Universitat Autònoma de Barcelona

The introduction of eco-design for promoting the use of eco-materials: the cork as building material

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Doctoral thesis

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Institut de Ciència i Tecnologia Ambientals (ICTA)
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By

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“Adopt the pace of nature: her secret is patience.”

Ralph Waldo Emerson

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List of acronyms, abbreviations and notation

1.4 DB eq.	1.4 dichlorobenzene equivalent emissions	1.4 emisiones equivalentes diclorobenceno
ADP	Abiotic depletion potential	Potencial de agotamiento abiótico
ADPE	Abiotic depletion potential for non fossil resources	Potencial de agotamiento abiótico de recursos no fósiles
ADPF	Abiotic depletion potential for fossil resources	Potencial de agotamiento abiótico de recursos fósiles
AECORK	Catalan Cork Association	Asociación Catalana de Empresarios de Corcho
AP	Acidification potential	Potencial de acidificación
APCOR	Associação patronal do setor corticeiro	Asociación patronal del sector corchero
C_2H_4 eq.	Ethylene equivalent emissions	Emisiones equivalentes de etileno
CED	Cumulative energy demand	Demanda de energía acumulada
CELIEGE	European Cork Federation	Federación Europea del Corcho
CEN/TC	European Committee for Standardization. Technical Committee	Comité Europeo de Normalización. Comité técnico
CML	Institute of Environmental Sciences of the Faculty of Science of Leiden University in the Netherlands	Instituto de Ciencias Ambientales en la Facultad de Ciencias de la Universidad de Leiden en Holanda
CO_2	Carbon dioxide	Dióxido de carbono
CO_2 eq.	Carbon dioxide equivalent emissions	Emisiones equivalentes de dióxido de carbono
CR	Neoprene	Neopreno
DCB	Dichlorobenzene	Diclorobenceno
DIN	German Institute for Standardization	Instituto alemán de normalización
DU	Declared unit	Unidad declarada
EE	Embodied energy	Energía embebida
EN	European norm	Norma europea
ENERPHIT	Certification Criteria for Energy Retrofits with Passive House Components	Criterios de certificación para la rehabilitación energética con componentes Passive House
EP	Eutrophication potential	Potencial de eutrofización
EPBD	Energy Performance of Buildings Directive	Directiva de eficiencia energética de los edificios
EPD	Environmental Product Declarations	Declaraciones Ambientales de Producto
EPS	Expanded polystyrene	Poliestireno expandido
ETICS	External Thermal Insulation Composite System	Sistema de aislamiento térmico exterior compuesto
EUROSTAT	Statistical Office of the European Communities	Oficina Estadística de las Comunidades Europeas
EVA	Ethylene-vinyl acetate	Etileno acetato de vinilo
FPF	Flexible Polymer Foams	Espumas de polímero flexible
FU	Functional unit	Unidad funcional

GFRP	Fiber glass	Fibra de vidrio
GW	Glass wool	Lana de vidrio
GWP	Global warming potential	Potencial de calentamiento global
HNO_3	Nitric acid	Ácido nítrico
HS	Harmonized Commodity Description and Coding System	Armonizado de Designación y Codificación de Mercancías
ICSURO	Catalan Cork Institute	Instituto catalàn del corcho
IIR	Butyl rubber	Caucho butílico
ILCD	International Reference Life Cycle Data System	Sistema Internacional de Datos de Referencia del Ciclo de Vida
IMF	International Financial Statistics	Estadísticas financieras internacionales
ISO	International Organization for Standardization	Organización Internacional de Normalización
LCA	Life cycle assessment	Análisis del Ciclo de Vida
MJ eq.	Mega joules equivalent	Mega Julios rquivalentes
NMVOC	Non-methane volatile organic compounds	Compuestos orgánicos volátiles distintos del metano
NR	Natural Rubber	Caucho natural
NZEB	Nearly zero-energy building	Edificios de consumo de energía casi nula
OE	Operating energy	Energía operativa
OLDP	Ozone layer depletion	Potencial de agotamiento de la capa de ozono
PA	Polyamide	Poliamida
PC	Polycarbonate	Policarbonato
PCOP	Photochemical oxidation	Oxidación fotoquímica
PE	Polyethylene	Polietileno
PET	Polyethylene terephthalate	Tereftalato de polietileno
PMMA	Polymethylmethacrylate	Polimetacrilato de metilo
PNI	Positive-Negative-Interesting	Positivo-Negativo-Interesante
PO_4^{3-} eq.	Phosphate equivalent emissions	Emisiones equivalentes de fosfato
PP	Polypropylene	Polipropileno
PS	Polystyrene	Poliestireno
PU	Polyurethane	Poliuretano
PVC	Vinyl polychloride	Policloruro de vinilo
RDPs	Rural development programs	Programas de desarrollo rural
REDECOR	Thematic Network of Cork Oak and Cork	Red Temática del alcornoque y el corcho
RETECORK	European Network of Cork-Producing Territories	Red Europea de Territorios Productores de Corcho
RPF	Rigid Polymer Foams	Espumas rígidas poliméricas
Sb eq.	Antimony equivalent emissions	Emisiones equivalentes de antimonio
SETAC	Society of Environmental Toxicology	Sociedad de Toxicología y Química

	and Chemistry	Ambiental
SL/Q	Silicone elastomers	Elastómeros de silicona
SME	Small and medium-sized enterprises	Pequeñas y medianas empresas
SO_2 eq.	Sulphur dioxide equivalent emissions	Emisiones de dióxido de azufre equivalentes
SW	Stone wool	Lana de roca
TPU	Thermoplastic polyurethane	Poliuretano termoplástico
UN Comtrade	United Nations Commodity Trade Statistics Database	Base de datos estadísticos del comercio de las Naciones Unidas
XPS	Extruded polystyrene	Poliestireno extruido

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Summary

Cork is a natural, renewable material, typically concentrated in Mediterranean areas. The cork oak forests are mainly located in the Iberian Peninsula, and, therefore, where the most cork extraction activity is located. Cork is sustainability extracted from cork oak outer bark without damaging the tree or affecting biodiversity. The main current application of cork is as closure for wine and champagne bottles. The present dissertation has taken up the baton of a previous study about the Catalan cork sector carried out to analyse different system and subsystems of the sector from an environmental approach. That study highlighted the need of investigation in new field: diversification of cork products, giving more added value to the resource, and avoiding the excessive concentration of cork sector applications in wine markets.

The main objective of this dissertation was to address the diversification of cork sector, promoting its use in the building sector through the use of an interdisciplinary methodology framework from an environmental approach. This thesis was supported by several specific studies related to the economic characterization of the Iberian cork sector, the environmental assessment of current system for building insulation and the introduction of eco-design methods for the diversification of cork market.

The characterization of the Iberian cork sector identified important differences between Portuguese, Spanish and Catalan sectors. The formers are producers and processors of raw cork, acting as leader in the global market, and in the case of Portugal acting as a very powerful industry. Meanwhile, Spain sector is focussed on raw material and low intermediate basic cork products. Moreover, the building sector was identified as potential market on which promote cork material through the eco-design of new products.

Life Cycle Analysis (LCA) is an eco-design method used to assess the environmental impacts of products and systems throughout their life. This method was used to assess the current cork insulation product for buildings, and also the most common insulation materials and constructive solution on which could be installed. Results concluded that currently cork solutions did not fit the requirements to compete with the most common insulation materials, because caused more environmental impacts. So, the use of cork as a natural and renewable insulation material did not necessarily imply a better environmental performance in buildings. However, if manufacturing processes improve thanks to processes eco-innovation, this solution should be more efficient and can reach a better competitiveness of the product in the market. Moreover, the integration of LCA methodology with Thermal Dynamic simulation was also presented in this dissertation, to evaluate the energy saving renovation of an existing building. This integration was identified as suitable in the energy characterization of buildings and allowed obtaining more realistic results.

Once the initial situation was analysed, an eco-ideation process was carried out to generate new concepts of products, and the versatility of cork fitted perfectly with the creative methods used, due to the singular combination of cork properties. Some specific physical characteristics of cork, self-supporting, water vapour permeability and lightness, originated the most interesting concepts focused on the minimisation of materials use in the internal insulation systems or the treatment of moisture, in addition giving to the building a unique aspect due to the singular aesthetic of cork.

This dissertation has concluded the great convenience and possibilities of cork for its use in buildings, and the suitability of the life cycle thinking in the proposed interdisciplinary methodology.

Resumen

El corcho es un material natural, renovable y típicamente concentrado en el área Mediterránea. Los alcornocales están principalmente situados en la Península Ibérica, donde también se concentra la actividad de extracción del material. El corcho se extrae de una forma sostenible de la corteza del alcornoque sin dañar al árbol ni afectando su biodiversidad. La principal aplicación del corcho es como tapón para botellas de vino y cava. Este trabajo ha tomado el testigo de un estudio anterior sobre el sector catalán del corcho llevado a cabo para analizar los diferentes sistemas y subsistemas del sector desde una perspectiva ambiental. Este estudio destacó la necesidad de investigar en una nueva dirección: la diversificación de los productos de corcho, dando un mayor valor añadido al recurso, evitando la concentración excesiva del mercado del corcho en los productos del mercado vitivinícola.

El principal objetivo de este trabajo fue abordar la diversificación del sector del corcho, promoviendo su uso en el sector de la construcción a través del uso de un marco metodológico interdisciplinar desde una perspectiva ambiental. Esta tesis se apoya en diferentes estudios específicos relacionados con la caracterización económica del sector ibérico del corcho, la evaluación ambiental de los actuales sistemas de aislamiento en edificios y mediante la introducción de los métodos de ecodiseño con el objetivo de la diversificación del mercado del corcho.

La caracterización del sector ibérico del corcho identificó importantes diferencias entre los sectores de Portugal, España y Cataluña. Los primeros son principalmente productores y procesadores de materia prima, siendo líderes del mercado mundial, y en el caso de Portugal actuando como una potente industria. Mientras tanto, el sector español está centrado en la materia prima y productos básicos de corcho con un bajo o intermedio valor. Por otra parte, el sector de la construcción fue identificado como un mercado potencial en el que promover el corcho como material a través de ecodiseño de nuevos productos.

El Análisis del Ciclo de Vida (ACV) es un método de ecodiseño utilizado para la evaluación de los impactos ambientales de productos y servicios a lo largo de su ciclo de vida. Este método fue utilizado para evaluar los actuales productos aislantes de corcho para la construcción, así como además para analizar ambientalmente los materiales aislantes más utilizados y las soluciones constructivas donde se instalan. Los resultados concluyeron que las actuales soluciones aislantes de corcho no se ajustan a los requisitos para competir con los materiales aislantes comunes, porque generan mayores impactos ambientales. Por lo tanto, el uso del corcho como material natural y renovable no necesariamente implica un mejor desempeño ambiental de los edificios. Sin embargo, si se mejorasen los procesos de fabricación de estos productos a través de la ecoinnovación, se podrían conseguir productos más eficientes que pudieran mejorar su competitividad en el mercado. Además, la integración de la metodología ACV con simulaciones térmicas dinámicas es también presentada en este trabajo evaluando la rehabilitación de un edificio existente para el ahorro energético. Esta integración se consideró útil para la caracterización energética de edificios y permite obtener resultados más realistas.

Una vez analizada la situación inicial, se llevó a cabo un proceso de ecoideación para generar nuevos conceptos de producto. La versatilidad del corcho encajó perfectamente con los métodos creativos utilizados, debido a la singular combinación de las propiedades del corcho. Algunas propiedades físicas del corcho, como su capacidad portante, su permeabilidad al vapor de agua y su ligereza, originaron la mayoría de los conceptos más interesantes y enfocados en la minimización del uso de

materiales en los sistemas de aislamiento térmico por el interior o en el tratamiento de humedades. Además se destacó la singular estética del corcho para dotar al edificio de un aspecto único.

Este trabajo ha llegado a la conclusión de la gran conveniencia y posibilidades del corcho para uso en los edificios, y además de la idoneidad del concepto del ciclo de vida en la metodología interdisciplinar propuesta.

Resum

El suro és un material natural, renovable i típicament concentrat a l'àrea Mediterrània. Les alzines sureres estan situades, principalment, a la península Ibèrica, on també es concentra l'activitat d'extracció del material. El suro s'extreu d'una manera sostenible de l'escorça de l'alzina sense danys per a l'arbre ni afectació a la biodiversitat. La principal aplicació del suro és com a tap per a ampolles de vi i de cava. Aquest treball pren el relleu d'un estudi anterior sobre el sector català del suro dut a terme per a analitzar els diferents sistemes i subsistemes del sector des d'una perspectiva ambiental. Aquest estudi va destacar la necessitat d'investigar en una nova direcció: la diversificació dels productes de suro, amb la qual es doni un valor afegit més gran al recurs, tot evitant la concentració excessiva del mercat del suro en els productes del món vitivinícola.

El principal objectiu d'aquest treball va ser abordar la diversificació del sector del suro, promovent-ne l'ús en el sector de la construcció a través de l'ús d'un marc metodològic interdisciplinari des d'una perspectiva ambiental. Aquesta tesi se sustenta en diferents estudis específics relacionats amb la caracterització econòmica del sector ibèric del suro, l'avaluació ambiental dels sistemes actuals d'aïllament en edificis i mitjançant la introducció dels mètodes d'ecodisseny amb l'objectiu de diversificar el mercat del suro.

En la caracterització del sector ibèric del suro es van identificar diferències importants entre els sectors de Portugal, Espanya i Catalunya. Els primers són principalment productors i processadors de matèria prima, líders del mercat mundial en aquest camp, i en el cas de Portugal, a més, compta amb una potent indústria. En canvi, el sector espanyol està centrat en la matèria prima i en productes bàsics de suro amb un valor baix o mitjà. D'altra banda, es va identificar el sector de la construcció com un mercat potencial per a promoure-hi el suro com a material a través de l'ecodisseny de nous productes.

L'Anàlisi del Cicle de Vida (ACV) és un mètode d'ecodisseny emprat per a l'avaluació dels impactes ambientals de productes i serveis al llarg del seu cicle de vida. Es va fer servir aquest mètode per avaluar els actuals productes aïllants de suro per a la construcció, així com per analitzar ambientalment, a més, els materials més utilitzats i les solucions constructives en les quals s'instal·len. Els resultats van concloure que les actuals solucions aïllants de suro no s'ajusten als requisits per a competir amb els materials aïllants comuns, perquè generen més impactes ambientals. Per tant, l'ús del suro com a material natural i renovable no necessàriament implica un millor funcionament ambiental dels edificis. No obstant això, si es milloressin els processos de fabricació d'aquests productes a través de l'ecoinnovació es podrien aconseguir productes més eficients que poguessin millorar-ne la competitivitat en el mercat. A més, en aquesta treball també es presenta la integració de la metodologia ACV amb simulacions tèrmiques dinàmiques a l'hora d'avaluar la rehabilitació d'un edifici existent per a l'estalvi energètic. Aquesta integració es va considerar útil per a la caracterització energètica d'edificis i permet obtenir resultats més realistes.

Un cop analitzada la situació inicial, es va dur a terme un procés d'ecoideació per a generar nous conceptes de producte. La versatilitat del suro va encaixar perfectament amb els mètodes creatius utilitzats, a causa de la singular combinació de les propietats del suro. Algunes propietats físiques del suro, com la capacitat portant, la permeabilitat al vapor d'aigua i la lleugeresa, van originar la majoria dels conceptes més interessants i enfocats a la minimització de l'ús de materials en els sistemes

d'aïllament tèrmic per a l'interior o en el tractament d'humitats. A més, va destacar la singular estètica del suro per a dotar l'edifici d'un aspecte únic.

Aquest treball ha arribat a la conclusió de la gran conveniència i possibilitats del suro per a utilitzar-lo en els edificis, així com de la idoneïtat del concepte del cicle de vida en la metodologia interdisciplinària proposada.

Preface

This doctoral thesis was developed within the research group SosteniPrA (Sustainability and Environmental Prevention) at the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB) from October 2013 to September 2016; as well as, during the four-month star (May-September 2015) at the Environmental and Planning Department (DAO) of the Universidade de Aveiro, in Aveiro, Portugal.

This dissertation addresses the diversification of cork sector beyond wine and champagne markets through an eco design interdisciplinary methodological framework. The research assesses the environmental convenience of the current cork insulation products in buildings, and proposes new concepts of cork products for being applied in buildings.

The structure of the dissertation is organised into 6 main parts and 10 chapters. For clarity, the structure of the doctoral thesis is further outlined in Figure 0. This flow chart can be used throughout the reading of this manuscript as a *dissertation map*.

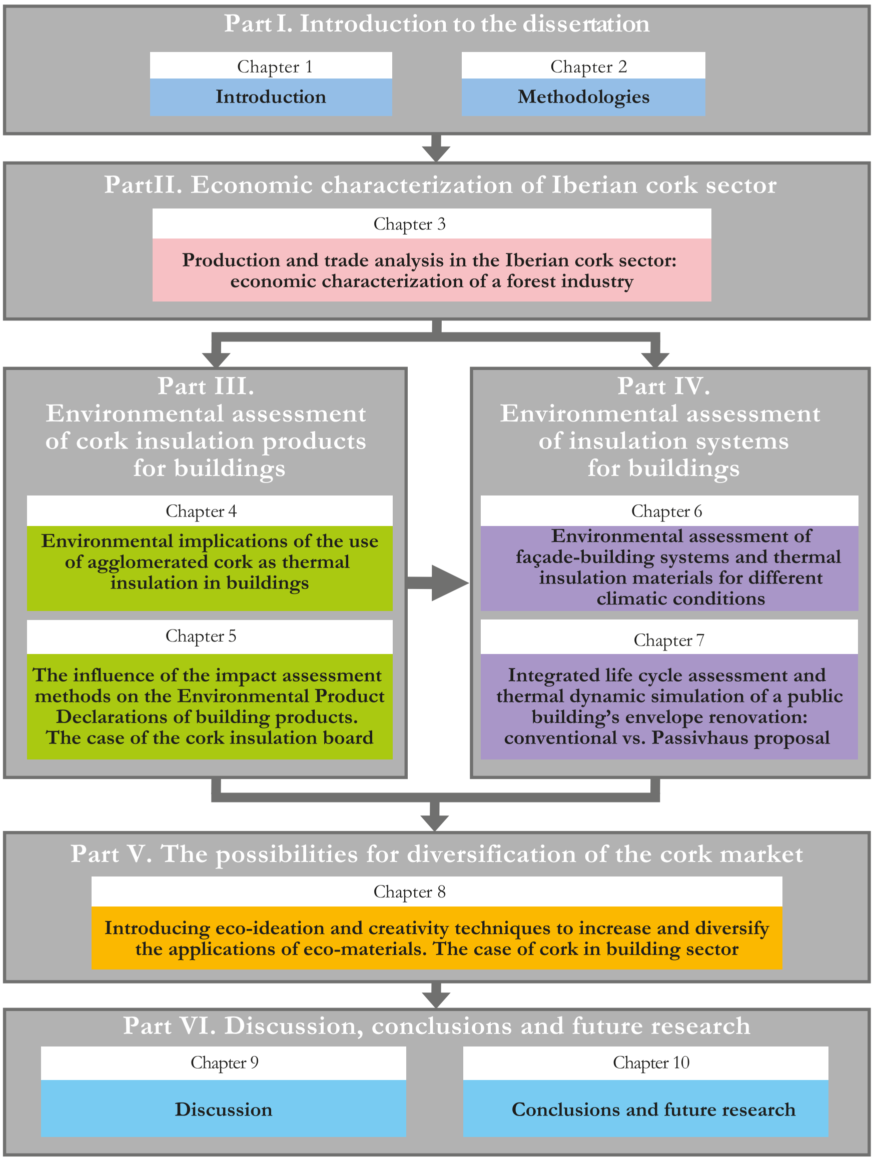

Figure 1.1. Map structure of the dissertation

Part I. Introduction to the dissertation

Part I is composed of two chapters. **Chapter 1** introduces the design process and the eco-design methodology carried out. Moreover, it contextualises cork as a natural, renewable and local raw material of Mediterranean areas; describing its properties and applications. After that, the European building sector is introduced from an environmental approach. At the end of this chapter, the justification and objectives of this dissertation are explained. **Chapter 2** describes the methodologies followed during the dissertation: economic tools, environmental tools, energy efficiency tool and product design tools.

Part II. Economic characterization of Iberian cork sector

Part II is composed of **Chapter 3** [*Production and trade analysis in the Iberian cork sector: economic characterization of a forest industry*]. This chapter describes the current global trade patterns in the Iberian Peninsula, where Portugal and Spain are world leaders. It also characterises the productive profile from an economic approach of each subsectors and identifies their differences. Finally, it highlights their strengths and weakness, and proposes strategies of improvement for the future.

Part III. Environmental assessment of Spanish cork insulation products for buildings

Part III focuses on the environmental evaluation of an insulation product made of cork and manufactured in Catalonia (Spain). **Chapter 4** [*Environmental implications of the use of agglomerated cork as thermal insulation in buildings*] presents a cradle to gate evaluation, and quantifies the total potential environmental impacts caused during their production and assesses the stages and operations of the production that most contribute to these impacts. **Chapter 5** [*The influence of the impact assessment methods on the Environmental Product Declarations of building products. The case of the cork insulation board*] evaluates the influence of the LCA method selection in the performance of environmental assessment of building products. This analysis is carried out in the framework of the related standards to the environmental assessment of buildings.

Part IV. Environmental assessment of insulation systems for buildings

Part IV focuses on the environmental assessment of constructive systems for the thermal insulation of buildings. **Chapter 6** [*Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions*] presents the environmental evaluation of a series of combination between type of façade system, insulation materials used and different locations for the building construction. This chapter includes not only the production of the components of the façade system but also the installation phase and the transport to the building site. **Chapter 7** [*Integrated life cycle assessment and thermal dynamic simulation of a university building's envelope renovation: conventional vs. Passivhaus proposal*] realises an evaluation of the convenience of an energy renovation of a real building, comparing different renovation proposals, and also different alternatives of insulation materials.

Part V. The possibilities for diversification of the cork market

Part V is composed of **Chapter 8** [*Introducing eco-ideation and creativity techniques to increase and diversify the applications of eco-materials. The case of cork in building sector.*]. This chapter describes the process of eco-ideation carried out during two interdisciplinary creative sessions and a product design stage for the conceptualization of new cork products in building sector. Moreover, it presents the main concepts generated at the end of the process.

Part VI. Discussion, conclusions and Future research

Part VI includes **Chapter 9** on which a general discussion between different parts of the dissertation, to interrelate the specific findings between them. **Chapter 10** provides the general conclusions of the dissertation and proposes future fields of research associated with the cork sector.

The dissertation is mainly based on the following published papers in peer-reviewed indexed journals:

- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Production and trade analysis in the Iberian cork sector: Economic characterization of a forest industry. Resources, Conservation and Recycling. 2015;98:55–66. doi:10.1016/j.resconrec.2015.02.011.
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions. Journal of Cleaner Production. 2016;113:102–13. doi:10.1016/j.jclepro.2015.11.090.
- Sierra-Pérez J, Boschmonart-Rives J, Dias AC, Gabarrell X. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. Journal of Cleaner Production. 2016;126:97–107. doi:10.1016/j.jclepro.2016.02.146.
- Sierra-Pérez J, López-Forniés I, Boschmonart-Rives J, Gabarrell X. Introducing eco-ideation and creativity techniques to increase and diversify the applications of eco-materials: The case of cork in the building sector. Journal of Cleaner Production. 2016; 137:606-616. doi:10.1016/j.jclepro.2016.07.121

Moreover, the following paper are also extracted from this dissertation and are submitted in peer-reviewed indexed journals

- Sierra-Pérez J, Boschmonart-Rives J, Dias AC, Arroja L, Gabarrell X. Influence of impact assessment methods on the Environmental Product Declarations of building products: The case of cork insulation board. *Submitted in April 2016.*
- Sierra-Pérez J, Rodríguez-Soria B, Boschmonart-Rives J, Gabarrell X. Integrated life cycle assessment and thermal dynamic simulation of a public building's envelope renovation: conventional vs. Passivhaus proposal. *Submitted in July 2016.*

The following oral communications and posters presented to congresses and conferences also form part of this doctoral thesis:

- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. The potential applications of eco-materials in the improvements of the sustainability of buildings. The case of the cork. Oral presentation. 6th International Conference on Harmonisation between Architecture and Nature. Eco-Architecture 2016. Alicante (Spain). 07/2016.
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. LCA of cork insulation board manufacturing and its environmental performance in renovation of buildings. Poster. 1st esLCA Workshop: "Life Cycle Management in the construction and energy sectors". Madrid, Spain. 23rd June, 2016.
- Sierra-Pérez J, Boschmonart-Rives J, Demertzi M, Dias AC, Gabarrell X. Life Cycle Assessment of the use of natural materials as thermal insulation in buildings. The case of the white agglomerated and expanded cork boards. Oral presentation. ISIE Americas Meeting 2016 "Industrial Ecology And Green Transformation". Bogotá (Colombia); 05/2016.
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Embodied energy vs. operating energy in dwellings façade: a case study of Spain. Oral presentation. Global Cleaner Production & Sustainable Consumption Conference. Sitges-Barcelona (Spain); 11/2015
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Environmental implications of cork as thermal insulation in façade retrofits. Oral presentation. 10th Conference on Advanced Building Skins. Bern (Switzerland); 11/2015
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Embodied energy in façade retrofit systems with different thermal insulation materials. Poster. 7th International Conference on Life Cycle Management. Bordeaux (France); 09/2015
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Environmental implications in the substitution of non-renewable materials by renewable materials through their entire life-cycle: a case study of cork as thermal insulation in building sector. Poster. SETAC Europe 25th Annual Meeting. Barcelona (Spain); 05/2015.
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Evaluation of the metabolism of the cork sector in the Iberian Peninsula: an environmental view. Oral presentation. 11th International Society For Industrial Ecology (ISIE) Socio-Economic Metabolism Section Conference and The 4th ISIE Asia-Pacific Conference, Melbourne (Australia); 11/2014.
- Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X., La ecoinnovación y el ecodiseño como futuras estrategias de desarrollo del sector corchero en España. Technical communication. XII Congreso Nacional de Medio Ambiente, Madrid (Spain); 11/2014.

[*Note:* Each Chapter from 3 to 8 presents an article –either published or under review- and they can be read independently from the others. For this reason, an abstract and a list of keywords are presented at the beginning of the chapter, followed by the main body of the article].

In addition, during the dissertation period the opportunity has been given to work in other papers, co-supervision of master thesis and research projects, provided further knowledge on the application of industrial ecology and sustainability assessment tools.

Papers:

- Martha Demertzi, Jorge Sierra-Pérez, Joana Amaral Paulo, Luis Arroja, Ana Dias. Environmental performance of expanded cork slab and granules through life cycle assessment. Journal of Cleaner Production. Under review.

Co-supervision of Master thesis:

- Antonio Larramendi. Máster en Energías Renovables y Sostenibilidad Energética. Universitat de Barcelona. Título: Estudio energético de los procesos de fabricación de diversos productos de aislamiento térmico para construcción fabricados en corcho, desde un punto de vista ambiental. Defensa: Junio 2016. Qualificacion: 8/10.
- Eduardo Basantes. Master's Degree in Interdisciplinary Studies in Environmental, Economic and Social Sustainability. Universitat Autònoma de Barcelona. Title: Natural insulation materials for buildings from a life-cycle perspective: a review. Defense: September 2016

Projects:

- "Valoraciò ambiental de la rehabilitació energètica de les zones menys eficients de l'AMB mitjancant ACV". AJUTS RECERCA CANVI CLIMÀTIC AMB. AMB (Area Metropolitana de Barcelona). Co-supervision. Student: Sergio García Pérez.

PART I

INTRODUCTION TO THE DISSERTATION

Chapter 1
INTRODUCTION

Chapter 1 introduces different concepts that will be addressed in this dissertation. First, the design process and eco-design methodology is presented, explaining its approaches and methods used. Secondly, the cork sector is introduced and the most important concepts are described: cork oak forests, cork oak tree, cork as a raw material, cork applications and a brief state of art of the research. After that, to justify the dissertation and explain its objectives, the European building sector is introduced from an environmental approach.

This chapter is structured as follows:

- Introduction to eco-design
- Overview of the cork resource
- Environmental approach of European building sector
- Justification to the dissertation.
- Objectives of the dissertation.

1. Introduction to the dissertation

Nowadays the consideration of environmental criteria in the various activities of society is a fact and new challenges are being faced to move towards sustainability. The Brundtland Commission of the United Nations proposed a philosophical definition for sustainable development (SD): "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. A more specific term understands SD, as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs. This concept emphasizes the evolution of human society from the responsible economic point of view, in accordance with environmental and natural processes [2]. Moreover, SD is usually referred to three pillars: social, environmental and economic (Figure 1.1) [3]; including more common terms such as personal responsibility, quality of life, health, welfare, happiness, democratic participation and cooperative behaviour.

Figure 1.1.A popular way of representing Sustainable Development (SD) [3].

The term industrial ecology (IE) refers to a set of tools, principles, and perspectives borrowed and adapted from ecology for the analysis of industrial systems including their impacts on society and the environment of the systems' material, energy, and information flows [4,5]. The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the manmade system, in order to achieve a pattern of industrialization that is not only more efficient, but that is intrinsically adjusted to the tolerances and characteristics of the natural system [6]. IE provides a powerful prism through which examine the impact of industry and technology and associated changes in society and the economy on the biophysical environment. It examines local, regional and global uses and flows of materials and energy in product, processes, industrial sectors and economies and focuses on the potential role of industry in reducing environmental burdens through the product life cycle. One of the principles of IE is the improvement of the efficiency of industrial processes, related to the dematerialisation of industrial output and the energy use through the redesign of product processes and equipment [6].

That is to maximize energy efficiency, save raw materials and reduce maximum levels of contamination, which often means being more competitive [7].

In this regard, a more advanced concept is circular economy. Circular economy systems keep the added value in products for as long as possible and eliminate waste. They keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value. Transition to a more circular economy requires changes throughout value chains, from product design to new business and market models, from new ways of turning waste into a resource to new modes of consumer behaviour. This implies full systemic change, and innovation not only in technologies, but also in organisation, society, finance methods and policies [8]. For that, eco-innovation strategies are designed to aim to produce quality products with less environmental impact, whilst innovation can also include moving towards more environmentally friendly production processes and services. Ultimately they will contribute towards the reduction of greenhouse gases or the more efficient use of various resources [9].

The cork sector is a traditional part of the economy in south-western Mediterranean areas. This sector already contributes to sustainability by making products with cork; a material of organic origin that is renewable and local. In addition to this, the cork sector in Catalonia has moved towards economic, social and especially environmental sustainability by generating new knowledge, and improving its current productive systems by employing cleaner production strategies. The cork sector perceived the environment as something inherent to its raw material, but besides, it is continuously trying to improve on an environmental level. The present dissertation is the continuation of a previous thesis, that developed a global environmental assessment of the Catalan cork sector that established strategic decisions to improve existing systems from the industrial ecology perspective [10]. Additionally, many of the cork companies are starting to think about implementing strategic tools for this purpose such as eco-design, eco-innovation, cleaner production and even carbon footprint eco-label implementation.

Next sections present an overview of the main fields of knowledge addressed in the dissertation. First, eco-design method will be introduced explaining its principles and basis, in addition of the main eco-design tool used in this study, Life Cycle Assessment (LCA). Second, cork oak forests and the cork oak tree will be presented, introducing the cork as a resource and its main applications. Third, the environmental approach of the European building sector will be introduced, from its regulatory and legislative framework.

1.1. Principles of eco-design

This section presents an overview of the eco-design field, introducing the design process on which is based, and the main objectives of this activity. Moreover, LCA concept and method is also presented.

1.1.1. The design process

Design as problem solving is a natural and the most ubiquitous of human activities. Design begins with the acknowledgment of needs and dissatisfaction with the current state of affairs, and realization that some action must take place in order to solve the problem [11]. Product development and design in industry today is a multi-facetted activity, often characterised by a large organizational structure, the involvement of many persons representing different specialities and departments such as research, design, production, marketing and management. Many researchers including Ullman, Pugh and Andreasen have developed the design process models [12–14]. The most common way of representing the design process is as a chain of tasks or events with milestones and decisions (Figure 1.2).

