being a heavyweight construction system with a high thermal energy storage capacity of materials used in the building. Compared with other archetypes, high-rise office has higher energy needs in warm countries and single-family in moderate and cold countries; being this single-family with a concrete structure is highly dependent on the insulation (the higher the insulation level, the lower the operational energy).

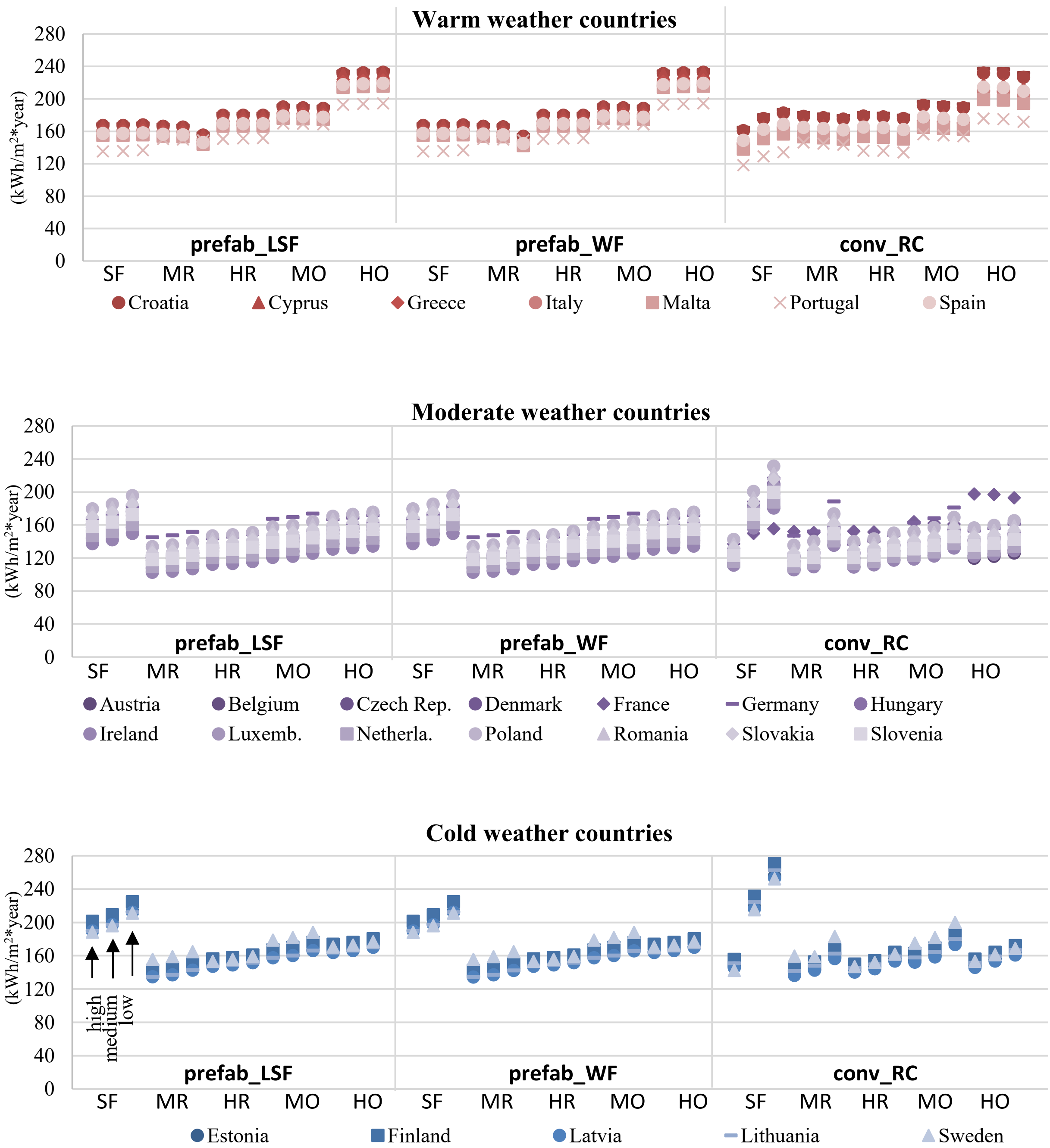


Figure 38 Operational energy per m² for prefabricated light steel framing (prefab_LSF) and wooden framing (prefab_WF); and conventional reinforcing concrete (conv_RC) buildings in EU-27 countries divided into SF, MR, HR, MO and HO, and insulation level.

b) Life cycle impacts

Figure 39 presents the NRE per m^2 and Figure 40 presents GW per m^2 for prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO, and HO; with different insulation levels (low, medium, high). Total GW varies from 0,1-4,3 tonCO_{2eq}/m^2 (warm countries 1,1-3,5; moderate countries 0,1-4,3; and cold countries 0,3-3,5 tonCO_{2eq}/m^2). Impacts partially reproduce energy use variation (see Figure 38) with higher impacts for single-family (SF) houses. However, GW is more dependent on the emission factor of the electricity mix (e.g., with a high share of renewable or nuclear power) than on archetypes, construction materials, insulation level, or even weather. For example, the range of the energy needs of an SF in France is 135-155 kWh/m^2*year, and the GW range is 420-820 kgCO_2eq*year. By contrast, Hungary, Bulgaria, or Luxemburg have roughly similar energy needs but have twice or three times the GW value (country´s and archetypes' energy needs per m^2 presented in appendix III). The impact range is bigger within moderate and cold countries than in warm countries, though it is noticed that the moderate countries group is the largest.

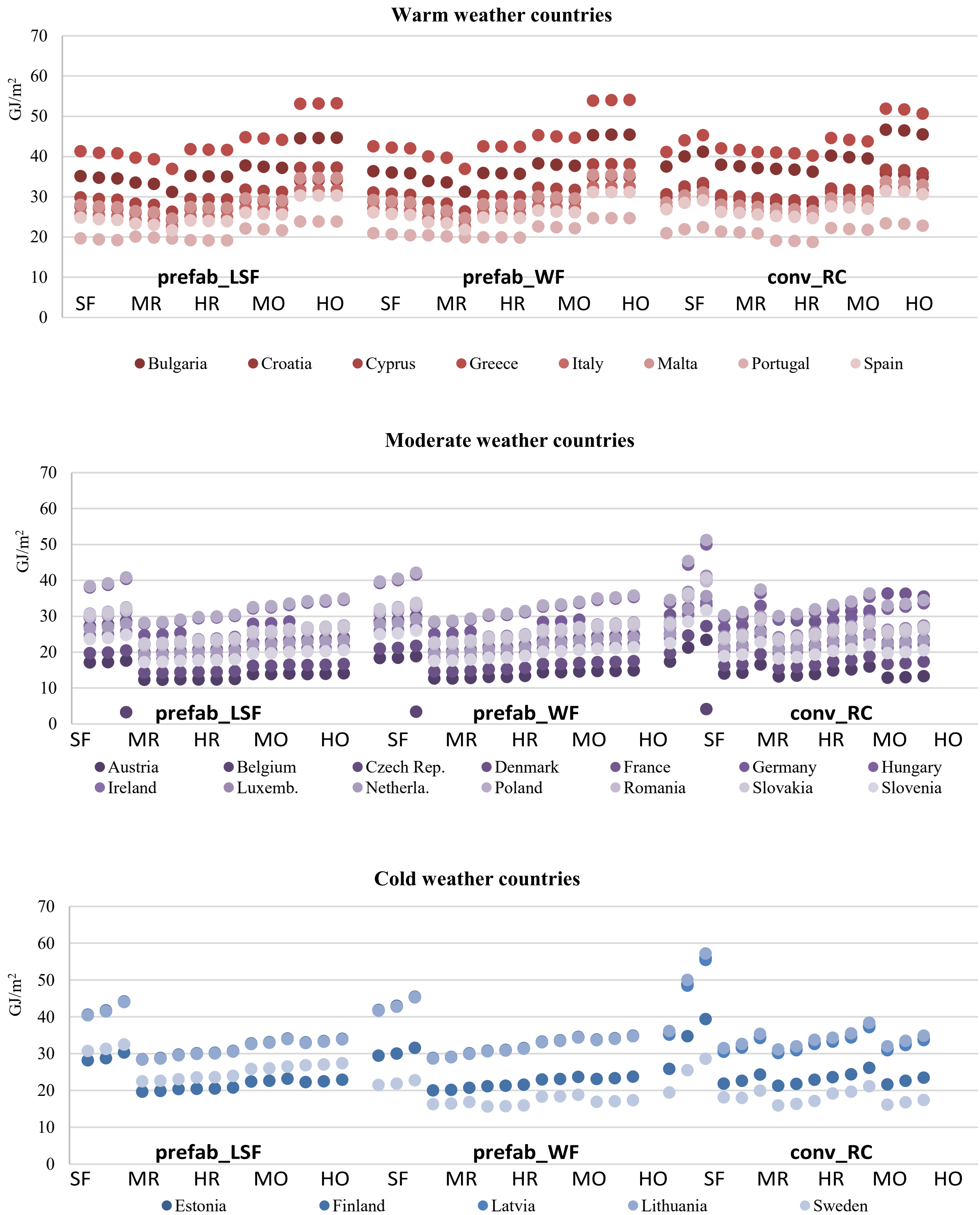


Figure 39 NRE per m² of prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO and HO, and insulation level.

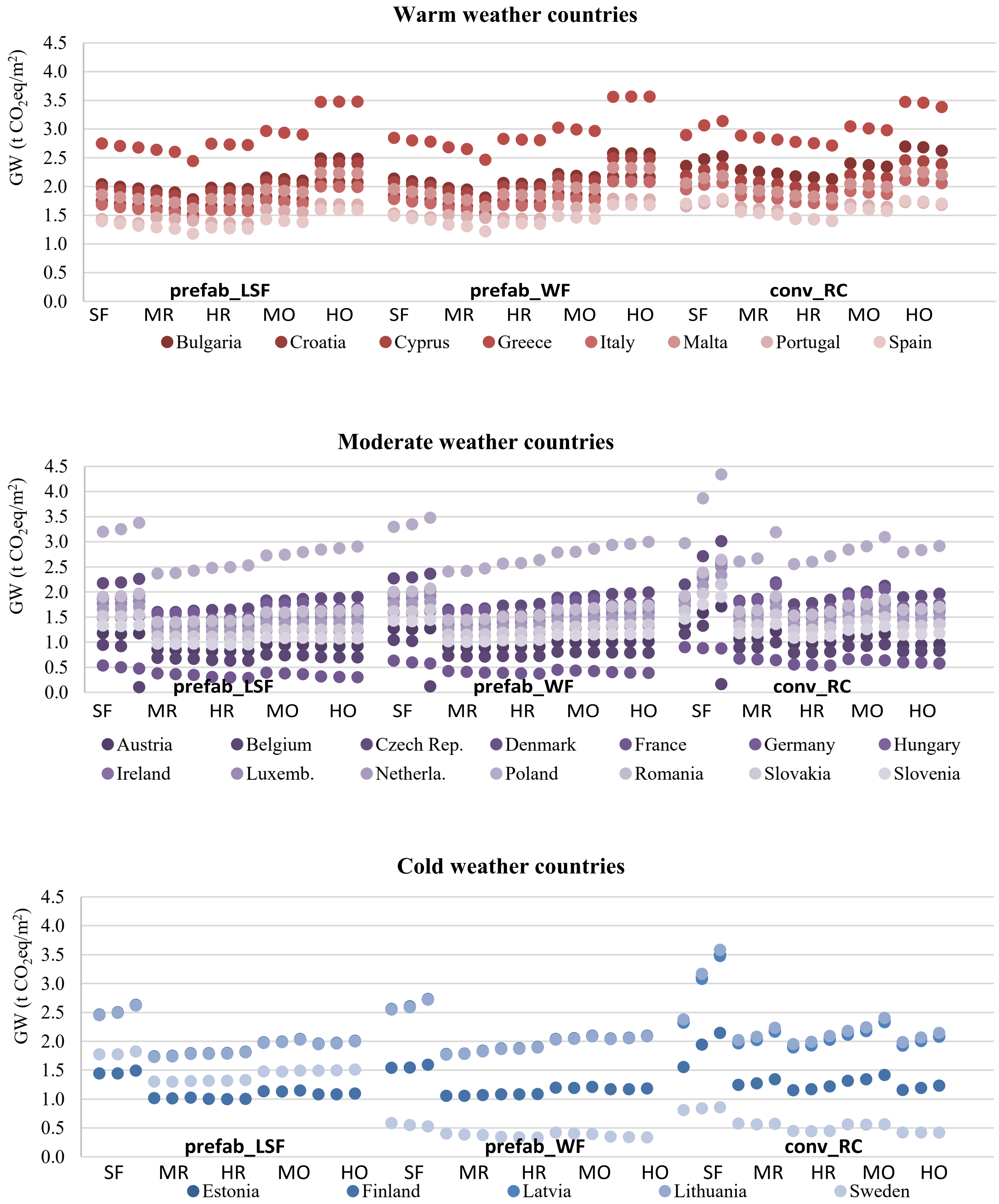


Figure 40 GW per m^2 of prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO and HO, and insulation level.

c) Life cycle costs

Figure 41 presents the average life cycle costs per m^2 for prefab_LSF, prefab_WF, and conv_RC buildings in the EU-27 countries. Costs range are 1.1-3.6 k€ / m^2 for prefab_LSF; 1.1-4.1k€ / m^2 for prefab_WF, and 1.2-6.0 k€ / m^2 for conv_RC. The conv_RC costs range is slightly higher than prefabricated solutions, but the three ranges overlap. Conv_RC buildings costs is more variable than both prefabricated as it is more dependent on each country-specific cost, namely labor and electricity cost.

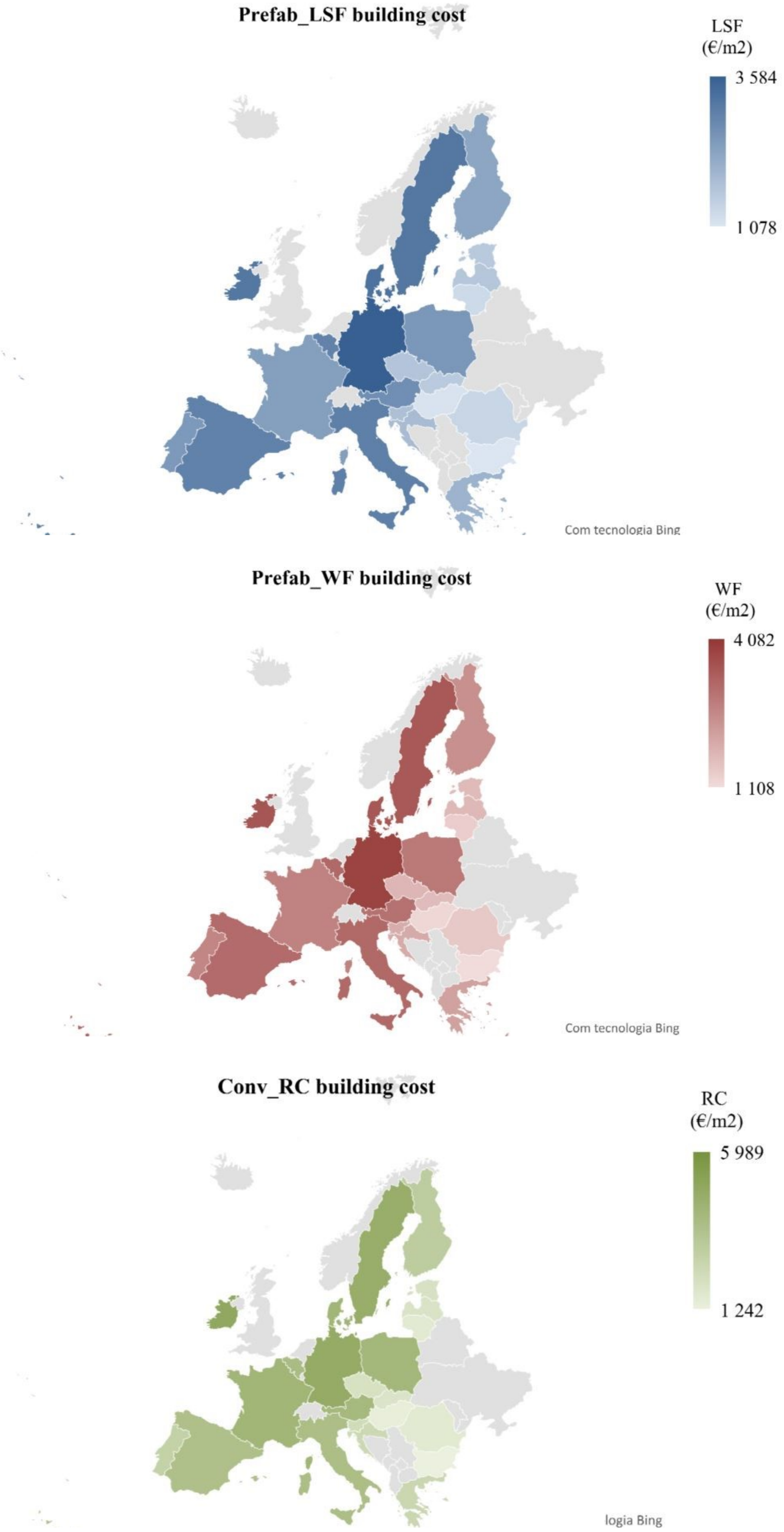


Figure 41 Average total life cycle costs per m^2 for prefab_LSF (blue), prefab_WF (red), and conv_RC (green) buildings in EU-27 countries.

