Universidade de Aveiro Departamento de Ambiente e Ordenamento
2016

Martha Demertzi

Avaliação do desempenho ambiental do setor corticeiro através da Avaliação do Ciclo de Vida

Evaluation of the cork sector's environmental performance through Life Cycle Assessment

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Evaluation of the cork sector's environmental performance through Life Cycle Assessment

Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenharia do Ambiente, realizada sob a orientação científica da Doutora Ana Cláudia Relvas Vieira Dias, Equiparada a Investigadora Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro e do Doutor Luís Manuel Guerreiro Alves Arroja, Professor Associado com Agregação do Departamento de Ambiente e Ordenamento da Universidade de Aveiro.

Este trabalho foi financiado pela Fundação para a Ciência e Tecnologia através de uma Bolsa de Investigação (BI/UI88/6436/2013) no âmbito do projeto "Pegada de carbono de cortiça: das árvores aos produtos" (PTDC/AGR-FOR/4360/2012)

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agradecimentos

Esta tese foi desenvolvida no Departamento de Ambiente e Ordenamento da Universidade de Aveiro. O apoio financeiro que permitiu o início e conclusão da presente tese foi atribuído pela Fundação para a Ciência e Tecnologia (Projeto "Pegada de carbono de cortiça: das árvores aos produtos", PTDC/AGR-FOR/4360/2012) através de uma bolsa de investigação (BI/UI88/6436/2013).

É importante agradecer pela colaboração as várias empresas portuguesas do setor de cortiça (Amorim & Irmãos S.A., Amorim Revestimentos S.A., Amorim Cork Composites S.A, Amorim Isolamentos S.A, CorkSupply Portugal S.A. e DOFcork S.A.) que forneceram dados primários dos seus processos de produção. Estes dados reforçaram a base da presente tese e melhoraram o resultado final. Além disso, a oportunidade dada para visitar as instalações industriais, a fim de ver e compreender os processos envolvidos no setor da cortiça e a ajuda na recolha de informação necessária, facilitou a presente tese.

Gostaria de agradecer aos meus supervisores Doutora Ana Cláudia Relvas Vieira Dias e Professor Doutor Luís Manuel Guerreiro Alves Arroja pela sua supervisão e apoio ao longo dos anos. Com a sua ajuda, conhecimento e orientação ajudaram a conclusão desta tese.

O meu maior obrigado à minha família. Aos meus pais, Eva e Kostas, às minhas irmãs, Melina e Georgina e à minha avó, Martha. Nada seria o mesmo sem o vosso apoio e amor. Agradeço também à minha família portuguesa, Natália e Joaquim, Sérgio e Benfas pelo seu tempo, carinho e ajuda durante todos os meus anos em Portugal. Finalmente, o meu obrigado à todos os meus amigos.

acknowledgements

This thesis was developed at the Department of Environment and Planning, of the University of Aveiro. The financial support that enabled the initiation and conclusion of the present thesis was awarded by the Foundation for Science and Technology (Project "Carbon footprint of cork: from the trees to the products", PTDC/AGR-FOR/4360/2012) through a research grant (BI/UI88/6436/2013).

It is important to acknowledge the collaboration with various Portuguese cork companies (Amorim & Irmãos S.A., Amorim Revestimentos S.A., Amorim Cork Composites S.A, Amorim Isolamentos S.A, CorkSupply Portugal S.A. e DOFcork S.A.) that provided primary data from their production processes. These data strengthened the base of the present thesis and improved the final outcome. Additionally, the given opportunity to visit the industrial installations in order to see and understand the processes involved in the cork sector and the overall help in the collection of needed information, facilitated the present thesis.

I would like to also thank my supervisors Doctor Ana Cláudia Relvas Vieira Dias and Professor Doctor Luis Manuel Guerreiro Alves Arroja for their supervision and support over the years. Your help, knowledge and guidance helped the completion of this thesis.

I owe my greatest thank you to my family. To my parents, Eva and Kostas, my sisters, Melina and Georgina and to my grandmother, Martha. Nothing would be the same without your support and love. To my Portuguese family, Natalia, Joaquim, Sérgio and Benfas for their time, care and help throughout all my years in Portugal. Last but not least, to all my friends.

To all of you, my greatest thank you!

palavras-chave Avaliação do ciclo de vida, gases com efeito de estufa, impacte ambiental, setor corticeiro, sustentabilidade

resumo

A relevância do setor corticeiro do ponto de vista ambiental tem vindo a aumentar graças à transição, quer da indústria quer dos consumidores, para um mercado mais sustentável. A avaliação do impacte ambiental dos produtos de cortiça pode ser feita através da avaliação do ciclo de vida (ACV) para identificar as etapas e os processos mais influentes ao longo do seu ciclo de vida.

Atualmente, existem poucos estudos de ACV disponíveis e a maioria deriva de dois países, Portugal e Espanha (os líderes do setor da cortiça). No entanto, os estudos existentes muitas vezes excluem a etapa de fim-de-vida ou quando ela é incluída consideram apenas um destino final, nomeadamente o aterro sanitário. Além disso, a maioria dos estudos existentes não considera a emissão e remoção de carbono biogénico no cálculo da pegada de carbono porque estas emissões são consideradas neutras (todo o carbono sequestrado na floresta vai ser emitido durante as etapas de fabrico, uso e fim-de-vida). Adicionalmente os estudos atuais consideram que todas as emissões ocorrem num tempo específico que pode não ser muito realista uma vez que as emissões podem ocorrem ao longo do tempo considerado no ciclo de vida do sistema.

A presente tese tem o objetivo de enriquecer e ampliar o conhecimento do setor corticeiro. Vários estudos de caso de produtos de cortiça representativos (rolhas de cortiça natural, pavimento flutuante de cortiça, placas e regranulado de cortiça expandida) estão incluídos nesta tese a fim de identificar as etapas e os processos mais influentes em cada caso do ponto de vista ambiental. A contribuição dos produtos de cortiça para várias categorias de impacte ambiental é feita através do uso de ACV. Adicionalmente, a etapa de fim-de-vida das rolhas de cortiça natural é avaliada separadamente considerando várias alternativas e cenários para identificar a melhor opção em termos ambientais.

Além disso, é desenvolvido e apresentado um modelo de simulação para o cálculo da pegada de carbono do setor corticeiro na sua totalidade. O objetivo deste modelo é facilitar a avaliação de todo o setor da cortiça, não só por etapa e processo, mas também por produto e na sua totalidade. Assim, este vem apoiar a tomada de decisões do setor, a fim de melhorar a sua pegada de carbono total.

Adicionalmente uma abordagem de ACV mais recente é aplicada, a avaliação dinâmica do ciclo de vida. Ao contrário da abordagem tradicional (estática), que considera que todas as emissões e alterações climáticas ocorrem num tempo específico (geralmente 20, 100 ou 500 anos), a abordagem dinâmica considera as emissões e alterações climáticas que ocorrem em cada ano do horizonte temporal escolhido para o estudo. A consideração da abordagem dinâmica é aplicada pela primeira vez neste setor e fornece mais uma alternativa na avaliação da pegada de carbono do setor corticeiro.