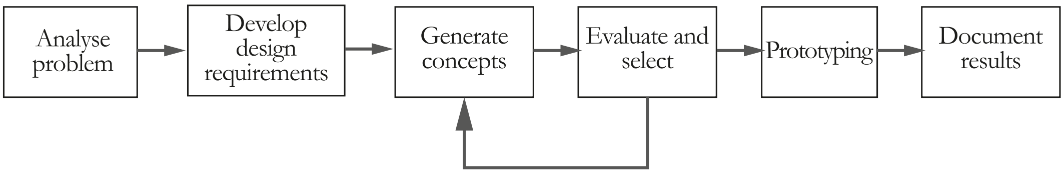

Figure 1.2. The Design process, (Adapted from Ullman, 2003)

The design process is characterised by analysis and synthesis in an iterative manner on different levels of details:

- Analyse the problem: design work always starts with an analytical phase where the problem is to be understood. The first step in the problem-solving process, therefore, is to formulate the problem in clear and unambiguous terms. Defining the problem is not the same as recognizing a need. Once a need has been established, engineers define that need in terms of an engineering design problem statement. To reach a clear definition, they collect data, run experiments, and perform computations that allow that need to be expressed as part of an engineering problem-solving process. The problem definition statement results from first identifying a need.
- Develop design requirements: Based on this problem analysis, a requirement specification should be established. Design requirements state the important characteristics that design must meet in order to be successful. In order to identify the design requirements for the solution is to use the concrete example of a similar, existing product, noting each of its key features. To complete the requirements step of the design process, a design brief should be write; a document that holds all of the key information for solving your problem in one place.
- Generate concepts: Next resources are allocated, design records are established and concepts are generated – synthesis phase. The concept generation stage of product development is where the skill, experience and creativity are used to generate design solutions, which solve the established brief. There are many methods for basic generation, mainly based in creativity techniques, among them: brainstorming and collaborative creative sessions. Creativity in the design process is regarded as a powerful tool, it is often characterized by the occurrence of a 'creative leap', which is not easy to be described in logical rules of conventional design theory [15].
- Evaluate and selection of concepts: Once the concepts are generated, the evaluation and selection are conducted by means of calculations, computer simulations or prototype testing – analysis phase. The measured product performance and properties are then compared to the specification and the synthesis and analysis is iterated until the result is satisfactory. The methods and tools applied in this dissertation will be explained in more detail in Chapter 2.
- Prototyping: Prototypes are a key step in the development of a final solution, allowing the designer to test how the solution will work and even show the solution to users for feedback.

- Document results: One of the most important activities in design is documenting the work, clearly communicating the solution to the design problem so someone else can understand what it has been created. Usually this consists of a design or technical report.

While conventional design represents current or typical professional practice, new theories and techniques continuously emerge from design research and practice [16]. Many design for X (DFX) techniques have been developed, including design for manufacture and assembly, design for quality, design for cost or design for environment. DFX techniques intend to go beyond functional requirements and provide other beneficial characteristics from various points of view [17]. But currently the seeking synergies between techniques benefit the resulted product and indeed, the user's need. One of the most extended methods is design for environment (DFE), also known eco-design.

1.1.2. Eco-design concept

Nowadays the consideration of environmental criteria in the various activities of society is a fact, as it is the case in the field of design. The activity that incorporates such criteria in the core of design processes is eco-design; whose main objective is to increase the efficiency of products or services, generating the minimal environmental impacts throughout their life cycle [18]. Eco-design is based in the design and engineering principles, and in turn, it is integrated with environmental sciences. From the formers, eco-design gets its pragmatic and synthesis character; while from environmental science, it obtains the analytical nature. That is why the eco-design methodology can promote a spiral of more effective and interconnected knowledge with the related scientific knowledge [19].

According ISO 14006:2011 [20] (replacing the previous Spanish standard UNE 150301), eco-design can be understood as a process integrated within the design and development that aims to reduce environmental impacts and continually to improve the environmental performance of the products, throughout their life cycle from raw material extraction to end of life. This definition indicates the necessary global approach of the life cycle, which means that the designer extends its environmental design perspective beyond the phases of production and use. Regarding to ISO 14050:2005 [21], life cycle is defined as the consecutive and interlinked phases of a product system, from raw material acquisition or generation of natural resources to the final disposal. These consecutives phases follow the logical order that can be seen in Figure 1.3, and are explained below:

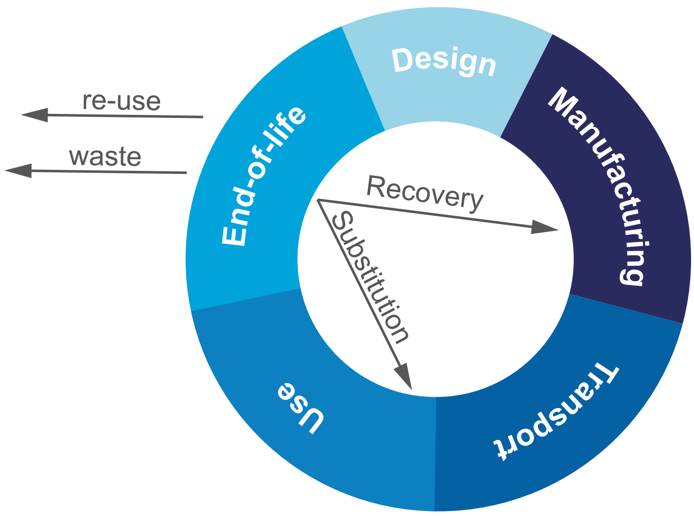

Figure 1.3. Diagram of the life cycle of a product

- At the <u>design phase</u> begins the life of a product, starting from the requirements established by designers. Design is considered one of the most important in economical terms, because approximately between 70 and 80% of the total cost is committed at this time [22]. Moreover, according to the German Federal Environment Agency, 80% of the environmental impacts of products are also committed during the design phase [23].
- The <u>production phase</u> includes all processes of extraction and processing of raw materials, production and assembly of product components, including associated processes of transport and packaging activities. In the case of non-energy related products, this phase is where the environmental impacts are

more noticeable, since all the processes involved require large amounts of energy resources [24].

- The transport phase is related to the distribution of products between the production and use location, on which the distance between them has a great importance in the associated environmental impacts. The globalisation of trade and the relocation of production have increased its environmental impact year after year, due to increased this distance. Moreover, this factor causes an increase in the quantity and quality of packaging for products to be transported, with the environmental impact it produces [25].
- The use phase has different significance between energy-related products and non-energy related product. The former requires energy to perform their function throughout its lifetime, for instance buildings. The latter does not require virtually of these resources, for instance building materials. In the case of energy-related products the environmental impacts are concentrated in this phase, reaching 80% of total impacts in the case of buildings [26].
- At the end-of-life phase ends the life of the product and in which different strategies can be applied. This is the fundamental phase when close the cycle and make that elements or materials from product could be integrated into other product (Recovery, substitution). Moreover, if the waste treatment is the unique option, it has to be the most environmentally friendly as possible.

The design of a product is the most important phase in the life of a product, especially from the point of view of functionality, cost and the environment. Decisions made at the design stage remain with a product until it's End-of-Life. The decisions made before manufacture will have important environmental impacts and have to be supported by an LCA as early as possible, to minimise them [27]. For that, the European directives have focused here the control, which, in combination with the common eco-design tools, aim to find a balance between environmental cost and the function performed by the product.

1.1.3. Eco-design methods and tools

Eco-design methodology is applied using the diverse available tools, along the different stages of the design process. Several product-related eco-design method have been developed by distinct environmental impact reduction purpose. A common goal for these methods is to measure and describe the environmental impact of products and services [28]. Hence they focus mainly on how to reduce the environmental impact of products throughout their life-cycle by focusing on specific environmental aspects while keeping the functionality of the product unchanged [29]. There are a great variety of tools, with different objectives and designed for specific sectors. The number of these tools is very large; they can be classified depending on the purpose of use and in what phases are applied.

A first group of tools is used as preliminary design analysis, in order to establish the different design requirements and specifications; specifying the strategies to apply. These tools approach the structural characteristics of the product, taking part in the definition of the requirements to perform its function. Among the main these preliminary tools are eco-design checklist [30] and guidelines for specific sectors [31]. Moreover, different Spanish governmental organizations have been developed their own eco-design guidelines to meet the demands of their productive fabric [32,33].

A second group of tools are used in intermediate stages to obtain a more detailed design, where they help in the assessment and choice among alternatives or design concepts. This type of tools focus on the environmental impacts of products with some requirements already set and tries to minimise them by keeping the specifications. The most extended tools are MET-matrix (Material cycle, Energy use and Toxic emissions Matrix) [30] and Life Cycle Assessment (LCA) [34]. The former is a semi-quantitative tool that focuses on the inventory of inputs and outputs. The latter, LCA, is an extension of MET-matrix, which includes the characterization of the environmental impacts related to the inventory. LCA is one of the most common eco-design method is Life Cycle Assessment (LCA). In order to understand complex environmental problems, LCA is used to create holistic view of the total environmental performance throughout the life cycle of a product or service. It was initially introduced in the 70s by different studies for companies like Coca-Cola or the U.S. Environmental Protection Agency [35,36], and subsequently regulated by the SETAC (Society of Environmental Toxicology and Chemistry) guidelines [37]. This tool will be explained in detail in Chapter 2. Moreover, some more advanced tools have been developed, such us edTOOL [38], developed by Inèdit and Sostenipra research group. edTOOL aims to improve the sustainability of products and services by implementing eco-design in companies in a step-by-step intuitive way. This tool guide companies through the process of eco-design implementation, and propose with recommendations for the environmental improvement.

Thirdly, there are a number of tools used to communicate the environmental qualities of products once released to the market. Environmental Product Declarations (EPDs) are voluntary manifestations indicating the environmental aspects of a product or service, providing quantified environmental data. ISO 14025: 2006 marks all requirements and must include default parameters to be used and, where appropriate, additional information to explain the methodology used in environmental analysis of the product. Focusing on the building sector, the specific standard for the development of EPD for building material is EN 15804 and the standard related to the assessment of environmental performance of buildings are EN 15978. On the other hand, the European Commission developed the concession of eco-label [39]. This eco-label is granted by meeting certain environmental requirements based on a rubric of the product. These labels are based on environmental characteristics of the product and the stages of the product life cycle. The main objective of these tools is to promote demand and supply of those products that cause less impact on the environment. This allows the buyer or the user to compare the environmental performance of products based on the cycle of life through communication of accurate and verifiable information that is not misleading.

Finally, in the Spanish context, it has been created some public commissions to promote eco-design in different levels of the economic and productive sectors. In the case of Catalonia, "La Caixa" and Fundación Forum Ambiental launched the Eco-innovation Lab in 2014. It is a program to identify, classify and define business success cases increased competitiveness through the incorporation of eco-innovation strategies. Moreover, Generalitat de Catalunya constituted the Interdepartmental Commission of eco-design, its functions are to define, coordinate and prioritize the actions of the Generalitat de Catalunya in the field of eco-design and support the department responsible for the environment in the implementation, monitoring and evaluation of the actions of the Catalan Eco-design Programme.

1.2. Overview of the cork resource

The next section presents an overview of cork oak forests and the cork oak tree, introducing the cork as a resource and its main applications. First, cork oak forests and the cork oak tree will be introduced explaining some of their unique characteristics and emphasising the environmental roles that this tree has. Following this, cork will be introduced briefly focusing on its physical and chemical composition, the types of raw cork materials that can be obtained from the tree and pointing out some of the main applications of cork and manufactured by cork-processing industry. Several photographs of cork and the cork oak tree (Quercus Suber L.) cycle are shown in Figure 1.4.

(a) Cork oak tree under 40 years (not previously exploited)

(b) Cork oak tree being stripped

(c) Cork oak tree after stripping

(d) Cork piled up at a forest collection point

Figure 1.4. The cork oak tree cycle and cork as a resource. Source: Jesús Boschmonart

1.2.1. Cork oak forest

The cork oak forests are typical of the Western Mediterranean region due to their adaptation to the geographical area and, of course, the environmental conditions (Table 1.1) [40]. The real area of the distribution of cork oak forests is not known exactly, but worldwide it is estimated that it occupies a surface of between 2.3 - 2.4 million hectares, and that about 200,000 tonnes of raw cork is extracted yearly [41]. This uncertainty is understandable because data was estimated from the individual registers of different countries, with their respective methodologies and with different year references. Cork oak forests are concentrated in Portugal, Spain. Algeria and Morocco, concentrating the production of cork in Portugal and Spain. This issue will be address in Chapter 3.

Table 1.1. Cork oak tree basic environmental conditions

Aspect	Description	Reference
Latitude	31º N – 45º N	[42,43]
Longitude	9º11' W – 15º E	[43]
Altitude from sea level	0-2000 metres (optimal 600 m)	[43]
Mean annual precipitation	600-1000 mm. (it can survive under 400 mm)	[42–44]
Mean annual temperature	13-16ºC. (can survives up to 19ºC)	[45,46]
Type of soil	very tolerant: siliceous and sandy soils	[42,44]
Soil pH	acidic soils: 4.8 and 7.0	[42,47,48]

Cork oak forests have a relevant role to play against desertification and for soil conservation. This aspect is fundamental for the future viability of these ecosystems. The soil is richer in organic matter and is characterised for having better infiltration, water storage, nutrient retention, aeration and root growth capacities. The cork oak leaves are renewed yearly, this means that old leaves, fruits, small branches and animal excrement accumulates and decomposes in the soil returning nutrients and organic matter to the system [49]. By promoting the infiltration of rain and preventing soil erosion, cork oak forests also contribute to hydrology cycle regulation [49,50].

The profitability of cork oak forests requires correct management to guarantee the persistence of the species, biodiversity and productivity, at the same time as other ecological, economical and social benefits are obtained which impact society. Forest management plays a key role influencing the thickness and quality of raw cork: optimal cork oak management should be oriented towards the periodical removal of cork according to established legislation; in addition this would contribute to the sustainable management of these forests [51]. Treatments reducing stand density stimulate vegetative activity and production of cork slabs with thickness suitable for industrial processing [51].

Most of the present cork oak forests appeared from mid 19th century due to the increasing value of cork, as well as the demand for cork stoppers [49]. These forests provide multiple economic activities, such as livestock grazing, hunting, mushroom collection and honey production, but most of their economic value derives from cork extraction [45,52]. Besides the extraction of cork and other goods, these forests afford other services to society such as private amenities and public recreation opportunities [53], and providing numerous indirect environmental services: wildlife habitat, soil erosion prevention, carbon storage, hydrology regulation, etc. Without the cork incomes, these forests would collapse economically, causing serious ecological and social consequences [54] such as the substitution of this ecosystem by others that while more lucrative would cause the loss of regional employment [55].

If the forests are managed adequately cork production can be guaranteed for the future. Nowadays, there are different certification labels of sustainable forest management that indicates that the certified product was made under an established set of criteria and indicators aimed at promoting sustainable forest management [56]. Several sustainable forest management certification schemes have been developed, but nowadays the certification of the Forest Stewardship Council (FSC) [57] and the Programme for the Endorsement of Forest Certification (PEFC) [58] are becoming the most extended and widely implemented for cork oak forests. Currently, in Portugal there are approximately 70,000 hectares of cork oak forests certified [59] and forestry associations have estimated that they are due to reach 150,000 ha in the near future [49].

1.2.2. Cork oak tree

The cork oak tree (Quercus Suber L.) is a native, endemic and evergreen species, from the Fagaceae family, that grows in western Mediterranean schlerophyllous forests. It is usually between 18-20 metres tall, with a broad, round-topped head and a glossy green colour. The leaves are 4 to 7 cm long, weakly lobed or coarsely toothed, dark green above, paler below, with the leaf margins often down-curved [60]. The acorns are 2 to 3 cm long, in a deep cup fringed with elongated scales. Cork oak trees can survive for centuries [60]; between 250-350 years [42]. This species is special because it has an thick outer bark formed by a continuous layer of suberised cells that constitute the external envelope of the stem and branches [61] known commonly as cork, that is a natural, renewable raw material and local to Mediterranean areas.

The cork oak tree has the capacity to survive a scarcity of water during summer, and is well adapted to this condition by reducing its transpiration and accounting with a system of deep roots that allow it to obtain water from the subsoil [49,62]. The cork oak tree is expected to be severely affected by climate change due to the increased intensity and duration of the drought periods expected for this region [63] and especially because of its high sensitivity to drought in the initial stages of its development [50].

Another important fact that characterises the cork oak tree is its resistance to fire. In fact, it is thought that the outer bark of the tree could have been an evolutionary adaptation to a Mediterranean climate where fire was an important ecological factor [14]. After a fire, while many of the other tree species merely regenerate from seeds or resprout from the base of the tree; the cork oak branches, protected by cork, quickly regrow and recompose the tree canopy [52]. This is a clear advantage compared to other species that after a fire return to an initial stage of development [49]. Cork extraction is a key factor determining post-fire cork oak survival: unstripped trees present the highest survival rates, while the trees that have been recently stripped are the most susceptible to die if a forest fire occurs [64,65].

1.2.3. Cork as raw material

As a resource extracted directly from a tree, cork is a natural raw material, and the periodical regeneration of the tree [66], makes cork a renewable resource. Cork is composed of dead cells with walls that are impermeable due to a chemical compound known as suberin which is responsible for the unique and remarkable properties of cork [67]. In fact, all trees produce layers of suberised cells to protect themselves, but only the cork oak tree has the capacity to regenerate its outer bark by adding annual rings of cork [49].

The main components of cork are 40% suberin, 22% lignin, 20% polysaccharides (hemicelluloses and cellulose), 15% extractives (waxes and polyphenols), and 1% ash [51]. The elemental chemical composition of cork is 67% carbon, 23% oxygen, 8% hydrogen and 2% nitrogen [49].

The unique chemical and physical properties of this raw material include its low density, low permeability to liquids and gases, elasticity, compressibility, resilience, chemical inertness, good heat and acoustic insulating properties, resistance to microbial growth and an ability to adhere to a glass surface [68,69]. Table 1.2 shows some of the particular properties of the cork raw material.

Table 1.2. Main properties of cork as a raw material. Source: Adapted from [43,70]**.**

Property	Description
Density	120–200 kg m^{-3}.
Humidity	At 20ºC and 65% relative humidity of the environment, the cork humidity is about 6% because of the low density of the material and the high quantity of gases contained in its cells.
Specific weight	Very low: the average is 0.18 g cm^{-3}, but it ranges from 0.12-0.24 g cm^{-3}.
Impermeability	Very impermeable. It absorbs less than 18-20% of the water fact that favours the conservation of the material and its avoidance of rot.
Floatability	Very high. The high quantity of air in the cells and their permeability make cork an excellent floating.
Compressible	Very high. A natural cork stopper of 24 mm in length can be compressed to 16 mm.
Flexibility and elasticity	The limit of elasticity is approximately 5 kg cm^{-2}.
Resilience	It is a material resistant to elasticity for years.
Odour and flavour	Neutral. For this reason, it can be used for packaging food products.
Heat conductivity (λ)	0.040–0.045 $Wm^{-1}K^{-1}$.
Thermal diffusivity (α)	$1 \cdot 10^{-7}$–$1.5 \cdot 10^{-7}$ m^2s^{-1}.
Flammability	It is very difficult to ignite and poorly combustible because it needs a lot of oxygen to burn. However, cork dust can be used as a combustible in boilers.
Acoustic isolating	It is very absorbent of sound for low and medium frequencies.
Percussion insulating	Good insulating properties for acoustic percussion; for this reason it can be used in laminate flooring.
Vibration insulating	Excellent to cushion vibrations.
Electrical insulating	Excellent electric insulator.
Heat of combustion	Between 6,500-7,000 kcal kg^{-1} (similar to vegetal coal).
Durability	Very high. Cork is difficult to alter.
Oxidation	Does not rust due to the action of air or humidity.
Malleability	Easily workable, especially if the cork has been previously boiled.
Friction	Good resistance to movement and friction.

1.2.4. Cork applications

Cork has a wide range of traditional applications, due to its unique combination of valued physical properties. Cork stoppers suppose the most important applications, having the highest added value and largest market; mainly wine and champagne stoppers. Natural cork stoppers are punched direct from the best quality cork bark, the reproduction cork[1], and they are mainly used to put at the top of wine bottles [71]. Champagne stoppers are made by cork waste from natural cork manufacturing, which are transform into granulates. A basic graphic explanation of the manufacturing processes for these two important products is represented in Figure 1.5.

Regarding the natural cork stoppers, the reproduction cork is obtained from the 3rd extraction onwards and is considered the most valuable. After the stripping, the cork planks are stabilised by storing for at least 6 months to oxidise the polyphenols and stabilise the cork texture. The stabilised planks are boiled in clean water for at least an hour to make them more pliable and to fully expand the lenticels. The gas in the cells expands to create a very tight, uniform cell structure. Boiling causes the cork to increase in volume and become flatter and smoother; at the same time, the microflora population is significantly reduced. After boiling, the planks are dried and stored at controlled humidity and temperature for some weeks then sorted by thickness and quality (dependent on porosity and level of structural defects). After this ‘resting’ period, the stoppers are punched (manually or automatically) and the remaining material sorted and classified for use as agglomerate stoppers, discs or agglomerated products. Each raw cork stopper is cut to size, polished and graded. The final quality depends on the raw material and the processes adopted by the manufacturer [71,72].

In the case of champagne stoppers, are made up of an agglomerated cork body and two natural cork discs. Champagne cork stoppers present a larger diameter than natural cork stoppers for still wine, because they provide better mechanical resistance and make for greater compression against the neck of the bottle because it is essential to retain the high internal pressures in bottles to preserve the quality of the content. These types of closures are chemically and mechanically very stable, and for this reason they are an inexpensive solution for assuring a good seal for over 2 years [73].

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[1] Reproduction cork is the cork from the third extraction onwards which represents the best quality raw material; is mainly intended to natural cork stopper production. However, only those planks with sufficient thickness will be destined for natural cork stopper production.

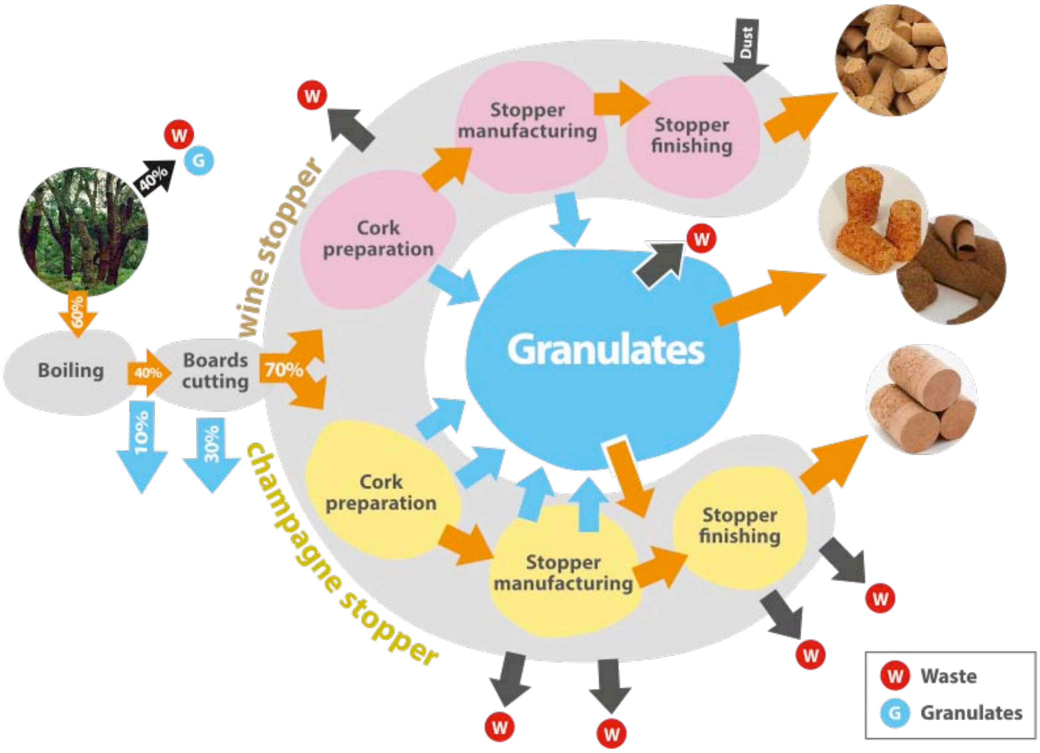

Figure 1.5. Diagram of the cork flows in the manufacturing of wine and champagne stoppers

The rest of cork applications are manufactured using cork granulates generated from forestry and industry cork wastes. Forestry wastes comprise different kinds of raw materials such as virgin cork[2], second cork[3], little pieces of reproduction cork, reproduction planks with defects, cork of tree branches, cork of fired trees etc., while, wastes from the natural industry comprises raw materials from the preparation of natural cork products, natural cork stopper production (pieces of cork resulting from the process of cutting into strips process, pieces of punched strips, rejected stoppers etc.), and natural disc production: pieces left from cutting into strips, the cork's back layer and the belly layer generated in lamination, pieces left from punched out cork slices and rejected discs [74]. The granulate size must be between 0.25 - 8 mm, and which their specific weights must be between 55 - 75 kg/m³.

In principle the granulate industry can be divided basically into two types: white cork granulates and black cork granulates. On the one hand, white cork granulate by-products are mainly intended to alimentary uses such as stoppers for wines, beers, champagnes, ciders etc., and for this reason a pre-treatment or preparation is required in order to clean the raw material before processing it to meet the health requirements of the final product. On the other hand, black cork granulate is intended to non-alimentary uses such as insulation panels, flooring, decoration, so on. In these cases, cleaning is not required. White cork granulate has a higher market price that black, and for this reason companies prefer to produce white. Despite, white cork granulate being preferable for the production of stoppers, it can be used for other applications [74]. The main application of granulates are the production of

[2] Virgin cork is those raw material generated because of the extraction of the first periderm of the tree, it presents deep fractures and a deformed structure. It is a cork obtained when the tree is between 35 and 40 years old.

[3] Second cork is generated after the second extraction and it contains deep fractures. Sometimes a small part of this could be used as reproduction cork.

cork/rubber composites and general-purpose agglomerates [71]. In the case cork/rubber composites, the main application is as gaskets for automobiles and oil containers: besides being impervious to liquids, the low Poisson ratio of cork means that these gaskets do not suffer from excessive lateral expansion [75]. In the case of agglomerated cork, the main applications are shoe soles, memo-boards, gifts and insulation boards [72]. The latter is the cork application that focuses the present dissertation.

From the manufacturing approach, there are different processes to transform granulates into insulation cork products. On the one hand, the expanded agglomeration is made through a process agglutinating granules of crude virgin cork, mainly falca (which has a high extractive level and functions as a natural inter-granular binder) and other types of cork of inferior quality. The agglomeration is carried out by the autoclave process, which also works as a mould. The granules are subjected to heat and pressure, with superheated steam. These are usually produced in the form of boards of different thicknesses (though other forms may be obtained), followed by corrections in size and squareness. One or both of the larger sides of the slabs may be sanded. This is a natural product, of vegetable origin. No synthetic agents are used, therefore it is a product with excellent ecological characteristics [72]. On the other hand, the agglomeration composite with natural or synthetic resins is another option that maintains all the properties of cork and is able to acquire extra characteristics. It can take on numerous forms and combinations and therefore occupies an advantageous position compared with other composite materials. Agglomerates are made out of a process of agglutinating the cork granules with a specific, pre-determined granulometry and density, through the joint action of compression, temperature and an agglutinating agent, depending on the final product desired [76].

1.2.5. Previous environmental studies in the cork sector

One of the principal strategies followed for the cork sector, especially in the Iberian Peninsula, is to advance towards sustainability. The environmental approach of sustainability has been mainly addressed trough the collection of quality data from the activities that compose the cork sector along its supply chain, assessing their associated processes.

On the one hand, Portugal is the worldwide leader of the cork sector, and it has showed a great interest in cork research, also the environmental implications of the cork sector and its products. Previously that, Portugal led the cork research, and it has mainly focused in the material characterisation for wine and champagne sector, in order to analyse the factors that influence in the correct developed of the cork aim [42,71,72,77–79]. The environmental research activity has been focused in the characterisation of the forestry [80] and industrial activities, among them: cork stoppers, floating floor, insulation boards, etc. [81–83]. The majority of these studies concluded the convenience of using cork from an environmental approach. The wide experienced in the environmental characterisation of cork products has resulted in a carbon footprint simulation model. This model allowed to assess the carbon footprint of cork products for different cork oak systems, in different countries and with different conditions. Moreover, the research in the Portuguese cork sector has been also addressed the design field. A noticeable project was carried out with the main objective of developing new products to put into market [76,84,85]. This project intended to promote the use of cork in common products that currently are made from less sustainable materials.

In the case of Spain, Catalan cork sector has led the environmental studies thanks to the dynamism of the cluster formation: a geographical concentration of companies, institutions and agents involved in the cork market. Studies where developed within a research project that aims to assess the cork sector from an environmental perspective, through the study of its subsectors: the cork oak forest and cork extraction, the natural cork stopper, cork granulates and the champagne cork stopper; identified as the most representative [73,74,86–88]. The project conclusions highlighted, in addition of the good physical and chemical properties that make it an ideal raw material for many applications, that cork is an excellent material from an environmental point of view. But also after analysing each cork subsector, the integrated scope allowed to determine greener and global strategies to recommend cork sector in order to continue advancing towards sustainability [88]. Moreover, this project concluded the necessity of the diversification of cork market because currently the wine and champagne markets focus the majority of industrial activities of the sector. The present dissertation has continued this line of research and has addressed some of the identified challenges.

The research activity in cork field is intense but is still very spread in different research centres along Iberian Peninsula. It is important to join efforts and interchange knowledge to not overlap same lines of research at the same time. In this regard a close collaboration between Portuguese and Catalan research groups from the University of Aveiro and the Autonomous University of Barcelona has already resulted in scientific studies [89] and European projects, gathering their results of raw cork to obtain a broad picture of the Iberian forestry cork sector. This collaboration has continued with other join research that is presented in this dissertation.

1.3. Environmental approach of European building sector

This section introduces the European building sector from an environmental approach and focusing on the related policies and regulations

1.3.1. Overview of the European building sector

The construction sector plays an important role in the European economy. It generates almost 10% of GDP and provides 20 million jobs, mainly in micro and small enterprises. Construction is also a major consumer of intermediate products (raw materials, chemicals, electrical and electronic equipment, etc.) and related services. Because of its economic importance, the performance of the construction sector can significantly influence the development of the overall economy [90]. The sector could contribute significantly to job creation by increasing its activity in some very promising areas, such as the renovation of buildings and in infrastructure, with support through, for example, appropriate policies to promote demand but also to encourage investment. Thus, the construction sector plays an important role in the delivery of the Europe 2020 Strategy on smart, sustainable and inclusive growth. Furthermore, the Commission's Communication on the 'Energy Roadmap 2050' points out that higher energy efficiency in new and existing buildings is key for the transformation of the EU's energy system [91].

Buildings account for 40 % of total energy consumption in the Union. It is estimated that embodied energy in building products was around 1.9 Million TJ in 2011. Steel and aluminium together are responsible for approximately 51 % of the total embodied energy in building materials with concrete responsible for another approximately 17 % of the total embodied energy in building materials [92]. The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions [93]. Unfortunately this industry tends to lag behind other industries in terms of taking advantage of new technologies and innovative practices [94]. Hopefully the sustainability concerns of Horizon 2020 (resource efficiency and climate action) will have a strong impact on the future of the European construction industry. Indeed, the influence of resource efficiency on building sector is clearly expressed by the milestone below included in the COM 571 [95]: "By 2020 the renovation and construction of buildings and infrastructure will be made to high resource efficiency levels. The life cycle approach will be widely applied; all new buildings will be nearly zero-energy and highly material efficient and policies for renovating the existing building stock will be in place so that it is cost-efficiently refurbished at a rate of 2% per year. 70% of non-hazardous construction and demolition waste will be recycled".

A sustainable construction sector plays a crucial role for reaching the EU's long term 80-95% greenhouse gas emission reduction objective. According to the Roadmap for moving to a competitive low carbon economy in 2050 [91], the cost efficient contribution of the buildings sector would be around 40 to 50% reduction in 2030 and around 90% in 2050 [96]. The needed investments would contribute substantially to the competitiveness of the European construction sector. The sector has also an important role to play in adaptation to climate change and resilience to natural and man-made disasters by promoting long-term disaster proofed investments. However, the construction sector is confronted by a number of structural problems, such as a shortfall of skilled workers in many companies, low attractiveness to young people due to the working conditions, limited capacity for innovation and the phenomenon of undeclared work [90].