5.1.3.3 Results at the building-level

Three cities were selected as case studies representing different climate zones within the EU territory: Lisbon (warm weather countries), Berlin (moderate weather countries), and Stockholm (cold weather countries). The five typologies with different materials and insulation levels were assessed in these three cities. This section presents detailed operational energy, environmental impacts, and costs of the archetypes in these three cities.

a) Operational energy

Figure 42 presents the final annual energy for each city, typology, structural material, and insulation level; divided into lighting and equipment, heating, and cooling. Operational energy roughly varies between 100-200 kWh/m^2 * year. In Lisbon, the cooling needs are higher than the heating, and the opposite occurs in Stockholm. The insulation level influences more conv_RC buildings than prefab_LSF and prefab_WF, and single-family than all the other typologies.

In Lisbon, operational energy varies between 100 kWh/m^2*year (for single-family conv_RC high insulation) and 181 kWh/m^2*year (for high-rise offices with prefab_LSF and prefab_WF). The insulation level does not influence operational energy except in single-family conv_RC buildings. In some typologies, conv_RC buildings use less energy than prefab_LSF and prefab_WF (especially highly insulated) by decreasing cooling needs.

In Berlin, operational energy varies between 113 kWh/m^2*year (for single-family conv_RC high insulation) and 183 kWh/m^2*year (for single-family conv_RC low insulation). In Berlin, operational energy can be the lowest as buildings have lower cooling needs than Lisbon and lower heating needs than Stockholm. In Stockholm, operational energy varies between 123 kWh/m^2*year (for single-family conv_RC high insulation) and 213 kWh/m^2*year (for single-family conv_RC low insulation).

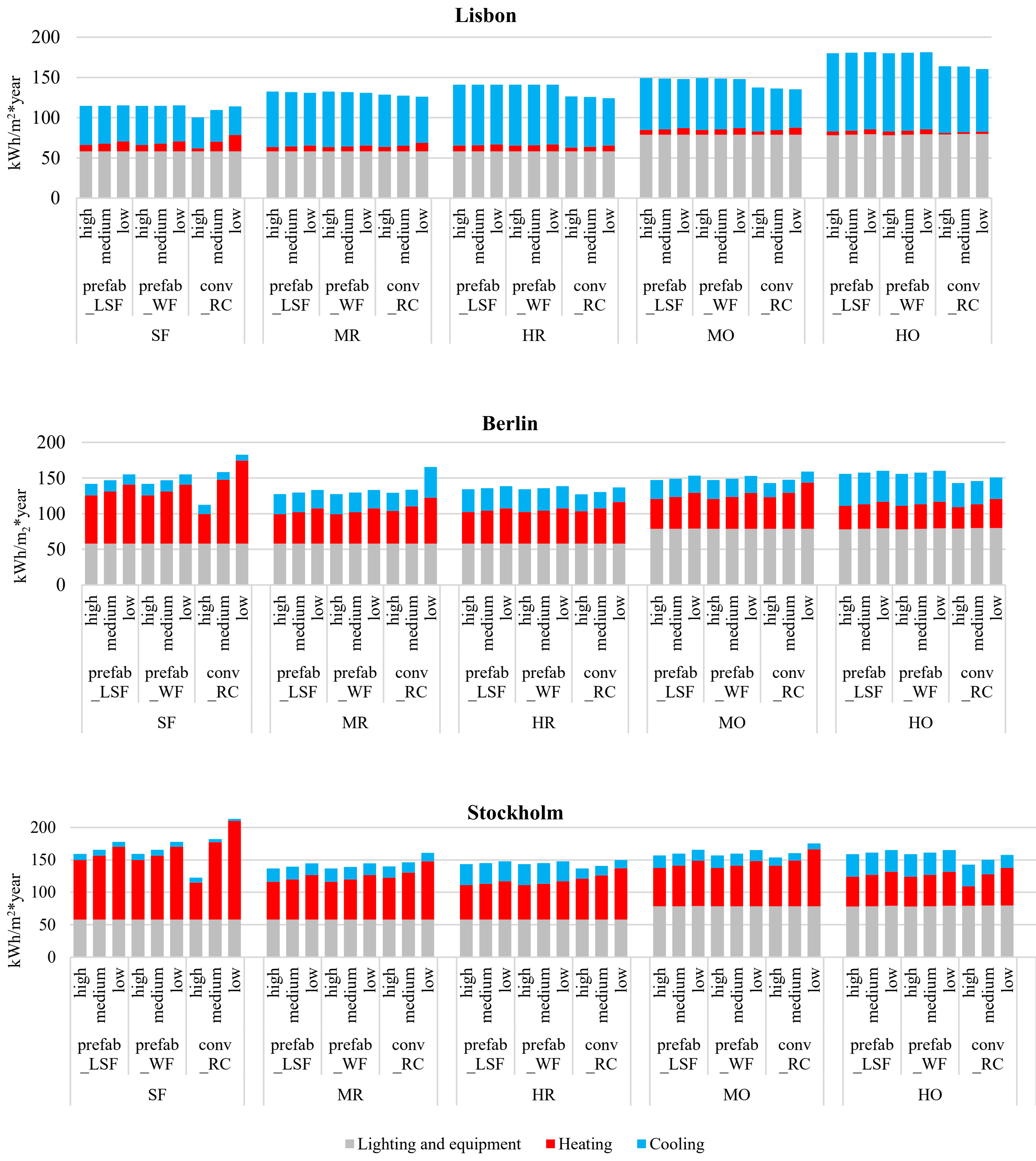


Figure 42 Annual operational energy for each city, typology, structural material, and insulation level: divided by energy use.

b) Life cycle impacts

Figure 43 presents GW per m^2 for each archetype with medium insulation that varies between 0.3 and 2.1 $tonCO_2eq/m^2$. The highest values are for Berlin, Single-Family (SF) in conv_RC, and the lowest for Stockholm high-rise residential (HR) and high-rise office (HO) in prefab_LSF. Buildings in Stockholm have the lowest impacts due to Sweden's electricity mix, followed by Lisbon (slightly lower than Berlin) due to lower energy needs.

Operational impacts are the most significant (roughly 70-90%) followed by embodied impacts (10-30%), except for GW in Stockholm (operational 35-60%; embodied 40-65%). At the end-of-life, impacts can decrease to less 10% (when using prefab_LSF) except for GW in Stockholm, which decreases to less 45%. Within residential buildings, Single-Family (SF) generally has more impacts (more 5-40%) than the other typologies (except for conv_RC in Lisbon). Office buildings have up to +20% impacts of the residential buildings with identical volumetry (when comparing MO with MR and HO with HR).

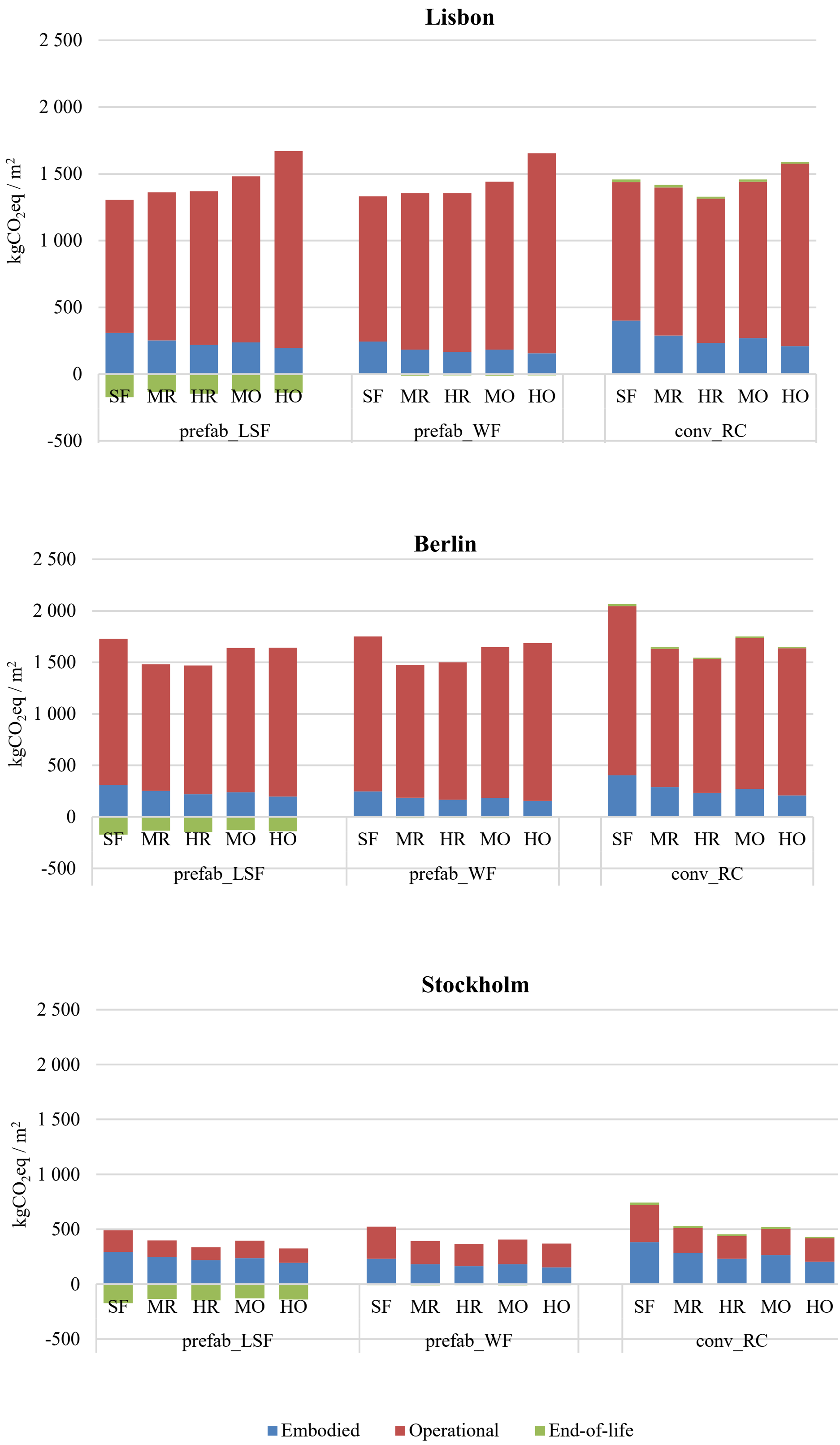


Figure 43 GW per m^2 for each city, structural material, and typology: divided by life cycle phase.

c) Life cycle costs

Figure 44 presents the LC costs per m^2 for each archetype with medium insulation. Costs vary between 2.1-6.2 k€/m^2. The highest costs are for single-family (SF) in conv_RC in Berlin and Stockholm, and the lowest for residential buildings in prefab_LSF and prefab_WF in Lisbon.

Operational costs are the most significant (50-90%), followed by embodied costs (10-50%), with end-of-life costs negligible. SF in Berlin and Stockholm costs 20-40% more than the other typologies, and in Lisbon, SF costs 2-15% more. Office buildings in prefab_LSF and prefab_WF in Lisbon and Berlin cost 7-20% more than identical residential buildings (MO compared with MR and HO with HR). Each country's costs of living influences costs: mainly by the costs of electricity (increasing the costs of a single-family house that is more energy-intensive) and labor (increasing the costs of the more labor-intensive RC).

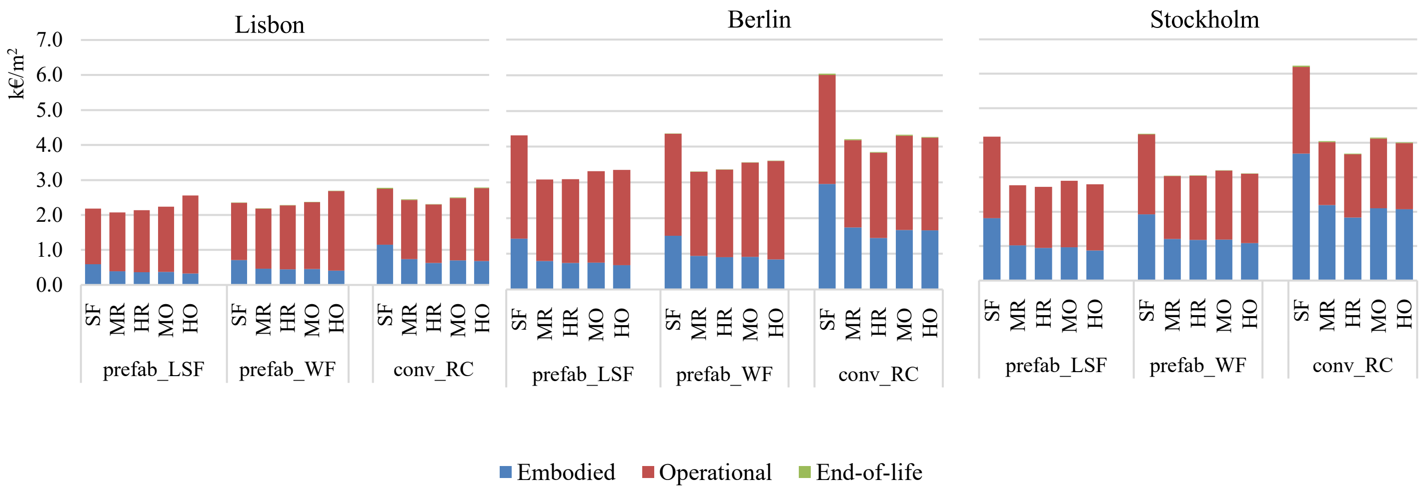


Figure 44 Costs per m^2, per city, structural material, and archetype: divided by LC phase.

5.1.3.4 Contribution to EU-targets

The EU Commission considers that the "*built environment provides low-costs and short-term opportunities to reduce emissions*," setting a 90% reduction target by 2050 compared to 1990 levels (EC, 2011). Prefabricated and conventional buildings have similar operational performance, so the benefits of reducing the operational impacts of buildings (by replacing old inefficient buildings with new ones) were not considered, and the focus was given to embodied and EoL impacts reduction. New buildings reduce operational needs by 25-40% (Nemry and Uihlein, 2008b), and prefabrication can further reduce the impacts of buildings (reducing embodied and EoL impacts) by less 3-6%.