A presente tese destaca a importância da inclusão do carbono biogénico sequestrado e emitido no cálculo da pegada de carbono. Quando é incluído o setor é um sumidouro de carbono (pegada de carbono igual a -956,042 t CO_2 eq. por ano) e quando é excluído é uma fonte de carbono (pegada de carbono igual a 172,844 t CO_2 eq. por ano).

keywords Carbon footprint, cork sector, environmental impact, life cycle assessment, sustainability

abstract The relevance of the cork sector from an environmental point of view is currently increasing thanks to the transition, both of industry and the consumers to a more sustainable market. The evaluation of the environmental impact of the cork products can be done through life cycle assessment (LCA). This is a tool used for the evaluation of the entire life cycle of a product (from the extraction of the raw materials to the final disposal of the product) in order to identify the most influential stages and processes along the life cycle.

Currently, there is a limited number of LCA studies ON cork found in literature and the majority derives from two countries, Portugal and Spain (the leaders of the cork sector). Those studies, usually exclude the end-of-life stage and when it is included they only consider one destination, namely landfilling. The majority of the existing studies doesn't consider the emission and removal of biogenic carbon in the calculation of the carbon footprint since they are considered neutral (all biogenic carbon sequestered at the forest will be completely emitted during the stages of manufacturing, use and end-of-life). Additionally, the current studies consider that all the emissions occur in a specific time (reference year) and this might not be very realistic since the emissions may occur along the time considered in the life cycle of the system under study and this may influence the final conclusions reached.

The present Ph.D. thesis aims to enrich and extend the knowledge of the cork sector. Different case studies of the most representative cork products (natural cork stoppers, cork floating floor, expanded cork slab and regranulates) are included in this thesis in order to identify the most influential stages and processes in each case from an environmental point of view. The contribution of the cork products for various environmental impact categories is done through the use of LCA. Additionally, the end-of-life stage for used natural cork stoppers is evaluated separately considering various alternatives and scenarios in order to identify the most efficient option from an environmental point of view.

Moreover, a simulation model for the calculation of the carbon footprint of the entire cork sector is developed and presented. The goal of this model is to facilitate the evaluation of the entire cork sector not only per stage and process but also per product and as a total. Thus, it can be very useful for the decision-making of the sector in order to decrease its total carbon footprint.

Additionally, a more recent approach is applied as well, the dynamic life cycle assessment. On the contrary of the traditional (static) approach that considers that all the emissions and climate change impacts occur on a specific time (usually 20, 100 or 500 years), the dynamic approach considers the emissions and impacts occurring in each year for the temporal horizon chosen for the study. The dynamic life cycle approach is applied for the first time on the cork sector and provides another alternative for the carbon footprint evaluation of the cork sector.

The present thesis highlights the importance of including the sequestered and emitted biogenic carbon in the carbon footprint calculation of the cork sector. When biogenic carbon is included in the calculations, the cork sector is a carbon sink (carbon footprint equal to -956,042 t CO_2 eq. per year) and when it is excluded the cork sector is a carbon source (carbon footprint equal to 172,844 t CO_2 eq. per year).

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List of Acronyms, Abbreviations and Notation

A	Acidification
APCOR	Portuguese Cork Association
BEES	Building for Environmental and Economic Sustainability
BSI	British Standards Institution
CC	Climate Change
CF	Carbon Footprint
CH_4	Methane
CHP	Combined Heat and Power
CML	Centre of Environmental Science of Leiden University
CO	Caron monoxide
CO_2	Carbon dioxide
COMPETE	Operational Program Thematic Factors of Competitiveness
DEFRA	Department for Environment, Food and Rural Affairs
DGRF	General Directorate of Forest Resources
dLCA	Dynamic Life Cycle Assessment
EDP	Energy of Portugal
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Program
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
ERSE	Regulatory Entity of Energy Services
ETH	Swiss Federal Institute of Technology
FAO	Food and Agriculture Organization of the United Nations
FE	Freshwater Ecotoxicity
FCT	Foundation of Science and Technology
FEDER	European Regional Development Fund
FEu	Freshwater Eutrophication
FU	Functional unit

GHG	Greenhouse Gases
GVA	Gross Value Added
H_2O_2	Hydrogen peroxide
HDF	High density fiberboard
HTC	Human Toxicity Cancer Effects
HTNC	Human Toxicity Non-cancer Effects
IFN	National Forest Inventory
ILCD	International Reference Life Cycle Data System
INE	National Institute of Statistics
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITC	International Trade Center
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
ME	Marine Eutrophication
MFRD	Mineral and Fossil Resource Depletion
MSW	Municipal Solid Waste
N_2O	Nitrous oxide
NaCl	Sodium chloride
$NaHSO_4$	Sodium bisulfate
NaOH	Sodium hydroxide
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
NO_x	Nitrous oxide
OECD	Organization for Economic Co-operation and Development
OD	Ozone Depletion
PAS	Publicly Available Specification
PCR	Product Category Rule
PEF	Product Environmental Footprint
PO_4^{3-}	Phosphate

POF	Photochemical Ozone Formation
SCI	Science Citation Index
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulfur dioxide
TCA	Trichloroanisole
tLCA	Traditional Life Cycle Assessment
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TE	Terrestrial Eutrophication
UK	United Kingdom
UN	United Nations
UNAC	Union of the Mediterranean Forest
UNEP	United Nations Environment Program
USA	United States of America
UV	Ultraviolet
WBCSD	World Business Council for Sustainable Development
WEEE	Waste Electrical and Electronic Equipment
WMO	World Meteorological Organization
WRI	World Resources Institute
WWF	World Wide Fund for Nature
WWTP	Waste Water Treatment Plant

Chapter 1
Introduction

1.1 Background and motivation

Cork is the outer bark of the cork oak tree and it is extracted for commercial use. Due to its versatility and unique characteristics (e.g. elasticity, durability and impermeability), cork can be used in a variety of sectors for the manufacturing of various products (e.g. wine industry, construction and sports). The versatility of cork as a material together with its ecological properties has facilitated the growth of the cork sector in Portugal and its multi-sectorial functions (construction, automotive, footwear, etc.). The importance of cork is not only economic but also environmental (APCOR, 2015). Thus, currently there is an increasing interest regarding the performance of cork in environmental terms. However, there is not yet an extensive literature focusing on the environmental impacts related to cork (e.g. emissions from the forest management processes and manufacturing processes).