1.3.2. Regulatory and legislative in building's framework

At the European level, the main policy driver related to the energy use in buildings is the Energy Performance of Buildings Directive (EPBD). Implemented in 2002, the Directive has been recast in 2010 (EPBD recast, 2010/31/EU) [93] with more ambitious provisions. Through the EPBD introduction, requirements for certification, inspections, training or renovation are now imposed in Member States prior to which there were very few. One of the new aspects of the EPBD is the introduction of the concept of nearly zero-energy building (NZEB). As EPBD defined, NZEB means a building that has a very high-energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. This represents an ambitious target that must be multidisciplinary approached [97]. Of all the new aspects set out by the new directive this one seems to be the one with most difficult enforcement by Member states. The article 9 of the European Directive establishes that, by the 31st of December of 2020, all new constructions have to be nearly zero-energy buildings; for public buildings, the deadline is even sooner – the end of 2018. This very ambitious target would be more easily fulfilled if eco-efficient thermal insulators were to be used.

Energy efficiency and renewable energy use in buildings is covered extensively by existing policy at the EU level. However, these efforts need to be complemented with policies that promote resource efficiency, and to cover a broader range of impacts, taking into account the full lifecycle of buildings. Improving the resource efficiency along the lifecycle of buildings will make the construction sector more competitive as well as reduce material use and environmental impacts associated with our built environment [98]. The life cycle of buildings extends from the extraction of raw materials, through the construction and use phases to demolition and eventual waste disposal and/or reuse. Resources are used, and environmental impacts created, throughout the lifecycle of buildings. Environmental impacts of resource use are understood as the quantified or qualified impacts associated with the actual use of resources. The environmental impact of the use of material resources in buildings arises at various stages of the building life-cycle, from the impact associated with the material extraction, through to processing and production of construction products, transport, construction itself, the use of the building including renovation and maintenance and eventual demolition and reuse or disposal. Each of these stages has an associated environmental impact, and it is important to know what stages, materials or constructive solution are the responsible for the most significant impacts [99]. For that, some standard related to the environmental assessment of buildings or building materials have been developed.

The standards related to the environmental assessment of buildings have been developed by the CEN/TC 350, the technical committee responsible for the development of horizontal standardized methods for the assessment of the sustainability aspects of new and existing construction works. All of these are based on LCA information, and are defined by different scope. At building level, the standard EN 15978 [100] specifies the calculation method, based on LCA and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment. The standard is applicable to new and existing buildings and refurbishment projects. And at product level, the standard EN 15804 [101] provides core product category rules for all construction products and services. It provides a structure to ensure that all Environmental Product Declarations (EPD) of construction products, construction services and construction processes are derived, verified and presented in a harmonized way. Moreover, the framework standard has a global approach for sustainability. On the one hand, the package of social standards for sustainable construction is covered by the assessment of health effects of buildings on the building occupants and neighbours (indoor air quality, noise, dust, etc.) are covered in. These standards of CEN/TC350 provide the horizontal methodology and standardized quantitative and qualitative social indicators for the assessment of social performance of buildings: EN 15643-3 [102] and EN 16309 [103]. On the other hand, the assessment of economic performance is one aspect of sustainability assessment of buildings under the general framework of EN 15643-4 [104]. This standard provides specific principles and requirements for the assessment of economic performance of buildings taking into account technical characteristics and functionality of a building. The framework applies to all types of buildings, and is relevant for the assessment of the economic performance of new buildings over their life cycle as well as existing buildings over their remaining service life.

1.3.3. Environmental studies of buildings

Focusing in the environmental approach of the sustainability, building sector has a wide experience in developing environmental studies. The life cycle thinking has a great acceptance in this sector, using mainly the LCA method in the environmental assessment of building sector [105]. LCA is employed for the selection of environmentally preferable products as well as for the evaluation and optimization of construction processes [106]. The LCA studies can be divided by scope and system boundaries. On the one hand, the studies can be focused in the evaluation of whole buildings of parts of them, including constructive solutions or building materials. On the other hand, the main life cycle approaches carried out in these studies are cradle-to-gate, cradle-to-grave and cradle-to-cradle.

LCA is widely used to compare different alternatives in the design of buildings, mainly focused on new building, more specifically, in residential buildings [99,107]. Few studies addressed the renovation of building, and their main goal was to assess the energy saving, limiting their scope to the assessment of operation energy; excluding the production and assembly of materials or constructive solutions [108,109]. Moreover, other studies have focused on the comparison of different alternatives of buildings design regarding the selection of constructive solution and building materials; such as exterior walls [110–112], the structure of the building [113] and, more recently, green roofs [114,115]. In these studies, the parameters used to compare different alternatives are the composition of the building system and the materials used in each solution along with considering the location of the building as a comparison between alternatives [116–118]. More specifically, LCA can also be a support tool in the selection of the building materials: mainly floors, roofs, the structure and insulation materials [119–123].

Among the building materials, the thermal insulation materials have recently drawn increased interest in the environmental field [124–127]. Currently, the European market is dominated by non-renewable insulation materials, among them: stone wool (SW), glass wool (GW), expanded polystyrene (EPS), extruded polystyrene (XPS) and the less widespread polyurethane (PU) [124,128]. Moreover, the market accounts for other alternative materials, including renewable materials; on which few studies from a life cycle perspective have been published, among them: kenaf-fibres, cotton, jute, flax, hemp and cork [78,127–130]. The importance of these materials has been increasing due to the strategic minimization of the use of non-renewable materials to reduce the environmental impact of buildings. However, renewable insulation materials still have not undergone sufficient development to be implemented comprehensively in the building sector. In this regard, cork is one of the most widespread renewable materials used as thermal insulation, especially in northern Europe, but the environmental implications of these products' manufacturing are still not widely known.

1.4. Justification of the dissertation

This section presents the motivation and justification of the present dissertation. Cork is a natural, renewable and local raw material, which use could contribute positively to environment. In this regard, all the strategies developed by the cork sector have to be focused on sustainability that is fundamental in the current context of societal development. For that, the present research, focused on the diversification of cork market, requires an exhaustive environmental approach.

This dissertation is motivated by the following facts:

- Previous studies have concluded **the need of the cork market's diversification** to overcome the identified sector's weakness, to extend the cork market beyond the wine and champagne markets.
- Previously, it is elemental to **analyse the cork sector from an economic approach**; assessing intensively the different subsectors that compose the Iberian sector to obtain their production and trade characteristics. This approach will give criteria focused on the improvement of the competitiveness of the global sector, and it will be identified the potential sector of application of cork material.
- This current research analysed the application of cork in **the building sector due to its identified potential for the cork insulation products market,** due to both cork is already present in the market and the its valuated combination of physical properties. So the environmental assessment of the most common insulation systems in buildings and the current insulation cork products is necessary. **LCA methodology** is used to carry out these evaluations, while continuing the previous work developed in the sector.
- **The predisposal of the cork sector to environmental issues** presents an excellent opportunity to apply creativity and plan for future challenges from both the sectorial and individual perspective. In particular, **eco-design** methodology could be a strategy implemented to ensure that cork products become even better from an economical and ecological viewpoint. Also, **eco-innovation** in the sector is essential to progress towards greening production.
- One special motivation of particular relevance nowadays in the present dissertation is the role of cork as we face **climate change**. The **environmental implication of the use of cork as insulation material in buildings** will be calculated in order to evaluate the contribution of the cork sector in this aspect.

1.5. Objectives of the dissertation

The main objective of this dissertation is to address the diversification of the cork sector, promoting its use in the building sector through the use of an interdisciplinary methodology framework from an environmental approach. This methodology has been supported by several studies related to the economic characterization of the Iberian cork sector, the environmental assessment of current system for building insulation and the introduction of eco-design for the diversification of cork market.

In order to achieve this main objective, the following goals are outlined:

- To obtain a broad picture of the Iberian cork sector from its economic characterisation.
- To identify the opportunities for improvements and weakness of this sector regarding its productive characteristics.
- To evaluate the environmental impacts associated with the manufacture of the current cork building product, including the cork extractions.
- To evaluate the influence of the LCA methods in the development of Environmental Product Declaration in the case of building products made of a natural material.
- To quantify, assess and compare environmentally the common insulation system of building with the current insulation cork products.
- To assess the adequacy of energy renovation practices of buildings using an integrated life cycle and thermal dynamic simulation assessment.
- To introduce eco-design methodology in the ideation of new cork products that improves the existing in the building sector.
- To apply creativity techniques for identifying potential uses of cork in buildings beyond cork insulation boards.
- To propose and develop new concepts of product for being applying in building sector as an example to validate the highest-potential product concepts in the cork industry.

Chapter 2
METHODOLOGIES

Chapter 2 details the methodological framework of this dissertation by defining the methods and tools employed and describing the main characteristics of the case studies. This dissertation develops a sustainability assessment of the diversification of an eco-material, in this case cork material. To do so, an interdisciplinary methodological framework is here proposed. First, it will be introduced the economic analysis carried out to the cork sector in order to characterize it in production and trade terms. Second, the sustainable assessment tool "life cycle assessment (LCA)" will be introduced briefly by describing its main phases and its particular aspects. Third, the dynamic thermal simulation modelling using in the building case study will be presented. Subsequently, the product design approach was used to generate and select the alternatives of product concepts will be detailed. Finally, the case studies included in this dissertation will be introduced and contextualized.

This chapter is structured as follows:

- Economic approach: Production and trade analysis of a forest sector
- Environmental approach: Life cycle assessment methodology
- Energy efficiency approach: Dynamic thermal simulation modelling of buildings
- Product design approach: Generation of alternatives and concept selection
- Overview of the case studies

2. Methodologies

Figure 2.1 illustrates the different approaches integrated in the sustainability assessment, which results into a combination of tools from the disciplines of economy, environmental science, energy efficiency and product design. The assessment is performed as three main scales: at sector scale, product scale and building scale.

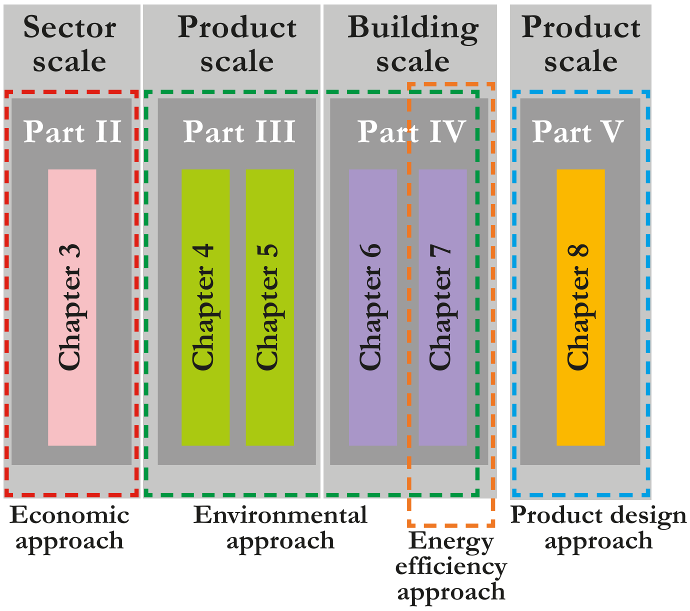

Figure 2.1. Overview of the interdisciplinary methodological framework of this dissertation

2.1. Methods

2.1.1. Economic approach: Production and trade characterization of a forest sector

The analysis of the competitiveness of sectors mainly focused in the international trade provides a better understanding of the recent competitiveness situation of a specific sector and therewith at providing a scientific fundament for decision makers in production and economy. Other forest sectors have used this kind of method for the same reasons, among them: the German forest industry sector [131] and the European wood fuel [132,133].

In the case of this dissertation, the aim of this method was to analyse the global trade of an industry based on a natural resource; the cork. This resource has a high geographic concentration in the Iberian Peninsula, so its international trade has significant characteristics and this method mapped the current trade patterns. Through this empirical analysis, the productivity can be characterized of each link of the supply chain and the capacity of this industry to generate wealth, identifying this for the different subsectors identified. To obtain this economic characterisation, the data collection was carried out from regional, national and continental statistical offices. To illustrate the distribution of cork flows around the world, it was used a graphical tool, JFlowMap [134]. Flow maps are visualizations that represent entities flowing between geographical locations (movement of goods and people, airline or network traffic, etc.) with lines connecting the flow sources and the destinations. Flow maps usually do not accurately show the exact migrations paths, instead they are aimed to answer questions such as: Where on the map are the sources and the destinations of the flows? What is happening within a specific location? In which direction do the migrants go? Where are the largest and the smallest flows? In the case of this dissertation, it served to show the importance of Iberian Peninsula in the worldwide trade of cork market.

In this regard, the main source of information for international trade was the United Nations Commodity Trade Statistics Database [135], from which the specific research on the trade-off countries was performed by nation. Moreover, these data were contrasted with the data provided by ESTACOM-EUROESTACOM [136], EUROSTAT [137], BACI [138] and APCOR [41] to ensure that there are no substantial differences. This point will be detailed in Chapter 3. The products are categorized by the Harmonized Commodity Description and Coding System (or HS); a tariff nomenclature for internationally standardized system of names and numbers to classify traded products as developed by the World Customs Organization[4]. In this case, cork and its manufacturers belong to the 45th group, in which four subgroups are defined by the six-digit code classification. The prevalence of the subgroup related to natural cork (450110), natural cork stoppers (450310) and agglomerated cork stoppers (450410) have been identified [139] .

Regarding the national or regional production, the specific data from Portugal, Spain and Catalonia were collected from their specific Departments or offices. In the case of Portugal, Gabinete de Estratégia e Estudos from the Portuguese Department of Economy and Employment was the source of data. The data from Spain were collected from the Spanish Department of Agriculture and Environment. And in the case of Catalonia, the data were collected from the Spanish Department of Agriculture and Environment and the regional government office, Generalitat de Catalunya.

Once the data was collected and processed, the results for different subsectors were compared. This methodology will be detailed in Chapter 3.

2.1.2. Environmental approach: Life Cycle Assessment

The LCA is one of the most used tools used to assess the sustainability of products, processes and services. The Society for Environmental Toxicology and Chemistry (SETAC) defined LCA as "An objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal" [140].

LCA is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisitions (cradle), via production and uses phases, to waste management (grave) [34]. There are four phases in an LCA studies: Definition and scope definition, Inventory analysis, Impact assessment and Interpretation.

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[4] http://www.wcoomd.org/fi

2.1.2.1. Definition of goal and scope

Definition of goal and scope is the first phase of an LCA study, where purposes and intentions must be outlined noting the reasons for carrying out the study, the intended audience and whether the wished-for results are used in comparative assertions. The scope should be defined to ensure that the grade of detail of the study is compatible and sufficient to address the proposed goal. The scope includes (a) the description of the system under study, (b) its functions, (c) the functional unit, (d) the system boundaries, (e) the allocation procedure rules, (f) the methodology of impact assessment and the selected impact categories, (g) data requirements, (h) assumptions established, and, other requirements [141]. All these aspects are important and relevant, but the functional unit, the system boundaries and allocation are often the most widely discussed:

The functional unit (FU) is a key element of LCA, which has to be clearly defined, and it refers to a measure of the function of the system under study and it provides a reference to which the inputs and outputs can be associated. It is essential to ensure the comparability between similar LCA studies.

The system boundaries delimit the unit processes that are going to be included in the system. Defining system boundaries is partly based on choices that should be detailed and justified in order to provide confidence in the study. The system boundaries should notice which stages; unit processes and flows are to be considered in the study.

Allocation procedure is a practice to distribute environmental burdens among products or processes. Different methodological approaches can be found, but the ISO 14041 [141] indicates that system expansion including the functions of co-products is preferred to dividing environmental burdens among systems [142]. However, cut-off criteria must often be used to simplify the complexity of the systems: especially for multifunction systems and open-loop recycling systems [143,144]. Cut-off rules should be clearly understood and described, but they are fundamental to avoid infinite interconnected systems. The environmental burdens of multifunction systems can be divided up according to different factors such as economic or mass balance. Allocation is one of the most controversial topics in LCA methodology [142].

2.1.2.2. Inventory analysis

The inventory analysis phase, or life cycle inventory (LCI) is the phase where all the data related to the study is collected. The inventory analysis identifies and quantifies all the inputs and outputs of the system under study during its life cycle: raw materials and energy consumption, co-products and by-products generated, solid wastes and those released into the air, water or soil. The inventory analysis is generally the phase that requires most time, especially when local quality data are collected. LCI represents the first basic results of an LCA study.

Inventory data is typically collected by means of survey questionnaires, which after being validated, are transformed and adapted to the FU, and can often be presented in tables which facilitate the structuring and storage of the information. An example of these tables can be observed in Table 2.1.

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Table 2.1. Example of an inventory table for an LCA study.

INPUTS			
From the technosphere		From nature	
Type	Quantity (units)	Type	Quantity (units)
Materials	kg/UF	Water	l/UF
Fuels	kg/UF (MJ/UF)	Minerals	kg/UF
Energy	MJ/UF	Biomass	kg/UF
Transports	km/UF		
Water (l)			
OUTPUTS			
To the technosphere		To nature	
Type	Quantity (units)	Type	Quantity (units)
Product	Units/UF (kg/UF)	Emissions to air	kg/UF
Co-products	Units/UF (kg/UF)	Emissions to water	kg/UF
By-products	Units/UF (kg/UF)	Emissions to soil	kg/UF
Wastes for treatment	kg/UF		

2.1.2.3. Impact assessment

The impact assessment phase, or life cycle impact assessment (LCIA), is expected to evaluate the potential environmental impacts transforming hundreds of inventory inputs and outputs into a few impact categories, thus attempting to understand these impacts. LCIA results determine the relative importance of each item on the inventory and add a set of indicators, or a single global indicator. In addition, LCIA is very useful to identify which processes of the system under study contribute most to those potential environmental impacts, and allow for a comparison of products and services. In fact, LCIA analyses the potential environmental effects of the system under study on human health, ecosystems and natural resources [145] providing information for the interpretation phase.

Some of the LCIA elements are mandatory while others are optional [146], as can be observed in Figure 2.2. During the initial goal and scope phase the impact categories to be analysed must be selected and clearly indicated. Following this, the classification and characterisation steps are mandatory, while normalisation is optional:

- Classification corresponds to a process in which all the environmental interventions identified in the inventory (inputs and outputs) are grouped in different impact categories or indicators, according to the environmental effects they are expected to contribute. For example, SO2, NOx, NHx, etc., emissions are classified in the Eutrophication Potential category.
- Characterisation is the calculation of impact category indicators using specific characterisation factors that are available to practitioners in literature, databases, and LCA support tools [145]. Characterisation factors are factors derived from characterisation model which allows all substances that contribute to this category to be reduced to a single reference substance [147]. For example, the classified SO2, NOx, NHx, etc., emissions are reduced to an equivalent substance: SO2 equivalent.
- Normalisation is the calculation of category indicator results relative to reference values. The objective of this step is to place LCIA indicator results into a broader context and to adjust the results with common dimensions. The advantage is that by using different criteria, the impact categories can be transformed into a numerical score of environmental impact, thus making it easier to make decisions, but also losing certain information. The

normalisation step by grouping and weighting can approximate the results in particular areas of protection such as human health or ecosystems. However, limitations are important, and for this reason this practice is optional and often LCA studies avoid carrying out this step.

- Grouping is a semi-quantitative process that involves sorting and/or ranking results across impact categories.
- Weighting refers to using numerical factors based on value choices to facilitate comparison across impact category indicators.

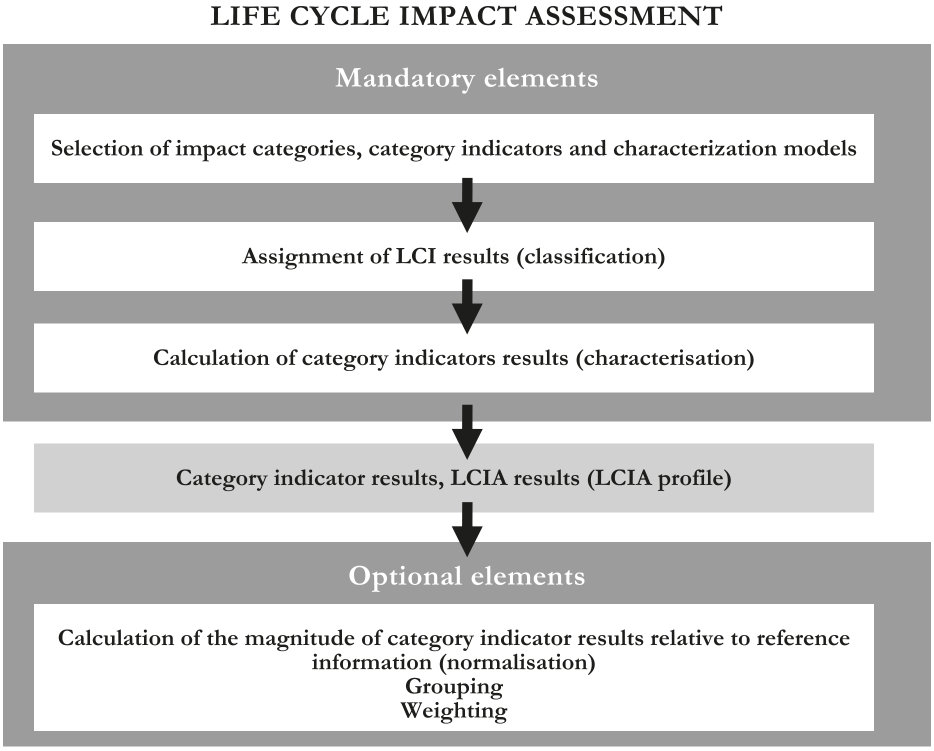

Figure 2.2. Elements of the LCIA phases of an LCA. Source: [34].

2.1.2.4. Interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together. The interpretation phase should indicate the consistency of the results according to all the aspects defined during the goal definition and scope phase. In this last phase of LCA, it is necessary to outline conclusions, explain limitations that have occurred, and provide recommendations. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the quality of the data collected.

2.1.2.5. LCA specifications of this dissertation

The LCA specifications regarding the functional unit and system boundaries (goal and scope) and the methods and indicators (impact assessment) are here described.

(a) Goal and scope: Functional unit and system boundaries

The functional units used in this dissertation were:

- the mass (kg) of insulation board with an area (A) of 1 m^2 that provides a thermal resistance R-value of 1 m^2 K/W (Chapter 4). The heat flow through a building construction depends on the temperature difference across it, the conductivity of the materials used (λ) and the thickness of the materials. The thickness and the conductivity are properties of the material. A greater thickness means less heat flow and so does a lower conductivity. Together these parameters form the thermal resistance of the construction. The thermal resistance is proportional to the thickness of a layer of the construction and inversely proportional to its conductivity. A construction layer with a low thermal conductivity (e.g. XPS, λ=0.032 W/m K) is a good insulator; one with a high thermal conductivity (e.g. concrete, λ=1.28 W/m K) is a bad insulator.

- the necessary quantity of materials (kg) and energy (MJ) to construct 1 m^2 of the three different façades systems (Chapter 6) with an insulation material with a thermal resistance of R=3.7 (m^2K/W).
- the necessary quantity of materials (kg) and energy (MJ) to renovate the total envelope surface of a determined building under study (Chapter 7), including different solutions of façades, roofs, slab-on-ground and windows. The renovation was according to obtain the required indoor comfort for the defined geographic location.

The system boundaries used in this dissertation were Cradle to gate, Cradle to site and Cradle to grave. Figure 2.3 present the life cycle stages included in each system boundaries. In Chapter 4 and 5, a cork insulation board was environmental assessed by meas of LCA methodology from a cradle to grave approach. Chapter 6 present a LCA of different combination of façade solution and different insulation materials from a cradle to site approach, to analyse diverse installation systems for each materials. In Chapter 7, a complete building renovation is environmental assessed, including all the life cycle phases (Cradle to grave).

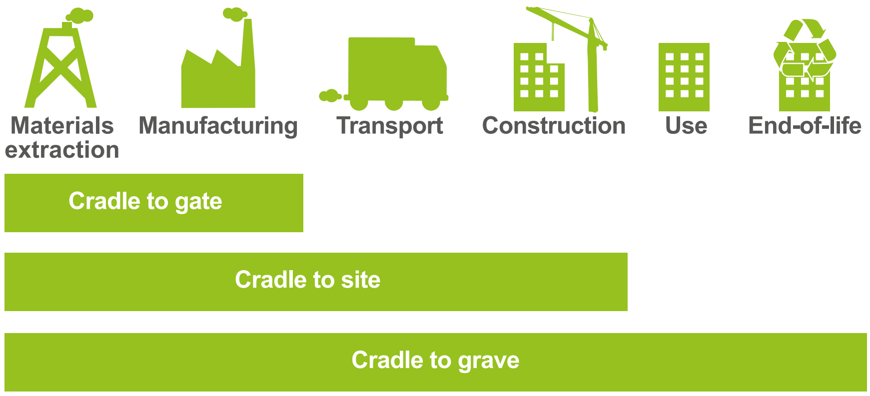

Figure 2.3. Life cycle phases included in each system boundaries used in the dissertation

(b) Life cycle impact assessment: Methods and indicators

The LCIA was performed according to the averaged out inventory of the sector and following ISO 14040 [34,141] requirements. LCIA methods can be at the midpoint and at the end point, depending on the level at which the impacts are quantified [148]. The mid-point level is a problem oriented approach, where the impact is close to the intervention (e.g., global warming in terms of CO_2 eq.), while the endpoint level is damage-oriented approach where indicators are expressed in recognisable values to society, which are also called areas of protection: human health, natural environment and natural resources (e.g., effects of global warming in terms of DALY) [149].

The main characterisation method used was the CML-IA version 4.1 [150] which is the reference method determined by the European standard EN 15804 that presents the core rules for performing an EPD of building products [101] and the standard EN 15978 [100] that specifies the calculation method for environmental assessment of buildings. Moreover, in Chapter 5, a comparison between CML method and other methods was done: ReCiPe [151] and ILCD [149]. Table 2.3 reports the mid-point impact categories considered in the dissertation. The software Simapro 8.1 [152] and the ecoinvent 3.2 database were used to obtain the environmental information related to the processes involved for the materials, energy and transport [153].

Moreover, the cumulative energy demand [154] is also used due to the importance of the life cycle energy of buildings (Table 2.2).

Table 2.2. Description of the impact category included in Cumulative Energy Demand [154] **.**

Environmental impact			Description
Cumulative energy demand or Embodied energy	CED EE	MJ	Accounts for the primary energy use

Table 2.3. Impact categories included in the LCIA methods used in the dissertation: CML, ReCiPe, ILCD

	CML			ReCiPe			ILCD		
Global Warming	Global warming potential	GWP	kg CO2 eq	Climate change	CC	kg CO2-Eq	Climate change	CC	kg CO2 eq
Depletion	Abiotic depletion potential for fossil resources	ADPF	MJ	Fossil depletion	FRD	kg oil-Eq	Mineral, fossil & resource depletion	MFRD	kg Sb eq
	Abiotic depletion potential for non fossil resources	ADPE	kg Sb eq	Metal depletion	MRD	kg Fe-Eq			
				Water depletion	WPD	m3	Water resource depletion	WRD	m3 water eq
	Ozone depletion potential	ODP	kg CFC-11 eq	Ozone depletion	OD	kg CFC-11-Eq	Ozone depletion	OD	kg CFC-11 eq
Acidification	Acidification potential	AP	kg SO2-eq	Terrestrial acidification	TA	kg SO2-Eq	Acidification	A	mol H+ eq
Eutrophication	Eutrophication potential	EP	kg PO4 -- eq	Freshwater eutrophication	FE	kg P-Eq	Freshwater eutrophication	FEu	kg P eq
				Marine eutrophication	MEP	kg N-Eq	Marine eutrophication	MEu	kg N eq
							Terrestrial eutrophication	TEu	mol N eq
Photochemical oxidation	Photochemical ozone creation potential	POCP	kg C2H4 eq	Photochemical oxidant formation	POF	kg NMVOC	Photochemical ozone formation	POF	kg NMVOC eq
Land occupation	Land use	LU	m2yr	Agricultural land occupation	ALO	m2yr	Land use	LU	kg C deficit
				Natural land transformation	NLT	m2			
				Urban land occupation	ULO	m2yr			
Toxicity	Freshwater aquatic ecotoxicity	FAETP	kg 1,4-DCB-Eq	Freshwater ecotoxicity	FET	kg 1,4-DCB-Eq	Freshwater ecotoxicity	FE	CTUe
	Freshwater sediment ecotoxicity	FSETP	kg 1,4-DCB-Eq						
	Human toxicity	HTP	kg 1,4-DCB-Eq	Human toxicity	HT	kg 1,4-DCB-Eq	Human toxicity, cancer effects	HTC	CTUh
							Human toxicity, non-cancer effects	HTNC	CTUh
	Marine aquatic ecotoxicity	MAETP	kg 1,4-DCB-Eq	Marine ecotoxicity	MET	kg 1,4-DCB-Eq			
	Marine sediment ecotoxicity	MSETP	kg 1,4-DCB-Eq						
	Terrestrial ecotoxicity	TETP	kg 1,4-DCB-Eq	Terrestrial ecotoxicity	TET	kg 1,4-DCB-Eq			
Ionising radiation	Ionising radiation	Ionising radiation	DALYs	Ionising radiation	IR	kg U235-Eq	Ionising radiation HH	IR HH	kBq U235 eq
							Ionising radiation E (interim)	IR E	CTUe
Particulate matter				Particulate matter formation	PMF	kg PM10-Eq	Particulate matter	PM	kg PM2.5 eq

2.1.3. Energy efficiency approach: Dynamic thermal simulation modelling of buildings

Modern building regulations require buildings to be built with high levels of insulation and very airtight. Therefore, these buildings can suffer from overheating during the summer often requiring a complete change of cooling/ventilation strategy after the building is built.

Building simulation began in the 1960s and became the hot topic of the 1970s within the energy research community. During these two decades, most of the research activities were devoted to studies of fundamental theory and algorithms of load and energy estimation. The studies had resulted in the many refinements of the transfer function technique [155,156] and well-known simplified methods such as the degree-day method, equivalent full load hour method, and the bin method, to predict the energy consumption of buildings [5].

Dynamic Simulation Modelling (DSM) allows to create a very detailed thermal model of your proposed building to accurately assess any heating, cooling and ventilation issues it may have once it is built. This means that it can be considered the design and positioning of solar shading, passive stack ventilation, night-time cooling, temperature sensors etc. so these can be implemented as cost effectively as possible.

The DSM process takes into account a wide range of different influencing factors such as the properties shape and orientation, shading from neighbouring properties, fabric insulation, window and door performance, different types of heating/cooling systems and their efficiencies, heating controls, lighting, thermal mass of the building, air leakage rates, ventilation, hot water storage efficiencies together with different renewable technologies and their individual efficiency influences.

In this dissertation, DSM was used to calculate the energy saving in the renovation practice, assessing the convenience of the environmental implication in the different constructive alternatives for the building's case study. The energy simulation was carried out with a Computational Fluid Dynamics Simulation module (CFD) of the program Design Builder [157]. The model includes the details of transmittances and infiltrations of the original building, and the results of energy consumption, thermal loads and temperature conditions shall be compared with real data obtained in the building. These data were obtained from the real thermal characterisation of the building. For that, the blower-door test was first made, combined with thermography (Figure 2.4) and smoke pens to measure and observe the infiltrations of the building. Moreover, the transmittances of the different closures were measured, and with the exterior thermography, the transmittances of different thermal bridges were calculated via the differences in surface temperatures. To conclude, the temperatures inside the building and the energy demand for heating were measured. The energy demand was obtained by measuring the temperature of the input and output of the heated water in the secondary circuit of the heat exchanger system used for the heating system. Details will be explained below (Section 2.2) and developed in Chapter 7.

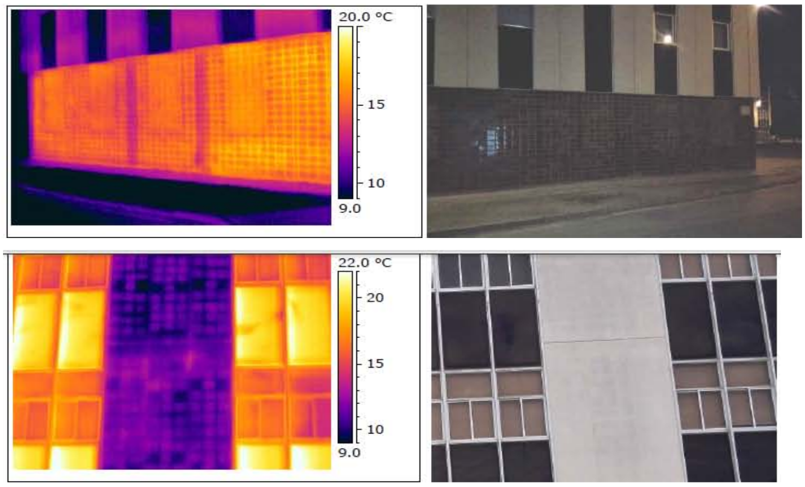

Figure 2.4. Thermography of building envelope to detect thermal bridges

Once the building was thermally characterised, a mathematical model was developed with Design Builder. Moreover, the pattern of use was included. Thus, this helped to validate the mathematical model simulated with the program, and different renovation projects can be simulated with the knowledge that the results obtained will be adequate.