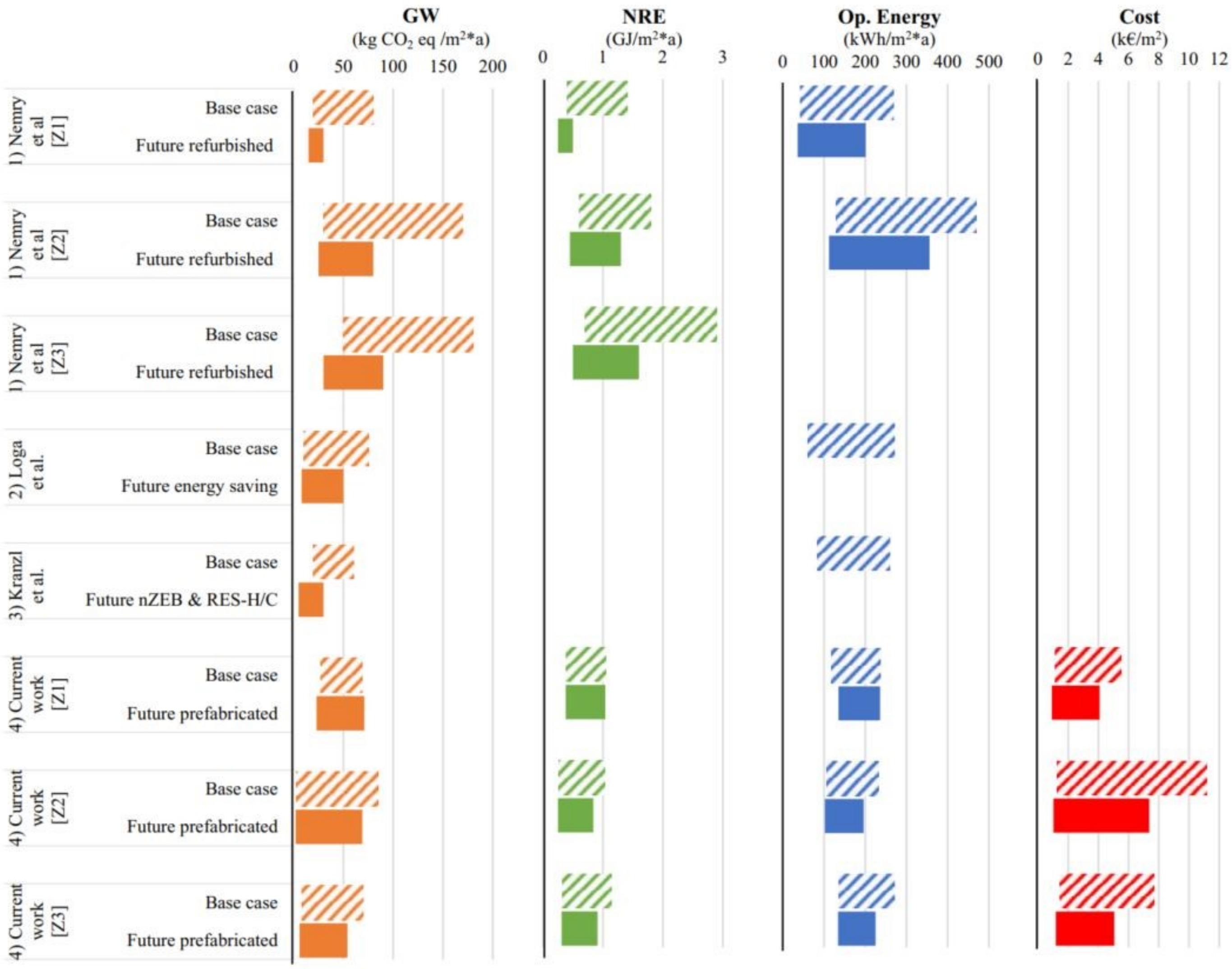
5.1.4 Discussion

Figure 45 presents current and previous work outcomes (detailed results are presented in table III.9 – III.14). Results roughly fit the results range of previous work even though differences in scopes and system boundaries, impact categories, future scenarios, and main assumptions may lead to differences in results. Some studies present future impacts as a percentage of base case scenarios, making it difficult to draw conclusions among different studies and compare different environmental measures. All studies present more extensive ranges in all the categories at base case scenario due to higher variability and heterogeneity of the building stock, demonstrating how difficult it is to draw the baseline.

Compared with the IMPRO project [36], the present work presents a lower reduction potential for both GW and NRE. The difference arises from goal and scope definition. IMPRO assesses old buildings and, for most buildings, considers only refurbishment, excluding the construction stage. In IMPRO, reduction potentials for most archetypes and retrofitting measures are at least 20% (compared to 1990 baseline) [36], which are higher than the reduction potential of the present work. IMPRO compares new and old buildings, focusing on use phase efficiency.

In contrast, the current work compares new buildings with similar operational performance, thus neglecting the reduction of the impact achieved by replacing old inefficient buildings with new energy-efficient ones. Operational energy is highly dependent on the study's main assumptions: construction type and performance (insulation and inertia), users' profile, energy uses and sources, HVAC systems, among other factors. The present work presents a slight operational energy reduction between current and future prefabricated scenario base cases (smaller than the IMPRO results).

LC costs were not assessed in previous works: IMPRO includes the refurbishment measures pay off, and ENTRANZE energy costs savings [28]. The range of LC costs in the base case scenario is wider than for future prefabricated scenarios, showing the higher variability of conventional buildings' costs than that of prefabricated buildings. New energy-efficient conventional buildings are compared with new energy-efficient prefabricated ones in this comprehensive life cycle cradle-to-grave assessment (comparing equivalent alternatives with similar energy performance). This work accounts for the core indicators (impacts, costs, and operational energy), thus enabling an objective comparison of equivalent alternatives in future building stock replacement and growth.



NB1) IMPRO project (2006-2008); 2) TABULA project (2009-2012) & EPISCOPE projects (2012-2014); 3) ENTRANZE project (2012-2014); and 4) current work.

NB2) Z1 warm-weather countries (HDD < 2200); Z2 moderate-weather countries (HDD 2200-3300), and Z3) cold-weather countries (HDD > 3300), adapted from [58].

Figure 45 Range of results for the base case and future scenarios for the different archetypes in current and previous works

The embodied impacts of prefabricated buildings are lower than conventional as a consequence of the lightweight construction (using fewer and lighter materials) and an optimized construction system (taking less time, labor, and energy to be built). As prefabricated buildings can be more easily disassembled and materials recycled, they have fewer impacts at EoL, producing less waste with higher reuse and recycling rates (which would enable a more circular economy). Prefabrication can decrease building stock costs by up to 10%, decreasing materials use, labor, and construction time. Prefabrication production could be relocated to countries with lower impacts and costs, although transport ought to be balanced. Finally, a reduced construction time could be translated to an accountable added value, a benefit ignored by the present study.

Results show that the country's electricity mix influences the impacts more (mainly GW) than the weather, construction materials, or insulation. The insulation level influences more heavyweight construction (conventional) than lightweight construction (prefabricated) and buildings in moderate or cold countries than in warm countries. Different conclusions can be drawn at different aggregation levels, as discussed by (Geraldi and Ghisi, 2020; Stephan et al., 2013). At the building stock level, prefab and BAU scenarios present similar operational impacts due to similar energy needs of buildings (prefabricated and conventional) with similar energy performance (less than 1% variation). However, at a country- or building-level, the operational impacts of alternatives are different, showing that a building stock analysis at different levels (building, country, and European stock level) can lead to different conclusions (e.g., preferable insulation level or construction system in each country; or what measure should be adopted to reduce the impact of each building type).

Prefabrication can reduce building stock impacts and costs, but in different ways than conventional buildings. Most of the buildings' impacts (50-90%) are due to the operation phase, and as alternatives have similar energy performances, the reduction potential is diminished. Nevertheless, prefabrication can reduce embodied (up to -40%), EoL (up to -90%), and LC impacts (up to -10%). Costs presents a higher variability, with LC costs varying among different countries in the most extreme case by order of magnitude (e.g., LC costs in Luxembourg is ten times higher than in Bulgaria). This presents an opportunity to produce prefabricated buildings in countries with lower costs (labor, energy, materials), further decreasing costs, strengthening the domestic market, and leveraging prefabrication as an export product. Moreover, economies of scale were not considered and could enlarge the differences in costs and impacts between conventional and prefabricated.

The dynamic simulation tool integrated with BIM software is a quick method to assess the same building in different final locations. A modular LCI showed to be a rapid tool to build the LCI of buildings with the same construction system but with different forms, sizes, and final locations. The proposed modular LCI follows and expands the previously proposed component-based LCI (Ostermeyer and Claudio, 2017). Combining both approaches enabled the construction of a vast, reliable, and detailed database at a continental scale. The developed framework meets the initial goal to assess a technological innovation (building prefabrication) within a group of products in use (building stock), changeable by the flow (demolition and increasing rates) over time (from 2020 to 2050).

5.1.5. Conclusion

Prefabrication has been identified as a way to reduce the impacts of buildings. However, its wide adoption has not been previously assessed at the EU building stock scale. Results show that prefabrication alone cannot meet EU environmental targets but can (in addition to energy efficiency measures and the refurbishment of buildings) contribute to achieving the envisaged EU targets. Prefabrication presents an opportunity to reduce construction costs and increase sector productivity and sustainability.

The developed building stock model is a fast and reliable approach to forecast the market dynamics when introducing a new technological innovation. This framework combined a modular LCI with a BIM-based energy simulation, reducing LCA complexity and time needed. BIM methodology could also be used to build the LCI of buildings by associating costs and emission factors to each BIM element. Further developments include the integration of the modular LCI into the BIM software to balance embodied, operation, and EoL impacts and costs, enabling the assessment of buildings at the design stage by non-LCA experts. Both databases (costs and impacts) should be external and linked to the software to be easily updated to respond to regional and temporal variability.

CHAPTER 6 CONCLUSIONS

This chapter sums up research contributions and key findings. Limitations are discussed, pointing out future work.

6.1 Research contribution

This dissertation explored life cycle assessment and building stock approaches aiming to map the main differences between prefabricated and conventional buildings and identify opportunities to decrease buildings impacts and costs, both at the single building and the building stock level. The developed building stock approach combined archetypes definition, a novel modular life cycle inventory (LCI), BIM integration to calculate energy needs and build the inventory, and statistical data to estimate results at the country and EU-27 building stock levels. The building stock approach generated a large dataset of results combining construction approaches, typologies, structural materials, insulation levels, and final location while addressing regional variability; and can support decision making at the country and EU level. Results showed that the EU-27 regulatory framework should be locally adapted to embrace the regional variability in costs, energy needs, electricity mix, materials, and technology readiness level. Prefabrication can contribute to achieving the EU-27 environmental targets related to buildings but should be combined with other energy efficiency measures such as buildings' refurbishment and renewable energy adoption. The following contributions were made on the methodological level with the developed building stock assessment: BIM-LCA integration, a new modular LCI, and statistics aggregation. The developed BSM approach proved to be a streamlined approach to assess the impact of introducing a new technology in a large set of buildings; and could be used in different geographical contexts and assessing the introduction of other technologies in the building sector.

The life cycle assessment (LCA) developed and implemented to assess prefabricated and conventional buildings mapped differences in impacts, costs, materials usage, waste generated, and construction time. Two real houses were assessed, including alternatives of house sizes and layouts, structural materials, final house locations, and insulation levels. A cradle-to-site assessment of a modular single-family prefabricated house focused on the embodied impacts of prefabricated houses compared with conventional, considering different house sizes, final locations, and structural materials. Results show that the embodied impacts of prefabricated buildings are lower than conventional, being prefabricated wood and LSF the lowest. Embodied impacts can be reduced if the transport is optimized (distance, transported volume, and transport modes) and materials with lower embodied impacts are selected. The LCA accounted for the embodied and operational impacts of a prefabricated single-family house in different climatic regions, showing that lightweight prefabricated buildings may better adapt to different climates than heavyweight conventional and increased inertia or higher insulation level will increase energy needs in warm and tropical climates. The LC model developed included impacts, costs, materials, waste, and the production time of prefabricated single-family houses (LSF and wood-framed) and of conventional reinforced concrete houses (brick and concrete masonry). It was concluded that prefabricated buildings have less impacts, use fewer materials, produce a small fraction of waste, and take half the time to be built; although costs are roughly similar. Moreover, both costs and impacts can be reduced by adapting the buildings to the final location (insulation, local materials, and labor, reducing traveled distances); and leveraging materials reuse and waste recycling.

LCA is a very useful tool to assess the environmental performance of buildings; however, it is time-consuming and resource-intensive, discouraging the widespread use by stakeholders during design, construction, use, and demolition. A BIM-LCA approach proved to be a streamlined and simplified process that can be used by non-LCA experts such as designers and contractors (already using BIM), owners, and building managers (some of them already using digital twins).

6.2 Key findings

Table 27 presents the key results of the LCA of prefabricated and conventional single-family houses developed, following the characterization and main differences between prefabricated and conventional buildings presented in Table 3. The responses to the four research questions formulated in Chapter 1 and the main findings are discussed below. Appendix IV presents a table comparing scope, impact categories, results, and conclusions of publications (table IV.1). The abstracts of the journal articles (published and under-review) are also presented in Appendix IV.

Table 27. Prefabricated vs. conventional buildings: key results

Prefabricated vs. Conventional
Materials extraction & transformation
¼ of weight (up to) 65% less embodied impacts
Prefabrication & construction / assembly
½ the time to be built (less than) ¼ of construction waste (up to) 20% costs reduction (materials + construction)
Use
(less than) ¼ of maintenance waste similar or lower energy needs
End-of-life
¼ of waste demolition (up to) 40% more recyclable (up to) 20% of embodied impacts balanced at EoL

6.2.1 What are the embodied impacts of a prefabricated house?

The embodied phase is when conventional and prefabricated processes differ the most and when industrialization and digitalization of the construction sector may have a more profound impact. It is a well-defined phase performed by specialists (e.g., designers, contractors, builders), more controlled than the use phase (a longer period with different and unpredictable users) and EoL (in the far future, being difficult to forecast). Moreover, operational impacts have been the main focus of research and legislation and have gradually decreased, so embodied impacts now have a rising importance.

To respond to the research question, a cradle-to-site model of a prefabricated modular house and alternatives was implemented, including materials production, transport of materials and workers to plant, module production on the plant, transport of modules, workers, and material to the construction site and on-site modules assemblage and finishes. The results show evidence that in a *cradle-to-site* assessment, materials extraction and transformation is the most critical phase, followed by modules' prefabrication. However, transport-related impacts can represent 20% of embodied impacts in some alternatives, showing that transport may be significant in modular buildings. The house with LSF or timber structure has the lowest embodied impacts, and the concrete structure has the highest impacts. Moreover, embodied impacts increase linearly with gross floor area, with impacts per m^2 being similar among the different alternatives. So, area and materials are the critical issues in embodied impact assessment.

Embodied impacts can be decreased by reducing the gross floor area, using less energy and carbon-intensive materials, optimizing onsite production, and reducing transport-related impacts. The impacts of transporting modules and workers can be reduced by using less energy-intensive transport modes, transporting prefabricated panels instead of modules, or selecting local materials and workers to complete the onsite assemblage stage. The embodied phase is when most production, use, and EoL impacts are defined (Figure 4), so design and construction must be carefully performed to improve prefabricated buildings' life cycle and the construction process.

6.2.2 What is the balance between embodied and operational impacts of a prefabricated house?

Previous research in the literature concluded that lightweight construction (with less embodied impacts) could lead to increased operational impacts (Hacker et al., 2008) and that to achieve low energy standards, embodied impacts may increase. To respond to this research question, a life-cycle (LC) model was developed for a lightweight LSF prefabricated house with different insulation levels. A cradle-to-site assessment was performed, including materials, transport to plant, on plant prefabrication, transport to site, onsite construction and use phase, and embodied and operational impacts assessed.