Currently, a very limited number of Life Cycle Assessment (LCA) studies exists, focusing on the environmental impacts deriving from the production of raw cork and the manufacturing of some representative cork products (natural cork stoppers, champagne cork stoppers, black and white cork granulate). More specifically, two studies from Portugal (Dias et al., 2014; González-García et al., 2013) and one from Spain (Rives et al., 2012a) are found in literature regarding the forest management activities performed for the production of raw cork and their environmental impacts. Additionally, three studies are found focusing on the production of natural cork stoppers through LCA (Rives et al., 2011; Ecobilancio, 2010; PwC/Ecobilan, 2008). There is also one Spanish study focusing on the manufacturing of champagne cork stoppers and the environmental impacts associated to their production (Rives et al., 2012b). Regarding the use of cork products in the construction industry, there are two comparative studies that apart from the traditional construction material used for insulation (e.g. polystyrene and polyurethane), they consider the use of agglomerated cork and they study its production and environmental impacts (Pargana et al., 2014; Bribrián et al., 2010). There is another Spanish study that focuses on the production of cork granulates (both white and black) and evaluates through LCA the environmental impacts of their production (Rives et al., 2012c). Finally, there is a study considering an integrated environmental analysis of the main cork products in Spain (Catalonia) (Rives et al., 2013). Nevertheless, there is not a vast knowledge on the Portuguese cork sector through the application of life cycle thinking tools, such as LCA and Carbon Footprint (CF).

An aspect of cork that is currently poorly studied is the end-of-life stage. Usually, this stage is excluded from the studies or when included only landfilling is considered (Rives et al., 2011; PwC/Ecobilan, 2008). Furthermore, in LCA studies, cork is treated as wood even though their properties are different.

Another aspect that has not been studied yet in depth, in relation to cork, is biogenic carbon. During its growth, cork oak trees sequester carbon from the atmosphere. This carbon remains in raw cork and in the cork products manufactured and finally returns to the atmosphere (at the manufacturing and end-of-life stages). Those emissions, called biogenic carbon emissions are defined as carbon emissions related to the natural carbon cycle, as well as those resulting from the production, harvest, combustion, digestion, fermentation, decomposition and processing of biologically based materials (EPA, 2015). Currently, forest-based products in LCA studies are mostly considered to be carbon-neutral materials (Dias et al., 2014; Vogtländer et al., 2014; Sjølie and Solberg, 2011). It is considered that the entire amount of carbon sequestrated by the forest will be emitted into the atmosphere (at the manufacturing and end-of-life stages). Thus, biogenic carbon emissions are usually excluded from the calculations. Currently, the methodological aspects of biogenic carbon accounting is a controversial issue as several accounting methods exist but there is no accordance on which is the most appropriate.

In general, traditional LCA (tLCA) considers a specific time when emissions occur. However, this is not what actually happens considering that different processes occur during different years of the life cycle of a product resulting to environmental impacts along the life cycle. Another approach of LCA called dynamic LCA (dLCA) considers this aspect and accounts for the emissions occurring each year of the products' life cycle and thus, it is considered a more realistic representation (Levasseur et al., 2013, 2010; Pehnt, 2006). However, this approach has not been applied yet to the cork sector.

The present thesis was developed at the University of Aveiro from 2013 to 2016, under the scope of the project “Cork carbon footprint: from trees to products” (PTDC/AGR-FOR/4360/2012), financed by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal).

1.2 Objectives of the thesis

The main objective of this Ph.D. thesis is the assessment of the cork sector from an environmental point of view, considering as a case study the country of Portugal, due to its importance for the global cork sector. The thesis considers the existing gaps in the knowledge of the cork sector in order to add new input and primary data in the literature regarding the cork sector. Several specific goals are considered as presented is this section.

One of the specific objectives is to assess several environmental impacts relevant to the cork sector by using LCA. Those impacts are evaluated for some of the most representative products of the sector (natural cork stoppers, white agglomerated cork products, black agglomerated (expanded) cork products and black cork granules/regranulates). In order to evaluate the environmental sustainability of the cork sector, the various stages associated with the life cycle of different cork products (forest management, manufacturing, use and end-of-life) are considered and evaluated in order to identify the most influential stages and processes (hotspots). This assessment is an important enlargement of the current knowledge of the environmental impacts of the Portuguese cork sector that is limited to raw cork and natural cork stoppers impacts. Additionally, the LCA of the various products will provide information for the identification of the most influential stages and processes along their life cycle. The outcome of this part of the present thesis can be significant for the decision-making of the cork sector since the main hotspots during the cork products manufacturing can be identified in order to be improved in the future and help decrease the environmental impacts.

The end-of-life stage of cork is studied separately since there is a limited knowledge of this aspect. Thus, a part of the present thesis focuses on this stage in order to include and study different end-of-life destinations, such as incineration, landfilling and recycling. In this way, the importance of the chosen destinations can be evaluated and the most effective choice from an environmental point of view can be identified. Thus, the obtained results can be used to suggest alternatives for minimizing the environmental impact of the various cork products at their final destination in order to increase the sustainability of the entire cork sector. Consequently, the outcome of the present thesis will enrich the existing literature with more primary data from the Portuguese cork industry and will present quantitative results and conclusions regarding the end-of-life aspect of cork products.

Another specific objective of this thesis is the assessment of the CF of the entire cork sector, through the evaluation of the emissions and removals of greenhouse gases (GHGs), from the forest to the final disposal of the cork products. In this evaluation all the industrial processes of the most representative cork products are included. A life cycle approach is adopted, allowing the identification of the stages where GHG emissions and removals occur. For this purpose, a simulation model for the calculation of the CF of the entire cork sector is developed for the first time providing significant knowledge regarding the hotspots of the entire supply chain. The new model is applied to the Portuguese sector (considering the country's cork production) in order to obtain quantitative results for the sector and identify the hotspots. However, it is important to highlight the applicability of the simulation model to other countries considering different conditions or maintaining the default values provided. By using this model, the user can select the types of cork (virgin, second, reproduction or 'falca') and introduce their quantities, as well as the final destination and the percentages reaching the different options of final destinations considered (incineration, landfilling and/or recycling) of the produced cork products. In this way, the user is able to obtain the distribution of cork among the various cork products (in mass) and the CF of the various products, stages, industries and the entire cork sector.

The present thesis also considers the application of dLCA for the evaluation of the cork sector's CF. Since the tLCA is considered a static tool, the aim is to apply a more dynamic approach that considers one-year intervals for the evaluation of the GHG emissions. In this way, we can compare the differences between the results of these two LCA approaches (tLCA and dLCA) and reach conclusions regarding their influence on the CF calculation of the cork sector. This part also provides new information regarding the cork sector considering that there is no similar study found in literature.

Another specific objective is to assess the sequestration of carbon at the forest, its storage in cork products and its emission delay during the use period or disposal in landfills of the cork products is assessed for the first time from an LCA perspective. Some of the most established CF accounting methods (Greenhouse Gas Protocol (Bhatia et al., 2012), Publicly Available Specifications 2050 (BSI, 2011) and the International Reference Life Cycle Data System European Commission, 2010)) are applied in order to compare the magnitude of biogenic carbon emission delay during the use and end-of-life stages. This objective provides new knowledge regarding the importance of the cork products for this aspect. More specifically, the consideration of long use periods can result to long storage periods of carbon and thus, to different conclusions regarding the total CF of the cork products and the entire sector.