2.1.4. Product design approach: Documentation, generation of alternatives and concept selection

This dissertation has an important product design orientation, so different tools from product design was used (Figure 2.5). One part of the problem analysis was the documentation of cork market, identifying significant and innovative cork products. This search aims to collect information about manufacturing processes, product concepts and new applications, to be used as background in the concept generation process. This documentation has been developed during the whole thesis, although the result is shown in the final part of the thesis, prior to the generation of concepts.

Moreover, a product design approach was used in the final part of the present dissertation to develop new concepts of products made of cork for being applied in buildings. Later, the most adequate proposals were accurately evaluated and selected according to technical, economic and environmental criteria (Chapter 9). The main goal of the creative part of the dissertation is to generate a significant number of ideas with high potential of application, which will be evaluated by the participants using different evaluation techniques.

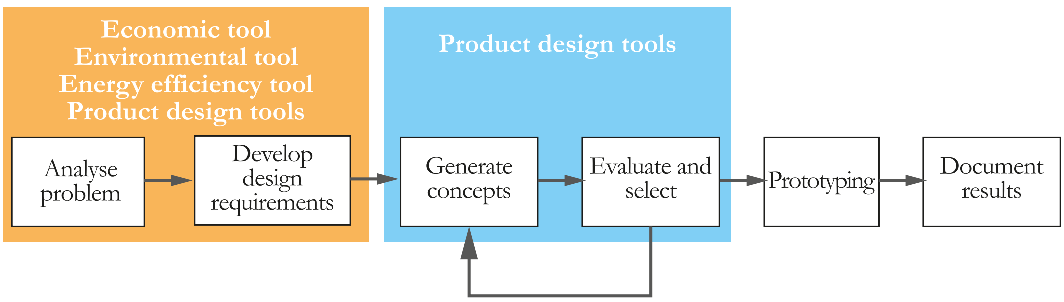

Figure 2.5. Distribution of tools in the different stages of the design process

The generation of concepts was based in the previous analysis, and their conclusions were the basis of the design requirements (Figure 2.6). On the other hand, the evaluation and selection of concepts was also based in the previous studies and in the know how of participants. For this purpose, the creative process was divided in two sessions because the targets of participants were different. The process of the generation of concepts includes three essential stages: (1) divergence, (2) transformation, and (3) convergence [158]. The divergent stage is an analytic process for searching the problem space, which can be described as "breaking the design problem into pieces". The transformation stage is a synthetic process for generating the solution space, characterized as "putting the pieces together in new ways". The convergent stage is an integration and evaluation process for finding applicable sub-solutions and optimal design solutions, described as "testing to discover the results of putting the new arrangement into practice". For this reason, each session was designed with different aims, selecting different techniques and participants. The selected techniques can be divided in creativity and selection and evaluation techniques. The details of techniques selected will be explained in Chapter 9.

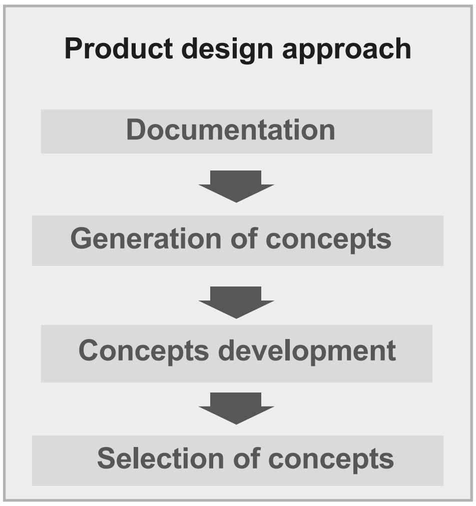

Figure 2.6. Product design approach used in the dissertation

The selection of participants was done by their expertise. In the first session, participants were selected deliberately interdisciplinary, aiming to achieve a holistic approach in which the overall knowledge of the group was greater than the sum of the knowledge of individuals. The integration of two profiles, on the one hand, a generalist profile related to creativity and design and on the other hand, an expert profile in any of the matters related to the subject to be addressed: energy efficiency of buildings, architecture and building. In the second session, all participants had a common denominator; they were part of the cork sector but with different expertise, including commercial specialists, design and architecture specialists, and marketing or production specialists. This session had the essential support of governmental and private cork associations, which facilitated the contact with the companies.

2.2. Overview of the case studies

2.2.1. Insulation cork board

The environmental assessment of an insulation cork board using for thermal insulation in buildings will be presented in Chapter 4. This product is manufactured in UPRODECO (Catalonia), which is the most relevant industry that produces this type of product in Spain (Figure 2.7). Previously, this firm was only focused in granulates, but it detected the opportunity to take advantage of them by manufacturing cork insulation boards. Its manufacturing processes are based in traditional machinery with basic technological development. Mainly, this insulation product is exported to Germany, where the use of natural building materials is more extended.

Figure 2.7. Insulation cork board used as case study in Part IV

Table 2.4. Main physical characteristics of cork insulation board under study

Product features	
Dimensions	1000x500x40 mm
Weight	3.6 kg
Density	171 kg/m^3
Thermal conductivity	0.042 W/mºC
Acoustic absortion 1000-4000 Hz	0.49-0.98
Compressive strength	336 KPa
Water vapor permebaility	487x10^{-14} mg/m-hPa
Fire reaction	M-4
Coefficient of linear expansion (-30ª to +30ºC)	7.7x10^{-5}

First of all, to obtain reliable data for the environmental assessment of the product, the process started with an initial meeting with the actors involved in the study: ICTA-UAB, UPRODECO and Institut Catatà del Suro. The main reason was that researchers knew in a detailed form the manufacturing process of this product. Besides on explained to the owner of the firm the questionnaire and the type of data that it contained. Appendix 1 presents the example of questionnaire models, including all the tables and information demanded. This questionnaire was based in the used by Jesús Boschmonart-Rives during the environmental assessment of the Catalan cork sector in 2011. Most of the data were local, but general processes were used from Ecoinvent [153] contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services.

Finally, the same study was developed in the main manufacturer of insulation cork products in the world, Amorim Isolamentos S.L., located in Vendas Novas (Portugal). During the research stay done at University of Aveiro, the same methodology that the presented in the present dissertation were assessed to the Amorim's cork boards and included in the doctoral thesis of Dra. Martha Demertzi.

2.2.2. Building at the Spanish Military Academy

The integrated life cycle assessment and thermal dynamic simulation methodology presented in Chapter 7 is applied into an existing building (Figure 2.8). This building is located at the Spanish Military Academy in Zaragoza (Spain), located in north-eastern Spain and its specific use is for educational purposes.

Figure 2.8. General view of the building under study

It has a constructed surface area of 4,033 m^2, distributed over a ground floor and two upper floors. This part of the dissertation was directly associated to the Centro Universitario de la Defensa (CUD) project, called "Development of a Strategic Plan Energy Renovation for the Ministry of Defence according to NZEB and LCA methodologies. Case Study: Typology of prefabricated buildings". This project aim was to propose an energy renovation plan under energy efficiency criteria during use from the current status of building, including also life cycle assessment associated to this renovation. Project participants characterized the current status of building using Computational Fluid Dynamics tools (Figure 2.4).

Table 2.5. General characteristics of the building

Building features	
* Number of floors	P + 2E
*Building floors area	3,923.21 m^2
Ground area	1,403.59 m^2
First floor	1,403.59 m^2
Second floor	1,116.03 m^2
* Building high	10.65 m
*Windows	358.27 m^2

The building under study forms part of a series of building built by the Spanish Ministry of Defence during 70s. The peculiarity of these buildings is the prefabricated system of its structure and envelope. The same project was replicated in several military units in Spain. So the analysis of this dissertation will be also valid for all of them. As commented in Chapter 7, the European Commission has imposed, through the EPBD Directive [93], the necessity of renovating public buildings to achieve their energy efficiency during the use phase. For that, this dissertation assessed the environmental implication of the required renovation comparing different renovation proposal. The constructive and particular characteristics of the building renovation will be detailed in Chapter 7, in addition of the environmental results.

PART II

ECONOMIC CHARACTERIZATION OF IBERIAN CORK SECTOR

Chapter 3

PRODUCTION AND TRADE ANALYSIS IN THE IBERIAN CORK SECTOR: ECONOMIC CHARACTERIZATION OF A FOREST INDUSTRY

3. Production and trade analysis in the Iberian cork sector: economic characterization of a forest industry

This chapter is based on the following published paper:

Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Production and trade analysis in the Iberian cork sector: Economic characterization of a forest industry. Resour Conserv Recycl 2015; 98:55–66.

· Preprint version in Universitat Autònoma de Barcelona repository:

http://ddd.uab.cat/pub/artpub/2015/132051/resconrec_a2015m5v98p55n2.pdf

· Published version by Resources, Conservation and Recycling Journal:

http://dx.doi.org/10.1016/j.resconrec.2015.02.011

Abstract

Cork oak forest grows endemically in the coastal regions of the western Mediterranean basin, particularly in the Iberian Peninsula. The cork agro-forestry systems play a key role in ecological processes, and the outer bark, or cork, can be extracted sustainability without damaging the tree or affecting biodiversity. Because of the properties of the cork, an important forestry and industrial structure has been developed around its most valuable goods. This paper describes the current global trade patterns in the Iberian Peninsula, where Portugal and Spain are world leaders. Although these countries bring most of their cork trade flows together with the rest of the world, there are clear differences between these sectors. The aim of this study was to identify these differences and to characterize each analysed sector from an economic perspective. The primary difference between the sectors lies in the characteristics of their supply chain and their capacity to generate wealth from raw cork. Portugal primarily produces and processes raw cork into products with high added value. Spain bases its cork sector on raw material and half-manufactured cork, and it is not able to use the full potential that cork provides. Catalonia is an exception because it is the global leader in the champagne stopper market. To encourage the development of the entire cork sector, every link in the supply chain should be strengthened through the establishment of companies and the generation of employment, and therefore the development of rural areas. Moreover, this industry must establish its own development strategies for the future, thereby increasing its investment in R&D and innovation in relation to the opportunities identified as follows: the potential for diversification beyond the wine market, the improvement potential for forest management and the enhancement of sustainability and eco-efficiency in every link of the cork supply chain.

Keywords

Cork industry; international trade; Iberian Peninsula; cork supply chain; natural resource economics; Research and development, sustainability

Highlights

- The current global trade patterns of the Iberian cork sector are described.
- Portugal primarily produces and processes raw cork into products with high added value
- Spain bases its cork sector on raw material and half-manufactured cork, and it is not able to use the full potential that cork provides.
- Catalonia is an exception because it is the global leader in the champagne stopper market.
- Cork sector must establish its own development strategies for the future

PART III

ENVIRONMENTAL ASSESSMENT OF SPANISH CORK INSULATION PRODUCTS FOR BUILDINGS

Chapter 4

ENVIRONMENTAL IMPLICATIONS OF THE USE OF AGGLOMERATED CORK AS THERMAL INSULATION IN BUILDINGS

4. Environmental implications of the use of agglomerated cork as thermal insulation in buildings

This chapter is based on the following published paper:

Sierra-Pérez J, Boschmonart-Rives J, Dias AC, Gabarrell X. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. J Clean Prod 2016;126:97–107.

· Published version by Journal of Cleaner Production:

http://dx.doi.org/10.1016/j.jclepro.2016.02.146

Abstract

The market for insulation material is playing a crucial role in Europe's energy transformation, due to its influence on energy consumption in buildings. The introduction of renewable materials for thermal insulation is recent, and little is known so far about its environmental implications. This study analyses the environmental performance of a cork insulation board, made of agglomerated cork from forestry cork wastes, by means of cradle-to-gate Life Cycle Assessment methodology. The results indicate that the use of natural insulation materials does not necessarily imply a reduction of environmental impacts due to manufacturing processes with a low technological development. In this case, the most influential stage is the manufacturing stage, in which the board agglomeration and the cork trituration have the highest impacts. The most influential inputs are both the transport used during the life cycle and the large quantities of electricity and diesel in the manufacturing stage. Some strategies have been identified to reduce the environmental impact, such as promote the acquisition of local raw cork to reduce transportation from the manufacturer, improve the efficiency and productivity of manufacturing processes and improve the product design to help increase its market share. Moreover, the inclusion of biogenic carbon contained in forest-based building materials affects the Global Warming Potential results considerably. However, it is very important to consider how this biogenic carbon is calculated and how the product is managed after its lifetime.

Keywords

Insulation materials, LCA, cork, renewable material, sustainable construction, building energy

Highlights

- Environmental impacts of cork insulation board have been assessed.
- The majority of environmental burdens are concentrated at the manufacturing stage.
- Transport and energy consumption are the most influential factors in the life cycle.
- Great potential for environmental improvement throughout the manufacturing of cork board.

Chapter 5

INFLUENCE OF IMPACT ASSESSMENT METHODS ON THE ENVIRONMENTAL PRODUCT DECLARATIONS OF BUILDING PRODUCTS: THE CASE OF CORK INSULATION BOARD

5. Influence of impact assessment methods on the Environmental Product Declarations of building products: The case of cork insulation board

From this chapter, a paper has been extracted and submitted in a peer-review indexed journal.

Abstract

Environmental information has increasingly become of interest in the building design process, and Environmental Product Declarations (EPDs) are a useful eco-design tool that allows building designers and architects to obtain environmental information of building products. The European standard EN 15804 that presents the core rules for performing an EPD of building products defines a reference Life Cycle Assessment method for obtaining the environmental performance of products. This article presents a comparison between the characterization and normalization results from the reference LCA method and the most common LCA methods in the environmental field. Additionally, the relevance of the impact categories that are not included in the standard is assessed. The study uses cork insulation boards as a case study and concludes that the results vary depending on both the LCA method that is used and the impact categories that are included. On the one hand, the results indicate a need to revise and update the currently used standard. On the other hand, the scientific community should reach a consensus on the best way to model environmental impacts, and the methods should be improved to increase their reliability.

Keywords

Building materials, LCA, Environmental Product Declaration (EPD), Impact categories, Insulation materials.

Highlights

- A comparison between the most common LCA methods with the reference in standard is presented.
- A cork insulation board EDP is used as case study, for assessing the main differences
- The results vary depending on both the LCA method and the impact categories selected
- In next standard revisions an updating of reference LCA methods and impact categories has to be carried out

5.1. Introduction

The building sector represents a leading environmental sector; in the case of Europe, the energy consumption and environmental impacts represent an important part of the total [185]. This has led to an increase in the environmental awareness in the different parts of the sector. In addition to the concerns about energy efficiency during building use, the selection of less impactful materials and the design of more sustainable construction products are common strategies that have been implemented. This causes an increase in the use of eco-design tools for the communication of environmental information by the manufacturers of building materials. In a transparent and feasible way, the Environmental Product Declarations (EPDs) provide the environmental information of the building materials and products by means of the Life Cycle Assessment (LCA) methodology. This tool quantifies, identifies and communicates the potential environmental impacts of products over their entire life cycle.

The European standard EN 15804 that presents the core rules for performing an EPD of building products [101] determines the CML-IA version 4.1 [150] as the reference method for environmental assessments and includes the following six midpoint impact categories: abiotic depletion potential for non-fossil resources (ADPE), abiotic depletion potential for fossil resources (ADPF), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP) and photochemical oxidation potential (POCP). Table 5.1 presents the description of each impact category.

Table 5.1. . Description of the impact categories included in the standard EN 15804+A1 [150]

Environmental impact			Description
Abiotic depletion potential for non fossil resources	ADPE	kg Sb eq	Non-renewable resources depletion due to extraction and consumption of minerals and fossil fuels
Abiotic depletion potential for fossil resources	ADPF	MJ	
Acidification potential	AP	kg SO_2- eq	Forest and lakes destruction by acid rains caused by acid air emissions
Eutrophication potential	EP	kg PO_4 -- eq	Lack of oxygen and algae development in water streams or soil due to too high nitrogen and phosphorus concentrations
Global warming potential	GWP	kg CO_2- eq	Climate change and global warming due to gases (carbon dioxide, methane) which emissions increase greenhouse effect in the atmosphere
Ozone depletion potential	ODP	kg CFC-11 eq	Thinning of the stratospheric ozone layer as a result of anthropogenic emissions.
Photochemical ozone creation potential	POCP	kg C_2H_4 eq	Formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants

Recently, in the life cycle field, other updated and complete methods, such as ReCiPe [151] and ILCD [149], have been developed. These LCA methods include more impact categories, such as land occupation, toxicity, ionising radiation or particulate matter, and in some cases, the methods adopt different characterization models. Because of the different origination of the existing types of building materials, it could be interesting to analyse other impact categories to extend the information provided by EPDs and not disregard relevant impacts. In this regard, in the CEN/TC 350 group that is responsible for the development of horizontal standardized methods for the assessment of the sustainability of construction work, a scientific debate currently exists regarding other additional indicators in the next revision of the EPD for the building materials standards.

The present article aims to evaluate the influence of the selection of the impact assessment method on the LCA outcome in the case of building materials, according to the EN 15804:2014 for construction products [101]. One of the objectives of this research is to be an example for evaluating the importance of including more impact categories in the next revision of the EPD for the building materials standards, in addition to those already included. The case study used in the article is the production of cork insulation boards by means of LCA methodology, considering all processes involved in their forest and industrial stages, from the extraction of the raw cork in the forest to obtaining the final product [203]. All the flows related to the product are taken into consideration: raw materials, energy, transports, emissions, etc.

5.2. Materials and methods

5.2.1. Description of the case study: cork insulation board

A life cycle inventory of cork insulation board is used as the basis for the comparison between methods. The product consists in agglomerated cork boards made of forestry cork waste, and it is produced in the largest factory of cork insulation boards that are manufactured in Catalonia, Spain. The declared unit (DU) used in this LCA study is defined as the mass (7.2 kg) of insulation board with an area (A) of 1 m^2 that provides a thermal resistance R-value of 1 m^2K/W [127,128]. To establish the quantity of the insulation material, the following equation (Equation 1) is used:

$$DU = R\lambda\rho A \qquad \text{(Equation 1)}$$

where R represents the thermal resistance (m^2K/W) that is a heat property and a measurement of the temperature difference by which a material resists heat flow. The greater the R value, the more insulation material. The λ factor is the thermal conductivity (W/m K), the most important property of any thermal insulation material. In the case of the product under study, the thermal conductivity is 0.035 [189]. ρ corresponds to the density of the material, in this case 35 kg/m^3. A is the surface of the façade (m^2), which is 1 m^2.

The life cycle system is divided into different stages according to EN 15804:2014+A1 [101], and the present study includes the product stage and all its sub-stages (Figure 5.1). The product stage begins with obtaining raw material from the forest and its further processing. Then, the raw material is transported to the factory where the product is manufactured. In the case of the cork insulation board, the main manufacturing stages are granulates and board production.

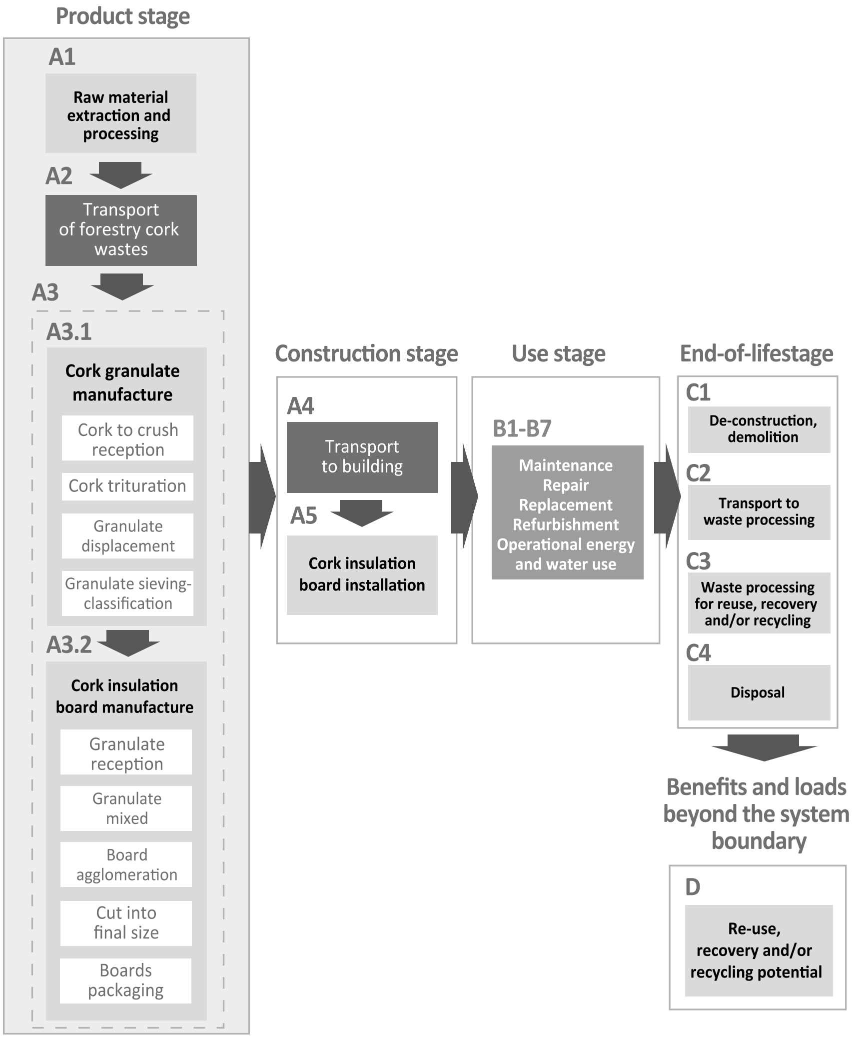

Figure 5.1. Diagram of the cork insulation board life cycle based on EN 15408. The study includes A1, A2 and A3 stages.

The inventory table (Table 5.2) includes all the inputs for each stage and their related process in the Simapro software used in the study [152]. The database used to obtain the environmental information related with the processes involved with materials, energy and transport is the Ecoinvent 3.1 database [153]. In the case of the information of the cork oak forests, land use is taken from the raw extraction in Catalonia, and the productivity of cork is determined by hectare [174]. The inventory also includes the information about the land use of the factory facilities. The environmental information of land use is not obtained from Ecoinvent. In the case of ReCiPe, the impact of land occupation is the quantity of m^2 per year. In the case of the ILCD method, the impact of land occupation in terms of the *kg C deficit* is calculated according to the ILCD Handbook [149]. Finally, the allocation procedure is conducted on a mass allocation basis in the raw material extraction stage because of the production of different types of cork.

Table 5.2. Inventory data to produce the FU of cork insulation boards (R=1 m2 K/W)

Inputs	Unit	Quantity	Ecoinvent process
A1 - Raw materials extraction			
Water	m^3	3.62E-03	tap water production, conventional treatment, Europe without Switzerland
Fungicide (Thiophanate-methyl 45%)	kg	3.03E-03	[thio]carbamate-compound production, RER
Workers to stripping	km	1.71E+00	transport, passenger car, large size, diesel, EURO 3, RER
Workers to scratching	km	5.01E-01	transport, passenger car, large size, diesel, EURO 3, RER
Cork to meeting point	km	5.32E+01	transport, tractor and trailer, agricultural, CH
Distribution of auxiliary materials	km	1.00E+02	transport, freight, light commercial vehicle, Europe without Switzerland
Workers to shrub clearance and road maintenance	km	8.63E-01	transport, passenger car, large size, diesel, EURO 3, RER
Forestry tractor	km	1.00E+00	transport, tractor and trailer, agricultural, CH
Forest land use	m2a	2.67E+03	*Not obtained from Ecoinvent*
A2 - Transport to the manufacturer			
From the forest	km	2.40E+02	transport, freight, lorry 16-32 metric ton, EURO3, RER
A3 - Manufacturing			
Industrial land use	m2a	5.60E-01	*Not obtained from Ecoinvent*
A3.1 - Granulate manufacture			
Diesel for internal displacements	MJ	7.63E+00	diesel, burned in building machine, GLO
Electricity	kWh	4.40E+00	market for electricity, medium voltage, ES
A3.2 - Board manufacture			
Electricity	kWh	1.45E+00	market for electricity, medium voltage, ES
Diesel boiler	MJ	4.24E+01	heat production, light fuel oil, at boiler 10kW, non-modulating, Europe without Switzerland
Polyurethane (PU)	kg	1.68E-01	polyurethane production, flexible foam, RER
Transport (PU)	km	2.00E+01	transport, freight, light commercial vehicle, Europe without Switzerland
HPDE	kg	4.55E-02	polyethylene production, high density, granulate, RER

5.2.2. LCA methods

The case study has been analysed by means of the LCA methodology that is referenced in the CML-IA EPD standard [150] because it is the reference LCA method in the EN 15804 standard. Moreover, the most frequent midpoint LCA methodologies are used in the study: ReCiPe 2008 [151] and ILCD 2011 [204]. CML 2002 is one of the first LCA methods developed in the 90's by the Institute of Environmental Sciences of Leiden University. It is still a reference LCA method and considers ten impact categories in the baseline version. On the one hand, in addition to being one of the most widespread LCA methods, ReCiPe is an updated extension of the CML method. ReCiPe 2008 is a method that was designed to help with the interpretation of a long list of emissions and consumed resources that resulted from the inventory and determines eighteen impact categories at midpoint level. On the other hand, ILCD is a compilation by the Joint Research Centre of the European Commission of 156 different characterization models belonging to 12 different life cycle impact assessment (LCIA) methodologies that choose the most appropriate model, based on a predefined set of assessment criteria, including CML 2002 and ReCiPe. Table 5.3 presents all the impact categories included in each LCA method used in the study, showing the correspondence between them.

To compare impact results across methodologies, the impact scores for each impact categories were converted in common metrics, following the approach proposed by Dreyer et al. [205] and used in some studies on which LCA methods are compared [206–209]. The selection of a reference substance and unit conversion factors are taken from [206,210].

Table 5.3. Impact categories included in the LCIA methods considered: CML, ReCiPe, ILCD

	CML			ReCiPe			ILCD		
Global Warming	Global warming potential	GWP	kg CO2 eq	Climate change	CC	kg CO2-Eq	Climate change	CC	kg CO2 eq
Depletion	Abiotic depletion potential for fossil resources	ADPF	MJ	Fossil depletion	FRD	kg oil-Eq	Mineral, fossil & resource depletion	MFRD	kg Sb eq
	Abiotic depletion potential for non fossil resources	ADPE	kg Sb eq	Metal depletion	MRD	kg Fe-Eq			
				Water depletion	WPD	m3	Water resource depletion	WRD	m3 water eq
	Ozone depletion potential	ODP	kg CFC-11 eq	Ozone depletion	OD	kg CFC-11-Eq	Ozone depletion	OD	kg CFC-11 eq
Acidification	Acidification potential	AP	kg SO2-eq	Terrestrial acidification	TA	kg SO2-Eq	Acidification	A	mol H+ eq
Eutrophication	Eutrophication potential	EP	kg PO4 -- eq	Freshwater eutrophication	FE	kg P-Eq	Freshwater eutrophication	FEu	kg P eq
				Marine eutrophication	MEP	kg N-Eq	Marine eutrophication	MEu	kg N eq
							Terrestrial eutrophication	TEu	mol N eq
Photochemical oxidation	Photochemical ozone creation potential	POCP	kg C2H4 eq	Photochemical oxidant formation	POF	kg NMVOC	Photochemical ozone formation	POF	kg NMVOC eq
Land occupation	Land use	LU	m2yr	Agricultural land occupation	ALO	m2yr	Land use	LU	kg C deficit
				Natural land transformation	NLT	m2			
				Urban land occupation	ULO	m2yr			
Toxicity	Freshwater aquatic ecotoxicity	FAETP	kg 1,4-DCB-Eq	Freshwater ecotoxicity	FET	kg 1,4-DCB-Eq	Freshwater ecotoxicity	FE	CTUe
	Freshwater sediment ecotoxicity	FSETP	kg 1,4-DCB-Eq						
	Human toxicity	HTP	kg 1,4-DCB-Eq	Human toxicity	HT	kg 1,4-DCB-Eq	Human toxicity, cancer effects	HTC	CTUh
							Human toxicity, non-cancer effects	HTNC	CTUh
	Marine aquatic ecotoxicity	MAETP	kg 1,4-DCB-Eq	Marine ecotoxicity	MET	kg 1,4-DCB-Eq			
	Marine sediment ecotoxicity	MSETP	kg 1,4-DCB-Eq						
	Terrestrial ecotoxicity	TETP	kg 1,4-DCB-Eq	Terrestrial ecotoxicity	TET	kg 1,4-DCB-Eq			
Ionising radiation	Ionising radiation	Ionising radiation	DALYs	Ionising radiation	IR	kg U235-Eq	Ionising radiation HH	IR HH	kBq U235 eq
							Ionising radiation E (interim)	IR E	CTUe
Particulate matter				Particulate matter formation	PMF	kg PM10-Eq	Particulate matter	PM	kg PM2.5 eq

5.2.3. Normalization of the impact assessment results

The environmental impact scores of LCA are often expressed in complex units and reflect environmental impacts in a way that does not directly correspond to perceptible problems or prevailing threats [211]. The LCA results are absolute values that are difficult to interpret with an adequate environmental context. The normalization results are expressed in the same unit for each impact score, so it makes easier comparisons between impact scores of different impact categories [212]. Normalization makes it possible by translating abstract impact scores for every impact category into relative contributions of the product to a reference situation. This reference situation could be one person's share of all emissions and resource usage in the world, continent or country during one year.

The normalized values allow for the identification of the most relevance impact categories through the product life cycle because comparisons between impact categories and between LCA methods are possible. In the present study, CML and ReCiPe methods have used normalization factors based on the 2000 effect levels for Europe [211]; the ILCD method used the normalization factors based on Europe EU-27 from 2010 [213]. The normalized results have been referenced to Global Warming, to obtain the relevance of each impact category with respect to the most accepted impact category.

5.3. Results and discussion

5.3.1. Environmental impacts according to the EPD of cork insulation boards

This section presents the results of characterizing the environmental impact in the production of cork insulation board using the CML 2002, ReCiPe 2008 and ILCD methods. Table 5.4 presents the total results for each LCA methods and also the results after the metric conversion. Some unit conversion factor could not be calculated, so it is indicated as NA (Not Available).

The following sub-sections will comment on the different results of LCA by the reference impact categories in the EN 15804 for the three methods. Moreover, Table 5.5 the quantity of the impact for each stage and their relevance in the life cycle. The results are organized in decreasing order to facilitate the reading of the table.