Results show that operational impacts are the most significant, but embodied impacts can reach up to half of the total impacts in houses with low energy needs, being mainly influenced by materials (exterior wall, floor, and roof). As expected, houses located in a warm tropical climate have lower energy needs, followed by houses located in a temperate Mediterranean climate, while houses in the cold continental climate have the highest needs. The lightweight prefabricated house with medium insulation has similar energy needs to conventional heavyweight houses in moderate and cold climates but lower energy needs in tropical climates, showing that lightweight construction responds better to cooling needs than heavyweight. Increasing the insulation level reduces impacts in cold and moderate climates but increases in tropical countries due to increased cooling needs. Buildings' weight and insulation level must adapt to the local climate to reduce operational impacts. Energy and materials with high embodied impacts should be avoided to reduce embodied impacts.

6.2.3 What are the main differences between a prefabricated and a conventional house?

There is no "one" unique type of conventional and prefabricated building, so the most typically built prefabricated (LFS and wood-framed) and conventional single-family houses (in south Europe in reinforced concrete) were identified and assessed to draw a comparison and account for the differences (previously identified in Table 3). Results show that prefabricated houses weight ¼ of a conventional, produce the same fraction of waste, and at EoL is around 40% more recyclable. Embodied impacts could represent more than half of total life cycle impacts, and prefabricated houses have up to 65% less embodied impacts. There are differences within each construction approach: within prefabrication, the prefabricated wood house has fewer impacts, while the prefabricated LSF has slightly lower costs; within conventional, the reinforced concrete house with single-layer concrete masonry has roughly more 40% impact than double-layer brick masonry, and both have similar cost.

Costs variation of alternatives is not significant (below 20%) because prefabricated houses use fewer materials, but prefabricated materials (wood and steel) cost more than conventional (concrete and bricks). Materials are responsible for more than 60% of the embodied and EoL costs, representing a significant cost reduction opportunity.

6.2.4 What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?

A stock-based approach was developed to respond to this research question combining archetypes, BIM-based dynamic energy simulation, modular life cycle inventory (LCI), and a statistic-based stock aggregation. Impacts and costs of the buildings stock were calculated from 2020 to 2050, considering the business as usual and prefabrication adoption scenarios. The results from BSM developed and implemented showed that different conclusions can be drawn together at different aggregation levels.

At the building level, results show that prefabrication can reduce the embodied impacts of buildings due to lightweight construction and a more efficient construction process (less time, labor, and energy), but differences exist within different typologies. Life cycle impacts per area are higher for single-family houses (due to a higher wall-to-floor ratio) or offices (due to increased energy needs).

At the embodied stage, single-family houses have the highest impacts, and wood structure buildings have the lowest. During the use phase, lightweight prefabrication in high-rise office buildings can increase energy needs (due to increased cooling needs) but decrease the energy needs of less insulated single-family or multifamily buildings (due to decreased heating needs). So, an energy simulation is essential to select the adapted to the climate, use, volume, constructive system, and insulation level. At EoL, prefabricated buildings can be disassembled with less waste and higher recycling rates.

At a country level, results showed that insulation significantly influences single-family houses in moderate and cold countries and has a minor influence in warm countries. Impacts (mainly carbon-related categories) are more influenced by the country's electricity mix than climate, materials, or insulation level. The insulation level influences more conventional heavyweight construction than lightweight prefabricated construction; and buildings in moderate or cold countries than in warm countries. The cost range of conventional buildings is generally higher than prefabricated, although partially overlapping. Costs are highly sensitive to each country-specific costs – such as labor and electricity cost – being highly variable from country to country.

At the EU-27 building stock scale, the reduction potential is limited, as the yearly replacement rate of the building stock is low (below 2%), as previously concluded in literature (Lavagna et al., 2018; Nemry and Uihlein, 2008a). Nevertheless, results show that impacts could be reduced by around -5% by 2050 when comparing BAU to a prefabricated scenario, even though having similar energy needs and consequently similar operational impacts. Buildings' costs could be reduced by up to -10% by decreasing materials used, labor, and construction time. Prefabrication alone cannot meet the EU environmental targets regarding buildings but can be combined with energy efficiency measures and buildings refurbishment.

The developed and implemented framework responded to the initial goal of assessing prefabrication wide adoption within the EU-27 building stock from 2020 to 2050. Both approaches – *bottom-up* using archetypes and grounded in real case studies and alternative data, and *top-down* aggregating results using national statistics data – create a vast but still accurate database, expressing the regional variability within the EU-27 territory. The developed building stock model has proven to be a streamlined approach to assess a large set of alternatives in a vast territory.

6.3 Limitations and future work

Limitations were previously discussed through results, discussion, and conclusion sections in chapters 4 and 5. Generic background data was used when primary data was not available, and assumptions made when data was unknown (declared throughout this thesis). More complete and disaggregated data would render conclusions with a higher definition level. Some prefabrication benefits – e.g., optimization through mass production, the added value of reduced construction time, and potential reuse of parts – and challenges – e.g., initial investment and materials price fluctuation – were not considered, being highly variable and difficult to predict. Archetypes may not represent the broad variety of existing buildings, but the comparison is expected to hold. The conventional process could also be improved leading to impact reduction and wood can be used in conventional buildings. The effect of combined measures such as combining prefabrication with nZEB, renewable energy systems, or buildings refurbishment was out of the scope of this work.

Future work includes the development of an algorithm linked to the BIM model to automatically generate a set of archetypes combining different parameters: layouts, volumetrics, window to wall ratios, buildings elements compositions, and automatically extracting quantities and energy needs in different locations. It is envisioned that costs and impacts databases should be external and linked to the model to be easily updated, thus adapting to regional and temporal variability. The BIM-LCA approach could be used to assess individual buildings at an earlier stage by non-LCA experts and when changes can profoundly influence buildings' costs and impacts. Nearly zero energy buildings (nZEBs), buildings' refurbishment and the use of renewable energy systems will be included in the BSM and major sources of uncertainties addressed: related to future building stock (size and characterization), costs, emissions, and climate. Finally, the building stock approach developed can also be applied to other contexts: regional or temporal contexts or assessing other disruptive technologies, e.g., onsite 3D printing, shipping containers or recycled materials use.

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APPENDICES

Appendix I – Prefabricated buildings market

The prefabricated buildings represent around 8.3% of sold construction products, with prefabricated buildings of steel representing 15.9 billion, wood 8.4 billion, and plastic, concrete, or aluminum 3.7 billion according to 2017 data for a total sold production of 340 billion (European Commission, 2019b). Core benefits of prefabrication include reduced construction time and the relocation of part of the construction process to the plant, both crucial for some fast-developing countries in urgent need of housing but with no local labor and material capacity. For professional clients (office and retail), the reduced construction time is highly valuable. Some challenges are also identified: the misconception of lower quality, similar or higher cost (e.g., the costs of a prefabricated building is similar to a conventional, varying from 800 to 1000 €/m^2)., need to hire more than one contractor (to perform site work), lack of knowledge of licensing, insurance, and financing entities (autarchies, insurers, and banks), among other issues.

Traditionally conventional Portuguese construction is based on heavyweight construction, first using stone masonry and now brick or concrete masonry. In central and north Europe, lightweight wood buildings are more commonly used than in South Europe. Currently, more lightweight buildings are being constructed in Portugal, and the market demand for prefabricated buildings keeps up market acceptance of lightweight construction. Prefabricated buildings in Portugal are a growing niche, with the number of prefabricated companies being small but growing. The first prefabricated companies produced wood-based prefabricated holiday houses (*bungalows*), or heavy prefabricated structures (e.g., concrete elements). Currently, prefabricated companies use LSF or wood-framed structures, both in-service buildings and housing.

The visits to prefabricated companies in Portugal showed that some established construction companies have a specific prefabricated production line (with an independent brand) and a specific commercial segment (and product). Smaller companies focus on the internal market producing prefabricated houses (mainly single-family), and more prominent companies the external market as an export product mainly to: i) fast-developing countries (such as Venezuela or Angola) or ii) countries with higher labor costs (such as France). Differences can be perceived from the interviews to US prefabrication companies, much larger companies with scale economies.

Appendix II –Environmental targets

European Green Deal (2019)

> *"Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, the European Green Deal will transform the EU into a modern, resource-efficient, and competitive economy, ensuring:*
> - *no net emissions of greenhouse gases by 2050*
> - *economic growth decoupled from resource use*
> - *no person and no place left behind."* (The European Commission, 2019a)

At the end of 2019, the EU Commission presented the European Green Deal aiming to be the first climate-neutral continent in 2050 (and 55% GHG reduction by 2030 compared to 1990). This challenge is seen as an opportunity to create jobs and growth, address energy poverty, reduce external energy dependency and improve health and wellbeing. Several new and existing initiatives have been framed by the European Green Deal, some of them influencing buildings and the construction sector (further detailed below):

- **New European Bauhaus**: shaping more beautiful, sustainable, and inclusive forms of living together
- **Level(s):** European framework for sustainable buildings
- **Climate Pact**: empowering citizens to shape a greener Europe.
- **Renovation Wave:** doubling the renovation rate to cut emissions, boost recovery, and reduce energy poverty
- **New Circular Economy:** changing how we produce and consume:
- **A new Industrial Strategy**: for a green and digital Europe
- **Waste framework**:

New European Bauhaus (2021)

> *"The New European Bauhaus is a creative initiative, breaking down boundaries between science and technology, art, culture, and social inclusion, to allow design to find solutions for everyday problems."* (The European Commission, 2020b)

Recently launched, the New European Bauhaus is a discussion platform, a space of encounter and discussion towards more inclusive, accessible, inspiring, and sustainable buildings and living spaces. Being part of the Green Deal action plan, the New European Bauhaus focus on environmental, economic, and cultural principles combining design, sustainability, accessibility, affordability, and investment, and a meeting point with "*all creative minds: designers, artists, scientists, architects, and citizens."*

Level(s) (2020)

> *"Level(s) is an assessment and reporting framework that provides a common language for sustainability performance of buildings. Level(s) promotes lifecycle thinking for buildings and provides a robust approach to measuring and supporting improvement from design to end of life for both residential buildings and offices. Level(s) uses core sustainability indicators, tested with and by the building sector, to measure carbon, materials, water, health and comfort, climate change impacts, taking into account lifecycle costs and value assessments."* (Dodd et al., 2017)

Officially launched in 2020, Level(s) promotes a common platform to assess and improve buildings' sustainability, flexibility, resource deficiency, and circularity, proposing a lifecycle thinking approach towards the EU carbon neutrality target. Level(s) framework assesses buildings in six macro-objectives, with specific indicators and metrics:

1. Minimize GHG emission along building LC
2. Resource-efficient and circular material LC
3. Efficient use of water resources
4. Healthy and comfortable spaces
5. Adaptation to climate change
6. Optimize LC costs and value

Level(s) supports the construction sector to reduce resource and energy consumption and carbon emissions to achieve the EU Green Deal and EU Circular Economic Action Plan goals.

Climate Pact (2020)

> *"Climate Target Plan 20303 aims to cut net greenhouse gas emissions in the EU by at least 55% by 2030 compared to 1990. Energy efficiency is an essential component for action, with the construction sector as one of the areas where efforts must be ramped up. To achieve the 55% emission reduction target, by 2030 the EU should reduce buildings' greenhouse gas emissions by 60%, their final energy consumption by 14% and energy consumption for heating and cooling by 18%."* (The European Commission, 2020a)

The aim of the Climate Pact is to make buildings "*more climate-friendly*," renovating the existing ones and construction better using low-carbon materials. The Climate Pact initially has four focusing areas: i) green areas ii) green mobility, iii) efficient buildings, and iv) training for green jobs. The efficiency buildings initiative aims at making buildings energy- and resource-efficient.

Renovation Wave (2020)

> *"The Renovation Wave is part of the Green Deal, which sets the objective of climate-neutrality by 2050 at EU level. It aims to at least double the annual renovation rate by 2030, to foster deep energy renovation and mobilise forces at all levels towards these goals."* (Haines et al and goleman, daniel; boyatzis, Richard; Mckee, 2020)

The renovation waves is aims to trigger the EU buildings' renovation aiming to achieve the following key principles: energy efficiency, affordability, decarbonization and integration of renewables, life-cycle thinking and circularity, high health and environmental standards, twin challenges of the green and digital transitions, respect for aesthetics and architectural quality.

New industrial strategy for Europe (2020)

> *"The twin ecological and digital transitions will affect every part of our economy, society and industry. They will require new technologies, with investment and innovation to match. They will create new products, services, markets and business models. They will shape new types of jobs that do not yet exist which need skills that we do not yet have. And they will entail a shift from linear production to a circular economy."* (The European Commission, 2020c)

A new industrial strategy will be implemented to address present and future challenges and reflect European values: social, labor, and environmental. Europe's industry is already shifting from products to services and is a leading market in clean technologies with a substantial innovation capacity. Moreover, the digital technologies are changing industry, contributing to the European Green Deal, with more circular manufacturing and business models, allowing industry to be more productive, workers to be more skilled, and supporting the decarbonization of the economy (decoupling of economic growth from environmental impacts). Some technologies (like 3D printing) are critical, disruptive, and can supply clean and affordable energy and raw material. Mainly, the construction industry must also evolve as *"Europe also needs to address the sustainability of construction products and improve the energy efficiency and environmental performance of built assets",* and *"a more sustainable built environment will be essential for Europe's transition towards climate-neutrality."*

New Circular Economy (2020)

> *"Building on the work done since 2015, the new Plan focuses on the design and production for a circular economy, with the aim to ensure that the resources used are kept in the EU economy for as long as possible."*(European Commission, 2020d)

The new circular economy plan aims at achieving the Green Deal targets (climate neutrality by 2050 and decoupling economic growth from resource use) while ensuring the long-term competitiveness of the EU. Designing sustainable products is at the core of a sustainable product policy framework with the following sustainability principles: durability, reusability, upgradability, and reparability; reduce hazardous chemicals, and increasing energy and resource efficiency; increasing recycled content; ensuring performance and safety; remanufacturing and high-quality recycling; reducing carbon and environmental footprints; restricting single-use and premature obsolescence; ban on the destruction of unsold durable goods; product-as-a-service or producers responsibility throughout LC; digitalization of product information; rewarding sustainability performance.

The construction sector is identified as one key sector in The Strategy for a Sustainable Built Environment document to be launched this year (2021). Circularity in construction and buildings will be promoted by: addressing the sustainability performance of construction products, the durability, and adaptability of built assets, using Level(s) to integrate life cycle assessment in public procurement, material recovery in construction, and demolition waste; reduce soil sealing.

Waste framework (2008)

> *"By 2020, the preparing for re-use, recycling, and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the list of waste shall be increased to a minimum of 70 % by weight."*

The Waste Framework Directive defines the concepts and the principles in waste management, including definitions of waste, recycling, and recovery, with the definition of the waste hierarchy: the best option is waste prevention, followed by reuse and recycling. Disposal is the last resource and should be avoided.