In general, the present thesis deals with existing gaps regarding the evaluation of cork sector through LCA and considers the less studied aspects. Furthermore, this thesis provides a deeper knowledge of the cork oak sector and suggests new management strategies to be considered in the future for the improvement of the sector's sustainability.

1.3 Structure of the thesis

This doctoral thesis consists of modified versions of published or submitted scientific papers in peer-reviewed Science Citation Index (SCI) journals. The paper modifications considered the harmonization of literature references, since the submitted/ published papers had different reference styles depending on the journal guidelines, and document formatting in order to ease the readability of the text.

The thesis is organized in 5 chapters. The first chapter briefly presents the main context, objectives, structure of the thesis and the published work that resulted from the present thesis.

The second chapter serves as an introduction to the main topic of the thesis, the cork oak sector considering its current situation both globally and in Portugal. In the same chapter, the main cork industries and cork as a material is discussed.

Furthermore, in chapter two, the methodology used in the studies of this thesis is introduced. More specifically, LCA and CF are defined in detail, their importance in the environmental evaluation of products and their impacts is showcased, as well as their advantages and disadvantages. Additionally, different biogenic carbon calculation methods are presented and the importance of its consideration or exclusion in LCA is highlighted. Another section of chapter two includes the state-of-the-art of the LCA studies concerning cork not only as a material but also during its production at the cork oak forest considering the various management activities.

Chapter three deals with the environmental evaluation of various representative cork products through LCA (natural cork stoppers, cork floating floor and expanded cork slab and granules). It presents quantitative results for the use of cork for the production of different materials used in the wine sector (that presents the greatest consumption of cork) and also the construction sector. More specifically, chapter three consists of various scientific papers, "**Cork stoppers supply chain: potential scenarios for environmental impact reduction**" (published in the Journal of Cleaner Production), "**Environmental performance of a cork floating floor**" (published in the journal Materials & Design) and "**Environmental performance of expanded cork slab and granules through life cycle assessment**" (submitted), focusing on the environmental performance of natural cork stoppers, cork floating floor and expanded cork slab and granules, respectively. Moreover, this chapter focuses on a poorly studied aspect of cork that is its final disposal and presents another published study "**Evaluation of different end-of-life management alternatives for used natural cork stoppers through life cycle assessment**" (published in the journal Waste Management). This study presents the environmental performance of different end-of-life destinations and scenarios for the end-of-life stage of used natural cork stoppers.

Chapter 4 integrates the results of the aforementioned studies, as well as studies in the literature and raw data of Portuguese cork industries and presents the development of a CF simulation model for the cork oak sector. This chapter is based on another scientific paper "**A carbon footprint simulation model for the cork oak sector"** (submitted). This study explains in detail how the simulation model was developed and the quantitative results obtained from its application in the case of Portugal (cork production approach). The relatively new concept of dLCA is introduced in the same chapter through the scientific paper "**Evaluating cork sector's**

carbon footprint through traditional and dynamic life cycle assessment” (submitted). This study presents the comparison of the results when applying this approach instead of tLCA.
The last chapter, chapter 5, concludes and provides suggestions for future studies regarding the cork oak sector.

1.4 Scientific work resulting from this Ph.D. thesis

This doctoral thesis is based on the following scientific papers in peer-reviewed SCI journals (both published and currently under review):

1. Demertzi M., Silva R.P., Neto B., Dias A.C., Arroja L., 2016. **Cork stoppers supply chain: potential scenarios for environmental impact reduction.** Journal of Cleaner Production 112: 1985–1994. http://dx.doi.org/10.1016/j.jclepro.2015.02.072

2. Demertzi M., Garrido A., Dias A.C., Arroja L., 2015. **Environmental performance of a cork floating floor.** Materials & Design 82: 317–325. http://dx.doi.org/10.1016/j.matdes.2014.12.055

3. Demertzi M., Sierra-Pérez J., Amaral Paulo J., Arroja L., Dias A.C., 2016. **Environmental performance of expanded cork slab and granules through life cycle assessment.** (Submitted).

4. Demertzi M., Dias A.C., Matos A., Arroja L., 2015. **Evaluation of different end-of-life management alternatives for used natural cork stoppers through life cycle assessment.** Waste Management 46: 668–680. http://dx.doi.org/10.1016/j.wasman.2015.09.026

5. Demertzi M., Amaral Paulo J., Arroja L., Dias A.C., 2016. **A carbon footprint simulation model for the cork oak sector.** Science of the Total Environment 566–567: 499–511. http://dx.doi.org/10.1016/j.scitotenv.2016.05.135

6. Demertzi M., Amaral Paulo J., Arroja L., Dias A.C., 2016. **Evaluating the carbon footprint of the cork sector through traditional and dynamic life cycle assessment.** (Submitted).

Additionally, the following oral presentations in national and international conferences resulted from this doctoral thesis:

1. Demertzi M., Garrido A., Dias A.C., Arroja L., 2014. **The environmental performance of a floating cork flooring. O desempenho ambiental de um pavimento flutuante de cortiça.** Jornadas Científicas Sobre a Cortiça e Suas Aplicações. Porto, Portugal. (National).

2. Demertzi M., Dias A.C, Arroja L., 2015. **End-of-life management alternatives for natural cork stoppers through life cycle assessment.** 2nd Discussion Forum on Industrial Ecology and Life Cycle Management. Coimbra, Portugal. (International).

3. Demertzi M., Dias A.C, Arroja L., 2015. **Environmental evaluation of end-of-life alternatives for natural cork stoppers.** 6th International Congress of Energy and Environment Engineering and Management (CIIEM15). Paris, France. (International).

4. Demertzi M., Dias A.C, Arroja L., 2015. **Recycling of used natural cork stoppers for the production of construction materials.** 3rd Edition of the International Conference WASTES: Solutions, Treatments and Opportunities. Viana do Castelo, Portugal. (International).

5. Demertzi M., Dias A.C, Arroja L., 2015. **Carbon footprint of the cork oak sector. Towards a Sustainable Bioeconomy.** Innovative Methods and Solutions for the Agriculture and Forest Sectors. Barcelona, Spain. (International).

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Chapter 2

Literature review

2.1 Cork sector

2.1.1 Overview of the cork oak forests globally and in Portugal

Quercus Suber L., commonly named cork oak, is a medium-sized, slow-growing, evergreen tree. Cork oak forests are mainly located in the western and central Mediterranean basin, namely in the countries of Portugal, Spain, France, Italy, Morocco, Algeria and Tunisia. A total of 2,139,942 hectares of cork oak forests is unevenly distributed among those countries (34%, 27%, 3%, 3%, 18%, 11% and 4%, respectively) (APCOR, 2014). The annual production of raw cork reaches 201,428 tonnes (t) mainly due to the production in the Iberian Peninsula (Portugal represents almost 50% and Spain 31% of the total raw cork production). Figure 1 shows the distribution of the cork oak forests throughout the Mediterranean region, the annual raw cork production in mass (t) and its respective contribution (in percentage).