Table 5.4. Environmental impacts in the production of the DU of cork insulation board according to the three LCA methods including the conversion to reference substance

CML according EN 15804			ReCiPe			ILCD		
Impact category	Method metric	Common metric	Impact category	Method metric	Common metric	Impact category	Method metric	Common metric
GWP 100	kg CO2-Eq 1.2E+1	kg CO2-Eq 1.2E+1	GWP100	kg CO2-Eq 1.2E+1	kg CO2-Eq 1.2E+1	CC	kg CO2-Eq 1.2E+1	kg CO2-Eq 1.2E+1
ADPF	MJ 1.8E+2	kg oil-Eq 4.4E+0	FDP	kg oil-Eq 4.3E+0	kg oil-Eq 4.3E+0	MFRD	kg Sb eq 1.90E-06	NA NA
ADPE	kg Sb eq 1.8E+2	NA NA	MDP	kg Fe-Eq 4.7E-1	kg Fe-Eq 4.7E-1			
			WDP	m3 2.8E-2	m3 2.8E-2	WRD	m3 5.6E-3	m3 5.6E-3
OLDP	kg CFC-11 eq 1.9E-6	kg CFC-11 eq 1.9E-6	ODP inf	kg CFC-11-Eq 1.9E-6	kg CFC-11-Eq 1.9E-6	OD	kg CFC-11 eq 5.0E-4	kg CFC-11 eq 5.0E-4
AP	kg SO2-Eq 5.3E-2	kg SO2-Eq 5.3E-2	TAP 100	kg SO2-Eq 5.0E-2	kg SO2-Eq 5.0E-2	A	mol H+ eq 6.5E-2	kg SO2-Eq 5.3E-2
EP	kg PO4 -- eq 1.5E-2	kg PO4 -- eq 1.5E-2	FEP	kg P-Eq 1.3E-3	kg PO4 -- eq 3.9E-3	Feu	kg P-Eq 1.6E-1	kg PO4 -- eq 4.8E-1
			MEP	kg N-Eq 2.3E-2	kg PO4 -- eq 9.6E-3	Meu	kg N eq 1.3E-3	kg PO4 -- eq 5.4E-4
						Teu	mol N eq 2.6E-2	kg PO4 -- eq 2.0E-1
PCOP	kg C2H4 eq 2.5E-3	kg NMVOC 4.2E-3	POFP	kg NMVOC 4.8E-2	kg NMVOC 4.8E-2	POF	kg NMVOC 4.8E-2	kg NMVOC 4.8E-2
LU	m2yr 3.7E-1	m2yr 3.7E-1	ALOP	m2yr 2.2E-1	m2yr 2.2E-1	LU	kg C deficit 1.5E+1	m2yr 1.5E+0
			NLTP	m2 1.7E-3	NA NA			
			ULOP	m2yr 2.8E-2	m2yr 2.8E-2			
FAETP 100a	kg 1,4-DCB-Eq 2.2E+0	NA NA	FETP inf	kg 1,4-DCB-Eq 1.5E-1	kg 1,4-DCB-Eq (freshwater) 1.5E-1	FE	CTUe 9.3E+1	kg 1,4-DCB-Eq (freshwater) 9.5E-2
FSETP 100a	kg 1,4-DCB-Eq 5.0E+0	NA NA						
HTP 100a	kg 1,4-DCB-Eq 3.5E+0	kg 1,4-DCB-Eq 3.5E+0	HTP inf	kg 1,4-DCB-Eq 2.1E+0	kg 1,4-DCB-Eq 2.1E+0	HTC	CTUh 3.6E-7	kg 1,4-DCB-Eq 1.7E+0
						HTNC	CTUh 3.3E-6	kg 1,4-DCB-Eq 5.1E+1
MAETP 100	kg 1,4-DCB-Eq 1.7E+2	NA NA	METP inf	kg 1,4-DCB-Eq 1.30E-01	kg 1,4-DCB-Eq (freshwater) 6.10E-01			
MSETP 100a	kg 1,4-DCB-Eq 9.6E+0	NA NA						
TAETP 100a	kg 1,4-DCB-Eq 3.3E-3	kg 1,4-DCB-Eq (freshwater) 6.5E-1	TETPinf	kg 1,4-DCB-Eq 1.6E-3	kg 1,4-DCB-Eq (freshwater) 3.1E-1			
Ionising radiation	DALYs 3.9E-8	kg U235-Eq 1.0E+0	IRP HE	kg U235-Eq 2.1E+0	kg U235-Eq 2.1E+0	IR HH	k U235 eq 2.1E+0	k U235 eq 2.1E+0
						IR E	CTUe 6.8E-6	NA NA
			PMFP	kg PM10-Eq 2.0E-2	kg PM2.5 eq	PM	kg PM2.5 eq 6.9E-3	kg PM2.5 eq

5.3.1.1. Global warming/Climate change

The quantity of CO_2 –eq emitted for the DU of cork insulation boards is exactly the same for all methods because they use the same characterization factors and the same methodology to obtain the results. Thus, the order of relevance of the different stages is also the same for all three methods. In this case, the industrial stage of the production process, the board and the granulate manufacturing, are the most impactful, with contributions of 45.3% and 23.0%, respectively.

5.3.1.2. Depletion

The impact categories related to any type of depletion are very different between the three methods, despite the Ozone Depletion Potential (ODP) that it is included in all methods. In the case of resource depletion, the CML method differentiates between fossil (MJ) and non-fossil resources (kg Sb eq). ReCiPe divides the resource depletion in fossil (kg oil-Eq), metal (kg Fe -Eq) and water (m^3). Finally, ILCD differentiates between resources (kg Sb eq) and water (m^3). The metric conversion was only possible for fossil depletion between CML and ReCiPe, resulting similar because are based on similar models and factors. In the case of fossil and mineral depletion the comparison was not possible because combining mineral and fossil depletion in CML and ReCiPe was too uncertain. The water depletion was only possible between ReCiPe and ILCD, and results were very different because of the methodology used. ReCiPe does not have any implemented characterization method and only takes into account the volume of water that was used. In the case of ILCD, the results are negative because the methodology considers that the water used in the system is restored to the geosphere and is available for new uses. For ReCiPe, the water depletion impact is 5 times higher than the ILCD one. The results for ODP are similar according to the weight of each stage, but the total impact is different in the case of the ILCD method and is 260 times greater than the result obtained in CML and ReCiPe methods.

The results for the different impact categories agree that the most impactful stage is the board manufacturing (3.2), unless for WRD in ReCiPe; on which the stage that is most influential is the granulate manufacturing (34.6%). Moreover, the metal depletion for ReCiPe resulted raw cork extraction as the most impactful stage, more than 70% of total impact.

5.3.1.1. Acidification

Acidification is expressed in one impact category for each method. In the case of CML and ReCiPe, acidification is expressed in terms of kg SO_2-Eq, and the results are quite similar. For the ILCD method, the results are expressed in terms of moles H+ eq. After the metric conversion the results in kg SO_2-Eq the results were similar, and also the distribution of impacts among the stages of the system was similar.

5.3.1.2. Eutrophication

The different types of impacts related to eutrophication are treated differently by each method. In the case of CML, only one category includes all types of eutrophication, and its impacts are expressed in kg PO_4 – eq. In ReCiPe and ILCD, the eutrophication is expressed in terms of freshwater (kg P-Eq) and marine eutrophication (kg N-Eq). Additionally, in ILCD, terrestrial eutrophication (molc N eq) is assessed. Once the impact categories had comparable metric, the impact scores resulted significantly different between similar impact categories, varying by +/- 1 order of magnitude.

In addition, results by life cycle stage were quite different. For instance, in ReCiPe, the most relevant stage for freshwater eutrophication is raw cork extraction (41.8%), whereas in ILCD, the most relevant stage is the granulate manufacturing (35.7%), as in the case of CML. The same applies to the marine eutrophication category; in ReCiPe, the most impactful stage is the granulate manufacturing (40%), whereas in ILCD, the most relevant stage is the raw cork extraction (41.8%). In the case of terrestrial eutrophication, only the ILCD method considers this category, where the granulate manufacturing is the most impactful stage.

5.3.1.3. Photochemical oxidation

In this impact category, the different methods assess different emissions to air and kg C_2H_4 –eq in the case of CML and kg NMVOC in the case of ReCiPe and ILCD. The impact score for CML was converted in kg NMVOC, but the result was 10 times lower than ReCiPe and ILCD.

According to the CML method, the most relevant stage in terms of photochemical oxidation is the board manufacturing (33.5%) and raw cork extraction (31.6%). For ReCiPe and ILCD, the granulate manufacturing is the most impactful stage (approximately 33%), followed by the raw cork extraction stage (26.3% and 25.8, respectively).

Table 5.5. Environmental impacts in the production of the DU of cork insulation board according to the three environmental assessment methods under study

CML							ReCiPe							ILCD						
GWP	Stage	Total	A3.2	A3.1	A1	A2	CC	Stage	Total	A3.2	A3.1	A1	A2	CC	Stage	Total	A3.2	A3.1	A1	A2
	%	100.0	45.3	23.0	21.5	10.1		%	100.0	45.3	23.0	21.5	10.1		%	100.0	45.3	23.0	21.5	10.1
ADP F	Stage	Total	A3.2	A3.1	A1	A2	FRD	Stage	Total	A3.2	A3.1	A1	A2	MFR D	Stage	Total	A3.2	A3.1	A1	A2
	%	100.0	47.3	21.8	20.3	10.7		%	100	46.7	22.0	20.5	10.9							
ADP E	Stage	Total	A3.2	A3.1	A1	A2	MRD	Stage	Total	A1	A3.1	A2	A3.2							
	%	100.0	47.3	21.8	20.3	10.7		%	100.0	72.6	10.8	10.0	6.7		%	100.0	43.9	23.2	21.0	11.9
							WRD	Stage	Total	A3.1	A3.2	A1	A2	WRD	Stage	Total	A3.2	A3.1	A2	A1
								%	100.0	34.6	34.1	27.2	4.0		%	100.0	92.8	61.2	-0.7	-53.2
ODP	Stage	Total	A3.2	A3.1	A1	A2	OD	Stage	Total	A3.2	A3.1	A1	A2	OD	Stage	Total	A1	A2	A3.2	A3.1
	%	100.0	43.9	23.3	20.9	11.9		%	100.0	44.2	23.1	21.0	11.8		%	100.0	78.1	15.9	3.1	2.9
AP	Stage	Total	A3.1	A3.2	A1	A2	TA	Stage	Total	A3.1	A3.2	A1	A2	A	Stage	Total	A3.1	A3.2	A1	A2
	%	100.0	33.4	31.8	22.8	12.1		%	100.0	33.7	30.4	22.8	13.2		%	100.0	33.7	30.3	22.8	13.2
EP	Stage	Total	A3.1	A3.2	A1	A2	FE	Stage	Total	A1	A3.1	A3.2	A2	FEu	Stage	Total	A3.1	A1	A2	A3.2
								%	100.0	41.8	29.6	21.9	6.7		%	100.0	35.7	24.5	22.1	17.7
	%	100.0	40.0	24.9	24.6	10.6	MEP	Stage	Total	A3.1	A3.2	A1	A2	MEu	Stage	Total	A1	A3.1	A3.2	A2
								%	100.0	39.3	23.3	21.8	15.6		%	100.0	41.8	29.6	21.9	6.7
														TEu	Stage	Total	A3.1	A3.2	A1	A2
															%	100.0	45.2	22.5	18.8	13.5
POC P	Stage	Total	A3.2	A1	A3.1	A2	POF	Stage	Total	A3.1	A1	A3.2	A2	POF	Stage	Total	A3.1	A1	A3.2	A2
	%	100	33.5	31.6	25.6	9.3		%	100	32.8	26.3	20.7	20.2		%	100	33.1	25.8	20-8	20.3

A1 - Raw cork extraction; A2 - Transport to manufacturer; A3.1 - Granulate manufacture; A3.2 - Board manufacture

CML

LU	Stage	Total	A1	A3.1	A2	A3.2
	%	100	43.0	24.6	22.3	10.1
FAETP	Stage	Total	A1	A3.1	A3.2	A2
	%	100.0	58.8	21.0	13.2	7.0
FSETP	Stage	Total	A1	A3.1	A3.2	A2
	%	100.0	61.0	20.9	11.0	7.1
HTP	Stage	Total	A1	A3.1	A2	A3.2
	%	100	57.1	24.3	9.5	9.1
MAETP	Stage	Total	A3.2	A1	A3.1	A2
	%	100.0	95.9	2.6	1.0	0.5
MSETP	Stage	Total	A1	A3.1	A2	A3.2
	%	100.0	57.8	20.7	11.0	10.5
TETP	Stage	Total	A3.2	A1	A3.1	A2
	%	100.0	46.3	21.9	20.6	11.3
Ionising radiation	Stage	Total	A3.1	A3.2	A1	A2
	%	100	60.3	21.4	12.7	5.6

ReCiPe

ALO	Stage	Total	A1	A3.1	A3.2	A2
	%	100.0	41.1	34.9	16.7	7.3
NLT	Stage	Total	A1	A2	A3.1	A3.2
	%	100.0	45.9	27.5	19.2	7.5
ULO	Stage	Total	A1	A2	A3.1	A3.2
	%	100.0	45.1	44.3	6.9	3.6
FET	Stage	Total	A1	A3.1	A3.2	A2
	%	100.0	62.5	17.2	14.1	6.2
HT	Stage	Total	A1	A2	A3.1	A3.2
	%	100	42.6	24.5	18.6	14.3
MET	Stage	Total	A1	A3.1	A2	A3.2
	%	100.0	62.2	16.8	10.7	10.3
TET	Stage	Total	A2	A1	A3.2	A3.1
	%	100.0	61.7	22.4	8.1	7.8
IR	Stage	Total	A3.1	A3.2	A1	A2
	%	100	52.5	31.5	11.1	4.9
PMFP	Stage	Total	A3.1	A1	A3.2	A2
	%	100.0	31.3	26.7	24.6	17.4

ILCD

LU	Stage	Total	A1	A2	A3.1	A3.2
	%	100.0	50.7	29.4	14.0	5.9
FE	Stage	Total	A1	A3.1	A2	A3.2
	%	100.0	64.9	13.5	11.5	10.1
HTC	Stage	Total	A1	A3.2	A3.1	A2
	%	100.0	54.9	20.2	14.9	10.0
HTNC	Stage	Total	A1	A2	A3.1	A3.2
	%	100.0	74.0	11.2	7.7	7.1
IR HH	Stage	Total	A3.1	A3.2	A1	A2
	%	100.0	52.5	31.5	11.1	4.9
IR E	Stage	Total	A3.2	A3.1	A1	A2
	%	100.0	38.2	37.4	15.8	8.6
PM	Stage	Total	A1	A3.2	A3.1	A2
	%	100.0	30.6	30.6	25.7	13.1

5.3.2. Identification of other relevant impact categories

The impact categories that were analysed in the previous sections are included in the EN 15804 standard. Currently, because the development of the new environmental assessment methods and the updating of others already exists, the environmental assessment can be extended to other impact categories. Therefore, this standard can be disregarding relevant information for the environmental performance of the product. In this section, the rest of the impact categories included in CML, ReCiPe and ILCD methods are assessed to analyse the importance of taking into account more impact categories into the standard.

First of all, it is important to identify the most relevant impact categories in the product under study. This information is obtained through the normalization of the resulting values for each method, and then these normalized values are normalized again to a reference impact category. It is necessary to highlight that the normalisation is never included in the EPD and is included only for additional information, as in the present study. In this case, climate change has been chosen for all methods because of its acceptance in the LCA field (Table 5.6). It can be noted that of the impact categories included in the standard, fossil depletion, terrestrial acidification, and freshwater and marine eutrophication have significance relevance.

Table 5.6. Comparison of environmental scores (after characterisation and normalisation) normalised to Global Warming = 1

		CML	ReCiPe	ILCD
Included in EN 15804 standard	Climate change	1.00	1.00	1.00
	Fossil depletion	2.25	2.55	3.77
	Metal depletion	0.10	0.60	
	Water depletion	-	-	0.05
	Ozone depletion	0.08	0.08	0.07
	Terrestrial acidification	1.35	1.33	1.05
	Freshwater eutrophication		2.85	0.65
	Marine eutrophication	0.34	2.06	1.16
	Terrestrial eutrophication		-	0.69
	Photochemical oxidant formation	0.62	0.79	1.14
Not included in EN 15804 standard	Agricultural land occupation		0.05	
	Natural land transformation	349.1	1.5E+07	1.89
	Urban land occupation		25.5	
	Freshwater aquatic ecotoxicity	4.54	12.53	8.04
	Freshwater sediment ecotoxicity	9.49		
	Human toxicity	2.95	3.11	7.62 4.68
	Marine aquatic ecotoxicity	1.65	14.04	-
	Marine sediment ecotoxicity	0.11		
	Terrestrial ecotoxicity	0.01	0.18	-
	Ionising radiation	0.27	0.31	1.40 -
	Particulate matter formation	-	1.23	1.37

If the rest of the impact categories are taken into account, most of them have more significance than global warming or climate change, particularly in the cases of land use, freshwater ecotoxicity human toxicity and marine ecotoxicity (Table 5.6). The significance of the particulate matter impact category is higher than the reference category, but only for ReCiPe and ILCD methods, because it is not included in the CML method.

In the case of land use, the results are very different between three methods due to the different models and scope used in each one. For example, CML and ILCD cover impacts from both land occupation and transformation whereas ReCiPe distinguishes between type of land and its use (occupation or transformation). In the case of ReCiPe normalisation result for natural land transformation is not comparable because it does not take into account the time. In general land use results are so high because of the land occupation of cork oak forests (Table 5.5), particularly for CML method. This occupation is long term, and the productivity of the Catalan cork oak forests is still relatively low; from 63,000 ha, 7,200 tonnes of raw cork are obtained [190]. Moreover, the factory where the boards are manufactured also occupies an area of approximately 20,000 m2, but this value is insignificant compared to the cork oak forest area. The categories related to "impacts of land use" covers a range of consequences of human land use and the temporary unavailability of land. It makes a distinction between use of land with impacts on the resource aspect and use of land with impacts on biodiversity, life support functions, etc. Table 5.5 presents the characterization results for all of the rest of the impact categories related to land use and confirms that the raw cork extraction concentrates the majority of the impacts related to land use. However, this category has to be more thoroughly developed because of the inconsistency and the differences of the results between each of the methods [214,215].

The categories related to freshwater ecotoxicity are expressed differently in each LCA methods. In the case of the CML, this category distinguishes between freshwater aquatic ecotoxicity (kg 1,4-DCB-Eq) and freshwater sediment ecotoxicity (kg 1,4-DCB-Eq). ReCiPe and ILCD have only one impact category expressed in kg 1,4-DCB-Eq and CTUe (Comparative Toxic Units), respectively. The conversion into a common metric was not possible in the case of CML. ReCiPe and ILCD results (after metric conversion) was quite similar, being ILCD results 30% lower than ReCiPe. Regarding the normalisation, the relevance of these categories has similar relevance in each method, and the most relevant stage is the same for all of the LCA methods (Table 5.5). Raw cork extraction assumes that more than 60% of the total impacts are related to freshwater ecotoxicity.

Regarding the impact categories that analyse human toxicity, CML and ReCiPe have a unique category with the same unit (kg 1,4-DCB-Eq), but the results differ both for the total impact and the importance of each life-cycle stage. The human toxicity from the CML was 60% higher than the value for the human toxicity from ReCiPe. The ILCD method expresses the human toxicity impacts in two categories: with cancer effects and without cancer effects. The raw cork extraction concentrates the majority of the impacts in all of the categories related to human toxicity for all LCA methods (Table 5.5).

In the case of marine ecotoxicity, results for both characterization and normalisation could not be compared due to the ReCiPe and ILCD had only a unique impact category and in the case of CML, the marine aquatic and sediment ecotoxicity were assessed separately.

Finally, terrestrial ecotoxicity, ionising radiation and particulate matter formation are the rest of the impact categories that are not included in the standard. Except for ionising radiation, these impact categories are not available in the three LCA methods; thus, a comparison is not possible. In the case of ionising radiation, the CML and ReCiPe methods obtained similar results, regarding the relevance of each stage. In the case of ILCD, ionising radiation is expressed in two impact categories: ionising radiation HH and ionising radiation E. They have the same results as ReCiPe, both for impact values and for the relevance of each stage (Table 5.5), because they used the same characterization factors.

5.3.3. General comparison between the LCA methods

From a general view, if all the impact categories of the LCA methods are considered, the most influential stage for all LCA methods is raw cork extraction (A1), concentrating a third of the total impacts. If only the CML 2002 method and the impact categories included in the EPD standard are considered, the most impactful stage is the board manufacturing stage (A3.2). In the case of using the ReCiPe or ILCD method for assessing the EPD standard, the most influential for the majority of the stages is raw cork extraction (A1), the same as if all the impact categories are included.

From a detailed view, the results obtained for the three LCIA methods show significant differences between them, both the type of the impact categories included in each LCA method and their results. Moreover, the current EPD standard only includes seven impact categories. This study also includes an assessment of the relative importance of other existing impact categories in comparison with the current EPD standard. The results present that the misleading categories from the standard show relevant information about the environmental performance of the product as well as differences in the relevance of each life-cycle stage. Some impact categories have different approaches in each LCA method, and in the case of the land use, the methodology is not well understood. In the next updates of the EN 15804 standard, policy makers should consider these results in addition to results from future studies. This gives an idea of the importance of the LCA method selection, e.g., in this case, to communicate the environmental performance of building materials.

5.4. Conclusions

During the material selection in building design, decisions are increasingly focused on their environmental aspects. The EPDs of building materials allow building designers and architects to obtain an indicator to compare the environmental information between different materials. This paper addresses the case of cork insulation boards to show the need for assessing the actual reference impact categories and assessment methods under the EN 15804 by performing a comparison among the primary impact assessment methods.

The differences in the results between the analysed LCA methods vary depending on the impact categories included in the study and, in some specific impact categories, with different methodological approaches. On the one hand, if the EPD from the cork insulation board is assessed under the current standard, the environmental results for the CML method are different from the ReCiPe and ILCD results. On the other hand, if other impact categories are included in the assessment, the results are different from the EPD standard. However, in this case, the global results are similar for all the methods. The most relevant impact categories included in the EPD standard are climate change, fossil depletion, terrestrial acidification and eutrophication.

On the other hand, the relevance is high for some of the impact categories not included in the standard, such as land occupation, freshwater and marine ecotoxicity, human toxicity and particulate matter formation. Therefore, their incorporation into the EPD should be assessed to make more complete information available in the selection of materials during building design. This type of analysis should be conducted for other products, and in the next updates of the standard EN 15804, policy makers should consider these results. Regarding the differences between the results of the three LCA methods, the scientific community should reach a consensus on the best way to model environmental impacts. Additionally, some methods, such as land use, should be improved to increase their reliability.

PART IV

ENVIRONMENTAL ASSESSMENT OF INSULATION SYSTEMS FOR BUILDINGS

Chapter 6

ENVIRONMENTAL ASSESSMENT OF FAÇADE-BUILDING SYSTEMS AND THERMAL INSULATION MATERIALS FOR DIFFERENT CLIMATIC CONDITIONS

6. Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions

This chapter is based on the following published paper:

Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions. J Clean Prod 2016;113:102–13.

· Preprint version in Universitat Autònoma de Barcelona repository:

http://ddd.uab.cat/pub/artpub/2016/145989/jouclepro_a2016m02v113p102.pdf

· Published version by Journal of Cleaner Production:

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Abstract

In the European Union, the building sector accounts for more than 40% of the total energy consumption and environmental impacts, representing the area with the greatest potential for intervention. In addition to the existing policies that promote energy efficiency in buildings, the embodied energy and the environmental impacts contained in the building materials should be considered. In the case of the construction of insulation façade systems, the environmental implications are different depending on the type of façade system, the insulation materials used and the location of the building. This article aims to provide all of this information for Spain, including not only the production of the components of the façade system but also the installation phase and the transport to the building site. The results show that the most impactful alternative is the ventilated façade combined with the most impactful insulation materials of stone wool and expanded polystyrene. Meanwhile, the most advisable façade in all of the climate zones is the external thermal insulation system combined with any type of insulation. The environmental impacts of insulation materials are very different. Moreover, it is recommended that further studies complete these results with the economic and social implications of the use and maintenance phases for robust decision-making.

Keywords

Life cycle assessment, cradle to gate, embodied energy, embodied carbon, buildings, Spain.

Highlights

- LCA comparison of insulation materials applied in façade systems has been developed
- The Spanish climate factor is introduced in the cradle-to-site LCA
- The most sustainable option is the external thermal insulation system with glass wool
- Stone wool represents 30-50% of impacts for all of the façade systems analysed
- The choice on the type of insulation material has great environmental implications

Chapter 7

INTEGRATED LIFE CYCLE ASSESSMENT AND THERMAL DYNAMIC SIMULATION OF A PUBLIC BUILDING'S ENVELOPE RENOVATION: CONVENTIONAL VS. PASSIVHAUS PROPOSAL

7. Integrated life cycle assessment and thermal dynamic simulation of a public building's envelope renovation: conventional vs. Passivhaus proposal

From this chapter, a paper has been extracted and submitted in a peer-review indexed journal.

Abstract

The need to improve the energy efficiency of buildings has introduced the concept of nearly zero-energy buildings to European energy policies. Moreover, a percentage of the building stock will have to be renovated annually to attain high energy performance. Conventional passive interventions in buildings are focused on increasing the insulation of the building envelope to increase its energy efficiency during the operating phase, but often the intervention practices imply the incorporation of embodied energy in the building materials and increase the associated environmental impacts.

This paper presents and evaluates a comparison of two different proposals for a real building renovation. The first proposal was a conventional project for energy renovation, while the second was a low-energy building proposal (following the Passivhaus standard). This study has analysed the proposals using an integrated life cycle and thermal dynamic simulation assessment to identify the adequacy of each renovation alternative regarding the post-renovation energy performance of the building, including an evaluation of the introduction of a renewable insulation material in the low-energy building proposal, specifically a specific cork solution. The most significant conclusion was the convenience of the renovation, achieving energy savings of 60% and 80% for the conventional and Passivhaus renovation (ENERPHIT), respectively. The former supposed less embodied energy and environmental impacts but also generated less energy savings. The latter increased the embodied impacts in the building, mainly for the large quantity of insulation materials. The environmental implications for both proposals can be compensated in a reasonable period of time, over 2 years in the majority of alternatives and impact categories. However, the ENERPHIT project was 30% better than the conventional proposal if the total lifespan of the building was considered. The introduction of cork did not fit the requirements to compete with the common non-renewable insulation materials because it did not imply a better environmental performance in buildings, but cork insulation solutions currently present ample room for improvement.

Keywords

Zero-energy building, ENERPHIT, insulation materials, embodied energy, operating energy, cork, circular economy, industrial ecology, life cycle thinking.

Highlights

- Conventional and Passivhaus proposals for a university building's renovation are compared.
- The energy renovation achieved high energy savings for both proposals, between 60% and 80%.
- The Passivhaus proposal is 30% better than the conventional one considering the total lifespan of the building.
- The use of cork as insulation material for envelope renovation is assessed.
- Cork does not fit the requirements to compete with the common non-renewable insulation materials.

7.1. Introduction

7.1.1. Background

The building sector is one of Europe's main environmental challenges, accounting for more than 40% of the continent's energy consumption and environmental impacts [185]. Nevertheless, it is the area with the greatest potential for intervention [186], as improving the sustainability of buildings is crucial to the energetic transformation of the European Union [91]. More sustainable construction and efficient use of buildings in the EU would decrease the final energy consumption by 42%, greenhouse gas emissions by approximately 35%, all extracted materials by more than 50% and water use by up to 30% [95]. The existing energy policies promote energy efficiency and renewable energy use in buildings, such as the European Energy Performance of Buildings Directive 2002/91/EC (EPBD) [185]. The EPBD introduces the concept of nearly zero-energy buildings (NZEB) and establishes that all new construction must be NZEB by the 31st of December 2020. Moreover, Directive 2012/27/EU [243], published in 2012 and effective as of 2014, requires all countries of the EU to energetically renew 3% of public administration buildings on an annual basis.

Some efficient building practices to transform the current building stock are active measures, while others are passive interventions. The former aim to conserve energy in building equipment and maintenance by including system controls or via the installation of renewable energy generating systems. The latter are used to reduce energy consumption in the building envelope; one of the most extended practices is to increase the insulation of the building envelope: façades, roofs and windows [244]. Therefore, the insulation materials have an important role because they influence the use phase of the building. For example, the introduction of insulation in the building envelope can decrease the energy demand by 64% in summer and up to 37% in winter and can also decrease the CO_2 emissions [223]. Currently, the European market is still dominated by non-renewable insulation materials, including stone wool (SW), glass wool (GW), expanded polystyrene (EPS), extruded polystyrene (XPS) and the less widespread polyurethane (PU) [124,128]. Moreover, the market accounts for other alternative materials, including renewable materials. The importance of these materials has been increasing due to the strategic minimisation of the use of non-renewable materials to reduce the environmental impact of buildings. However, renewable insulation materials still have not undergone sufficient development to be implemented comprehensively in the building sector. Furthermore, the environmental implications of manufacturing these products are still not widely known.

Focusing on passive interventions, conventional building renovations should reduce the environmental impact during the operating phase to increase the indoor comfort through heating and cooling, lighting and operating appliances [109]. However, the intervention practices for energy savings imply the incorporation of embodied energy and environmental impacts into the building. These energy and environmental impacts are the sequestered energy in building materials throughout all of the processes of production, on-site construction, final demolition and disposal. If all efforts are focused on reducing operational energy, the relative importance of the embodied energy of materials will be more relevant with regard to the baseline situation [26,97,216]. For instance, the European Commission has taken the constructive methodology Passivhaus and its specific criteria for building renovation (ENERPHIT) as a reference for NZEB [245]. This standard, developed in Germany by the Passivhaus-Institut Darmstadt, is eminently focused on minimising the operating energy in buildings by intensively using insulation materials and more advanced equipment but not including the quantification of the environmental implications that this assumes. Otherwise, the relative share of embodied energy in low-energy buildings is more relevant than in conventional buildings, so the selection of insulation materials should have to take into account solutions with low embodied energy [246]. Therefore, according to the European Commission [95], the reduction of embodied energy needs to be further strengthened and complemented with policies for resource efficiency, which look at a wider range of environmental impacts across the life cycle of buildings and infrastructure. In this way, life cycle thinking represents a basic concept of considering the entire product system life cycle from the "cradle to the grave" and aims to prevent impact trade-offs between life cycle phases [217]. There is a strict interplay among all the phases of a building life cycle, as each one can affect one or more of the others, highlighting the relevance of the life cycle approach for performing a reliable and complete building energy and environmental assessment [237].

7.1.2. Literature review

Life cycle assessment (LCA) methodology can be used to quantify and identify the potential environmental impacts throughout a building's life cycle [34] and to evaluate the potential benefit of different renovation measures. LCA has wide acceptance in the building sector and is used to compare different alternatives in the design of buildings. Most studies have focused on comparisons of different alternatives for building design regarding the selection of constructive solutions and building materials [110,111,123,188], while others have focused on new buildings (more specifically, residential buildings) [99,107]. Few studies have addressed the renovation of buildings, and their main goal was to achieve a great energy savings, limiting their scope to the assessment of operation energy, often neglecting embodied impacts during production and assembly of materials or constructive solutions [108,109]. It is important to note that the renovation of the EU's ageing building stock was indicated by the European Commission as key to meeting the EU's objectives to reduce greenhouse gas emissions and energy demand by 20% [90].

Between the few studies that took into account both the embodied energy and the operating energy of the renovated building different levels, can be distinguished. On the one hand, at building level, the final balance had been assessed between the energy savings during operation and the environmental impacts related to the building material incorporation [109,246]. On the other hand, at material level, some studies assessed the combination of different building materials in the renovation of buildings, analysing the influence on the energy and environmental performance after the renovation [108,244]. A notable gap has been identified in the literature because different types of building renovation have not been compared; for instance, low-energy buildings have not been compared with the conventional systems that are currently utilised in European countries. In this regard, the application of the standard Passivhaus for building renovations is a reference for the European Union. Thus, it should be compared with conventional renovation systems beyond residential buildings [247,248], integrating a thermal dynamic simulation in the LCA methodology to assess the post-renovation building energy consumption in a more realistic way [108]. Moreover, it is important to note that it is necessary to analyse large buildings, in addition on housing, because this could show relevant differences in the selection of building materials during the design phase.

Additionally, the insulation materials have an important role because, in addition to influencing the use phase of the building, they also affect the environmental impacts of construction [227,249,250]. Thus, their convenience must be assessed, including also alternative materials as renewable materials, to increase the knowledge about their environmental implications and thermal performance [203]. As commented above, the importance of renewable insulation materials has increased, and previous studies have environmentally assessed some of these, including kenaf-fibres, cotton, jute, flax, hemp and cork [128–130,203]. Cork is one of the most studied from an environmental perspective [81,87,127,203] and one of the most widespread renewable materials used as thermal insulation, especially in northern Europe [78,190]. Moreover, the environmental importance of cork is the key role that it plays in ecological processes, such as water retention, soil conservation, and carbon storage [88]. Concerning carbon storage, part of the carbon fixed by cork oak trees is transferred to cork products, giving cork products the potential to mitigate climate change by storing carbon for long periods (up until the end-of-life of cork products) [77,191,192].

This article presents the environmental assessment of different projects for the renovation of a Spanish university building using an integrated life cycle and thermal dynamic simulation assessment. A comprehensive analysis of different alternatives for renovation and insulation materials was performed to identify the adequacy of each renovation proposal regarding the post-renovation energy performance of the building. The alternative proposals are: (a) the conventional renovation project developed by the Spanish Ministry of Defence and another more efficient one developed specifically for this study using the (b) Passivhaus criteria for the renovation of buildings, ENERPHIT. Moreover, the use of renewable insulation materials is simulated in the ENERPHIT proposal using cork instead of GW, one of the most common insulations in ENERPHIT.