Appendix III – Building stock approach

Table III.1 EU-27 Building stock characterization in 2019: area, heating & cooling degrees days, and annual increase or replace rate

		area	heating & cooling degrees days		annual increase & replacement rate	
	Countries	Mm²	HDD	CDD	increase	replace
Z2	Austria	484	3 280	40	var.	1.2%
Z2	Belgium	516	2 532	40	var	1.2%
Z1	Bulgaria	240	2 153	164	var	1.2%
Z1	Croatia	133	2 076	192	var	1.2%
Z1	Cyprus	51	693	754	var	1.2%
Z2	Czech Rep.	407	2 998	40	var	1.2%
Z2	Denmark	446	3 027	2	var	1.2%
Z3	Estonia	49	3 883	1	var	1.2%
Z3	Finland	311	5 483	1	var	1.2%
Z1	France	3 548	2 247	88	var	1.2%
Z2	Germany	4 388	2 801	46	var	1.2%
Z1	Greece	442	1 449	373	var	1.2%
Z2	Hungary	391	2 381	150	var	1.2%
Z2	Ireland	253	2 707	0	var	1.2%
Z1	Italy	3 008	1 814	306	var	1.2%
Z3	Latvia	68	3 623	3	var	1.2%
Z3	Lithuania	112	3 391	12	var	1.2%
Z2	Luxemburg	27	2 754	59	var	1.2%
Z1	Malta	21	515	756	var	1.2%
Z2	Netherlands	975	2 514	40	var	1.2%
Z2	Poland	1 322	2 952	49	var	1.2%
Z1	Portugal	496	1 109	167	var	1.2%
Z2	Romania	466	2 568	124	var	1.2%
Z2	Slovakia	172	2 899	65	var	1.2%
Z2	Slovenia	90	2 601	73	var	1.2%
Z1	Spain	1 950	1 671	248	var	1.2%
Z3	Sweden	596	5 120	1	var	1.2%
	EU-27	20 963	2 909	111		1.2%

NB: Z1 warm-weather countries (HDD < 2200); Z2 moderate-weather countries (HDD 2200-3300), and Z3) cold-weather countries (HDD > 3300), adapted from Nemry & Uihlein (2008)

Table III.2 EU-27 Building stock characterization in 2019

		building area				residential						non-residential			
		residential		non-residential		single-family		medium-rise		high-rise		medium-rise		high-rise	
	Countries	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm	%
Z2	Austria	315	65%	170	35%	198	41%	98	20%	16	3%	144	30%	25	5%
Z2	Belgium	348	67%	168	33%	285	55%	56	11%	10	2%	143	28%	25	5%
Z1	Bulgaria	173	72%	67	28%	97	40%	64	27%	12	5%	57	24%	10	4%
Z1	Croatia	104	78%	30	22%	84	63%	17	12%	3	2%	25	19%	4	3%
Z1	Cyprus	44	86%	7	14%	34	67%	8	16%	1	3%	6	12%	1	2%
Z2	Czech Rep.	264	65%	143	35%	143	35%	103	25%	18	5%	121	30%	21	5%
Z2	Denmark	322	72%	124	28%	235	53%	74	17%	13	3%	105	24%	19	4%
Z3	Estonia	37	76%	12	24%	17	35%	17	35%	3	6%	10	21%	2	4%
Z3	Finland	211	68%	100	32%	150	48%	53	17%	8	3%	85	27%	15	5%
Z1	France	2 713	76%	836	24%	1 980	56%	624	18%	109	3%	710	20%	125	4%
Z2	Germany	3 002	68%	1 386	32%	1 801	41%	1 021	23%	180	4%	1 178	27%	208	5%
Z1	Greece	373	84%	70	16%	160	36%	179	40%	34	8%	59	13%	10	2%
Z2	Hungary	286	73%	105	27%	212	54%	63	16%	11	3%	90	23%	16	4%
Z2	Ireland	179	71%	74	29%	172	68%	7	3%	2	1%	63	25%	11	4%
Z1	Italy	2 678	89%	331	11%	1 392	46%	1 098	36%	187	6%	281	9%	50	2%
Z3	Latvia	51	75%	17	25%	24	35%	24	35%	4	6%	14	21%	3	4%
Z3	Lithuania	70	63%	42	37%	35	31%	29	26%	5	4%	36	32%	6	6%
Z2	Luxemburg	18	66%	9	34%	13	48%	4	15%	1	3%	8	28%	1	5%
Z1	Malta	18	86%	3	14%	11	52%	6	29%	1	5%	2	12%	0	2%
Z2	Netherlands	592	61%	383	39%	474	49%	101	10%	18	2%	325	33%	57	6%
Z2	Poland	886	67%	436	33%	567	43%	275	21%	44	3%	371	28%	65	5%
Z1	Portugal	400	81%	96	19%	248	50%	128	26%	24	5%	81	16%	14	3%
Z2	Romania	386	83%	79	17%	247	53%	116	25%	19	4%	67	14%	12	3%
Z2	Slovakia	102	59%	70	41%	64	37%	33	19%	6	4%	59	34%	10	6%
Z2	Slovenia	74	82%	17	18%	56	62%	15	16%	3	3%	14	16%	2	3%
Z1	Spain	1 612	83%	338	17%	677	35%	806	41%	145	7%	287	15%	51	3%
Z3	Sweden	397	67%	199	33%	258	43%	119	20%	20	3%	169	28%	30	5%
	EU-27	15 654	73%	5 309	27%	9 635	47%	5 136	22%	899	4%	4 512	23%	796	4%

Table III.3 EU-27 Building stock forecast for 2050

		total building area in 2050				residential in 2050						non-residential in 2050			
		residential		non-residential		single-family		multi-family		high-rise		medium-rise		high-rise	
	Mm²	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%
Austria	510	332	65%	179	35%	209	41%	103	20%	17	3%	152	30%	27	5%
Belgium	516	348	67%	168	33%	285	55%	56	11%	10	2%	143	28%	25	5%
Bulgaria	250	180	72%	70	28%	101	40%	67	27%	13	5%	59	24%	10	4%
Croatia	133	104	78%	30	22%	84	63%	17	12%	3	2%	25	19%	4	3%
Cyprus	42	36	86%	6	14%	28	67%	7	16%	1	3%	5	12%	1	2%
Czech	407	264	65%	143	35%	143	35%	103	25%	18	5%	121	30%	21	5%
Denmark	379	274	72%	105	28%	200	53%	63	17%	11	3%	89	24%	16	4%
Estonia	49	37	76%	12	24%	17	35%	17	35%	3	6%	10	21%	2	4%
Finland	366	248	68%	118	32%	176	48%	62	17%	10	3%	100	27%	18	5%
France	3 548	2 713	76%	836	24%	1 980	56%	624	18%	109	3%	710	20%	125	4%
Germany	4 351	2 977	68%	1 374	32%	1 786	41%	1 012	23%	179	4%	1 168	27%	206	5%
Greece	442	373	84%	70	16%	160	36%	179	40%	34	8%	59	13%	10	2%
Hungary	410	300	73%	110	27%	222	54%	66	16%	12	3%	94	23%	17	4%
Ireland	253	179	71%	74	29%	172	68%	7	3%	2	1%	63	25%	11	4%
Italy	2 876	2 560	89%	316	11%	1 331	46%	1 050	36%	179	6%	269	9%	47	2%
Latvia	68	51	75%	17	25%	24	35%	24	35%	4	6%	14	21%	3	4%
Lithuania	109	68	63%	41	37%	34	31%	29	26%	5	4%	35	32%	6	6%
Luxemb.	27	18	66%	9	34%	13	48%	4	15%	1	3%	8	28%	1	5%
Malta	22	19	86%	3	14%	11	52%	6	29%	1	5%	3	12%	0	2%
Netherla.	975	592	61%	383	39%	474	49%	101	10%	18	2%	325	33%	57	6%
Poland	1 320	885	67%	436	33%	566	43%	274	21%	44	3%	370	28%	65	5%
Portugal	496	400	81%	96	19%	248	50%	128	26%	24	5%	81	16%	14	3%
Romania	419	348	83%	71	17%	223	53%	104	25%	17	4%	61	14%	11	3%
Slovakia	172	102	59%	70	41%	64	37%	33	19%	6	4%	59	34%	10	6%
Slovenia	86	71	82%	16	18%	54	62%	14	16%	3	3%	13	16%	2	3%
Spain	1 950	1 612	83%	338	17%	677	35%	806	41%	145	7%	287	15%	51	3%
Sweden	737	491	67%	246	33%	319	43%	147	20%	25	3%	209	28%	37	5%
EU-27	20 915	15 581	73%	5 335	27%	9 601	47%	5 102	22%	893	4%	4 534	23%	800	4%

Table III.4 Table 27 EU-27 Forecasted new buildings from 2020 to 2050

		new building area 2020-2050				new residential 2020-2050						new non-residential 2020-2050			
		residential		non-residential		single-family		multi-family		high-rise		medium-rise		high-rise	
	Mm²	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%
Austria	205	133	65%	72	35%	84	41%	41	20%	7	3%	61	30%	11	5%
Belgium	186	125	67%	60	33%	103	55%	20	11%	4	2%	51	28%	9	5%
Bulgaria	98	71	72%	27	28%	40	40%	26	27%	5	5%	23	24%	4	4%
Croatia	48	37	78%	11	22%	30	63%	6	12%	1	2%	9	19%	2	3%
Cyprus	8	7	86%	1	14%	6	67%	1	16%	0	3%	1	12%	0	2%
Czech	146	95	65%	51	35%	51	35%	37	25%	7	5%	44	30%	8	5%
Denmark	86	62	72%	24	28%	45	53%	14	17%	2	3%	20	24%	4	4%
Estonia	18	13	76%	4	24%	6	35%	6	35%	1	6%	4	21%	1	4%
Finland	176	119	68%	57	32%	85	48%	30	17%	5	3%	48	27%	9	5%
France	1 277	977	76%	301	24%	713	56%	225	18%	39	3%	256	20%	45	4%
Germany	1 553	1 063	68%	491	32%	638	41%	361	23%	64	4%	417	27%	74	5%
Greece	159	134	84%	25	16%	58	36%	64	40%	12	8%	21	13%	4	2%
Hungary	163	119	73%	44	27%	88	54%	26	16%	5	3%	37	23%	7	4%
Ireland	91	64	71%	27	29%	62	68%	3	3%	1	1%	23	25%	4	4%
Italy	940	837	89%	103	11%	435	46%	343	36%	59	6%	88	9%	16	2%
Latvia	25	18	75%	6	25%	9	35%	9	35%	1	6%	5	21%	1	4%
Lithuania	37	23	63%	14	37%	12	31%	10	26%	2	4%	12	32%	2	6%
Luxemb.	10	6	66%	3	34%	5	48%	1	15%	0	3%	3	28%	0	5%
Malta	9	7	86%	1	14%	4	52%	3	29%	0	5%	1	12%	0	2%
Netherla.	351	213	61%	138	39%	171	49%	36	10%	6	2%	117	33%	21	6%
Poland	477	319	67%	157	33%	204	43%	99	21%	16	3%	134	28%	24	5%
Portugal	179	144	81%	34	19%	89	50%	46	26%	9	5%	29	16%	5	3%
Romania	116	96	83%	20	17%	62	53%	29	25%	5	4%	17	14%	3	3%
Slovakia	62	37	59%	25	41%	23	37%	12	19%	2	4%	21	34%	4	6%
Slovenia	28	23	82%	5	18%	17	62%	5	16%	1	3%	4	16%	1	3%
Spain	702	580	83%	122	17%	244	35%	290	41%	52	7%	103	15%	18	3%
Sweden	378	252	67%	126	33%	163	43%	75	20%	13	3%	107	28%	19	5%
EU-27	7 528	5 578	73%	1 950	27%	3 446	47%	1 914	37%	318	4%	1 657	23%	292	4%

Table III.5 The building area and population (2020-2050)

	Area per hab[1]		Area in 2020			Area in 2050	Population in 2020	Population in 2050	Population variation
EU-27	Residential (m^2/hab)	Service (m^2/hab)	Residential (Mm^2)	Service (Mm^2)	Total (Mm^2)	Total (Mm^2)	(Million)	(Million)	from 2020 to 2050 (%)
Austria	41	14	365	122	487	511	8.9	9.3	+ 5%
Belgium	35	10	406	112	518	537	11.5	11.9	+ 4%
Bulgaria	26	8	180	58	238	194	6.9	5.7	- 19%
Croatia	25	7	103	29	133	111	4.1	3.4	- 16%
Cyprus	49	10	43	9	52	61	0.9	1.0	+ 18%
Czechia	30	9	317	91	408	402	10.7	10.5	- 2%
Denmark	54	22	316	130	446	468	5.8	6.1	+ 5%
Estonia	28	9	37	12	49	46	1.3	1.3	- 6%
Finland	36	20	200	111	311	298	5.5	5.3	- 4%
France	39	14	2 605	953	3 558	3 707	67.2	70.0	+ 4%
Germany	39	13	3 274	1 120	4 394	4 369	83.1	82.7	- 1%
Greece	29	12	308	134	441	392	10.7	9.5	- 11%
Hungary	30	10	295	96	391	371	9.8	9.3	- 5%
Ireland	42	10	207	49	256	320	5.0	6.2	+ 25%
Italy	43	7	2 587	418	3 005	2 897	60.3	58.1	- 4%
Latvia	28	8	53	14	68	50	1.9	1.4	- 27%
Lithuania	31	9	86	26	112	86	2.8	2.1	- 23%
Luxembourg	34	10	21	6	27	34	0.6	0.8	+ 23%
Malta	33	10	17	5	22	28	0.5	0.7	+ 32%
Netherlands	38	18	669	313	982	1 024	17.4	18.1	+ 4%
Poland	25	10	937	383	1 321	1 187	37.9	34.1	- 10%
Portugal	39	10	397	100	497	453	10.3	9.4	- 9%
Romania	21	3	409	53	462	372	19.3	15.5	- 20%
Slovakia	25	7	134	38	172	162	5.5	5.2	- 6%
Slovenia	30	14	63	28	91	89	2.1	2.0	- 2%
Spain	34	8	1 608	359	1 966	2 051	47.3	49.4	+ 4%
Sweden	42	16	431	170	601	714	10.3	12.3	+ 19%

[1] Data from 2008 available in Enerdata (2008)

Table III.6 Structural materials share per region for each archetype

		SF	MR	HR	MO	HO
Warm weather countries	**RC**	100%	100%	100%	100%	100%
Moderate weather countries	**WF**	33%	-	-	-	-
	RC	67%	100%	100%	100%	100%
Cold weather countries	**WF**	50%	67%	-	67%	-
	RC	50%	33%	100%	33%	100%

Data based on new building defined on IMPRO study, ref (Nemry and Uihlein, 2008b)

Table III.7 Life cycle inventory of embodied phase

A1-A3 RAW MATERIALS

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Exterior wall (kg)	SF	13 872 / 14 617 / 15 426	15 286 / 16 031 / 16 840	61 972 / 62 102 / 64 230
	MR & MO	59 793 / 62 925 / 66 329	64 281 / 67 413 / 70 817	260 610 / 261 153 / 270 102
	HR & HO	119 736 / 126 165 / 133 152	131 941 / 138 370 / 145 356	534 919 / 536 034 / 554 402
Roof (kg)	SF	5 934 / 6 659 / 7 194	7 561 / 8 278 / 8 853	30 400 / 30 690 / 30 980
	MR & MO	24 507 / 27 502 / 29 711	31 541 / 34 535 / 36 931	125 552 / 126 750 / 127 947
	HR & HO	27 356 / 30 698 / 33 164	35 207 / 38 549 / 41 223	140 144 / 141 481 / 142 818
Floor (kg)	SF	7 637	7 931	36 657
	MR & MO	61 601	68 955	295 700
	HR & HO	182 555	204 349	867 306
Interior wall (kg)	SF	2 583	3 846	16 586
	MR	56 233	57 902	334 732
	HR	119 278	132 497	765 962
	MO	41 700	46 322	53 067
	HO	59 868	66 300	383 283
Stairs (kg)	SF	636	617	3 050
	MR & MO	3 818	3 703	18 301
	HR & HO	5 727	5 554	27 451
Door (kg)	SF	288	288	288
	MR	3 888	3 888	3 888
	HR	9 000	9 000	9 000
	MO	1 440	1 440	1 440
	HO	4 680	4 680	4 680
Windows (kg)	SF	3 018	3 846	2 570
	MR & MO	16 124	20 509	13 705
	HR & HO	60 350	76 910	51 394
Concrete structural core (kg)	SF	-	-	-
	MR & MO	171 500	171 500	171 500
	HR & HO	428 750	428 750	428 750

A4 TRANSPORT TO PLANT

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Transport of materials (tkm)	SF	1 698 / 1 772/ 1 839	1 934 / 2 007 / 2 077	-
	MR	19 593 / 19 900 / 20 180	21 114 / 21 420 / 21 710	-
	HR	47 638 / 48 126 / 48 599	51 210 / 51 699 / 52 182	-
	MO	18 950 / 19 256 / 19 537	20 413 / 20 719 / 21 009	-
	HO	44 442 / 44 931 / 46 403	47 685 / 48 173 / 48 656	-
Transport of workers (km)	SF	2 640	2 640	-
	MR & MO	7 920	7 920	-
	HR & HO	21 120	21 120	-