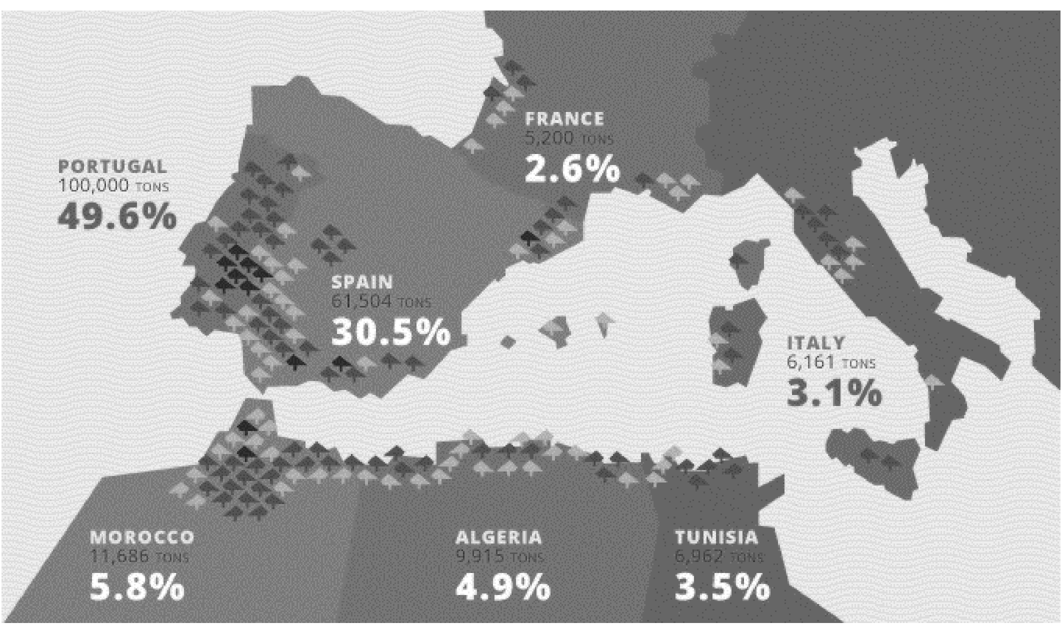

Figure 1: Cork oak forests distribution and annual raw cork production in mass and its respective percentage *(APCOR, 2014)*

The regions where cork oak adapts better seem to have specific characteristics. Table 1 presents the edaphoclimatic conditions in which cork oak thrives. Even though cork oak has its natural territory, there have been attempts for its cultivation in other parts of the world, such as Bulgaria (Petrov and Genov, 2004) and California, United States (Brooks, 1997). Even though the trees flourished, and some are still growing there, they did not reach a high quality. For example, the cork bark on the Californian cork oak trees turned to hard bark not appropriate for production use (Jelinek, 2015). Consequently, the different climatological conditions seem to be very important in order to obtain cork of high quality and none of the aforementioned countries has managed to develop a considerable cork industry.

Table 1: Edaphoclimatic conditions for the natural growth of cork oak (*adapted from: Amorim (2015*))

Parameter	**Conditions**
Altitude from sea level	100 to 300 meters
Precipitation	400 to 800 mm per year
Temperature	-5 ºC to 40 ºC
Soil	Sandy, chalk-free, low nitrogen and phosphorus, high potassium
Soil pH	4.8 to 7.0

Portugal is the world's leader in raw cork production. More specifically, cork is the second most dominant tree species of the country (736,775 hectares), representing 23% of the total forest area (APCOR, 2014). In Portugal, cork oak is considered the national tree and it is protected by law since the 13th century (Decree-Law 169/2001). The distribution of cork oak forests varies along the country. Figure 2 presents the occupation area of the tree species found in the Portuguese territory (in percentage) and additionally, the distribution of cork oak forests along the country. It can be noticed that the main quote of cork oaks (84%) is located in Alentejo, a southern region of Portugal (APCOR, 2014).

Environmentally, cork oak forests can contribute to climate change mitigation since they absorb carbon dioxide (CO_2) from the atmosphere and store it in their perennial tissues and in the soil as organic matter, retaining it for very long periods (Aronson et al., 2009). The same occurs in the case of the cork products since they can stay in use or at a landfill facility for long periods, storing part of the carbon contained in the cork harvested from the forest and delaying its return to the atmosphere (Dias and Arroja, 2014). Furthermore, cork oak forests support the biodiversity and survival of many indigenous animal species, some of which in danger of extinction. According to the World Wide Fund for Nature (WWF), cork oak forest area is a habitat to the number of 135 plant and 42 bird species (WWF, 2015).

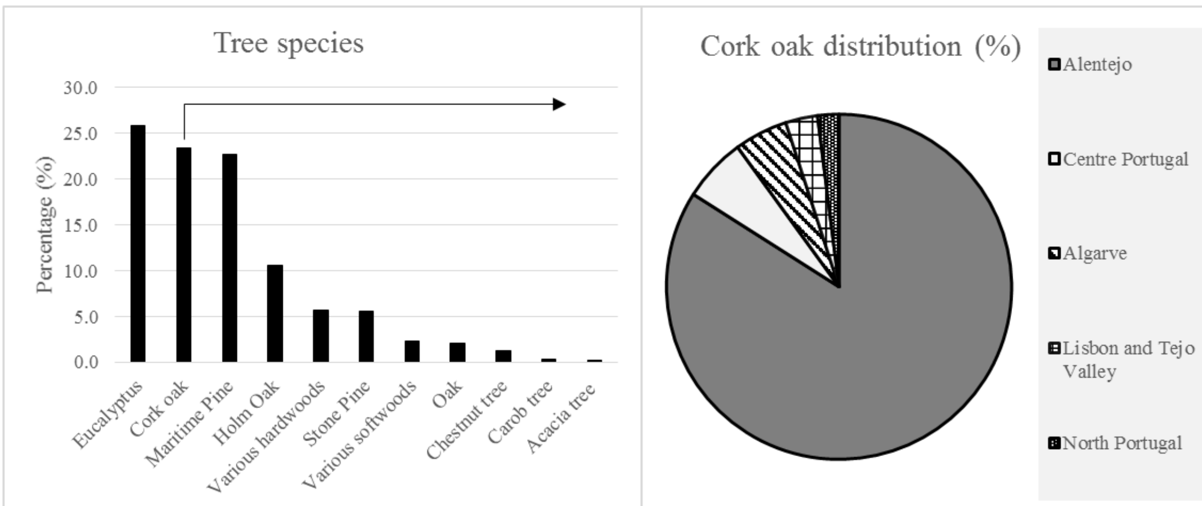

Figure 2: Occupation area of the tree species in Portugal and distribution of cork oak forests along the country *(adapted from: APCOR (2014) and IFN (2013))*

2.1.2 Overview of the cork sector in Portugal

The cork sector except for the environmental importance, also has a great social and economic importance for the country (APCOR, 2015). Socially, the cork sector is important due to the employment of a great number of workers. More specifically, the Portuguese cork industry has almost 650 factories and around 9,000 workers (APCOR, 2014). Consequently, the Portuguese cork sector is responsible for the employment of 2% of the total employed population in the country (APCOR, 2014; INE, 2013). Economically, the importance of the cork sector in Portugal is also significant. Portuguese cork exports account for around 2% of Portuguese goods exports and mean a trade balance of almost 700 million euros (APCOR, 2014). The significance of cork exports can be highlighted by the fact that over the last decade the exports of the cork sector contribute around 1.4% to 2.5% of the total annual value of exports (APCOR, 2011).