7.2. Energy and environmental assessment of building renovation

7.2.1. Description of the existing building

The assessed building is a university building located in the General Military Academy of the Spanish Army in Zaragoza, located in north-eastern Spain. It has a constructed surface area of 4,033 m^2, distributed over a ground floor and two upper floors. 3 modules compose the building: the east module is used for classrooms and for a conference hall; the west module, with only one upper floor, is used for offices; and the central module hosts the stairs. The real building occupation has been included in the energy simulations by using a pattern of use. For this purpose, the sensible and latent loads produced by the real number of people occupying each space and the existing computer equipment have been introduced. The building is used only between the hours of 7:30 and 14:30. The considered months of use are from October to June, with different load levels of use. Moreover, there is partial use until mid-July. Figure 7.1 shows a 3D render of the building simulated by Design Builder software [157] where the composition of the building can be observed. Floor plans of the building and its exact location are not provided for national security reasons.

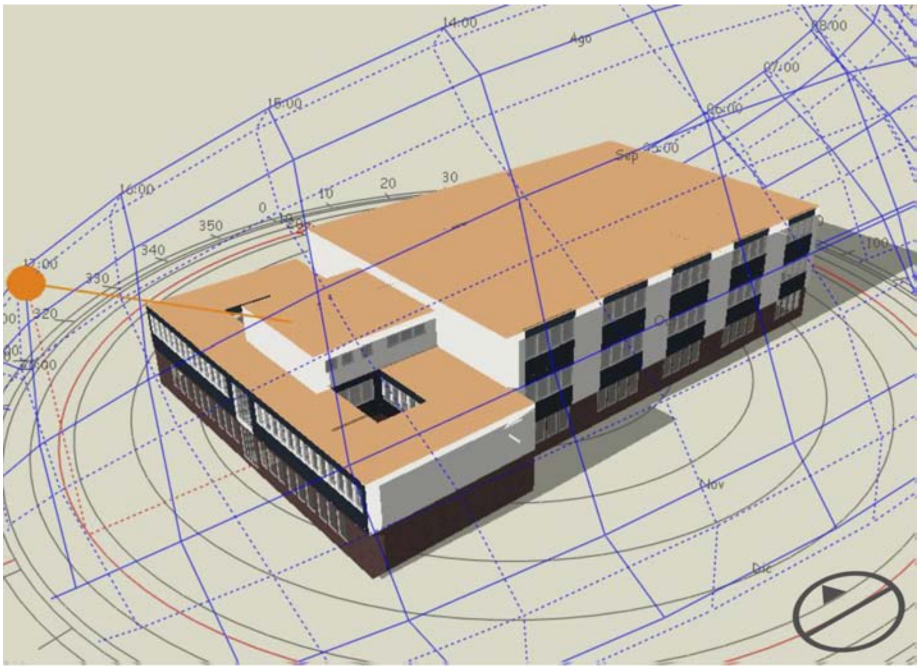

Figure 7.1. General view of the building simulated with DesignBuilder

It was built in the seventies following a similar design built in different military units. The existing building rules at that time did not require the installation of insulation material (also true for the actual situation of the building's envelope). Regarding the composition of the building's envelope, the facade of the ground floor is composed of (from indoor to outdoor) plaster, an interior wall of double hollow bricks, an air chamber and another wall of double hollow bricks. For upper floors, its composition is (indoor to outdoor) plaster, an interior wall of double hollow bricks, an air chamber, another wall of double hollow bricks, and a metal substructure to hold an outer sheet of prefabricated concrete panels or a curtain wall. The slab is made of 20 cm of reinforced concrete without insulation, coated with ceramic tile. The external cladding of the curtain wall is made of tinted glass. Regarding the roof, all modules have installed reinforced concrete slabs with cement fibre cover. Windows are composed of an aluminium frame without a thermal break and 6 mm of simple glass. Table 7.1 presents the characteristics of the building's envelope and the transmittances (U) of each different part of the envelope.

Table 7.1. Structural characteristics of the buildings envelope

Building features		**Transmittance**
* Number of floors	P + 2E	
*Building floors area	3,923.21 m^2	
Ground area	1,403.59 m^2	
First floor	1,403.59 m^2	
Second floor	1,116.03 m^2	
* Building high	10.65 m	
Ground area	3.65 m	
First floor	3.50 m	
Second floor	3.50 m	
* Building exterior area	4,403.78 m^2	
Total façade	1,596.60 m^2	

· Curtain wall	268.70 m²	U= 0.82 W/m²K
· Brick wall	838.60 m²	U= 0.76 W/m²K
· Prefabricated concrete	489.30 m²	U= 0.71W/m²K
Total roof.	1,403.59 m²	U= 1.10 W/m²K
· Inverted transitable flat	1,011.23 m²	
· Non transitable inclined (occupied)	287.56 m²	
· Non transitable inclined not occupied)*	104.80 m²	
Slab-on-ground	1,403.59 m²	
*Windows	358.27 m²	
Glass	268.70 m²	U= 6.10 W/m²K
Frame	89.57 m²	U= 5.70 W/m²K

The building is located in one climate zone denoted by D3 [251], which is the largest in Spain and is the climate zone with the second highest winter and summer severity [232]. If we take Zaragoza as a reference city, from the Spanish State Meteorological Agency, the annual average maximum temperature with a monthly base is 21ºC, and the annual average minimum temperature with a monthly base is 10 ºC.

7.2.2. Description of the renovation project proposals

Two proposals were assessed for the building renovation: firstly according to the conventional project of renovation in the Spanish Ministry of Defence and secondly following the Passivhaus standard for building renovation, ENERPHIT. In both cases, the energy renovation is performed inside the building for each plan, and the windows are also replaced.

7.2.2.1. Conventional renovation proposal

As commented before, the current building has not installed insulation in its envelope, so in accordance with the EPBD, the building has to be renovated to increase its energy efficiency of operation. For that, the Spanish Ministry of Defence is currently carrying out the renovation standard for this type of building, which exists in different military units across the country. The renovation project implies the installation of insulation material in the interior side of the envelope using extruded polystyrene (XPS). For that, it was necessary to demolish the existing interior brick wall and construct another. This project also includes the renovation of the tinted glass of the curtain wall façades. In the case of the roof, the existing reinforced concrete slabs with cement fibre cover are dismantled, and instead of them, an inverted flat roof was installed in the classroom side and a non-transitable deck roof with thermal insulation in the rest of the building, using XPS and stone wool (SW), respectively. In this renovation project, the slab-on-ground is not renovated.

7.2.2.2. ENERPHIT renovation proposal

In addition to the conventional renovation project, this study analysed a more efficient proposal of renovation, complying with the refurbishment standard ENERPHIT, based on the Passivhaus construction standard of nearly zero-energy buildings. The main requirements that buildings must comply with after the refurbishment of air conditioning are the final demands of heating and cooling of 25 kWh/m^2 year and the infiltrations through the envelope under a pressure test of 1 h^{-1} by 50 Pa. [252]. The ENERPHIT proposal included the same types of façades, but in the case of the curtain wall, the tinted glass is not renovated because the authors considered their current state to be good. Regarding the roof, in the classroom side, an inverted flat roof was installed, and in the rest of the building, a non-transitable deck roof. However, in this case, a distinction was made between occupied and unoccupied spaces. In occupied areas, the deck roof included insulation materials, and in unoccupied areas (stairs), it did not. The insulation material installed in all façades and roofs was GW. Moreover, in this proposal, the slab-on-ground was insulated with EPS, following the constructive detail in Figure 7.2.

7.2.3. Description of the constructive solutions under study

Figure 2 presents schemes of different constructive systems used in the study, either in the conventional project, the ENERPHIT project, or both. Moreover, Figure 7.2 explains the composition of each constructive solution and the elements incorporated in the building. The building under study had three types of façade and three types of roofs, in addition to the slab-on-ground. The façade systems included in both projects were the curtain wall façade, the brick wall façade and the prefabricated concrete façade. All of these were insulated by the inside, between an existing brick wall and a new double hollow bricks wall. Regarding the roof systems, the study included the inverted transitable flat roof, non-transitable deck roof and non-transitable flat roof, non-insulated. The latter system was only included in the ENERPHIT proposal, and it did not include insulation because it was installed in unoccupied areas. Regarding the slab-on-ground, a new floor structure was added, and also a thermal insulation board and a ceramic coating. This solution was only included by the ENERPHIT project.

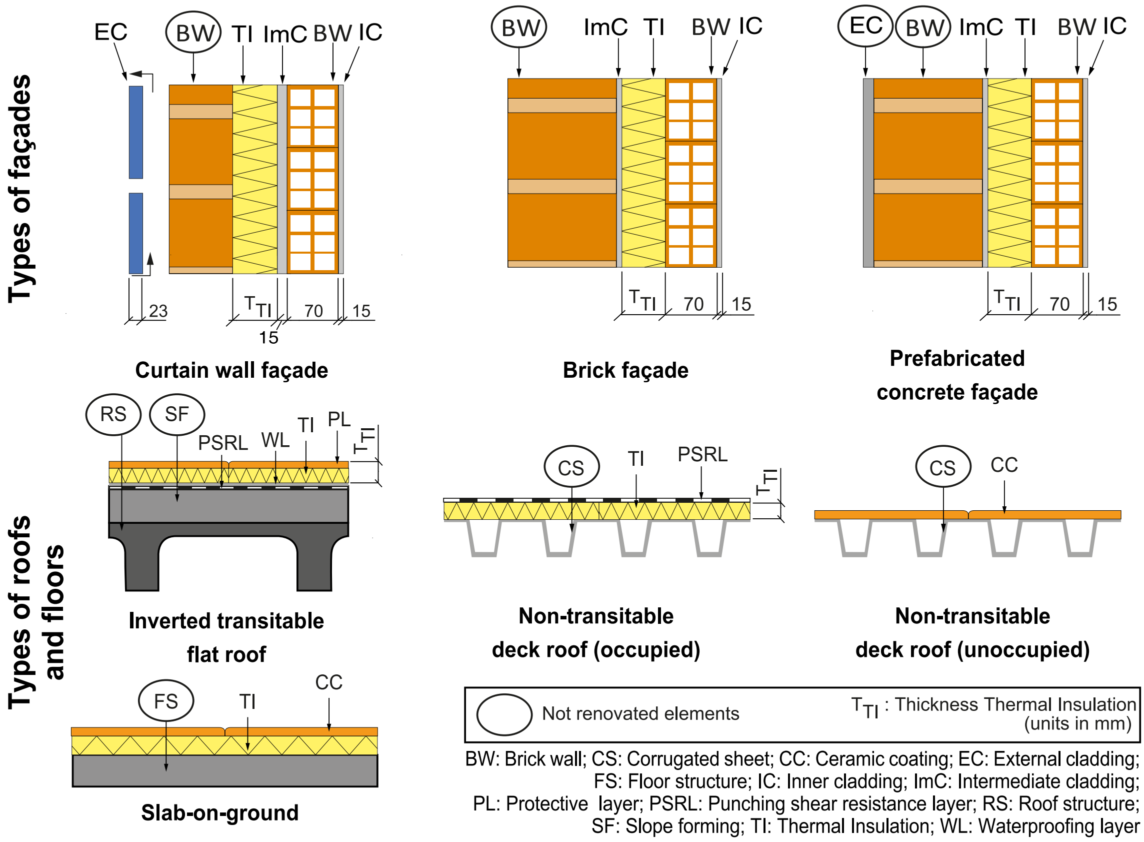

Figure 7.2. Constructive details of the types of façade, roofs and floors used in the renovation

The main difference between the two proposals was the insulation material required, with more insulation required in ENERPHIT than in the current project. Table 7.2 summarises the thickness and the type of insulation material installed in each proposal. Moreover, a natural alternative for insulation material was assessed in this study for the ENERPHIT project, the white agglomerated cork, and it will be commented on in a posterior sensitivity analysis. Another difference was the sealant that the ENERPHIT proposal uses to avoid infiltrations in windows, doors and contact surfaces between façades or façade and roof.

Table 7.2. Insulation material required for the proposal under study

	Thickness Thermal Insulation (m)				
	Current renovation		ENERPHIT renovation		
	XPS	SW	GW	EPS	White agglomerated cork
Curtain wall façade	0.05	-	0.14	-	0.15
Brick façade	0.05	-	0.13	-	0.14
Prefabricated concrete façade	0.05	-	0.14	-	0.15
Inverted flat roof	0.08	-	0.14	-	0.15
Non transitable inclined roof (occupied)	-	0.05	0.18	-	0.20
Non transitable inclined roof (not occupied)	*	-	0	-	0.00
Slab-on-ground	*	-	-	0.15	0.18

* This part of building is not included in this renovation project

Regarding the windows, they were different in each project but from the same manufacturer. In the case of the conventional renovation project, the selected windows had double glazed insulation [253]. In the case of the ENERPHIT project, windows had triple glazed insulation [254]. In addition, in the ENERPHIT project, sealing tape was placed in every nook of the building to avoid unwanted air infiltration, especially in windows and doors.

7.2.4. Functional unit and system boundaries

The functional unit (FU) selected for this study was 1 square metre of the different solutions of façades, roofs, slab-on-ground and windows that composed the envelope [188]. In this case, to renovate a given surface of the building case study according to two different renovation proposals, the FU was applied for the total area of each constructive solution. Moreover, the FU for the operating phase is the energy consumption for heating and cooling during a year under the same indoor thermal conditions.

The system boundaries of the study, according to the EN 15978 [100] standard related to the environmental assessment of buildings and the EN 15804:2014 [101] standard related to the environmental product declaration (EDP) of construction products, included, on the one hand, the production of the building material, transport from the factory to the site and the construction and installation processes. On the other hand, the end-of-life stage of the replaced building components also had to be taken into account. Finally, this study also included the use phase to calculate the energy savings achieved for each renovation alternative with respect the original state of the building (Figure 7.3).

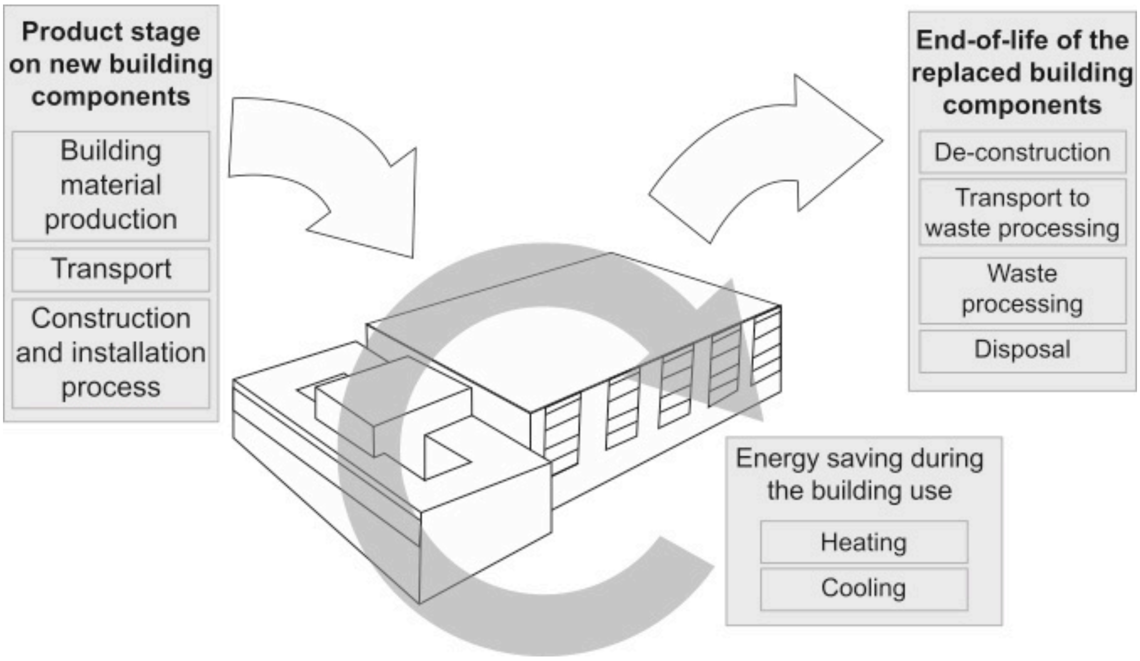

Figure 7.3. Information modules included in the evaluation of the evaluated building

7.2.5. Methodology

An integrated life cycle approach combining LCA and thermal dynamic simulation was implemented to assess the energy and environmental impact of the different projects for the building's renovation.

7.2.5.1. Environmental impact assessment of the alternative renovation proposals

The LCA methodology [255] was used in this study, conducting a process-based LCA framework to evaluate the environmental impact of the different renovation proposals according to EN 15978 [100] and EN 15804:2014 [101]. For the assessment of the product stage of new building components, this study has a cradle-to-site approach, meaning that the environmental impact analysis includes the production (extraction and processing of raw materials, transport to the manufacturer and manufacturing), transportation to the building site and installation in the building. With regard to the end-of-life of the replaced building components, only end-of-life was taken into account.

The assessment of the constructive solutions required data regarding the insulation materials, quantity, and installation. According to the established FU and the building's technical considerations, the Appendix 3 indicates the materials and energy content for each façade, roof and slab-on-ground, in addition to the elements replaced from the building. For the installation phase, the materials and energy for the assembly of all of the components were considered. In the case of windows, environmental information had been collected from environmental product declarations published by the manufacturers to obtain the environmental impacts per square metre [253,254].

According to the European standard that provides the core Product Category Rules (PCR) for all construction products and services, EN 15804:2014 [101], the following six midpoint impact categories from the CML 2 baseline 2002 [150] were included in the assessment: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (PCOP). Additionally, as noted above, the embodied energy (EE) had been included due to its increasing importance in the building energy demand.

The software Simapro 8.1 [152] and the ecoinvent 3.2 database were used to obtain the environmental information related to the processes involved for the materials, energy and transport [153].

7.2.5.2. Measurement of the energy savings

The energy simulation was carried out with a Computational Fluid Dynamics Simulation module (CFD) of the program DesignBuilder [157]. The model includes the details of transmittances and infiltrations of the original building, and the results of energy consumption, thermal loads and temperature conditions shall be compared with real data obtained in the building. These data were obtained from the real thermal characterisation of the building. For that, the blower-door test was first made, combined with thermography and smoke pens to measure and observe the infiltrations of the building. The blower-door test was carried out in five enclosures, which were composed of existing construction typologies. Therefore, the average infiltration of the building for a pressure difference of 50 Pascal was 46.53 air changes per hour. Most of the infiltrations come from the carpentry, the forged thermal bridge and the facilities. Later, the transmittances of the different closures were measured, and with the exterior thermography, the transmittances of different thermal bridges were calculated via the differences in surface temperatures. A difference was noted between the calculated transmittance and the measured transmittance in the brick walls, curtain wall, slab on grade floor and roof. To conclude, the temperatures inside the building and the energy demand for heating were measured. The energy demand was obtained by measuring the temperature of the input and output of the heated water in the secondary circuit of the heat exchanger system used for the heating system.

Once the building was thermally characterised, a mathematical model was developed with Design Builder. Moreover, the pattern of use was included. Thus, this helped to validate the mathematical model simulated with the program, and different renovation projects can be simulated with the knowledge that the results obtained will be adequate. Finally, the proposals for renovation were simulated under the conditions described above, obtaining the energy consumption for heating and cooling in the climatic area where the building is located. Moreover, a pattern for the use of classrooms had been included, taking into account their metabolic activity, the number of students and the operating schedule for each month of the year. From these data, the energy savings with respect to the original building could be calculated.

7.2.6. Inventory data

The inventory data for the production of materials used in construction and installation of the constructive solutions under study and for their transport to the building location were collected from different sources of information. In the Appendix 3, a comprehensive inventory for the demolition of each part of the building can be found, as can the energy used during the building renovation. This energy is similar for different proposals. Moreover, the Appendix 3 section contains the specific data for each process and the reference of the source where the data were collected. Table 7.3 summarises the total life cycle inventory for the two proposals for renovation and presents the total quantity of materials and resources in the renovation of the building following the above renovation projects.

Table 7.3. Life cycle inventory

Material	Conventional renovation	ENERPHIT renovation
Insulation material (kg)	5,155.4	28,457.9
Adhesive mortar (kg)	958.0	2,692.2
Gypsum (kg)	1,277.3	1,277.3
Base plaster (kg)	12,175.7	12,156.3
Water (kg)	39,595.7	39,595.7
Double hollow bricks (kg)	78,233.4	105,375.6
Cement mortar (kg)	33,209.3	33,209.3
Tempered glass (kg)	4,030.5	0.0
Metallic fixings (kg)	268.7	0.0
Screws (kg)	217.6	0.0
Waterproofing layer (kg)	2,807.2	2,597.6
Punching shear resistance layer (kg)	101.1	101.1
Ceramic tile (kg)	67,246.8	167,554.7
Corrugated sheet (kg)	2,511.1	2,511.1
TOTAL (kg)	**247,787.8**	**395,528.7**

The main assumptions made in the LCA were that the lifespan for the renovation action is 50 years, similar to that of other studies [108,246,247,256], and that the distance for transport from the factory to the building location is 100 km, the most representative value in the literature [123,238,239].

7.3. Results and discussion

7.3.1. Environmental implications of the building renovation

In this section, the resulting environmental impacts of each renovation are discussed. Moreover, the contributions of the insulation materials are analysed.

7.3.1.1. Environmental impact assessment of the alternative renovation proposal by a constructive solution

This section presents the results of the LCA of the incorporation of new materials into the building and the demolition and end-of-life of the replaced components for the two renovation proposals (Table 7.4). It can be noted that the most intensive alternative in the use of building materials, ENERPHIT, presents the highest environmental impacts. Its environmental performance is between 40% and 230% higher than that of the conventional proposal depending on the impact category considered, particularly in EP, ADP and EE. Meanwhile, the use of material in ENERPHIT is 60% higher in terms of weight and, consequently, price. As commented above, the significant difference between the two alternatives is the level of envelope insulation, and this thus has a great influence on the final results. However, this point will be addressed in the following section.

Table 7.4. Environmental impacts and embodied energy of the renovation proposals assessed

		Conventional renovation proposal							ENERPHIT renovation proposal						
		ADP	AP	EP	GWP	OLDP	PCOP	EE	ADP	AP	EP	GWP	OLDP	PCOP	EE
Façade	Curtain wall façade	8.5E+01	9.3E+01	3.8E+01	1.5E+04	1.3E-03	4.1E+00	2.1E+05	5.2E+01	3.6E+01	4.1E+01	9.0E+03	9.9E-04	1.5E+00	1.5E+05
	Brick façade	6.6E+01	3.6E+01	3.5E+01	1.2E+04	1.1E-03	1.8E+00	1.6E+05	8.7E+01	5.9E+01	7.0E+01	1.5E+04	1.7E-03	2.6E+00	2.4E+05
	Prefabricated concrete façade	1.1E+02	6.1E+01	6.1E+01	2.0E+04	1.8E-03	3.2E+00	2.7E+05	1.6E+02	1.1E+02	1.3E+02	2.8E+04	3.1E-03	4.8E+00	4.6E+05
	Windows	7.8E-01	1.2E+02	2.7E+01	2.4E+04	1.1E-03	7.3E+00	4.7E+05	8.5E-01	1.4E+02	2.9E+01	2.9E+04	1.3E-03	8.7E+00	5.6E+05
	Demolition	1.4E+01	2.1E+01	2.5E+00	1.7E+03	3.3E-04	8.7E-01	3.2E+04	1.3E+01	2.1E+01	2.3E+00	1.5E+03	2.8E-04	8.3E-01	3.0E+04
Roof	Inverted flat roof	2.0E+02	9.5E+01	7.0E+01	2.8E+04	2.3E-03	3.9E+00	4.9E+05	2.0E+02	1.3E+02	1.3E+02	2.9E+04	3.0E-03	4.3E+00	5.9E+05
	Deck roof (Occupied)	6.1E+01	4.5E+01	2.4E+01	6.6E+03	8.0E-04	1.3E+00	1.4E+05	4.9E+01	3.0E+01	3.2E+01	4.5E+03	7.3E-04	1.1E+00	1.5E+05
	Deck roof (Unoccupied)	-	-	-	-	-	-	-	6.3E+00	5.4E+00	4.9E+00	1.8E+03	9.2E-05	1.6E-01	1.7E+04
	Demolition	1.6E+00	1.3E+00	4.9E-01	2.3E+02	3.3E-05	5.2E-02	3.6E+03	1.6E+00	1.3E+00	4.9E-01	2.3E+02	3.3E-05	5.2E-02	3.6E+03
Floor	Slab-on-ground	-	-	-	-	-	-	-	3.7E+02	1.5E+02	1.1E+02	4.8E+04	2.4E-03	7.0E+00	8.7E+05
	Demolition	-	-	-	-	-	-	-	5.9E+01	5.4E+01	5.2E+01	2.0E+04	8.0E-04	1.4E+00	1.7E+05
	TOTAL	**5.5E+02**	**4.8E+02**	**2.6E+02**	**1.1E+05**	**8.7E-3**	**2.3E+01**	**1.8E+06**	**1.0E+03**	**7.4E+02**	**6.0E+02**	**1.9E+05**	**1.4E-02**	**3.2E+01**	**3.2E+06**

ADP: abiotic depletion (kg Sb eq); AP: acidification potential (kg SO2 eq); EP: eutrophication potential (kg PO4--- eq); GWP: global warming potential (kg CO2 eq); OLDP: ozone layer depletion (kg CFC-11 eq); PCOP: photochemical oxidation potential (kg C2H4 eq); EE: embodied energy (MJ)

Regarding the differences between the constructive solutions used in each proposal, the main difference is the inclusion of the slab-on-ground renovation. The insulation of the slab-on-ground was only included in the ENERPHY proposal, and its construction supposes 30% of the total quantity of insulation material in the ENERPHIT renovation. In the case that the slab-on-ground will not be insulated in the ENERPHIT project, the proposal will not fit with the technical requirements of the Passivhaus standard because the envelope has to be totally closed. Alternately, in the case of the curtain wall façade renovation, the conventional project has higher environmental impacts because this proposal substituted the tempered glasses and their metallic fixing. This substitution represents 10% of the total conventional renovation. As commented above, the ENERPHIT project considered the current glasses to be in good condition.

According to EN 15978, the environmental impacts of the decommissioning of the replaced components of the building have to be included in a renovation study. The contribution of decommissioning was higher in the ENERPHIT proposal because it included the renovation of the slab-on-ground. Meanwhile, the decommissioning represented between 1% and 10% of the total conventional renovation; the demolitions in the ENERPHIT renovation implied between 6% and 12% of the total environmental impacts. The façade and roof demolitions suppose similar environmental implications for all impact categories.

7.3.1.2. The contribution of insulation materials in the renovation proposals

As commented above, the most common passive solution in buildings increases the relevance of insulation materials with respect to the rest of the building materials. For that, the influence of the insulation materials on the environmental behaviour of the renovation proposals has to be observed. Table 7.5 shows the relation between the global impacts of each building renovation proposal and the impacts of their insulation solutions. Previously, Table 7.3 showed that the quantity of insulation material is more than 5 times higher in the ENERPHIT proposal than in the conventional proposal. If the contribution of the insulation material is calculated for each alternative, it can be noted that the contribution of insulation material to the global impacts is assumed to be between 10 and 27% in the case of the conventional renovation and between 28 and 47% in the case of the ENERPHIT renovation (Table 7.5). The intensity in the insulation of the building can be only valuated, knowing the energy saving. These data will be presented in following sections, and the adequacy of this alternative will be assessed.

Table 7.5. Comparison of the contribution of the insulation material in each renovation proposal

	ADP	AP	EP	GWP	OLDP	PCOP	EE
Conventional renovation	1.5E+02	7.2E+01	3.9E+01	1.5E+04	9.0E-04	4.6E+00	3.4E+05
ENERPHIT renovation	4.8E+02	2.4E+02	2.6E+02	4.5E+04	4.1E-03	1.1E+01	1.4E+06

> 40% of the global impact	25-40% of the global impact	10-20% of the global impact

Regarding the ENERPHIT proposal, the selected insulation material for the majority of the constructive solution was GW. Previous studies regarding the environmental performance of insulation material concluded that it has better environmental performance than XPS, EPS, PU and SW [188]. In the case of the conventional proposal, the insulation material most used was XPS, which also has good environmental performance but is not as good as GW. However, all of the most extended insulation materials are non-renewable, and this study considers it relevant to assess the combination of a passive standard of construction and an example of a renewable insulation material, in this case, cork.

7.3.1.3. The environmental performance of cork as thermal insulation

As commented above, cork is the renewable material most focused on in studies regarding the sustainability of different intermediate and final products [73,74,86,88,190], and the environmental performance of an insulation cork panel produced in the largest cork insulation board manufacturing factory in Catalonia, Spain was recently assessed [203]. This study concluded that the use of natural insulation materials does not necessarily imply a reduction of environmental impacts, having higher impacts than the majority of the most common insulation materials. The main reason was the low technological development of the cork board insulation manufacturing process, and for that, this study proposed improvement strategies for throughout its life cycle to make a more efficient and productive product. These strategies were focused on cleaner production, in addition to the promotion of the acquisition of local raw cork to reduce the transport distance to the manufacturer because, currently, the majority of raw cork comes from an average distance of 800 km.

The present study also simulated the use of the described ENERPHIT proposal, using cork as the insulation material in each constructive solution described above. The environmental information was collected from the Sierra-Pérez et al. [203] study. Table 7.6 presents the total results for the ENERPHIT proposal but, in this case, using cork for the thermal insulation of the building envelope. It can be observed that the environmental impacts of the cork alternative are higher for the majority of the impact categories, including the embodied energy (EE). In the case of the GWP, cork doubles the results of the ENERPHIT with GW. Additionally, as commented above, the option that includes the biogenic carbon contained in the cork boards is also taken into account, decreasing by approximately 50% the CO_2 of the global building renovation. Alternately, the results for a more environmentally friendly cork board, following the improvement scenario proposed by Sierra-Perez et al., had also been simulated to assess the potential for improvement. This option is equal to ENERPHIT with the GW option in the majority of the impact categories; ADP and EP have better results. If the biogenic carbon is included in the analysis, the global result of the building renovation, in kg of CO_2 –eq., is negative; that implies that the ENERPHIT project combined with improved cork boards can help to mitigate climate change. Regarding this, Sierra-Pérez et al. [203] had already discussed different end-of-life scenarios of cork insulation boards, concluding that cork insulation board will store the carbon dioxide indefinitely if the product is recycled for the manufacturing of another product with a lifespan of 50 years.

Table 7.6. Environmental impacts and embodied energy of ENERPHIT proposal combined with different cork alternatives

	ENERPHIT renovation							
	ADP	**AP**	**EP**	**GWP**	**GWP***	**OLDP**	**PCOP**	**EE**
Insulation Glass Wool (GW)	1.0E+03	7.4E+02	6.0E+02	1.9E+05	-	1.4E-02	3.2E+01	3.2E+06
Insulation cork board (current manufacturing)	5.5E+02	1.4E+03	6.0E+02	3.5E+05	1.9E+05	4.3E-02	6.4E+01	5.5E+06
Insulation cork board (improved manufacturing)	5.5E+02	1.4E+03	5.5E+02	2.1E+05	-4.0E+03	2.1E-02	6.2E+01	3.2E+06

* Includes the biogenic carbon contained in cork boards

7.3.2. Energy and environmental benefits in the operational phase

This section presents the results of the operating energy of the building from the real measurements carried out in the building for its current use and also the results of the simulations for the renovation proposals, including ENERPHIT with cork (Table 7.7). The operating energy is expressed in terms of heating and cooling. It can be observed that the heating energy decreases drastically with respect to the current state of the building for all proposals. The convenience of renovating Spanish buildings built before 1980, when the building rules did not require insulation, can be shown. Currently, the operating energy for heating is 641,287.9 kWh/year, while the operating energy for conventional and ENERHY renovation is 190,864.2 and 43,429.9 kWh/year, respectively. This supposes a reduction of 70% and 93% for conventional and ENERHY renovation. In the case of cooling energy, the results for operating energy are higher for both renovation projects with respect to the current state of the building due to the reduction of the natural ventilation of the building, as its insulation and sealing have been increased. This is because it has not included the mechanical ventilation system with heat recovery in the building renovation, as the regulation requires. If the building facilities had included it, ENERPHIT would require a more efficient system of heat recovery than conventional renovations. Currently, the operating energy for cooling is 36,603.5 kWh/year, while the operating energy for conventional and ENERPHIT renovation is 75,718.0 and 96,511.0 kWh/year, respectively. This represents an increase of 106% and 160% for conventional and ENERPHIT renovation. Moreover, the cork alternative for the ENERPHIT proposal is also assessed, resulting in higher energy savings than the conventional and ENERPHIT renovations with GW insulation.