A4 ON PLANT PREFABRICATION

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Electricity (kWh)	SF	12 000	12 000	-
	MR /MO	18 000	18 000	-
	HR /HO	24 000	24 000	-
Gas (kWh)	SF	2 200	2 200	-
	MR /MO	3 300	3 300	-
	HR /HO	4 400	4 400	-
Water (m3)	SF	66	66	-
	MR /MO	99	99	-
	HR /HO	132	132	-
Labor (hr)	SF	1 848	1 848	-
	MR /MO	2 772	2 772	-
	HR /HO	3 696	3 696	-

A4 TRANSPORT TO SITE

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Transport of materials and prefab parts	SF	33 967 / 35 437 / 36 781	38 684 / 40 147 / 41 530	151 523 / 152 942 / 154 360
	MR	391 869 / 397 995 / 403 608	422 280 / 428 406 / 434 205	1 223 987 / 1 225 728 / 1 235 874
	HR	952 753 / 962 524 / 971 977	1 024 209 / 1 033 980 / 1 043 640	2 833 926 / 2 836 378 / 2 856 083
	MO	378 996 / 385 122 / 390 735	408 525 / 414 378 / 420 177	1 154 232 / 1 155 973 / 1 166 120
	HO	888 841 / 898 612 / 908 065	953 693 / 963 464 / 973 124	2 446 926 / 2 449 378 / 2 469 083
Transport of workers	SF	8 800	8 800	17 600
	MR /MO	17 600	17 600	35 200
	HR /HO	35 200	35 200	70 400

A5 ASSEMBLAGE AND CONSTRUCTION

Electricity (kWh)	SF	6 000	6 000	24 000
	MR /MO	12 000	12 000	48 000
	HR /HO	18 000	18 000	52 364
Gas (kWh)	SF	550	550	2 200
	MR /MO	1 100	1 100	4 400
	HR /HO	1 650	1 650	6 600
Water (m^3)	SF	17	17	66
	MR /MO	33	33	132
	HR /HO	50	50	144
Labor (hr)	SF	1 848	1 848	14 784
	MR /MO	7 392	7 392	59 136
	HR /HO	22 176	22 176	177 408

Table III.8 Life cycle inventory of operational phase

B2-B5 MAINTAINANCE, REPAIR, REPLACEMENT, REFURBISHMENT

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
MATERIALS REPLACEMENT				
Exterior wall (kg)	SF	7 497 / 7 691 / 7 950	7 497 / 7 691 / 7 950	11 708 / 11 837 / 12 160
	MR & MO	31 529 / 32 344 / 33 430	31 529 / 32 344 / 33 430	49 234 / 49 778 / 51 136
	HR & HO	64 714 / 66 387 / 68 618	64 714 / 66 387 / 68 618	101 057 / 102 172 / 104 960
Roof (kg)	SF	5 018 / 5 888 / 6 468	5 018 / 5 888 / 6 468	8 080 / 8 660 / 9 240
	MR & MO	20 724 / 24 317 / 26 713	20 724 / 24 317 / 26 713	33 370 / 35 766 / 38 161
	HR & HO	23 133 / 27 144 / 29 817	23 133 / 27 144 / 29 817	37 249 / 39 923 / 42 596
Floor (kg)	SF	1 798	1 798	463
	MR & MO	14 505	14 505	3 732
	HR & HO	42 987	42 987	11 059
Interior wall (kg)	SF	1 769	1 769	6 270
	MR	35 698	35 698	126 540
	HR	81 686	81 686	289 560
	MO	28 558	28 558	101 323
	HO	40 875	40 875	144 894
Stairs (kg)	SF	150	150	457
	MR & MO	899	899	2 741
	HR & HO	1 349	1 349	4 111
Door (kg)	SF	252	252	252
	MR	3 888	3 888	3 888
	HR	9 000	9 000	9 000
	MO	1 440	1 440	1 440
	HO	4 680	4 680	4 680
Windows (kg)	SF	3 018	3 846	2 570
	MR & MO	16 093	20 509	13 705
	HR & HO	60 350	76 910	51 394
Maintenance waste (kg)	SF	19 502 / 20 566 / 21 404	20 330 / 21 394 / 22 232	27 799 / 30 508 / 31 411
	MR	123 336 / 127 745 / 131 227	127 753 / 132 161 / 135 643	233 210 / 236 149 / 239 902
	HR	283 220 / 288 903 / 293 808	299 780 / 305 463 / 310 368	503 429 / 507 218 / 512 679
	MO	113 573 / 117 981 / 121 464	118 165 / 122 573 / 126 055	182 682 / 185 621 / 189 375
	HO	238 089 / 243 772 / 248 676	254 649 / 260 332 / 265 236	354 443 / 358 232 / 363 693
TRANSPORT				
Transport of materials (tkm)	SF	975 /1 028 / 1 070	1 016 / 1 070 / 1 112	1 490 / 1 525 / 1 571
	MR	6 167 / 6 387 / 6 561	6 388 / 6 608 / 6 782	11 660 / 11 807 / 11 995
	HR	14 161 / 14 445 / 14 690	14 989 / 15 273 / 15 518	25 171 / 25 361 / 25 634
	MO	5 679 / 5 899 / 6 073	5 908 / 6 129 / 6 303	9 134 / 9 281 / 9 469
	HO	11 904 / 12 189 / 12 434	12 732 / 13 017 / 13 262	17 722 / 17 912 / 18 185
Transport of workers (km)	SF	300	300	300
	MR & MO	880	880	880
	HR & HO	1 980	1 980	1 980
Transport of waste (tkm)	SF	585 / 617 / 642	610 / 642 / 667	894 / 915 / 942
	MR	3 700 / 3 832 / 3 937	3 833 / 3 965 / 4 069	6 996 / 7 094 / 7 197
	HR	8 497 / 8 667 / 8 814	8 993 / 9 164 / 9 311	15 103 / 15 217 / 15 380
	MO	3 407 / 3 539 / 3 644	3 545 / 3 677 / 3 782	5 480 / 5 569 / 5 681
	HO	7 143 / 7 313 / 7 460	7 639 / 7 810 / 7 957	10 633 / 10 747 / 10 911
B6-B7 OPERATIONAL ENERGY USE				
Lisbon (kWh / year)	SF	22 856 / 22 664 / 22 586	22 856 / 22 664 / 22 585	19 756 / 21 608 / 22 447
	MR	216331 / 217 628 / 218 874	216 331 / 217 795 / 218 935	208 508 / 210 544 / 212 506
	HR	653 241 / 651 086 / 648 630	653 241 / 651 086 / 648 630	577 013 / 584 758 / 585 311
	MO	244 675 / 245 705 / 246 577	244 675 / 245 705 / 246 577	223 508 / 225 030 / 226 969
	HO	836 412 / 833 597 / 830 049	836 412 / 833 597 / 830 049	738 572 / 753 574 / 755 991
Berlin (kWh / year)	SF	30 5959 / 29 021 / 28 001	30 595 / 29 021 / 27 987	36 085 / 31 245 / 212 790
	MR	220 116 / 214 036 / 210 836	220 116 / 213 883 / 210 836	238 849 / 220 938 / 213 569
	HR	641 097 / 626 698 / 617 889	614 097 / 626 698 / 617 889	635 472 / 605 063 / 589 161
	MO	252 430 / 246 180 / 243 086	252 430 / 246 180 / 243 086	262 858 / 243 861 / 236 158
	HO	738 491 / 725 887 / 717 539	738 491 / 725 887 / 717 529	694 469 / 671 827 / 658 933
Stockholm (kWh / year)	SF	35 255 / 32 733 / 31 420	35 255 / 32 733 / 31 420	42 099 / 35 951 23 767
	MR	239 327 / 230 589 / 225 870	239 327 / 230 589 / 225 867	265 939 / 230 589 / 231 524
	HR	684 458 / 669 098 / 659 819	684 458 / 669 098 / 659 819	695 594 / 654 063 / 632 766
	MO	272 927 / 264 014 / 259 542	272 927 / 264 014 / 259 542	290 097 / 264 014 / 254 311
	HO	736 769 / 743 423 / 732 769	760 787 / 743 423 / 732 769	726 330 / 693 383 / 658 933

Table III.9 Life cycle inventory of end-of-life phase

C1-C4 DECONSTRUCTION / DEMOLITION				
	archetype	**prefab_LSF L / M / H**	**prefab_WF L / M / H**	**conv_RC L / M / H**
Electricity (kWh)	SF	1 364	1 364	1 364
	MR /MO	2 727	2 727	2 727
	HR /HO	4 091	4 091	4 091
Gas (kWh)	SF	125	125	125
	MR /MO	250	250	250
	HR /HO	375	375	375
Water (m3)	SF	4	4	4
	MR /MO	8	8	8
	HR /HO	11	11	11
Labor (hr)	SF	70	70	70
	MR /MO	280	280	280
	HR /HO	630	630	630
TRANSPORT				
Transport of workers (km)	SF	75	75	75
	MR & MO	300	300	300
	HR & HO	675	675	675
Transport of waste (tkm)	SF	1 019 / 1 063 / 1 103	1 161 / 1 204 / 1 246	4 546 / 4 558 / 4 631
	MR	11 756 / 11 940 / 12 108	12 668 / 12 852 / 13 026	36 720 / 36 772 / 37 076
	HR	28 583 / 28 876 / 29 159	30 726 / 31 019 / 31 309	85 018 / 52 091 / 85 682
	MO	11 370 / 11 554 / 11 722	12 248 / 12 431 / 12 605	34 627 / 34 679 / 34 984
	HO	26 665 / 26 958 / 27 242	28 611 / 28 904 / 973 124	73 408 / 73 481 / 74 072

		D REUSE & RECYCLE		
WASTE MANAGEMENT				
Demolition waste (kg)	SF	33 922 / 35 392 / 36 781	38 684 / 40 147 / 41 530	153 328 / 153 747 / 154 360
	MR	391 683 / 397 809 / 403 608	422 280 / 428 406 / 434 205	1 231 577 / 1 233 318 / 1 235 874
	HR	952 546 / 962 317 / 971 977	1 024 209 / 1 033 980 / 1 043 640	2 849 506 / 2 851 958 / 2 856 083
	MO	378 810 / 384 936 / 390 735	408 252 / 414 378 / 420 177	1 161 823 / 1 163 564 / 1 166 120
	HO	888 633 / 898 404 / 908 065	953 693 / 963 464 / 973 124	2 462 506 / 2 464 958 / 2 469 083

Table III.10 Energy needs per m^2 per year in each country for prefabricated LSF

										Prefab_LSF								
					SF			MR			HR			MO			HO	
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	157	**162**	171	117	119	122	128	130	132	138	140	144	149	151	154
2	**Belgium**	*2 532*	*40*	144	**149**	157	108	109	112	118	119	121	126	128	132	137	139	141
1	**Bulgaria**	*2 153*	*164*	169	**169**	170	168	167	157	182	182	182	192	191	191	234	235	236
1	**Croatia**	*2 076*	*192*	167	**167**	168	166	165	155	180	180	180	190	189	188	231	232	233
1	**Cyprus**	*693*	*754*	167	**167**	168	166	165	155	180	180	180	190	189	188	231	232	233
2	**Czech**	*2 998*	*40*	162	**167**	177	121	123	126	132	134	136	142	144	148	154	156	158
2	**Denmark**	*3 027*	*2*	162	**167**	176	121	123	126	132	134	136	142	144	148	154	156	158
3	**Estonia**	*3 883*	*1*	191	**198**	213	135	138	143	148	150	152	158	161	167	165	167	171
3	**Finland**	*5 483*	*1*	201	**209**	225	143	145	151	156	158	161	167	170	176	174	176	180
2	**France**	*2 247*	*88*	138	**142**	150	103	104	107	113	114	116	121	123	126	131	133	135
2	**Germany**	***2 801***	***46***	**168**	**174**	**183**	**145**	**147**	**152**	**144**	**146**	**149**	**167**	**170**	**174**	**167**	**169**	**172**
1	**Greece**	*1 449*	*373*	160	**160**	161	160	159	149	173	173	173	182	181	181	222	223	223
2	**Hungary**	*2 381*	*150*	165	**170**	180	123	125	128	135	136	139	145	147	151	157	159	161
2	**Ireland**	*2 707*	*0*	137	**142**	150	102	104	107	112	113	116	121	122	126	131	132	135
1	**Italy**	*1 814*	*306*	156	**156**	157	155	154	145	168	168	168	177	177	176	216	217	217
3	**Latvia**	*3 623*	*3*	190	**197**	212	135	137	142	147	149	152	158	160	166	164	166	170
3	**Lithuania**	*3 391*	*12*	190	**197**	212	135	137	142	147	149	152	158	160	166	164	166	170
2	**Luxemb.**	*2 754*	*59*	161	**166**	175	120	122	125	131	133	135	141	143	147	153	155	157
1	**Malta**	*515*	*756*	155	**155**	156	154	153	144	167	167	167	176	175	175	214	215	216
2	**Netherla.**	*2 514*	*40*	147	**152**	160	110	111	115	120	121	124	129	131	134	140	142	144
2	**Poland**	*2 952*	*49*	179	**185**	196	134	136	140	147	148	151	157	159	164	171	173	176
1	**Portugal**	***1 109***	***167***	**135**	**136**	**137**	**151**	**150**	**149**	**151**	**151**	**152**	**170**	**169**	**169**	**193**	**194**	**194**
2	**Romania**	*2 568*	*124*	175	**181**	191	131	133	136	143	145	147	154	156	160	167	169	172
2	**Slovakia**	*2 899*	*65*	169	**175**	185	126	128	132	138	140	143	149	151	155	161	163	166
2	**Slovenia**	*2 601*	*73*	158	**163**	172	118	120	123	129	130	133	139	141	144	150	152	155
1	**Spain**	*1 671*	*248*	157	**157**	158	157	156	146	169	169	169	179	178	177	218	219	219
3	**Sweden**	***5 120***	***1***	**188**	**196**	**211**	**156**	**159**	**165**	**153**	**155**	**159**	**179**	**182**	**188**	**170**	**173**	**177**