The cork extraction process is manual and there are specific time intervals between which the extraction is performed. There are four types of cork that are used for different cork products. The main target sector of cork products is the wine industry accounting for around 68% of the total cork produced (42% for natural cork stoppers and 26% for agglomerated cork stoppers), followed by the construction sector with almost 25% of the total cork produced (for materials used as flooring, insulation and coverings), while the rest 7% is used for other cork products such as sheets, strips and in general home and office decoration (APCOR, 2014). The main cork types and their most representative products are presented in Figure 3.

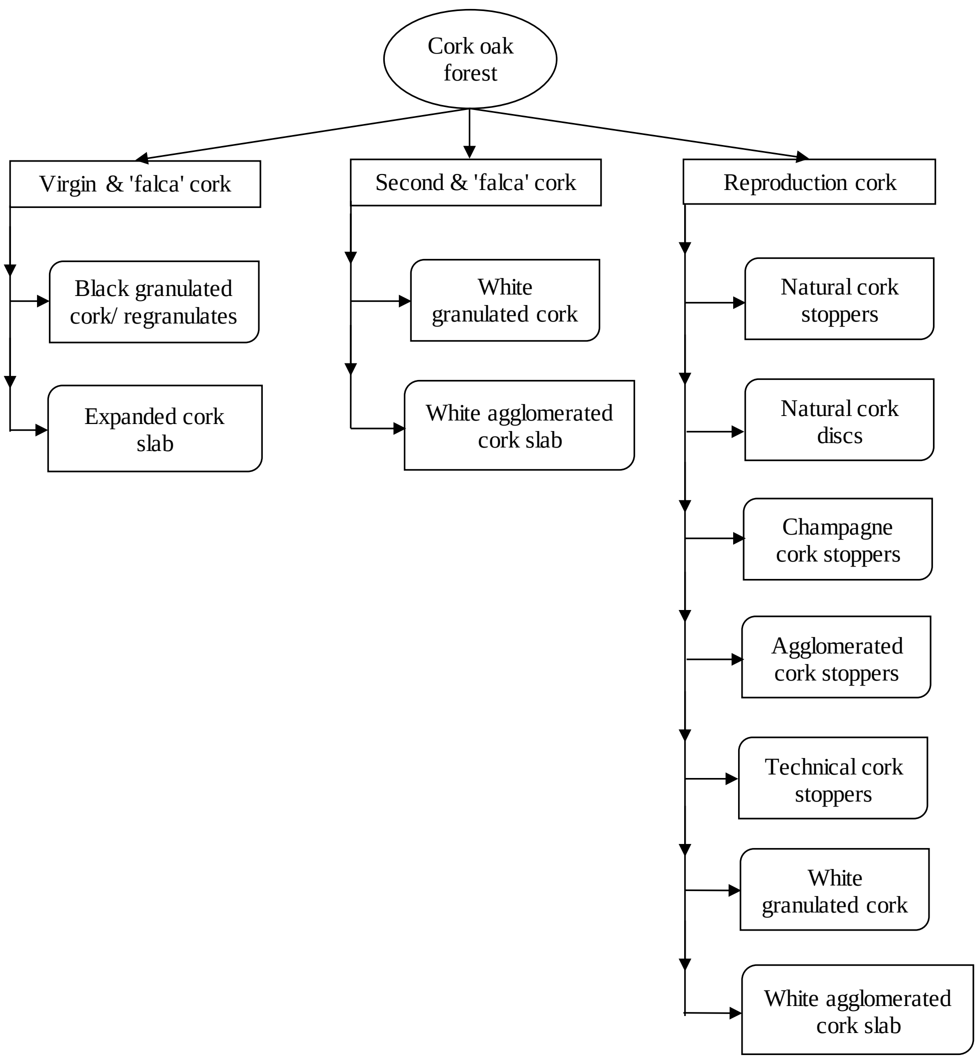

Figure 3: Main cork types and their main products *(based on Demertzi et al., 2016; APCOR, 2014; Rives et al. 2013, 2011; UNAC, 2013; Pereira, 2007)*

The first cork extracted, called virgin cork, is considered of lower quality because of the irregularities noticed on the exterior surface. This cork type is destined to the granulation and agglomeration industry for the production of expanded cork slabs and granules/ regranulates (100% natural cork product) used in construction. The products manufactured with this cork type have a characteristic black color. The second cork extracted is called second (or secondary) cork and it is still of low quality. This cork type is also sent to the granulation and agglomeration industry (where cork is mixed with resins) in order to produce white cork products, specifically granulated white cork and agglomerated cork slabs used in construction. Another cork type deriving from the cork oak tree is the 'falca' cork. This cork type is not obtained by cork extraction but from the pruning of the cork tree branches (performed in-between the harvestings) and is a mixture of cork, inner bark and wood. This cork type, after its separation from the wood, enters the flow of virgin and second cork in order to be used for the production of the above mentioned cork products. The third and ongoing extracted cork is called reproduction cork and it is considered of better quality. This cork type is mainly used for the production of the natural cork stoppers used in the wine industry for the sealing of wine bottles and natural cork discs used at the assembling of the agglomerated cork stoppers (in order to seal the bottle more effectively). The cork waste deriving from the production of the natural cork stoppers and discs (e.g. perforated planks) together with the lower quality planks of the reproduction cork type are used for the production of agglomerated cork stoppers (champagne, technical and agglomerated cork stoppers) as well as granulated white cork and white cork agglomerated cork slabs used in construction.

The industrial processing of cork is currently divided into four sub-sectors, as follows (APCOR, 2015):

- Preparation industry: includes the various operations following cork extraction, related to the selection and preparation of the reproduction cork (cork of high quality) in order to be cleaned from impurities and obtain the desired characteristics (such as thickness) for the following industry.
- Transformation industry: mainly represents the production of natural cork stoppers and discs. This industry receives the prepared planks from the preparation industry and is

closely related to the granulation industry since it is where the cork waste (from the production of the natural cork stoppers and discs) ends-up.