In global terms, the months of heating per year are from October to May, and the months of cooling are only June and July (not including August, which is a summer holiday month). For that, the importance of the reduction of the operating energy for heating is more significant for the energy savings. In this case, the energy savings are very relevant for both renovation proposals, decreasing the operating energy by 60.7% and 79.4% for the conventional and ENERHY renovations, respectively. For the alternative of the ENERPHIT renovation, using cork as an insulation material, the percentage of energy savings is slightly higher than that of the ENERPHIT renovation with GW, 80.4%. In the case of heating, the two alternatives of the ENERPHIT proposals have similar results, and the difference may be due to the adjustment of the thickness of the insulation boards. Regarding cooling, the differences are greater, and the reason could be the thermal inertia of cork, as the curtain wall concentrates high temperatures in summer and cork prevents its transmission into the building.

Otherwise, the good thermal properties of cork, thermal insulation and thermal inertia, can be fully exploited in buildings with less intensive construction solutions. In the case study, two double brick walls and external claddings with an excessive overall thermal inertia composed all façades. For instance, if cork composed envelopes with a light structure, such as wood, the influence of cork on the operating energy would be higher. This could be an important advantage of cork over other insulation materials.

Table 7.7. Operating energy and energy saving of the renovation proposals assessed

	Operating energy (KWh/year)		Energy saving	
	Heating	**Cooling**	**KWh/year**	**%**
Current building	641,287.9	36,603.5	-	-
Conventional renovation	190,864.2	75,718.0	411,309.3	60.7%
ENERPHIT renovation (GW)	43,429.9	96,511.0	537,950.6	79.4%
ENERPHIT renovation (Cork)	45,195.4	87,487.6	545,208.5	80.4%

Energy savings also implies a reduction of environmental impacts related to the energy generation. In the case of the heat production, the General Military Academy, where the building is located, hosts a small thermal power plant that uses a diesel boiler for heating production. In the case of the cooling production, electricity is used. Table 7.8 shows the environmental impacts avoided for energy savings. In the following section, the environmental impacts produced and avoided in the renovation practices will be compared.

Table 7.8. Comparison of embodied energy and environmental impacts with energy saving per year and renovation impacts payback for each proposal of renovation

		ADP	**AP**	**EP**	**GWP***	**OLDP**	**PCOP**	**EE**
Conventional renovation	Embodied energy and environmental impacts	5.45E+02	4.76E+02	2.59E+02	1.08E+05	8.73E-03	2.26E+01	1.77E+06
	Energy saving	8.96E+02	2.42E+02	1.25E+02	1.33E+05	2.25E-02	1.42E+01	1.47E+06
	Renovation impacts payback (years)	0.6	2.0	2.1	0.8	0.4	1.6	1.2
ENERPHIT renovation (GW)	Embodied energy and environmental impacts	1.01E+03	7.41E+02	6.01E+02	1.87E+05	1.44E-02	3.24E+01	3.23E+06
	Energy saving	1.16E+03	2.96E+02	1.62E+02	1.73E+05	2.95E-02	1.79E+01	1.92E+06
	Renovation impacts payback (years)	0.9	2.5	3.7	1.1	0.5	1.8	1.7
ENERPHIT renovation (Cork)	Embodied energy and environmental impacts	5.47E+02	1.41E+03	6.04E+02	1.89E+05	4.31E-02	6.41E+01	5.52E+06
	Energy saving	1.19E+03	3.23E+02	1.66E+02	1.77E+05	2.98E-02	1.89E+01	1.95E+06
	Renovation impacts payback (years)	0.5	4.4	3.6	1.1	1.4	3.4	2.8

Units of impact categories: ADP (kg Sb eq); AP (kg SO2 eq); EP (kg PO4--- eq); GWP (kg CO2 eq); OLDP (kg CFC-11 eq); PCOP (kg C2H4 eq)

* Includes the biogenic carbon contained in cork boards

7.3.3. Embodied energy and environmental impacts vs. energy savings

The environmental impacts derived from the different renovation proposals can be balanced with the environmental benefits of the energy savings. Generally, the embodied energy and environmental impacts of a building have to be assigned to the lifespan of the building after the renovation, in this case 50 years. However, Table 7.8 shows that the majority of the total impacts produced by the renovation project can be compensated by the energy savings during the operation phase in less than two and a half years, assuming 5% of its lifespan. Some impacts have a maximum payback of 4 years and 3 months in the ENERPHIT proposal with cork. If the embodied impact is divided into 50 years, the energy savings per year will be much larger than the embodied energy each year.

Regarding the different renovation proposals, the conventional renovation produces less environmental impacts and embodied energy but also generates less energy savings. For that, its renovation impacts payback is not much lower than that of the ENERPHIT renovation proposal, having similar magnitudes for ADP, GWP, OLDP and EE. It can be noted that, the lower the operation energy, the higher the embodied energy. If the results are compared for the total building lifespan (50 years), it can be observed that the final balance of energy savings for the ENERPHIT alternative is 30% better than the conventional proposal (Table 7.9). If the energy savings are translated in monetary terms, the economic savings for ENERPHIT are greater than that of the conventional proposal by approximately €2,000,000.

In the case of the ENERPHIT renovation with cork, the payback is higher than the ENERPHIT with GW option, except for EP and GWP, which have similar results. In the case of ADP, the payback time is lesser. The results of the final balance of energy savings for the total building lifespan are similar for both GW and cork. With the current conditions of cork board manufacturing, cork is not a good option for actual building renovation due to its embodied impacts. In the operating phase, cork has good behaviour due to its good thermal inertia, mostly in the summertime. However, its environmental and energy implications are also relevant and are not compensated by its advantages in the operating phase. According to [203], as a competitive insulation material in the building sector, the cork sector has to implement an overall improvement strategy and a series of eco-design strategies throughout the product's life cycle and manufacturing process. If the manufacturing improvements commented above were included, renovation with cork would reach the results of the GW option; thus, cork insulation products present ample room for improvement.

Table 7.9. Balance of the different proposals for energy saving of the building lifespan

	Total embodied energy (MJ)	Energy saving for 50 years (MJ)	Balance in 50 years (MJ)	Balance in 50 years (€) *
Conventional renovation	2.0E+06	7.3E+07	7.1E+07	6,532,000
ENERPHIT renovation (GW)	3.2E+06	9.6E+07	9.2E+07	8,464,000
ENERPHIT renovation (Cork)	5.5E+06	9.7E+07	9.2E+07	8,371,000

* The energy price was obtained from the data of the Spanish Statistical Office for 2015 (0.092 €/kWh)

In summary, the ENERPHIT proposal with GW allows for the attainment of more energy savings despite generating a significant increase in environmental impacts and embodied energy; however, these are compensated within a reasonable period of time, and the final balance for the total lifespan of the building is better than for the conventional proposal. In future research, it would be interesting to extend the scope of analysis to building facilities. In the case of ENERPHIT renovation, the heating and cooling systems are not required, but on the contrary, the heat exchanger will be installed with water coil support. Moreover, the economic factor should also be included to complete the variables to consider in making decisions regarding more efficient building renovations. This is because the cost of more intensive renovation proposals or the cork as an insulation material could influence the final decision.

7.4. Conclusions

The literature review showed various relevant gaps in the assessment of building renovations from an environmental perspective: comparison between different types of building renovations, i.e., low-energy buildings standards (ENERPHIT) and conventional projects; and the integration of the LCA methodology with thermal dynamic simulation to obtain more realistic results.

The most significant conclusion is the convenience of the renovation of Spanish buildings built before 1980, when the building rules did not require the insulation of buildings. Both renovation proposals achieved great energy savings, decreasing the operating energy by between 60% and 80%. On the one hand, the conventional renovation project supposes less embodied energy and environmental impacts but also generates less energy savings. On the other hand, the ENERPHIT renovation alternative supposes an increase of the quantity of insulation material with respect to the current insulation systems and also an increase of the embodied energy of the building, but it does avoid impacts due to the reduced building energy consumption, achieving an operational energy savings of approximately 80%. Moreover, the environmental implications for the material placement are compensated in a reasonable period of time for both proposals, over 2 years in the majority of proposals and impact categories, supposing 5% of the building lifespan. For the total building lifespan, the energy savings for the ENERPHIT alternatives are 30% better than that of the conventional proposal.

In summary, the lower the operation energy, the higher the embodied energy; it is closely related to the quantity of insulation material, which has a determinant role in the actions of building renovations. However, to be more coherent with the aims of low-energy building standards, materials with the least carbon and energy contents should be selected, in this case cork. The current products made of cork do not fit the requirements to compete with the most common insulation material because it does not imply better environmental performance of buildings. However, cork insulation products present ample room for improvement, as shown by simulations of the proposed strategies throughout their life cycles, and could become more efficient and productive products.

PART V

THE POSSIBILITIES FOR DIVERSIFICATION OF THE CORK MARKET BASED ON ECO-IDEATION TECHNIQUES

Chapter 8

INTRODUCING ECO-IDEATION AND CREATIVITY TECHNIQUES TO INCREASE AND DIVERSIFY THE APPLICATIONS OF ECO-MATERIALS: THE CASE OF CORK IN THE BUILDING SECTOR

8. Introducing eco-ideation and creativity techniques to increase and diversify the applications of eco-materials: The case of cork in the building sector

This chapter is based on the following published paper:

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Abstract

Cork is an eco-material that has recently been attracting growing interest due to the expanding strategy of sustainable product design, which aims to replace non-renewable materials in the building market. Until now, the cork sector has not taken advantage of the properties of this material and has been fully oriented towards traditional applications such as stoppers for wines and other beverages. The diversification of the cork market, through developing new products with higher added value, is the reason why eco-ideation (using different creativity techniques) can be helpful in creating new products and solutions.

The process of introducing eco-ideation was carried out during two interdisciplinary creative sessions and a product design stage. The results of the process were successful in terms of participation and the quantity and quality of ideas, which were characterised by searching, experimentation, participation and knowledge sharing. The versatility of cork fits perfectly with the creative methods of eco-ideation, as cork's good physical properties allow the diverse generation of new ideas for both applications and markets. The concepts generated in this study are in line with the approach of recognising cork's status as a natural, pure and noble material, taking advantage of the good properties of cork, and giving buildings unique traits due to the singular aesthetic of cork.

Keywords

Eco-design, eco-innovation, creativity, cork, building materials.

Highlights

- An eco-ideation process was carried out to develop new concepts of cork products.
- The results of the process were successful in terms of participation and the quantity and quality of ideas
- The versatility of cork fits perfectly with creative methods due to cork's good physical properties
- It is necessary to recognise cork's status as a natural, pure and noble material

PART VI

DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH

Chapter 9

DISCUSSION

Chapter 9 introduces an integrated discussion about different parts of the dissertation, to interrelate the specific findings between them. Part II to V are related to different topics but with the same common denominator: to develop an interdisciplinary methodological framework that facilities the introduction of eco-design for the diversification of cork.

9. Discussion

9.1. Competitiveness challenges in the Iberian cork sector

The initial part of this dissertation has shown a broad picture of the current situation of the Iberian cork industry, identifying the concentration of the cork market as a supplier of closures to wine and champagne sectors. For nearly three centuries, cork has been used to seal bottles of wine. Since the 1970s though, other forms of closures such as screw caps, plastic seals and metallic stoppers have compromised that dominance. However, none of them can match the features of natural cork; and cork is still considered the favourite material for reserve wines and wines that need to age in the bottle [71]. But cork presents some weakness in this market. On the one hand, cork replacement materials, plastic or aluminium, have a significant current market score. On the other hand, cork is exposed to currency fluctuations of a unique sector, so the short-term difficulties related to productivity or particular problems affect this secondary sector. So it is necessary to minimise excessive concentration in the wine market, because the relationship between cork and wine has been very beneficial so far, and it will continue to be so in the future; but focusing sector's strategies to manufacture low-cost products, with low quality and price; it should not be the future. It is very important to innovate and dedicate resources for R&D for new horizons to reduce its weakness.

As possible solution to this weakness, this dissertation identified market diversification of cork products beyond closures, producing more attractive products that generate more wealth. As noted in Chapters 3 and 8, Portugal has opted for a more profitable and effective strategy than that in Catalonia. It has carried out several initiatives, in both the public and private sectors, which have generated higher rates of added value for the market's products, including the eco-design of new products. For that reason, more research and development initiatives emerged, which have promised to turn the Portuguese cork sector in the most dynamic and advanced cork industry in the Iberian Peninsula and in the world. This shows the potential of eco-design for generating new products, new business, new employment opportunities in rural areas, less dependence on wine sector, etc. But this challenge must be addressed to ensure its overall sustainability. Moreover, Portugal has adopted cork as its national material, using it in the construction of Portuguese Pavilion in some international exhibitions such as Shanghai. In the Spanish case, cork is not considered a national own material, despite having a significant area of cork oak forest. This dissertation has therefore addressed this issue from three different approaches.

First, the great potential of cork to occupy the appropriate status as a noble and natural material, as in the wine and champagne sector, should be highlighted. But this status has to be extended to other markets where cork is currently a second-class material, such as building or some home and office accessories. Moreover, cork is currently used a secondary component of a main product, as a stopper for bottles, and it needs to become visible to be recognised as valuable material. But as commented in Chapter 8, its aggressive aesthetic could influence in the process of cork visibility, and the introduction of these products in the building market has to be accompanied by a strong component of aesthetic innovation and design that enhances their use.

Second, the cork sector has to take into account that the sustainability of cork needs to be fully exploited. The inherent sustainability of cork, as a natural and forest-based material, is not enough for the convenience of its use elsewhere. In other words, its use, as the main material of an end product, does not imply necessarily that the product is environmentally sustainable. Currently, finished products incorporate environmental impacts and energy at each link of the value chain. That is normal in any material transformation process, but in the case of eco-materials, these embodied impacts do not necessarily have to compromise the competitive advantages of the material. Moreover, there are many cork waste and by-products that are not being used, or used for products without added value, which should evolve into more interesting products given that the properties of cork are unique.

For that reason, the baseline scenario and the potential for improvements have to be known when deciding whether to select the material for the required functionality and also its environmental appropriateness. As pointed out during the dissertation, previous studies has already analysed the environmental performance of cork in a market when it co-exists with other non-renewable materials, mainly in Portugal [81–83] and Spain [73,74,86–88]. The present dissertation has continued this environmental approach and is extended to areas that were indicated for future research in this study: new potential cork products with a greater added value.

Moreover, the use of forest-based materials contributes to environmental sustainability as a result of their biogenic carbon content, which is fixed by the tree. This can help to mitigate the global warming potential for their ability to store carbon dioxide temporarily or even indefinitely. Nowadays, this is highlighted as probably one of the most important benefits of the use of eco-materials instead of non-renewable materials, but there is no consensus in the scientific field. Some authors consider that the claim that the storage of carbon in cork oaks can be allocated to cork products and that this gives these products a lower carbon footprint compared with competing products is difficult to uphold [275, 276], so it has to be addressed more deeply to ensure that the hypothetical basic premises are true, and cork really helps to avoid environmental impacts. Additionally, cork not only has the advantage of being a natural material for many applications, but also can be recycled generating other products or even produce energy [88].

Third, the promotion of cork should also have a positive impact on society. The social vector is a significant part of the cork sector because, on the one hand, the majority of cork oak forests are located in rural areas, mainly in the southern areas of the Iberian Peninsula, which have poor economic situation and high rate of unemployment. On the other hand, the increased use of cork leads to an increase in the cork oak forest needed, which would increase the existing surface area. As commented in Chapter 2, that fits in with Europe 2020 and the overall Common Agricultural Policy, and three long-term strategic objectives can be identified for EU rural development policy in the 2014-2020 period: namely improving the competitiveness of agriculture, the sustainable management of natural resources and climate action, and the balanced territorial development of rural areas. But, this thesis has limitations and it does not include an exhaustive analysis of the social implications of the promoting of cork use in building sector. It is proposed to extend the social implications of the diversification of cork market in future researches. Including, in addition to the rural areas where cork oak forests are located, workers, who manufacture the proposed new products, and consumers who will buy and use them.

9.2. The contribution of eco-design to the widespread use of cork

The Catalan cork sector has begun to adopt a culture of sustainability starting from studies in 2008 but it is still not carrying out eco-innovation processes. As noted before, this thesis has continued previous studies, developing eco-innovation strategies proposed to identify some weaknesses related to the sustainability of their processes. But compared with Portuguese cork sector, this has been an isolated case, because the sector still does not have a broad experience in eco-design activities. The use of LCA methods in Portuguese sector is more extended and hosts more experiences than Spanish sectors but on the other hand some projects, based on design intervention, have been developed and as commented in Part IV, have resulted mainly in products of formal nature. But these proposals did not follow eco-design methodology in a comprehensive way. The whole life cycle of new products did not take into account; for instance, the fact that the proposed products had intensive manufacturing processes. Moreover, this methodology could be applied to re-design existing products in order to add value.

The cork sector has to introduce innovation in the entire sector, from an increase in production efficiency to the creation of innovative products, including many different sectors: forestry, industrial, market. For that reason, the majority of innovation measures have to take into account this globalism. For example, the increase in production efficiency has to include every stage from the production of raw cork to the manufacture of end products. In this regard, the cork products that currently appear on the market have to be manufactured using the existing manufacturing technologies and they have to be adapted to them. These processes are designed for the manufacture of stoppers, and other different products have to be adapted to the current manufacturability, limiting their creativity to the current technology. So the ideas and design of new products have to take into account that these concepts should be used as a combination of 'technology pull' and 'market push' instruments (Figure 9.1). On the one hand, the need to produce a specific product in an efficient manner should lead the cork industry to develop new manufacturing technologies and processes or just adapt the existing ones, so it does not necessarily imply high investment in R&D. The emergence of new concepts of cork production with improved required technical performance or different shapes that currently can be achieved using current processes, must serve as a technical challenge to be achieved. On the other hand, the emergence of new products made of renewable materials in markets where their use is not very common may generate the need to boost the emergence of a greater variety of products and the inclusion of other renewable materials. But this boost should be supported for the good performance of these products in terms of functionality and aesthetics.

Figure 9.1. The role of the product design in the cork sector to combine "technology pull" and "market push"

Regarding the cork products for building, the construction sector has traditionally used cork in a limited way due to its low production and high price. This thesis reveals that technologies used in the cork industry are not environmentally suitable at the baseline scenario in the case of the current building insulation sector. As noted, the manufacturing processes of cork insulation products commit their environmental sustainability, although being simple products with a highly intensive use of raw material. In current conditions, cork does not have a great competitive advantage over common non-renewable insulation materials. Due to the importance of insulation materials in the life cycle energy of construction it is necessary to promote the use of insulation materials of renewable origin and low carbon and energy content. Furthermore, the main application of cork insulation products is focused on residential buildings and is commonly applied as a solution. These construction solutions have usually a huge quantity of layers in their composition, and one of the most valuable properties of cork, its thermal inertia, has not been fully exploited. Moreover, the cork can be used in combination with other natural materials, such as wood, to develop other types of products for buildings or any other sector. Finally, cork is not intended to be used widely in buildings, because the availability of cork elements produced in order to be used in construction is rather low.

The eco-ideation process carried out during this PhD has identified other ways of use cork in building, exploring other possibilities for cork beyond its use as insulation material in residential buildings (Figure 9.2). The main premise of the resulting ideas was to make cork visible, without hiding it inside façades and roofs. The approval of the cork use must include the accepted perception of cork as a noble material and the equalisation of cork with other natural materials used in architecture, with emotional and philosophical connotations. Moreover, the convenience of using cork in buildings is not only due to being a natural and renewable material, but also because of its favourable physical properties. For that reason, both have to be highlighted. In addition to its good thermal insulation other valuable properties, have been identified: it is permeable to water vapour, it has a good lightness-impact strength relationship and it is resistent to climatological phenomena. The proposed concepts put these properties in place and aim to provide other values for cork, with a view to ensuring that cork is not typecast. In fact, the objective of this thesis is to show the great potential of cork initially and that in the near future may be other similar initiatives.

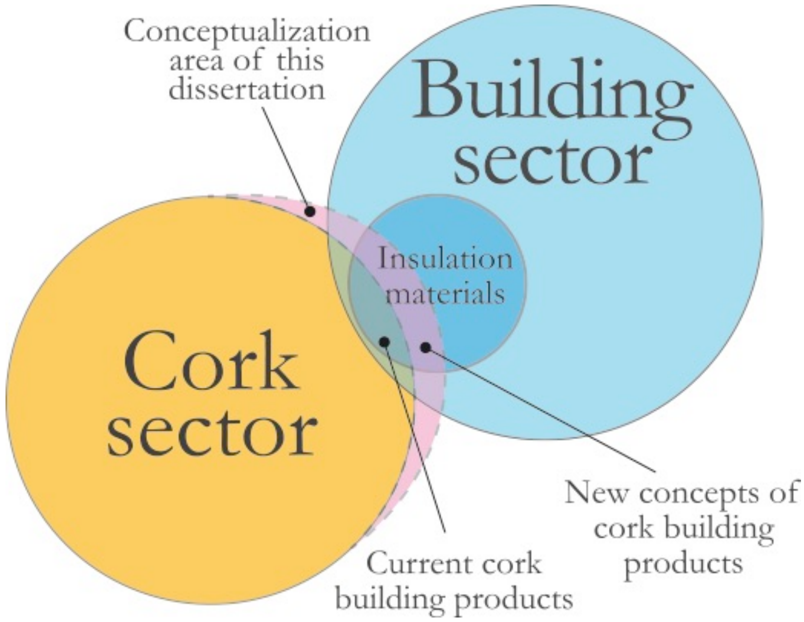

Figure 9.2. Scheme of the scope of the thesis between cork and building sector

This thesis has introduced the use of creative techniques and eco-design methodology for thinking up new products but placing the material and its physical properties as the central point. In this regard, cork has shown great potential for application in the different techniques used during the creative process. The proposed concepts indicate an example of ways in which cork can be used in buildings, beyond its current uses. Mainly, the concepts were the result of finding as solution to identified problems, and cork was proposed to solve them because of its physical properties. The positive and various physical properties of cork given creativity major avenues to finding possible ideas for products. Creative processes for generating new product ideas obtain more satisfactory results in the case of a versatile material. Moreover, the novelty of the application of cork in different markets contributed to the diversity and creativity of results [85]. In addition, creativity was also applied in the techniques selection and their hybridization, always bearing in mind the participants' profile and the initial information, besides the maximising of concepts. The positive response from participants suggests that in the sector more initiatives like this could be undertaken, and will be open to improving their competitiveness through eco-innovation.

After the development of the first product ideas such as cork could be used in the construction beyond the way currently used, the next step will be to develop these ideas physically involving different stakeholders. The development of prototypes will be the necessary next step for checking the functional performance of each concept. For that reason, previously, it should establish a close partnership with a manufacturer and researchers in the industry to investigate different areas of interest; among them the treatments for controlling the colour change of cork when is installed outside, alternatives surface finishing and manufacturing possibilities and the stability of large format boards. But as commented in the previous section, the cork industry also has to invest in the R&D of manufacturing technologies, to extend its productive capabilities.

9.3. The role of LCA in the environmental assessment of buildings

The incorporation of energy efficiency in the operation of buildings has increased the importance of embodied energy. For that reason it is important to quantify the energy and environmental impacts of the common materials and constructive solution used in buildings. Moreover, analysis of the operating energy and embodied energy does not need to be done separately, but in an integrated manner. In this way, it will enable optimisation of the design proposal in order to install the lowest quantity of materials to obtain he maximum energy saving. For that reason, the integration of LCA and thermal dynamic simulations proposed in this thesis allows more realistic results for decision-making to be obtained. So far, both methodologies have been applied individually, and as seen in the thesis, the results obtained have great importance in the decision-making process.

As seen throughout this study, the influence, in energy terms, of insulation materials is high. On the one hand, they facilitate the maintenance of indoor comfort in buildings. On the other, they represent a significant part of the total energy and impact sequestered in construction. For that reason, in the future they should represent one of the priorities for research in the building sector. As commented in the thesis, the importance of natural materials in building has increased recently due to the interest to construct in a more sustainable way; using local material with low transformation processes associated to them. In this regard, one of the objectives of this thesis was to extend knowledge about this kind of material to verify its suitability for insulation in buildings. And in the case of cork, it was found that the current cork building products and the related manufacturing processes have not yet achieved the required level of sustainability. This opens up a broad spectrum of possibilities for improvement, and as discussed in Chapter 4, there is great potential for improvement in terms of energy.

Furthermore, the location and the related climatic conditions are key in the design of buildings, and as commented in Chapter 6, the selection of insulation material and construction solutions are highly dependent on the climate zone where the building will be constructed. For that reason, the results of environmental studies on buildings have an important geographical component, and therefore they cannot be extrapolated directly. In this sense, few studies have been focused on Mediterranean climates and, for example, the studies carried out on low-carbon buildings were located in northern Europe countries. This thesis also intended to fill this gap, and compared a conventional project for building renovation with the Passivhaus proposal. Regardless of the economic variable, both proposals had similar environmental impacts and embodied energy payback; but the energy saving during the total lifespan of building was much greater in the case of the low-energy proposal. This may mean that the Passivhaus standards could also be useful in warmer climates.

Concerning the economic approach, assessment of the convenience of renovation practices presented in this thesis has been only concerned to environmental approach. And it was noted the need to extend this study first to an economic evaluation, to estimate the real situation of renovation projects. In this case the low-energy buildings were more feasible in terms of energy saving, but maybe the high cost of their construction would reduce that feasibility.

Regarding the social approach, the renovation practices used in the old Spanish building stock should include their appropriateness for inhabitants: whether they fit in with their lifestyles, priorities and needs. Renovation proposals are usually only addressed in energy efficiency terms, increasing the insulation of buildings and improving their accessibility. But the renovation of these obsolete buildings is also related to low-income and disadvantaged communities. That makes the issues involved more vast and complex, so a more consistent and wide approach is needed.

Moreover, the incorporation of a social approach in the assessment of buildings should be addressed on an urban scale. The sustainability of cities has been defined by quantitative studies usually assessing the urban metabolism (UM) as a global system in terms of buildings, energy, food, green spaces and landscape, mobility, urban planning, waste and water [283]. All of these vectors are related to society, and buildings are not isolated, but they interact with each other and with the urban environment. The methodology for the environmental assessment of buildings presented can be extended to a neighbourhood or a city to evaluate the energy-saving practices using a more global approach.

Chapter 10

CONCLUSIONS AND FUTURE RESEARCH

Chapter 10 addresses the main research findings and formulates a list of general final comments, based on the objectives established and extended conclusions presented in Chapters 3 to 8, and the discussion presented in Chapter 9.

10. Conclusions and future research

10.1. Conclusions

The following section describes the main conclusions derived from the present dissertation. Methodological aspects will be presented and commented, and then cork sector, European building sector and potential of cork as building material findings will be outlined according to the objectives described in Part I.

10.1.1. Methodological aspects

The interdisciplinary methodology used in the thesis was found to be adequate, due to the achieved global scope by its economic, environmental and product design approach. From each part of the methodology, the following conclusion were taken:

a) From the production and trade analysis of a forest sector

- This dissertation has carried out an exhaustive analysis about the international trade of Iberian cork industry, the worldwide processor. This analysis identified the great importance of this trade with respect its home market, because the important relationship with wine and champagne sector, very international markets.
- This study has allowed to provide a snapshot of the sector and its subsector and being aware of its strengths and weaknesses; and taking into advantage of the large quantity of data and different database of international and national statistical offices. It has also allowed to see differences between the same sector but in different countries and see how competitive are in each one.
- The present dissertation has also included a comparison between different available trade databases; concluding that data generally exhibit similar trends, although there are some fluctuations in one of the databases. This database was discarded because it does not provide an assessment of the reliability of an entire database or of individual data points.

b) From the LCA methodology

LCA was a very good sustainability tool to assess the cork insulation board and the insulation systems of insulation in buildings. It is recommended for future sector assessments. The main contributions of the present thesis associated to LCA were:

- The data collection process has resulted appropriate. As the information requested was very detailed, results and conclusions were very interesting. Otherwise, the degree of detail also translated into greater complexity of research, and in particular the calculations became more difficult and required more time and effort.
- One of the most important methodological contributions has been that the environmental implications of the use of cork as insulation material have been assessed, and the knowledge about the topic of the use of natural materials in building sector has been expanded.
- With regard of the constructive systems, LCA has been widely used for their environmental assessment; but the integration with the thermal dynamic simulation would extend its use in other research field, such as energy efficiency.

- The enlargement of the system boundaries in the case of buildings has been relevant, because the inclusion of the installation, use and end-of-life phases provides more relevant information to decision-making during the design and selection of materials and constructive solutions.
- This dissertation has introduced the quantification of embodied energy of insulation materials by means of LCA methodology, a topic with an increasing interest due to the minimising of the operating energy of buildings. And as pointed other authors, the embodied energy is not irrelevant, especially considering energy policies focusing on energy efficiency during use of buildings.
- The comparison between different LCA methods has shown the need of assessing the incorporation of additional impact categories in the next updates of the standard EN 15804.
- This dissertation has concluded the suitability of the life cycle thinking for the convenience evaluation of design proposal for building previous to its construction, both in the case of building materials and entire buildings. Moreover, in addition to the environmental approach, the economic and social ones should be addressed in future research.

c) From the Dynamic thermal simulation modelling of buildings

- The integration between LCA methodology and the thermal dynamic simulation has identified as suitable in the energy characterization of buildings. The environmental implications of the installation of additional building materials for increase the thermal insulation of building envelope has taken into account in the final balance. So it allows obtaining more realistic results.
- Moreover, in the literature review, it was identified a lack of studies that combine these two methodologies in the building renovation, and that also compares conventional proposals with low-energy proposal for renovation. This dissertation fills this gap and opens a door for future researches about the assessment of design building's proposals from a more realistic view.

d) From the generation of alternatives and concept selection

- The creativity workshop has been considered successful in terms of participation, and the quantity and quality of ideas; placing the experts in a favorable situation for creativity due to both the very different of their daily work and the interchanging of knowledge among other specialists with different expertise.
- Hybridization of creative techniques has enabled the adjustment of methods to the needs of the workshop, objectives and participants, to get the most out of each session.
- The versatility of cork has fitted perfectly with the creative methods of eco-ideation due to its good and varied physical properties that supposes a material with a combination of properties highly valued. For that, the generation of new ideas was more dynamic, extensive and diverse.

10.1.2. Economic characterization of the Iberian cork sector

The Iberian cork sector has been assessed from an economic approach, analysing its international trade and its production. The main findings are:

- Iberian Peninsula hosts most of the world's cork oak forests and cork processing industries, consolidating its hegemony despite the economic crisis that Iberian countries have suffered. Moreover, the Iberian Peninsula is the epicentre of the worldwide cork market.
- Portugal is a producer and a processor of raw cork, acting as a leader in the global market and acting as a very powerful industry. The Spanish cork industry is based on raw material and half-manufactured cork. Catalonia is an exception because it is the global leader in the champagne stopper market.
- Spain and Catalonia must improve the forest management of cork oak forests, because the lack of forest management in Spain; for example in Catalonia, 50% of Catalan cork oak forests are not managed in any way.
- The cork-manufacturing industry can play a crucial role in Iberian cork development, generating the development of different links in the supply chain, stimulating the development of rural areas where cork is the primary economic activity, with the establishment of companies that process the raw materials and providing employment opportunities.
- The primary weakness identified for all sectors is the excessive concentration of the cork sector in the wine market. Therefore, there is a potential opportunity for improvement through the diversification of cork products.
- The cork sector in the Iberian Peninsula should increase the investment in R&D and innovation for long-term strategies, taking into account the characteristics of renewable and non-infinite resources and its slow growth. Moreover, the development of new products should strengthen the sustainability and eco-efficiency in every link of the supply chain, and not only as an inherent attribute of cork material.
- Improving the forest management would increase the quantity and the quality of the extracted cork. The increased cork quality will improve the performance of the cork-manufacturing products, and the availability of higher quantity raw materials will ensure a supply for the cork-manufacturing industry.