Table III.11 Energy needs per m^2 per year in each country for prefabricated WF

										Prefab_WF								
					SF			MR			HR			MO			HO	
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	157	**162**	171	117	119	122	128	130	134	138	140	144	149	151	154
2	**Belgium**	*2 532*	*40*	144	**149**	157	108	109	112	118	119	122	126	128	132	137	139	141
1	**Bulgaria**	*2 153*	*164*	169	**169**	170	168	168	156	182	182	182	192	191	191	234	235	236
1	**Croatia**	*2 076*	*192*	167	**167**	168	166	166	154	180	180	180	190	189	188	231	232	233
1	**Cyprus**	*693*	*754*	167	**167**	168	166	165	154	180	180	180	190	189	188	231	232	233
2	**Czech**	*2 998*	*40*	162	**167**	177	121	123	126	132	134	138	142	144	148	154	156	158
2	**Denmark**	*3 027*	*2*	162	**167**	176	121	122	126	132	134	137	142	144	148	154	156	158
3	**Estonia**	*3 883*	*1*	191	**198**	213	135	138	143	148	150	152	158	161	167	165	167	171
3	**Finland**	*5 483*	*1*	201	**209**	225	142	145	151	156	158	161	167	170	176	174	176	180
2	**France**	*2 247*	*88*	138	**142**	150	103	104	107	113	114	117	121	123	126	131	133	135
2	**Germany**	***2 801***	***46***	**168**	**174**	**183**	**145**	**147**	**152**	**144**	**146**	**149**	**167**	**170**	**174**	**167**	**169**	**172**
1	**Greece**	*1 449*	*373*	160	**160**	161	160	159	148	173	173	173	182	181	181	222	223	223
2	**Hungary**	*2 381*	*150*	165	**170**	180	123	125	128	135	136	140	145	147	151	157	159	161
2	**Ireland**	*2 707*	*0*	137	**142**	150	103	104	107	112	113	117	121	122	126	131	132	135
1	**Italy**	*1 814*	*306*	156	**156**	157	155	155	144	168	168	168	177	177	176	216	217	217
3	**Latvia**	*3 623*	*3*	190	**197**	212	134	137	142	147	149	152	158	160	166	164	166	170
3	**Lithuania**	*3 391*	*12*	190	**197**	212	134	137	142	147	149	152	158	160	166	164	166	170
2	**Luxemb.**	*2 754*	*59*	161	**166**	175	120	122	125	131	133	136	141	143	147	153	155	157
1	**Malta**	*515*	*756*	155	**155**	156	154	153	143	167	167	167	176	175	175	214	215	216
2	**Netherla.**	*2 514*	*40*	147	**152**	160	110	111	115	120	121	125	129	131	135	140	142	144
2	**Poland**	*2 952*	*49*	179	**185**	196	134	136	140	147	148	152	157	159	164	171	173	176
1	**Portugal**	***1 109***	***167***	**135**	**136**	**137**	**151**	**150**	**149**	**151**	**151**	**152**	**170**	**169**	**169**	**193**	**194**	**194**
2	**Romania**	*2 568*	*124*	175	**181**	191	131	133	136	143	145	149	154	156	160	167	169	172
2	**Slovakia**	*2 899*	*65*	169	**175**	185	126	128	132	138	140	144	149	151	155	161	163	166
2	**Slovenia**	*2 601*	*73*	158	**163**	172	118	120	123	129	130	134	139	141	145	150	152	155
1	**Spain**	*1 671*	*248*	157	**157**	158	157	156	145	169	169	169	179	178	177	218	219	219
3	**Sweden**	***5 120***	***1***	**188**	**196**	**211**	**156**	**159**	**165**	**153**	**155**	**159**	**179**	**182**	**188**	**170**	**173**	**177**

Table III.12 Energy needs per m^2 per year in each country for conventional RC

				Conv_RC															
					SF			**MR**			**HR**			**MO**			**HO**		
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	122	**172**	198	116	120	148	120	122	129	130	134	145	120	122	126
2	**Belgium**	*2 532*	*40*	112	**157**	181	106	110	136	109	112	118	119	123	132	123	125	129
1	**Bulgaria**	*2 153*	*164*	165	**180**	187	183	181	179	183	182	180	197	195	193	237	237	232
1	**Croatia**	*2 076*	*192*	161	**176**	183	179	177	175	179	178	176	192	191	189	232	231	227
1	**Cyprus**	*693*	*754*	151	**166**	172	168	167	165	168	167	165	181	179	178	218	218	213
2	**Czech**	*2 998*	*40*	128	**180**	208	122	126	156	125	128	135	137	141	152	141	143	148
2	**Denmark**	*3 027*	*2*	129	**182**	210	123	127	157	126	129	136	138	142	153	142	144	149
3	**Estonia**	*3 883*	*1*	147	**219**	256	138	144	158	142	146	155	154	160	175	147	155	163
3	**Finland**	*5 483*	*1*	156	**231**	271	146	152	168	150	154	164	163	169	186	156	164	172
2	**France**	*2 247*	*88*	137	**150**	155	152	151	149	152	151	150	164	162	161	198	197	193
2	**Germany**	***2 801***	***46***	**130**	**187**	**216**	**147**	**152**	**188**	**137**	**141**	**148**	**163**	**168**	**181**	**153**	**156**	**161**
1	**Greece**	*1 449*	*373*	146	**159**	166	162	160	159	162	161	159	174	173	171	210	210	205
2	**Hungary**	*2 381*	*150*	129	**181**	209	122	127	157	126	129	136	137	142	153	142	144	149
2	**Ireland**	*2 707*	*0*	111	**156**	181	106	109	135	109	112	117	119	122	132	122	124	129
1	**Italy**	*1 814*	*306*	145	**159**	165	161	159	158	161	160	158	173	172	170	209	208	204
3	**Latvia**	*3 623*	*3*	146	**216**	253	136	143	157	140	144	154	152	158	174	146	154	161
3	**Lithuania**	*3 391*	*12*	151	**224**	262	141	148	162	145	150	159	158	164	180	151	159	167
2	**Luxemb.**	*2 754*	*59*	127	**179**	207	121	125	155	125	128	134	136	140	151	140	143	148
1	**Malta**	*515*	*756*	138	**151**	157	153	152	150	154	153	151	165	164	162	199	199	195
2	**Netherla.**	*2 514*	*40*	116	**163**	188	110	114	141	113	116	122	123	127	137	127	130	134
2	**Poland**	*2 952*	*49*	143	**200**	231	135	140	173	140	143	150	152	157	169	156	160	165
1	**Portugal**	***1 109***	*167*	118	129	134	146	145	144	136	136	134	156	155	154	176	175	172
2	**Romania**	*2 568*	*124*	137	**193**	222	130	135	167	134	137	144	146	151	163	150	153	159
2	**Slovakia**	*2 899*	*65*	133	**187**	215	126	130	161	130	133	140	141	146	157	146	149	154
2	**Slovenia**	*2 601*	*73*	123	**173**	199	117	121	149	120	123	129	131	135	146	135	138	142
1	**Spain**	*1 671*	*248*	149	**163**	169	165	164	162	165	165	162	178	176	175	214	214	210
3	**Sweden**	***5 120***	***1***	**142**	**215**	**252**	**159**	**159**	**183**	**147**	**152**	**162**	**175**	**182**	**200**	**153**	**161**	**169**

Table III.13 GW per m^2 per year in each country for prefabricated LSF

								Prefab_LSF							
		SF			MR			HR			MO			HO	
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 118	1 107	1 122	813	805	808	800	796	800	912	905	910	899	898	902
Belgium	886	867	100	640	629	627	610	604	605	709	698	698	678	674	675
Bulgaria	1 979	1 939	1 913	1 884	1 856	1 738	1 950	1 939	1 929	2 114	2 088	2 065	2 462	2 460	2 458
Croatia	1 687	1 647	1 619	1 593	1 567	1 466	1 635	1 624	1 614	1 782	1 757	1 735	2 057	2 054	2 051
Cyprus	1 919	1 879	1 852	1 824	1 796	1 682	1 884	1 873	1 864	2 045	2 020	1 997	2 378	2 377	2 374
Czech	2 114	2 136	2 208	1 556	1 559	1 583	1 614	1 618	1 638	1 786	1 790	1 820	1 846	1 856	1 877
Denmark	1 438	1 437	1 471	1 052	1 047	1 057	1 061	1 060	1 069	1 193	1 189	1 203	1 203	1 206	1 216
Estonia	2 404	2 449	2 581	1 692	1 704	1 749	1 763	1 769	1 792	1 939	1 953	2 002	1 934	1 949	1 983
Finland	1 386	1 390	1 443	970	968	984	972	970	978	1 094	1 092	1 111	1 054	1 057	1 070
France	477	445	422	334	319	308	276	267	261	350	334	324	289	280	275
Germany	**1 815**	**1 832**	**1 884**	**1 519**	**1 522**	**1 545**	**1 430**	**1 438**	**1 460**	**1 712**	**1 714**	**1 738**	**1 629**	**1 636**	**1 654**
Greece	2 691	2 651	2 628	2 593	2 561	2 400	2 716	2 705	2 695	2 923	2 894	2 868	3 447	3 449	3 450
Hungary	1 813	1 825	1 880	1 331	1 331	1 349	1 368	1 370	1 385	1 522	1 522	1 545	1 560	1 567	1 583
Ireland	1 708	1 716	1 765	1 253	1 251	1 266	1 282	1 283	1 296	1 430	1 429	1 449	1 459	1 465	1 479
Italy	1 625	1 585	1 557	1 532	1 506	1 409	1 568	1 557	1 548	1 711	1 687	1 665	1 972	1 968	1 965
Latvia	2 394	2 439	2 570	1 685	1 697	1 741	1 755	1 761	1 784	1 931	1 944	1 993	1 925	1 940	1 974
Lithuania	2 394	2 439	2 570	1 685	1 697	1 741	1 755	1 761	1 784	1 931	1 944	1 993	1 925	1 940	1 974
Luxemb.	1 714	1 722	1 771	1 257	1 256	1 271	1 286	1 287	1 301	1 435	1 434	1 454	1 465	1 470	1 485
Malta	1 798	1 758	1 731	1 704	1 677	1 570	1 755	1 744	1 735	1 908	1 884	1 861	2 212	2 209	2 206
Netherla.	1 597	1 601	1 644	1 170	1 167	1 180	1 191	1 191	1 203	1 332	1 330	1 348	1 354	1 358	1 371
Poland	3 138	3 193	3 325	2 320	2 335	2 380	2 451	2 464	2 499	2 685	2 700	2 756	2 820	2 842	2 880
Portugal	**1 371**	**1 335**	**1 310**	**1 413**	**1 388**	**1 365**	**1 338**	**1 332**	**1 327**	**1 556**	**1 534**	**1 512**	**1 669**	**1 665**	**1 661**
Romania	1 845	1 858	1 915	1 355	1 355	1 373	1 394	1 396	1 412	1 550	1 551	1 575	1 590	1 597	1 614
Slovakia	1 458	1 458	1 492	1 066	1 062	1 072	1 078	1 077	1 086	1 211	1 207	1 221	1 222	1 225	1 235
Slovenia	1 273	1 266	1 290	928	922	927	926	923	930	1 048	1 041	1 051	1 045	1 046	1 053
Spain	1 335	1 295	1 266	1 244	1 219	1 140	1 257	1 246	1 236	1 382	1 360	1 339	1 571	1 566	1 561
Sweden	**429**	**397**	**375**	**313**	**298**	**288**	**236**	**227**	**221**	**320**	**305**	**295**	**235**	**226**	**221**

Table III.14 GW per m^2 per year in each country for prefabricated WF

								Prefab_WF							
		SF			MR			HR			MO			HO	
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 226	1 216	1 234	868	859	865	889	885	897	980	972	981	993	992	997
Belgium	994	976	113	694	684	684	699	693	700	776	766	768	772	768	770
Bulgaria	2 087	2 049	2 025	1 939	1 913	1 780	2 038	2 028	2 019	2 181	2 156	2 135	2 556	2 555	2 553
Croatia	1 795	1 756	1 731	1 648	1 624	1 511	1 724	1 713	1 704	1 849	1 825	1 805	2 151	2 148	2 146
Cyprus	2 027	1 988	1 964	1 879	1 853	1 724	1 973	1 962	1 954	2 113	2 088	2 067	2 472	2 471	2 469
Czech	2 222	2 245	2 320	1 611	1 613	1 640	1 703	1 707	1 743	1 853	1 858	1 892	1 940	1 950	1 972
Denmark	1 546	1 547	1 583	1 106	1 102	1 114	1 150	1 149	1 169	1 260	1 257	1 273	1 297	1 300	1 311
Estonia	2 512	2 558	2 694	1 745	1 757	1 805	1 852	1 858	1 881	2 007	2 020	2 068	2 028	2 043	2 078
Finland	1 494	1 500	1 555	1 024	1 022	1 041	1 061	1 059	1 067	1 161	1 160	1 179	1 148	1 151	1 165
France	585	554	534	389	374	365	365	356	352	417	402	394	383	374	370
Germany	**1 922**	**1 941**	**1 996**	**1 574**	**1 576**	**1 602**	**1 519**	**1 527**	**1 550**	**1 779**	**1 782**	**1 808**	**1 723**	**1 730**	**1 748**
Greece	2 799	2 761	2 740	2 648	2 618	2 436	2 805	2 794	2 785	2 991	2 962	2 937	3 541	3 544	3 545
Hungary	1 921	1 934	1 992	1 386	1 385	1 406	1 457	1 459	1 488	1 590	1 590	1 617	1 654	1 661	1 678
Ireland	1 816	1 825	1 877	1 308	1 306	1 324	1 371	1 372	1 398	1 497	1 496	1 520	1 553	1 559	1 574
Italy	1 733	1 694	1 669	1 586	1 562	1 454	1 657	1 646	1 638	1 779	1 755	1 735	2 066	2 063	2 060
Latvia	2 502	2 548	2 682	1 738	1 750	1 798	1 844	1 850	1 873	1 998	2 012	2 060	2 019	2 034	2 069
Lithuania	2 502	2 548	2 682	1 738	1 750	1 798	1 844	1 850	1 873	1 998	2 012	2 060	2 019	2 034	2 069
Luxemb.	1 822	1 831	1 883	1 312	1 310	1 328	1 375	1 376	1 403	1 502	1 501	1 525	1 559	1 565	1 580
Malta	1 906	1 868	1 843	1 759	1 734	1 613	1 844	1 833	1 824	1 976	1 952	1 931	2 306	2 304	2 301
Netherla.	1 705	1 711	1 756	1 225	1 222	1 237	1 280	1 280	1 304	1 400	1 398	1 419	1 448	1 453	1 466
Poland	3 246	3 302	3 437	2 375	2 388	2 437	2 540	2 553	2 613	2 752	2 768	2 828	2 914	2 936	2 975
Portugal	**1 479**	**1 445**	**1 422**	**1 468**	**1 444**	**1 422**	**1 427**	**1 421**	**1 417**	**1 624**	**1 601**	**1 582**	**1 764**	**1 759**	**1 756**
Romania	1 953	1 967	2 027	1 410	1 410	1 431	1 483	1 485	1 515	1 618	1 619	1 646	1 684	1 692	1 709
Slovakia	1 566	1 567	1 605	1 121	1 117	1 129	1 167	1 166	1 186	1 278	1 275	1 292	1 316	1 319	1 330
Slovenia	1 381	1 375	1 402	983	976	985	1 015	1 012	1 028	1 115	1 109	1 122	1 139	1 140	1 148
Spain	1 443	1 405	1 378	1 298	1 276	1 187	1 346	1 335	1 326	1 450	1 427	1 409	1 665	1 661	1 656
Sweden	**537**	**506**	**487**	**367**	**353**	**345**	**325**	**316**	**311**	**388**	**373**	**365**	**329**	**321**	**316**