- Granulation industry: it includes the trituration of the lower quality planks and cork waste from the transformation industry. The cork granules produced in this industry can be used both as products (e.g. granulated white cork) and raw material for the activities in the following industry (e.g. for the production of agglomerated cork products).
- Agglomeration industry: it includes the production of agglomerated cork products, both with the use of resins (white agglomerated cork products) or naturally (expanded cork products), that are mainly used in construction but also for decorative purposes. This industry mainly uses cork granules as raw material that is the cork waste (e.g. perforated planks) deriving from the previously mentioned industries.

2.2 Life cycle assessment

2.2.1 Brief description of life cycle assessment

In the present thesis, the environmental performance of the cork oak sector is analyzed through LCA that is a technique used for the evaluation of the environmental impact of a product or service during its entire life cycle. The first LCA studies appeared around the late 1960s-early 1970s when environmental issues, such as pollution control, resource and energy efficiency, started emerging (Sundstrom, 1971; Boustead, 1974). However, it was in the late 1970s that the interest around the LCA topic started growing. In 1979 the Society of Environmental Toxicology and Chemistry (SETAC), a multi-disciplinary society with industrial, scientific and public representatives was founded. One of the main objectives of SETAC was and continues to be the establishment of a common methodology and standards regarding LCA. The "Code of practice" was one of the most important reports of SETAC aiming the improvement and harmonization of LCA methods (Consoli et al., 1993). Alongside to SETAC, since 1994, the International Organization for Standardization (ISO) started being involved in LCA for the standardization of LCA methods and procedures. The first ISO standard regrading LCA (ISO 14040) was published in 1997 and presented the main principles and framework for LCA (ISO, 1997). After a decade, the first ISO standard was followed by several newer ones, namely ISO 14041 (ISO, 1998), ISO 14042 (ISO, 2000a) and ISO 14043 (ISO, 2000b). In the early 2000s, the United Nations Environment Program (UNEP) in collaboration with SETAC, started the Life Cycle Initiative, an international partnership, in order to apply life cycle thinking practically and to improve the life cycle tools through better data and indicators. Nowadays, the importance of LCA continues increasing and being considered in the international policies such as the Green Public Procurement (European Commission, 2008), the Ecolabel Regulation (European Commission, 2009a) and the Ecodesign Directive (European Commission, 2009b). Furthermore, due to the growing interest in the environment and the climate change issues, the LCA continues gaining importance not only in the policy but also in the industrial sector. Currently, there is an increase of LCA use by industry in order to help reduce the environmental burdens of the goods and services life cycle. Additionally, LCA is used for the improvement of the competitiveness of a company's products and for communication purposes. Furthermore, LCA is also used in decision-making for the improvement of product design, and benchmarking of product system options (European Commission, 2015).

According to the two ISO standards on LCA, ISO 14044 (ISO, 2006a) and ISO 14040 (ISO, 2006b), LCA consists of four phases (Figure 4):

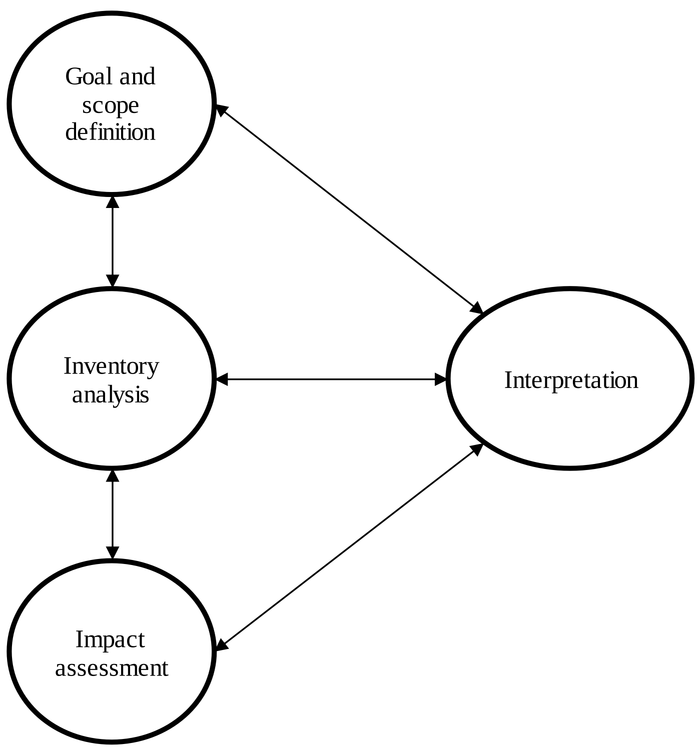

Figure 4: Phases of a LCA *(adapted from ISO (2006b))*

- Goal and scope definition determines the depth and direction that the study will have. The purpose is defined by stating the reason for which the assessment is conducted and the way in which the results will be used. The scope of the LCA defines basically:
    - Functional unit (FU): determines equivalence between systems and provides a reference to which the input and output data are normalized. The FU must be clearly defined and be measurable in order to facilitate the comparison of the results between different products and studies. All inventoried data are related to the FU.
    - System boundaries: define the stages and processes considered in the life cycle (e.g., extraction of raw materials, manufacturing, use and end-of-life) as well as the inputs and outputs (e.g., energy consumption and air emissions).
    - Cut-off rules: are criteria used in order to decide which inputs and outputs will be studied (considering mass, energy and environmental relevance). They have to be clearly stated and justified.
    - Environmental impact categories definition: involves the definition of the environmental impact categories to be included in the study depending on its scope and goal, with the objective of describing the impacts caused by the studied products. The impact categories are many (e.g., climate change, ozone depletion and acidification) but it is not obligatory to consider them all.
    - Data quality requirements: specify and characterize the data needed for the study and should be defined depending on the scope and goal of the study. They englobe various aspects such as time, geography, technology, sources and uncertainty.
    - Assumptions and limitations: there is a possibility that along the preparation of a LCA work, the data are not sufficient or available and thus, it is needed to make assumptions or exclusions. Those assumptions and/or limitations have to be mentioned in a transparent and detailed way in order to allow the reader to understand and identify them.
- Inventory analysis (LCI), where the unit processes of the system are analyzed in order to identify and also quantify energy, water, materials use and environmental releases

(i.e. air emissions, solid waste disposal and wastewater discharge). This description can be represented in process flow charts and also mass balance equations can be used to calculate the inputs and outputs of the system. This LCA phase contains various issues:

- Data collection: includes the gathering and treatment of the data and is usually the most work intensive part of the entire LCA. The collected data regard all the unit processes included in the system boundaries of the system under study and they can be quantitative or qualitative (when quantitative data are missing).
- Refining system boundaries: even though the initial system boundaries are specified in the previous phase, after the data collection it might be needed to redefine them due to exclusions, lack of data, etc.
- Allocation: when the system under study considers multifunctional production processes (e.g., processes related to reuse and recycling), it might be needed to apply allocation. This means that the input and/or output flows of a process are portioned to the product system under study. The ISO 14040-44 series (ISO, 2006a, b) recommend avoiding allocation whenever possible. This can be done through subdivision of certain processes or by expanding the system boundaries to include the additional functions related to them. When this is not possible, methods that reflect the physical relationship must be used, such as mass and energy content or using other relevant variables, such as economic value of the products, for the allocation of the impacts.