10.1.3. Environmental aspects of building sector

The LCA methodology has used to assess different constructive systems as well as to analyse the convenience of the energy renovation of a building case study. The main outlines are described:

- The simplest construction systems suppose less embodied energy and environmental impacts but also their performance during use is less. That is, the lower the operation energy, the higher the embodied energy; it is closely related to the quantity of insulation material, which has a determinant role in the actions of building renovations.
- The environmental assessment of buildings has revealed the high importance of the selection of insulation material due its influence both in the embodied impacts and the operating energy. The most influential factors were the climate conditions where the building is located and the composition of the constructive system.

- The low-energy renovations suppose an increase of the quantity of insulation material and, indeed the embodied energy, with respect to conventional systems. But it does avoid impacts due to the reduced building energy consumption, achieving an operational energy savings of approximately 80%, and obtaining environmental impacts paybacks similar to conventional renovation.
- In the case of the renovation practices, the renovation achieved great energy savings, decreasing the operating energy by more than 60%. The environmental implications for the material placement are compensated in a reasonable period of time for both proposals, over 2 years in the majority of proposals and impact categories, supposing 5% of the building lifespan.
- This dissertation has identified the necessity of updating the standards related to the environmental assessment of building: EN 15805 and EN 15978. The reference impact categories have to be extended to other such as: land occupation, freshwater and marine eco-toxicity, human toxicity and also the particulate matter formation; due to their relevance in the case study under assessment.

10.1.4. The adequacy of cork as building material

This dissertation has assessed the adequacy of cork as insulation material regarding environmental aspects and the potential uses of cork in buildings.

a) Environmental aspects

- Nowadays, the current insulation cork products do not fit the requirements to compete with the most common insulation material (EPS, XPS, SW, MW), because supposes more environmental impacts for the majority of the impact categories and also is an expensive alternative. So the use of natural insulation materials does not necessarily imply a better environmental performance in buildings, and the sustainability of natural materials has to be reinforced by its products.
- The most influential inputs in the life cycle of the cork insulation board discussed in this dissertation are transport and energy consumption (electricity and diesel) in the granulation and agglomeration processes.
- The manufacturing processes should be made more efficient and productive to increase the competitiveness of the product. The product design should be improved to help increase its market share. Moreover, it has to promote the acquisition of local raw cork to reduce the transport distance to the manufacturer
- But the cork insulation products present an ample room for improvement, as shown by the simulations of the proposed strategies through its life cycle to make more efficient and productive product.
- The inclusion of biogenic carbon in the environmental assessment of forest-based building materials improves the GWP results considerably. However, it is very important to analyse how this biogenic carbon is calculated and how the product is managed after its lifetime, because there is a scientific debate about this issue. For the majority of the end-of-life scenarios proposed in the study, the biogenic carbon helps to mitigate GWP caused by the boards' manufacturing. Current standards are unclear and do not allow consider biogenic carbon fixed in the product if it is not shown that its use will be for

a long time. But even in short cycles, renewable materials contribute to fixing CO_2, while non-renewable materials would never be fixed, or short periods.

- The low-energy buildings should take into account, in addition on the energy efficiency during the use, the incorporation of renewable materials with low carbon and energy contents. The development of cork building products with a high efficiency during their manufacturing could be been included in these low-energy buildings.

b) Potential uses of cork as building material

- The objective of this diversification is not to substitute cork for common insulation materials but to develop a new range of insulation products at a high level. The potential for substitution in volume terms is very low but from a market view is high. In this regard, cork can substitute for other materials, not only for insulation materials but also for external cladding on buildings.
- The concepts resulted in this study are in line with this approach, being an example of the sincere use of the material, taking advantage of the good properties of cork and giving to the building a unique aspect due to the singular aesthetic of cork.
- After the conceptualization and selection, the new ideas of products are going to develop to satisfy market and manufacturing requirements. Nowadays the cork industries present limitations in their manufacturing technologies, so they should invest in improving their productive capacities.
- The promotion of cork in the building market has to be set by recognising the cork status as natural, pure and sincere material, which currently does not correspond with its status in the wine sector, where cork is known to be the finest material for stoppers.
- The introduction of these products in the building market has to be accompanied by a strong component of aesthetic innovation and design that enhances their use, and not only for the most eco-friendly professionals. This requires an important investment in design or eco-design, taking into account environmental criteria; proposing new designs that improve and update current manufacturing processes, which are characterised by low technological development.
- The proposed concepts, as examples of this philosophy, aim to respect and demonstrate the pureness of cork, placing directly cork into buildings without coverings that hide it.
- Some specific physical characteristics of cork, self-supporting, water vapour permeability and lightness, originate the most interesting concepts focused on the minimisation of materials use in the internal insulation systems or the treatment of moisture.

10.2. Future research

In this section, future research will be addressed.

According to the proposed concepts, it would be very interesting to follow the next steps for, finally, putting into market new cork products that diversify the cork market:

- A deeper development of the potential concepts of product, involving different stakeholders
- The manufacturing of prototypes will be the necessary next step for checking the functional performance of each concept.
- The establishment of close partnership with manufacturers and researchers in the industry to produce the new products.

The following methodological aspects are advised for research to complement the present thesis:

- To extend the scope of this dissertation to include the social vector of the cork sector. As commented above, the cork industry has important social implications, especially in rural areas.
- To include the economic approach to achieve a more realistic situation for the decision-making in the case of building renovation.
- To extend the scope of the studies to urban scale. Regarding this, during the dissertation period the opportunity has been given to work in other projects related to the characterisation of the energy efficiency level of specific urban areas and their building, using a geospatial model in combination with LCA to assess the environmental impact caused by the retrofitting of these buildings.
- To implement the integrated assessment of LCA methodology with thermal dynamic simulations in new buildings to compare different conventional and low-energy buildings in Mediterranean climate.
- Homogenise LCA methodology to compare reliably similar studies and inventories, because currently same products obtain different impact assessment and different system boundaries are taking into account.
- Developing the understanding of the biogenic carbon in the case of forest-based materials, because it is one of the most important benefits with respect of non-renewable materials.

According to the study of the cork insulation board, it would be very interesting to make an in-depth study of the following topic:

- Planning and evaluating specific cleaner production strategies. For this purpose it would be necessary to perform pilot experiments to compare two or more technologies for the operations of the manufacturing process with the highest impact. In this case, transport and energy consumption.

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APPENDIXES

This section includes the following appendixes:

- Appendix 1. Cork insulation board questionnaire
- Appendix 2. Supplementary information for Chapter 6
- Appendix 3. Supplementary information for Chapter 7
- Appendix 4. Supplementary information for Chapter 8

Appendix 1. Cork insulation board questionnaire

Appendix 1 presents the questionnaire that was used to collect data from the cork insulation board manufacturer. This questionnaire is based on the questionnaire developed by Jesús Boschmonart-Rives for the project "Environmental assessment of the Catalan cork sector" in 2011. This project was part of the development and design of an environmental calculator "CO2RK" by Inèdit Innovaciò S.L. The main advantage was that the questionnaire was very user-friendly, in that everyone could supply the requested information in her or his own way. On the other hand, flexibility meant subsequently working very hard to homogenize the data from every questionnaire in order to have the same units and a common reference for all the experimental samples studied.

INVENTARIO ACV
PANELES DE CORCHO

Inventario para 1000 paneles de corcho

DATOS DE LA EMPRESA

NOMBRE DE LA EMPRESA

CALLE

MUNICIPIO

CÓDIGO POSTAL

PAÍS

PERSONA DE CONTACTO

TELÈFON DE CONTACTO

EMAIL:

INFORMACIÓN DE MATERIAS PRIMAS

AÑO BASE DEL CÁLCULO

CANTIDAD ANUAL PANELES CORCHO PRODUCIDOS (en unidades)

CARACTERÍSTICAS DEL PANEL

Superfície (m^2)

Grosor (mm)

Densidad (kg/m^3)

Conductividad térmica (W/(mK))

A - TRANSPORTE DE CORCHO PARA TRITURAR

A1 - Carga/Descarga de vehículos				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**

OBSERVACIONES

A2 - Recorridos de los vehículos (camiones mat. prima)					
CORCHO DE ORIGEN FORESTAL: **bornizo, segundero, refugos, quemado, etc.**			**CORCHO DE ORIGEN INDUSTRIAL:** **recortes de corcho natural procedentes de preparación, subproductos del picado, tapones defectuosos, etc.**		
Procedencia del corcho	*Distancia transporte*	*Cantidad corcho anual*	*Procedencia del corcho*	*Distancia transporte*	*Cantidad corcho anual*
(Lugar)	**km**	**kg**	*(Lugar)*	**km**	**kg**

OBSERVACIONES

B - FABRICACIÓN DE GRANULADO

B1 - Selección de corcho para diferentes aplicaciones		
Tipo de corcho	*Aplicación*	*Cantidad*
		kg
OBSERVACIONES		

B2- Desplazamiento del corcho de trituración a tolva				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

B3 - Trituración de corcho y eliminación de corcho defectuoso (partes no aprovechables)					
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*	*Rechazo de suro*
(nombre)	**kW**	**horas**	**kg**	**l**	**kg**
OBSERVACIONES					

B4 - Desplazamiento de corcho triturado a clasificación de granulado				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

B5 - Clasificación de granulados					
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*	*Rechazo de corcho*
(nombre)	**kW**	**horas**	**kg**	**l**	**kg**
OBSERVACIONES					

B6 - Desplazamiento de granulado y rechazo a embalaje				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**

OBSERVACIONES

B7 - Embalaje de granulados					
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*	*Rechazo de corcho*
(nombre)	**kW**	**horas**	**kg**	**l**	**kg**

OBSERVACIONES

B8 - Desplazamiento de embalaje a almacenamiento				
Máquina q	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nom)	**kW**	**hores**	**kg**	**l**

OBSERVACIONES

C - FABRICACIÓN PANEL

C1 - Recepción del granulados				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

C2 - Desplazamiento de granulados a mezclar				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

C3 - Mezcla de granulados				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

C4 - Desplazamiento mezcla a aglomeración de planchas				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**kg**	**l**
OBSERVACIONES				

C5 - Aglomeración de planchas							
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*	*Biomasa Leña / polvo*	*Cola de caseina*	*Cola de poliuretano*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**	**kg**	**kg**	**kg**
OBSERVACIONES							

C6 - Recorte de las planchas					
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*	*Rechazo de corcho*
(nombre)	**kW**	**horas**	**kg**	**l**	**kg**
OBSERVACIONES					

C7- Desplazamiento de paneles a embalaje				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**
OBSERVACIONES				

D - EMBALAJE

D1 - Recepción de los paneles acabados				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**

OBSERVACIONES

D2 - Embalaje				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad corcho*	*Polietileno (HDPE)*
(nom)	**kW**	**hores**	**núm. Paneles**	**(bolsas)**

OBSERVACIONES

D3- Desplazamiento de paneles a almacenamiento				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**

OBSERVACIONES

D4 - Almacenamiento de paneles acabados				
Máquina 1	*Potencia máquina*	*Tiempo de uso*	*Cantidad corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**

OBSERVACIONES

E - DISTRIBUCIÓN PRODUCT0

E1 - Carga/Descarga de los vehículos				
Máquina 1	*Potencia de máquina*	*Tiempo de uso*	*Cantidad de corcho*	*Gasoil*
(nombre)	**kW**	**horas**	**núm. Paneles**	**l**

OBSERVACIONES

E2 - Recorrida vehiculos (camiones, furgonetas, etc.)			
Clientes	*Distancia transporte camión*	*Distancia transporte barco*	*Cantidad corcho anual*
(nombre)	**km**	**km**	**paneles**

OBSERVACIONES

Appendix 2. Supplementary information for Chapter 6

This appendix contents the following supplementary information related with Chapter 6:

Supplementary table A. Inventory of insulation materials required to provide a thermal resistance by façade system in the climate zones established in Spain.

Supplementary table B. Inventory of the materials and energy per m^2 of ETICS façade system considered for the comparison of the thermal insulation materials.

Supplementary table C. Inventory of the materials and energy per m^2 of Ventilated façade system considered for the comparison of the thermal insulation materials.

Supplementary table D. Inventory of the materials and energy per m^2 of Internal insulation façade system considered for the comparison of the thermal insulation materials.

Supplementary table A. Inventory of insulation materials required to provide a thermal resistance by façade system in the climate zones established in Spain.

		XPS	EPS	PU	MW	SW
Thermal conductivity (λ) (W/m K)		0.032	0.035	0.023	0.039	0.036
Density (kg/m3)		20	35	31	130	21.8
		Weight (kg)				
ETICS	**Climate α**	0.35	0.67	0.39	2.76	0.43
	Climate A	0.96	1.83	1.06	7.57	1.17
	Climate B	1.36	2.61	1.52	10.79	1.67
	Climate C	1.88	3.60	2.10	14.91	2.31
	Climate D	2.06	3.95	2.3	16.35	2.53
	Climate E	2.21	4.22	2.46	17.48	2.71
Ventilated façade	**Clima α**	0.3	0.6	0.3	2.3	0.4
	Clima A	0.89	1.70	0.99	7.04	1.09
	Clima B	1.28	2.45	1.43	10.14	1.57
	Clima C	1.83	3.50	2.04	14.49	2.24
	Clima D	2-0	3.8	2.2	15.8	2.5
	Clima E	0.11	0.12	0.08	0.13	0.12
Internal insulation façade	**Climate α**	0.5	0.6	0.4	2.7	0.4
	Climate A	1.0	2.0	1.2	8.3	1.3
	Climate B	1.45	2.78	1.62	11.52	1.78
	Climate C	2.00	3.83	2.23	15.84	2.45
	Climate D	2.2	4.2	2.5	17.5	2.7
	Climate E	2.37	4.54	2.64	18.78	2.91

Supplementary table B. Inventory of the materials and energy per m^2 of ETICS façade system considered for the comparison of the thermal insulation materials.

	Ecoinvent 3.1 process				
	Material	**Processing**	**Kg**	**MJ**	**tkm**
Adhesive	Adhesive mortar production, CH		0.6		0.06
Dish-shaped dowels	Polypropylene production, granulate, RER	Injection moulding/RER	0.0168		0.00168
Inner cladding	Gypsum quarry operation, CH		0.8		
	Base plaster production, CH		7.626		0.7626
Ceramic block	Sand-lime brick production, DE		124.5		12.45
	Cement mortar production, CH		7.93		0.793
	Diesel, burned in building machine/GLO S			3.75	
	Tap water production, conventional treatment, Europe without Switzerland		12.4		
Mesh	Glass fibre production, RER		0.73		0.073
Intermediate cladding	Cement mortar production, CH		23.93		2.393
	Diesel, burned in building machine/GLO S			30.75	
Primer	Light mortar production, CH		3.15		0.315
External cladding	Light mortar production, CH		17.95		1.795
	Limestone production, crushed, washed, CH		14.99		1.499

Source: Metabase Itec, 2010

Supplementary table C. Inventory of the materials and energy per m^2 of Ventilated façade system considered for the comparison of the thermal insulation materials.

	Ecoinvent 3.1 process				
	Material	**Processing**	**Kg**	**MJ**	**tkm**
Adhesive	Adhesive mortar production, CH		0.6		0.06
Dish-shaped dowels	Polypropylene production, granulate, RER	Injection moulding/RER	0.0168		0.00168
Screws	Steel production, electric, low-alloyed, RER	Metal working, average for metal product manufacturing, RER	0.81		0.081
Inner cladding	Gypsum quarry operation, CH		0.8		0.08
	Base plaster production, CH		7.626		0.7626
Ceramic block	Sand-lime brick production, DE		124.5		12.45
	Cement mortar production, CH		7.93		0.793
	Diesel, burned in building machine/GLO S			3.75	
	Tap water production, conventional treatment, Europe without Switzerland		12.4		
Waterproofing	Synthetic rubber production, RER		0.82		0.082
	Synthetic rubber production, RER		1.32		0.132
Metallic profiles	Aluminium production, primary, ingot, UN-EUROPE	Sheet rolling, aluminum/RER S	1.0369		0.10369
External cladding	Light mortar production, CH		1.32		0.132

Source: Metabase Itec, 2010

Supplementary table D. Inventory of the materials and energy per m^2 of Internal insulation façade system considered for the comparison of the thermal insulation materials.

Ecoinvent 3.1 process					
	Material	**Processing**	**Kg**	**MJ**	**tkm**
Screws	Steel production, electric, low-alloyed, RER	Metal working, average for metal product manufacturing, RER	0.81		0.081
Metalic profiles	Aluminium production, primary, ingot, UN-EUROPE	Sheet rolling, aluminium/RER S	1.8		0.18
Inner cladding	Gypsum quarry operation, CH		0.8		0.08
	Base plaster production, CH		7.626		0.7626
Ceramic block	Brick production, RER		20.8		2.08
	Cement mortar production, CH		49		4.9
	Diesel, burned in building machine/GLO S			10.5	
	Tap water production, conventional treatment, Europe without Switzerland		12.4		

Source: Metabase Itec, 2010

Appendix 3. Supplementary information for Chapter 7

This appendix contents the following supplementary information related with Chapter 7:

Supplementary table A. Inventory materials required to renovate the building envelope with the two projects under study.

Supplementary table B. Inventory materials for the demolition of 1 m^2 of the existing internal brick wall to be replaced.

Supplementary table C. Inventory materials for the demolition of 1 m^2 of the existing curtain wall façade to be replaced.

Supplementary table D. Inventory materials for the demolition of 1 m^2 of the existing roof to be replaced.

Supplementary table E. Inventory materials for the demolition of 1 m^2 of the existing windows to be replaced.

Supplementary table F. Summary of the inventory data obtained from each data source.

Supplementary table A. Inventory materials required to renovate the building envelope with the two projects under study.

		Conventional renovation					
	Ecoinvent 3.1 process	**Curtain wall façade**	**Brick façade**	**Prefabricated concrete façade**	**Inverted flat roof**	**Deck roof**	**Quantity (Kg)**
Insulation (XPS)	Polystyrene production, extruded, CO2 blown, RER	145.1	264.2	452.8	1,011.2	-	1,873.3
Insulation (EPS)	Polystyrene production, expandable, RER	-	-	-	-	-	-
Insulation (SW)	Rock wool production, packed, CH	-	-	-	-	2,707.3	2,707.3
Insulation (GW)	Glass wool mat production, CH	-	-	-	-	-	-
Insulation (Cork)	(Sierra et al. 2016b)	-	-	-	-	-	-
Adhesive mortar	Adhesive mortar production, CH	161.2	293.6	503.2	0.0	0.0	958.0
Gypsum	Gypsum quarry operation, CH	215.0	391.4	670.9	0.0	0.0	1,277.3
Base plaster	Base plaster production, CH	2,049.1	3,731.4	6,395.2	0.0	0.0	12,175.7
Water	tap water production, conventional treatment, Europe without Switzerland	6,663.8	12,134.6	20,797.3	0.0	0.0	39,595.7
Double hollow bricks	Brick production, RER	13,166.3	23,975.7	41,091.4	0.0	0.0	78,233.4
Cement mortar	Cement mortar production, CH	5,589.0	10,177.4	17,442.9	0.0	0.0	33,209.3
Tempered glass	flat glass production, coated, RER	4,030.5	0.0	0.0	0.0	0.0	4,030.5
Metallic fixings	Aluminium production, primary, ingot, UN-EUROPE	268.7	0.0	0.0	0.0	0.0	268.7
	Sheet rolling, aluminium/RER S	268.7	0.0	0.0	0.0	0.0	268.7
Waterproofing layer	Synthetic rubber production, RER	-	0.0	0.0	2,022.5	784.7	2,807.2
Punching shear resistance layer	Polypropylene production, granulate, RER	-	0.0	0.0	101.1	0.0	101.1
Ceramic tile	Cement mortar production, CH	-	0.0	0.0	67,246.8	0.0	67,246.8
Corrugated sheet	Not included	-	0.0	0.0	0.0	2,511.1	2,511.1

Screws	Steel production, electric, low-alloyed, RER	217.6	0.0	0.0	0.0	0.0	217.6
	Metal working, average for metal product manufacturing, RER	217.6	0.0	0.0	0.0	0.0	217.6
Diesel (MJ)	Diesel, burned in building machine/GLO S	3,829.0	5,137.7	8,805.3	0.0	0.0	17,771.9 (MJ)

		ENERPHIT renovation							
	Ecoinvent 3.1 process	**Curtain wall façade**	**Brick façade**	**Prefabricated concrete façade**	**Inverted flat roof**	**Deck roof (Occupied)**	**Deck roof (Unoccupied)**	**Slab-on-ground**	**Quantity (Kg)**
Insulation (XPS)	Polystyrene production, extruded, CO2 blown, RER	-	-	-	-	-	-	-	-
Insulation (EPS)	Polystyrene production, expandable, RER	-	-	-	-	-	-	7,368.8	7,368.8
Insulation (SW)	Rock wool production, packed, CH	-	-	-	-	-	-	-	52.974
Insulation (GW)	Glass wool mat production, CH	1,440.2	7,877.7	4,176.2	5,561.8	2,033.0	-	-	21,089.0
Insulation (Cork)	(Sierra et al. 2016b)	7,021.1	11,933.0	21,912.6	26,423.4	10,179.6	0.0	44,718.4	122,188.2
Adhesive mortar	Adhesive mortar production, CH	161.2	293.6	503.2	829.2	0.0	62.9	842.2	2,692.2
Gypsum	Gypsum quarry operation, CH	215.0	391.4	670.9	0.0	0.0	0.0	0.0	1,277.3
Base plaster	Base plaster production, CH	2,047.5	3,718.7	6,390.1	0.0	0.0	0.0	0.0	12,156.3
Water	tap water production, conventional treatment, Europe without Switzerland	6,663.8	12,134.6	20,797.3	0.0	0.0	0.0	0.0	39,595.7
Double hollow bricks	Brick production, RER	17,734.2	32,293.8	55,347.6	0.0	0.0	0.0	0.0	105,375.6
Cement mortar	Cement mortar production, CH	5,589.0	10,177.4	17,442.9	0.0	0.0	0.0	0.0	33,209.3
Tempered glass	flat glass production, coated, RER	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Metallic fixings	Aluminium production, primary, ingot, UN-EUROPE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sheet rolling, aluminium/ RER S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waterproofing layer	Synthetic rubber production, RER	0.0	0.0	0.0	2,022.5	575.1	0.0	0.0	2,597.6

Punching shear resistance layer	Polypropylene production, granulate, RER	0.0	0.0	0.0	101.1	0.0	0.0	0.0	101.1
Ceramic tile	Cement mortar production, CH	0.0	0.0	0.0	67,246.8	0.0	6,969.2	93,338.7	167,554.7
Corrugated sheet	Not included	0.0	0.0	0.0	0.0	1,840.4	670.7	0.0	2,511.1
Screws	Steel production, electric, low-alloyed, RER	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Metal working, average for metal product manufacturing, RER	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diesel (MJ)	Diesel, burned in building machine/GLO S	2,821.4	5,137.7	8,805.3	0.0	0.0	0.0	0.0	16,764.3 (MJ)

Supplementary table B. Inventory materials for the demolition of 1 m^2 of the existing internal brick wall to be replaced.

The total results are calculated depends on each project and their demolition proposal.

Interior brick wall	Kg	Ecoinvent Process	ADP (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO4--- eq)	GWP (kg CO2 eq)	OLDP (kg CFC-11 eq)	PCOP (kg C2H4 eq)	Embodied energy
Gypsum	0.8	market for waste gypsum	9.0E-05	7.1E-03	1.2E-05	8.4E-03	1.9E-09	2.8E-04	2.1E-01
Double hollow bricks	49.0	market for waste brick, GLO	4.4E-03	3.2E-03	7.6E-04	5.2E-01	9.4E-08	1.2E-04	1.0E+01
Cement mortar	20.8	market for waste cement in concrete and mortar	2.7E-03	2.0E-03	4.9E-04	3.2E-01	5.4E-08	7.5E-05	6.1E+00
TOTAL			0.007140056	0.012309	0.001260673	0.843792	1.50727E-07	0.000478481	16.45589743

Supplementary table C. Inventory materials for the demolition of 1 m^2 of the existing curtain wall façade to be replaced.

The total results are calculated depends on each project and their demolition proposal

Curtain wall façade	Kg	Ecoinvent Process	ADP (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO4--- eq)	GWP (kg CO2 eq)	OLDP (kg CFC-11 eq)	PCOP (kg C2H4 eq)	Embodied energy
Yeso escayola de designación A, según la norma UNE-EN 13279-1	0.8	market for waste gypsum	9.0E-05	7.1E-03	1.2E-05	8.4E-03	1.9E-09	2.8E-04	2.1E-01
Double hollow bricks	49.0	market for waste brick, GLO	4.4E-03	3.2E-03	7.6E-04	5.2E-01	9.4E-08	1.2E-04	1.0E+01
Cement mortar	20.8	market for waste cement in concrete and mortar	2.7E-03	2.0E-03	4.9E-04	3.2E-01	5.4E-08	7.5E-05	6.1E+00
Tempered glass	15.0	market for waste glass, GLO	4.0E-03	2.5E-03	6.0E-04	4.5E-01	1.7E-07	1.5E-04	9.3E+00
Metallic profiles	1.0	market for waste aluminium, GLO	3.3E-04	2.6E-04	7.0E-05	4.4E-02	3.9E-09	1.7E-05	7.0E-01
TOTAL			**0.011459976**	**0.0151101**	**0.001934374**	**1.335407**	**3.23238E-07**	**0.000640668**	**26.45073693**

Supplementary table D. Inventory materials for the demolition of 1 m^2 of the existing roof to be replaced.

The total results are calculated depends on each project and their demolition proposal.

Roof	Kg	Material/Process	ADP (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO4--- eq)	GWP (kg CO2 eq)	OLDP (kg CFC-11 eq)	PCOP (kg C2H4 eq)	Embodied Energy
Cement fibre cover	12.8	market for waste cement-fibre slab, GLO	1.1E-03	8.6E-04	3.3E-04	1.6E-01	2.2E-08	3.5E-05	2.4E+00
Cement mortar	0.6	market for waste cement in concrete and mortar	7.8E-05	5.7E-05	1.4E-05	9.2E-03	1.6E-09	2.2E-06	1.8E-01
TOTAL			**0.001135185**	**0.000921737**	**0.000345821**	**0.1649338**	**2.31667E-08**	**3.67562E-05**	**2.529754**

Supplementary table E. Inventory materials for the demolition of 1 m^2 of the existing windows to be replaced.

The total results are calculated depends on each project and their demolition proposal.

Windows	Kg	Ecoinvent Process	ADP (kg Sb eq)	AP (kg SO2 eq)	EP (kg PO4--- eq)	GWP (kg CO2 eq)	OLDP (kg CFC-11 eq)	PCOP (kg C2H4 eq)	Embodied energy
Aluminium window frame	6.4	market for waste aluminium, GLO	2.1E-03	1.6E-03	4.5E-04	2.8E-01	2.5E-08	1.1E-04	4.5E+00
Glass	7.4	market for waste glass, GLO	2.0E-03	1.3E-03	3.0E-04	2.2E-01	8.3E-08	7.2E-05	4.6E+00
TOTAL			**0.00406837**	**0.002894278**	**0.000744828**	**0.5001198**	**1.07937E-07**	**0.000178582**	**9.074014732**

Supplementary table F. Summary of the inventory data obtained from each data source.

Source	Data obtained	Reference
CSIC, 2008	Constructive description and dimensions per façade solution	[229]
EnerPHit	Certification Criteria for Energy Retrofits with Passive House Components	[252]
Ministerio de Vivienda, 2013	Thermal parameters for calculations	[230]
Metabase Itec, 2010	Quantity of materials (kg/m^2 of façade) Diesel consumption (MJ/h) and working hours (h) for machinery	[266]

Appendix 4. Supplementary information for Chapter 8

This appendix contents the following supplementary information related with Chapter 8:

Supplementary table A. Results of the warm-up session

Supplementary table B. Results of the 1^{st} concept generation session

Supplementary table A. Results of the warm-up session

<table>
<tr><th>Sanitary</th><th>Chemical agent resistant</th><th>Machinery</th><th>Acoustic insulation</th></tr>
<tr><td colspan="2">1) Coverings for floors and walls in hospitals
2) Container of disinfection for surgical materials
3) Container for water purification
4) Handle for surgical instruments</td><td colspan="2">1) Coverings for floors and walls in industrial buildings
2) Soundproofing of cowlings or machine housings
3) Elements of cork on the packaging</td></tr>
<tr><td colspan="4">1) Acoustic coating for healthcare environments, anti-vibration machinery.
2) Absorbent material of contaminants and water purification.
3) Shock Protection
4) Protective helmets of noise made of cork</td></tr>
</table>

<table>
<tr><th>Construction</th><th>Sustainable</th><th>Leisure</th><th>Buoyancy</th></tr>
<tr><td colspan="2">1) Covering for roof. Natural sheet, revaluing the granulate
2) Tiles, insulation, protection UVA
3) Sanitary pipes
4) Rainproof and insulated blinds</td><td colspan="2"></td></tr>
<tr><td colspan="4">1) Floating pontoon fo boats at ports, which help absorb oils and oil spills in the harbour.
2) Cork boats, including acoustic insulation for motor.
3) Thermal insulation Cork. External furniture of a house in Cork, integrating home into the environment.
4) Emergency and modular homes</td></tr>
</table>

Fashion	Impermeable	Security	Lightness
1) Water boots 2) Waterproof jacket 3) Projected umbrella with cork, more elastic and resistant 4) Mobile Cases, hat, suitcase		Impact strenght Electrical insulation Playground Wood products	
1) Safety footwear. Thermal and electrical insulation, non-slip, waterproof. 2) Team 2 pieces for sea crossing 3) Overalls rafting or scuba diver 4) Tent with cork projected			

Sports	Compressible	Automotive	Shock absorption
1) Continuous coatings for gyms 2) Paving outdoor for playground 3) Boat			
1) Thermal and acoustic insulation of vehicles or aircraft 2) Protective coatings in sports facilities.			
1) Elements of interior design of vehicles, automotive and marine. 2) Textile Accessories: Tent applied to sports car and tent possible 3) Flooring and protection elements for sports halls, rehabilitation equipment.			

Feeding	Impermeable	Toys	Compressible
1) Tapas cooking 2) Plates, bowls, fish 3) Thermal insulation fridge, lunchboxes 4) Packaging of foodstuffs		1) Stress Ball 2) Packaging and box of cork 3) Make toys with 3D printing technology 4) Coatings for playground	

Stress Ball
Toy shaped to fit. 3D printing
Boxes

Leisure	Shock absorption	Toys	Non-toxic
1) Case for mobile or other electronic devices 2) Dianas 3) Protection of crockery (Combination or cork + glass manufacture) 4) Protecting joints (Wrist bands)			
1) Handles for bicycle 2) Lego cork 3) Educational Games 4) Items of personal protective equipment (helmets, wrist guards)			
1) Lego cork for children under 3 years manufactured with 3D printing technology 2) Packaging for protection and decoration 3) Elements of protection for people and utensils 4) Handles			

Supplementary table B. Results of the 1st concept generation session

Problem or need detected	Product ideas	How?
Rehabilitation of external walls in historical buildings	Self-supporting of cork allows the reversibility of the actions by reducing the perforations.	Increasing the thickness to avoid buckling. Assemblies of boards keeping the vertical and horizontal continuity.
Irreversible moisture in the rehabilitation of historical buildings walls	Wall cladding system using cork boards	Minimising of structure used due to self-supporting of cork. Breathability to water vapour avoids the ventilation systems. Cork as internal cladding
Lightweight roofs are fragility	Substitution materials, adding value to the interior finishing	Analyse the substitution and other possibilities of structure materials, including fire resistance.
Increase the roof insulation	Green roof for agriculture to increase the insulation	Cork can be use as support with an air chamber of the roof combined with a structure.
Noise pollution in environments with high transit	Room partition for offices, museums, hotels	Using cork attached to a metallic or plastic structure, facilitating changes in distribution and improving the acoustic insulation of spaces.
Interior insulation systems use a large quantity of materials	Use cork boards to insulate interior walls without an intensive metallic structure	The self-supporting of cork allows to minimize the conventional anchoring systems or use a new system.
Reduce condensations	Multilayer board of wood and cork.	Insulation part with air chambers of alveolar forms. Wood as external and internal cladding.
Low insulation in mobile or portable houses.	Housing unit made of cork, minimising the necessary.	Cork could completely be the enclosure using a wooden lightweight structure
The aesthetics of the cork is not accepted	Design new attractive textures for boards without coverings.	Research common manufacturing processes to introduce new aesthetic. Process adaptation