Table III.15 GW per m^2 per year in each country for conventional RC

	SF			**MR**			**HR**			**MO**			**HO**		
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 275	1 513	1 642	1 014	1 024	1 170	938	946	973	1 068	1 080	1 127	909	914	930
Belgium	1 093	1 256	155	841	845	948	760	764	781	874	880	911	789	792	803
Bulgaria	2 282	2 403	2 456	2 237	2 209	2 179	2 145	2 128	2 097	2 357	2 327	2 302	2 670	2 655	2 600
Croatia	1 982	2 076	2 117	1 905	1 880	1 854	1 812	1 797	1 770	1 999	1 973	1 950	2 238	2 225	2 178
Cyprus	2 113	2 218	2 265	2 050	2 024	1 996	1 958	1 942	1 913	2 155	2 128	2 104	2 427	2 413	2 362
Czech	2 075	2 638	2 941	1 774	1 810	2 143	1 722	1 749	1 817	1 921	1 961	2 077	1 867	1 891	1 940
Denmark	1 548	1 897	2 085	1 273	1 292	1 502	1 206	1 220	1 261	1 359	1 381	1 451	1 289	1 301	1 330
Estonia	2 262	3 033	3 435	1 930	1 989	2 138	1 877	1 918	2 016	2 086	2 147	2 307	1 913	1 993	2 070
Finland	1 479	1 869	2 074	1 196	1 222	1 295	1 123	1 141	1 189	1 268	1 294	1 374	1 129	1 167	1 204
France	824	810	803	621	607	594	526	517	507	617	603	590	570	561	548
Germany	**1 817**	**2 309**	**2 563**	**1 745**	**1 780**	**2 106**	**1 555**	**1 581**	**1 640**	**1 866**	**1 904**	**2 014**	**1 676**	**1 697**	**1 738**
Greece	2 821	2 992	3 068	2 835	2 802	2 766	2 744	2 724	2 685	3 000	2 965	2 935	3 447	3 430	3 359
Hungary	1 823	2 283	2 531	1 534	1 562	1 836	1 475	1 495	1 551	1 652	1 683	1 777	1 590	1 608	1 648
Ireland	1 780	2 223	2 462	1 494	1 520	1 784	1 433	1 453	1 506	1 606	1 636	1 726	1 543	1 561	1 598
Italy	1 877	1 961	1 998	1 789	1 765	1 740	1 696	1 681	1 656	1 874	1 849	1 827	2 087	2 074	2 031
Latvia	2 245	3 007	3 406	1 914	1 972	2 120	1 861	1 901	1 998	2 068	2 128	2 287	1 896	1 975	2 051
Lithuania	2 306	3 098	3 512	1 972	2 032	2 185	1 920	1 961	2 062	2 132	2 195	2 360	1 957	2 039	2 118
Luxemb.	1 761	2 197	2 432	1 476	1 502	1 761	1 415	1 434	1 486	1 587	1 616	1 704	1 523	1 540	1 577
Malta	1 981	2 074	2 115	1 904	1 879	1 852	1 811	1 796	1 769	1 997	1 971	1 949	2 236	2 223	2 176
Netherla.	1 660	2 054	2 267	1 380	1 402	1 638	1 315	1 332	1 379	1 479	1 504	1 584	1 411	1 426	1 459
Poland	2 895	3 792	4 272	2 553	2 616	3 140	2 525	2 571	2 681	2 795	2 864	3 050	2 768	2 809	2 889
Portugal	**1 580**	**1 637**	**1 662**	**1 584**	**1 562**	**1 539**	**1 404**	**1 395**	**1 373**	**1 643**	**1 621**	**1 601**	**1 702**	**1 690**	**1 654**
Romania	1 847	2 318	2 571	1 558	1 586	1 866	1 499	1 520	1 577	1 678	1 711	1 806	1 617	1 636	1 676
Slovakia	1 546	1 895	2 083	1 272	1 291	1 500	1 204	1 219	1 260	1 358	1 379	1 449	1 287	1 299	1 328
Slovenia	1 395	1 682	1 837	1 128	1 142	1 316	1 056	1 067	1 100	1 196	1 213	1 269	1 120	1 130	1 153
Spain	1 625	1 685	1 712	1 509	1 488	1 465	1 416	1 403	1 381	1 573	1 551	1 531	1 724	1 712	1 676
Sweden	**735**	**768**	**786**	**524**	**512**	**523**	**417**	**414**	**416**	**515**	**510**	**515**	**394**	**394**	**393**

Appendix IV – Publications

Table IV.1 Core articles for Ph.D. thesis

Title	**Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The “Moby” case study**	**Life-cycle assessment of a prefabricated house: addressing different insulation levels and final location**	**Prefabricated versus conventional construction: comparing life-cycle impacts of alternative structural materials**	**What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?**
Main research question	*What are the embodied impacts of a prefabricated house? And the influence of size, transport, structural materials?*	*What is the balance between embodied and operational impacts in lightweight prefabrication? And the influence of insulation level, final location, and HVAC system?*	*What are the impacts, cost, and waste of a prefabricated (steel and wood) house and a conventional one? Can prefabrication contribute to reducing buildings' impacts and costs?*	*What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?*
Scope	Embodied	Embodied and operational	Embodied, (operational) and end-of-life	Embodied, operational, and end-of-life
Aim	Assess the influence of structural materials, house size, and transport to the final location	Assess the influence of final location (climate, transport, and electricity mix), HVAC system, and insulation level	Compares 2 prefabs and 2 conventional houses: impacts, costs, waste, and production time	Assess prefabricated wide adoption at EU-27 scale Develop a building stock model
Case study	Moby – steel house	Moby – steel house	BA – LSF house	Parametric buildings
Subject	Prefabricated embodied impacts	Lightweight vs heavyweight	Different structural materials	EU-27 Building stock
Design alternatives	Steel LSF Wood Concrete	Steel (Lightweight) High insulated Medium insulated Low insulated Conventional (Heavyweight) (just for energy use)	LSF Wood Concrete 1 & concrete 2	LSF Wood Concrete
Final locations	7 cities	7 cities	Famalicão (near Porto)	3 cities (Lisbon=warm, Berlin=moderate and Stockholm=cold) + EU-27 capitals
Layout alternatives	One-bedroom Two bedrooms Three bedrooms Four bedrooms	One-bedroom	Three-bedrooms	Single-family Medium-rise residential High-rise residential Medium-rise office High-rise office
Use phase alternatives	-	Insulation levels HVAC systems	-	Insulation levels
Functional unit	/m^2 /house / hab	/ house during 50 years	/ house during 50 years / m^2 during 50 years	/m^2*year of building stock
Impact assessment categories	Energy GHG	Abiotic depletion Abiotic depletion (fossil fuels) Global warming Ozone layer depletion Photochemical oxidation Acidification Eutrophication Non-renewable energy	Abiotic depletion Abiotic depletion (fossil fuels) Global warming Ozone layer depletion Photochemical oxidation Acidification Eutrophication Non-renewable energy	Global warming Non-renewable energy
Main results (categories)	**Carbon** (ICE) **Embodied GHG** [0.4-0.7]	**Global warming** (tCO_2eq/m^2) Embodied 0.54 - 0.697 Operational 0.847 - 3.019 *	**Global warming** (tCO_2eq/m^2) Embodied 0.16 (Operational 1.2) ** End-of-life -0.6	**Global warming** (tCO_2eq/m^2) Embodied 0.3 Operational 1.1 End-of-life -0.2
	Energy (ICE) **Embodied E** [7.5-10]	**Non-renewable energy** (GJ/m^2) Embodied 7 Operational 39 * **big windows no sun control*	**Non-renewable energy** (GJ/m^2) Embodied 2.2 (Operational 15) ** End-of-life -0.5 *** based on statistical data*	**Non-renewable energy** (GJ/m^2) Embodied 4 Operational 13 End-of-life -0.8

Other results (categories)	_	**Abiotic deplet.** (gSbeq/m^2) Embodied 3.78 - 4.06 Operational 2.70 - 7.10 **Abiotic deplet.** (fossil GJ/m^2) Embodied 6.6 - 8.9 Operational 8.6 - 36.4 **Ozone layer** (gRCC-11/m^2) Embodied 0.04 - 0.06 Operational 0.25 - 0.92 **Photoch. oxid**.(gC_2H_4/m^2) Embodied 0.23 - 0.28 Operational 0.35 - 0.97 **Acidification** (kg SO_2 eq/m^2) Embodied 2.7 - 3.8 Operational 3.9 - 24.0 **Eutrophication** (kg PO_4eq/m^2) Embodied 1.0 – 1.1 Operational 1.2 – 5.2	**Abiotic deplet.** (gSbeq/m^2) Embodied 1.81 Operational 1.5 End of Life -0.01 **Abiotic deplet.** (fossil GJ/m^2) Embodied 2 Operational 15 End of Life -0.4 **Ozone layer** (gRCC-11/m^2) Embodied 0.033 Operational 0.1 End of Life -0.002 **Photoch. oxid**.(gC_2H_4/m^2) Embodied 0.075 Operational 0.4 End of Life -0.003 **Acidification** (kg SO_2 eq/m^2) Embodied 0.98 Operational 9.5 End of Life -0.07 **Eutrophication** (kg PO_4eq/m^2) Embodied 0.39 Operational 2.5 End of Life -0.06	
Other indicatores			Energy Cost Time Waste	Energy Cost Time Waste
Main conclusions	materials production is the most important phase in a cradle-to-site assessment, and that the structures with LSF framing or timber have the lowest impacts, while steel and concrete the highest. a larger house leads to lower impacts per inhabitant, but similar impacts per m^2 . the impacts of transportation can be significant for overseas locations.	Operational impacts are the most critical representing 40-95% of the total impacts. Embodied impacts can reach up to 60% of total impacts in the houses with lower operational needs. The use phase is influenced by i) energy needs (cooling, heating, and ventilation); the electricity mix of each country; and iii) insulation level.	In comparison with conventional construction, prefabricated construction has lower environmental impacts uses less materials, and produces a small fraction of waste, taking half the time to build. WF has the lowest environmental impacts for all the categories but slightly higher cost. LSF has the lowest life cycle cost.	Prefabrication can further decrease building stock impacts up to 6%, mainly by decreasing embodied and end-of-life (EoL) impacts while maintaining energy efficiency. Prefabrication can contribute to achieving the EU targets and reduce construction costs, increasing the construction sector's productivity and sustainability.
Recommend ations	focus on selecting less energy and carbon-intensive materials reducing the impacts of transportation of modules and workers by: i) reducing the distance from the plant to the site; ii) choosing less energy-intensive transport modes; iii) transport prefabricated panels instead of modules; iv) selecting local materials and workers to complete the onsite assemblage stage	reduce operational impacts by adapting to local climate, using the correct insulation level Reduce embodied impacts by avoiding the use of some materials (e.g., some metals such as zinc), transformation processes (e.g., wood treatment), and substances (e.g., some HVAC refrigerant)		Different aggregations levels (at the building, country, or building stock level) can lead to different results/conclusions. Impacts and costs are highly variable among each EU country, so policies should be adjusted.

Core articles for Ph.D. thesis (abstracts)

EMBODIED ENERGY AND GREENHOUSE GAS EMISSIONS ANALYSIS OF A PREFABRICATED MODULAR HOUSE[3]

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Abstract: Buildings are big consumers of energy and materials, and important producers of waste and emissions. Prefabrication presents an opportunity to reduce impacts in the building sector; however, few studies have focused on prefabricated houses and with contradictory findings. The main goal of this article is to assess the embodied energy (EE) and greenhouse gas emissions (GHG) of a prefabricated modular house, based on a modular system to enable different layouts. A "cradle-to-site" analysis was performed, including materials production, transport to plant, modules production, transport to site and final assemblage on site. Several house final locations were addressed to assess transport related impacts. Scenarios for alternative building structural materials (steel; concrete; timber and light steel framing (LSF)) and house size (bedroom number) were also analyzed. The calculated embodied impacts show that materials production is the most important phase (64-90% of EE and 59-87% of GHG) and that the structures with LSF framing or timber have the lowest impacts. Embodied impacts increase with the house size; however, a larger house leads to lower impacts per inhabitant, but similar impacts per m^2. The impacts of transportation (of modules, workers and finishes) vary significantly for the various house final locations and can be significant for overseas locations, which can jeopardize the potential benefits of modular prefabrication.

Keywords: Offsite construction; Residential building; Life-Cycle Assessment (LCA); Embodied energy (EE); Climate change.

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[3] Tavares, V., Lacerda, N., Freire, F. (2019). Embodied Energy and Greenhouse Gas Emissions Analysis of a Prefabricated Modular House: the "Moby" case study. Journal of Cleaner Production vol. 212, pp. 1044-105. https://doi.org/10.1016/j.jclepro.2018.12.028

LIFE CYCLE ASSESSMENT OF A PREFABRICATED HOUSE FOR SEVEN FINAL LOCATIONS AND THREE INSULATION LEVELS [4]

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Abstract: Prefabricated buildings are based on lightweight construction systems, with fewer materials and less embodied impacts than conventional buildings. However, the lower embodied impacts of lightweight buildings can be jeopardized by higher operational energy needs. A lightweight prefabricated house was assessed for seven house locations (addressing transport, climate, and electricity mix), three insulation levels, and two heat pumps. A life cycle model was developed for a prefabricated one-bedroom house with a steel structure, addressing materials, modular prefabrication, transport to site, onsite assemblage, and use phase. A building information model (BIM) was used to build the life-cycle inventory and perform the energy simulation. Impacts were calculated for abiotic resource depletion, abiotic depletion of fossil fuels, global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication, and non-renewable energy. Results show that operational impacts dominate (40-90%), but embodied impacts can be significant for the Mediterranean and tropical climates (up to 60%). Prefabricated buildings should have different insulation levels (low level in a tropical climate, medium in the Mediterranean, and high in the EU continental region) and avoid high embodied impacts materials. Lightweight prefabricated buildings use fewer materials and can have lower embodied and operational impacts than heavyweight conventional, thus reducing the overall life cycle impacts of the building sector.

Keywords: Building Information Modelling (BIM), Environmental impact, Energy, Insulation, Lightweight building, Prefabrication.

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[4] Tavares, V., Freire, F. (2021). Life cycle assessment of a prefabricated house for seven final locations and three insulation levels, under review in the Journal of Building Engineering.

PREFABRICATED VERSUS CONVENTIONAL CONSTRUCTION:

COMPARING LIFE-CYCLE IMPACTS OF ALTERNATIVE STRUCTURAL MATERIALS[5]

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Abstract: Prefabrication can have advantages in terms of materials and time efficiency, but the overall environmental and cost trade-offs between the two construction methods are unclear and influenced by the choice of the structural material. A life cycle assessment was carried out to compare two constructive systems (prefabrication and conventional) and different structural materials for a single-family house. Impacts, waste, costs, and production time were assessed for two prefabricated construction systems with lightweight steel frame (LSF) and wooden frame (WF) and two conventional construction systems with reinforced concrete with a single layer concrete block (RC1) or with a double-layer brick external wall (RC2). Results showed that WF has the lowest impacts followed by LSF, and that the LSF has the lowest cost, but differences are small. Embodied impacts can represent more than half of total life cycle (LC); prefabricated houses have up to 65% less embodied impact, and at the end-of-life (EoL) prefabricated LSF impacts are reduced due to recycling; thus, unveiling the importance of embodied and end-of-life phases. Prefabrication can decrease impacts, materials consumption, and waste generation, pushing forward circularity within the construction sector.

Keywords: Life cycle assessment (LCA); Life cycle costing (LCC); Light steel framing (LSF); Wood framing (WF); Reinforced concrete (RC); Construction and demolition waste (CDW).

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[5] Tavares, V., Soares, N., Raposo, N., Marques, P., Freire, F. (2021). Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. Journal of Building Engineering, Vol.41, 102705. https://doi.org/10.1016/j.jobe.2021.**102705**.

WHAT IS THE POTENTIAL FOR PREFABRICATED BUILDINGS TO DECREASE COSTS AND CONTRIBUTE TO MEETING EU ENVIRONMENTAL TARGETS?[6]

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Abstract: The European Union (EU-27) targets buildings' decarbonization by 2050, and prefabrication presents an opportunity to reduce buildings and construction sector impacts. A stock-based approach was developed to measure the influence of wide adoption of building prefabrication in the EU-27 building stock from 2020 to 2050. Impacts and costs of five typologies using conventional or prefabricated construction systems were assessed for three cities – Lisbon, Berlin, and Stockholm – and three insulation levels. Results were calculated at the building and country levels and then combined at the stock level. Global warming (GW) varies between 5kgCO_2eq/m^2 for prefabricated light steel framing (prefab_LSF) medium- or a high-rise in France and 85kgCO_2eq/m^2 for the conventional concrete single-family (SF) in Poland. Life cycle costs vary between around 900€/m^2 for multi-family buildings in prefabricated LSF in Bulgaria and over 11000€/m^2 for an SF in conventional concrete in Luxembourg. Prefabrication can further decrease building stock burdens up to 6% and reduce building stock costs up to 10%. The developed building stock model has proven to be a fast and reliable tool to forecast the market dynamics when introducing a technological innovation, such as prefabrication. Prefabrication can contribute to achieving the EU-27 targets and reduce construction costs, increasing the construction sector's productivity and sustainability.

Keywords: Building stock; Environmental Targets; Life-Cycle Costing; Life Cycle Assessment; Modular life cycle inventory; Prefabricated buildings.

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[6] Tavares, V., Gregory, J., Kirchain, R., Freire, F. (2021). What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? Journal of Building and Environment. Vol.206, 108382 https://doi.org/10.1016/j.buildenv.2021.108382.