- Impact assessment, where occurs the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the previous stage. Impact assessment should address ecological and human health effects as well as resource depletion. In this stage the establishment of a linkage between the product or process and its potential environmental impacts is attempted. This phase includes the following elements:
    - One mandatory step of this phase is the selection of impact categories, category indicators and characterization models (used to link inventory indicators to (sub)impact categories through causal relationship).

        - There are several methods that can be used for the impact assessment in an LCA study considering different environmental impact categories. Some of the most established methods are Eco-indicator 99 (Goedkoop and Spriensma, 2000), CML 2001 (Guinée et al. 2002), TRACI (Bare et al., 2003), ReCiPe (Goedkoop et al., 2008) and ILCD (European Commission, 2010). Thus, depending on the impact categories that need to be included in the study one method or a combination of methods can be chosen.
    - Classification: is a mandatory step of the impact assessment that assigns the LCI results to the selected impact categories. For example, CO_2 emissions can be classified into the global warming category.
    - Characterization: is a quantitative and mandatory step that provides a way to directly compare the LCI results within each impact category. In this step conversion factors (characterization/ equivalency factors) use formulas in order to convert the different inventory inputs into directly comparable impact indicators.
    - Normalization: is an optional step and it is applied to scale the data by a reference factor (e.g. a region's per capita environmental burden) in order to clarify the relative impact of a substance in a given context.
    - Grouping: is another optional step that consists of the sorting and ranking of the impact categories included in the assessment in a given priority (e.g. high, medium and low priority).
    - Weighting: is an optional step and it is defined as the process of converting indicator results by using numerical factors based on value choices. It is basically the application of quantitative measures of the relative severity of different environmental changes.
    - Data quality analysis: is an optional step that considers the better understanding of the significance, uncertainty and sensitivity of the LCI results.
- Interpretation is the final stage where the results of the inventory analysis and the impact assessment are being evaluated and tested in order to check their validity before making

and reporting conclusions, with a clear understanding of the assumptions used to generate the results. In this phase, the most significant environmental issues are identified and the main conclusions and recommendations are presented in order to improve the future environmental impacts of the products under study.

2.2.2 Advantages and limitations of life cycle assessment

The use of LCA methodology, for the evaluation of the environmental impacts of a product, is constantly gaining importance and its application for decision-making in services and organizations is rapidly growing. However, both the advantages and disadvantages of this methodology have to be acknowledged in order to make better decisions based on the obtained results.

One of the most important advantages of LCA is the possibility to consider the various stages of a product along its entire life cycle (e.g. extraction of raw materials, manufacturing, use and end-of-life). In this way it is easier to identify the stages that are more influential for the total environmental impact of the product and focus on those hotspots in order to improve their environmental performance and thus, the total environmental impact of the product under study (Ekvall et al., 2007). This can have great benefits both for industries and consumers. In the case of the former, following a more sustainable direction, the organization can develop and apply cleaner processes and product options, improving its image and brand value. In the case of the latter, LCA can point to a more sustainable consumption direction by offering better information for purchasing, transport systems, energy sources, to guide consumers. Furthermore, the transparency of LCA application supports the publication and public access of the environmental results, making it easier to obtain the desired information and the comparison of different results (e.g. comparison of different LCA results of various materials used for the manufacturing of the same product) (European Commission, 2010).

On the other hand, the collection of data needed for the evaluation of the environmental performance of a product through LCA, can be a difficult and time consuming process. The collection of information and raw data for a new or not yet studied product, can be even more difficult considering the amount of inflows and outflows needed for the correct and complete LCA evaluation. Another important disadvantage of LCA is the uncertainty involved in the studies (European Commission, 2010; Finnveden et al., 2009; Lloyd et al., 2007). Specifically, there are three categories of uncertainties related to LCA:

- Scenario uncertainty: the different choices made, e.g. allocation and cut-off, can cause significant variation of results which can be quantified through sensitivity analysis.
- Parameter uncertainty: the statistical uncertainty in data assessed analytically or by simulation can also result in variations.
- Model uncertainty: insufficient knowledge of the mechanism of the studied system, is difficult to quantify and can result to important variations.

Apart from the limitations that may be encountered by the use of LCA for the evaluation of the environmental impacts of a product, it is a commonly used tool for this objective. Furthermore, through the identification of the restricting characteristics, the understanding of the implications that those may have and by finding complementary tools, the outcome of a LCA study could be further improved.

2.2.3 Carbon footprint and biogenic carbon consideration in life cycle assessment

As mentioned, LCA takes into consideration various environmental impact categories (e.g., climate change, ozone depletion, acidification and photochemical ozone formation). One of them, and possibly the one that has gained distinct importance during the last decades is the climate change impact category used for the calculation of a product's CF. CF is the term used to describe the amount of GHG emissions caused by an activity, process or entity and it is a way for the assessment of their contribution to climate change. Thus, CF is basically a part of LCA since it only considers the impact category of climate change.

Considering that cork is a forest-based product, it sequesters and also emits biogenic carbon emissions. As previously mentioned, when cork is used for the manufacturing of different cork products, the carbon contained in that cork is stored for longer (during the use period and disposal of cork in landfills) and new cork replacing the extracted cork can grow and carry on carbon sequestration (Cherubini et al., 2011). Forest-based products are generally considered as potentially carbon-neutral materials considering that the amount of carbon sequestrated by the forest will be then emitted into the atmosphere at the manufacturing stage (e.g. burnt cork dust for thermal energy production) and at the end-of-life of the product (Althaus et al., 2009; Guineé et al., 2002).

Thus, tLCA often treats biogenic CO_2 emissions by excluding them from the assessment. Currently, even when carbon uptake during biomass growth is accounted for (as a negative emission) and the subsequent release as well (as a positive emission), the duration of storage is usually disregarded. More specifically, the effect of delaying the emission of the temporarily stored carbon is not taken into account resulting in incomplete conclusions (Garcia and Freire, 2014; Brandão et al., 2013, 2010; Müller-Wenk et al., 2010). However, based on a newer insight, biogenic CO_2 should be considered in the calculation of the environmental impact of the forest-based products since it is more realistic (Levasseur et al., 2012, 2010). In literature, there are various methods suggested for the consideration of the biogenic emissions in the calculations as presented in this section.

- **The Moura-Costa method**

The Moura-Costa method is one of the oldest methods suggested for the calculation of carbon sequestration and temporary storage (Moura-Costa and Wilson, 2000) under the Clean Development Mechanism in the context of Land Use, Land-Use Change and Forestry (LULUCF) of the Kyoto Protocol. This method uses a ton-year approach and considers an equivalency factor between kg CO_2-eq and kg CO_2-year in order to account for a credit for carbon binding and storage for the years that carbon doesn't return to the atmosphere.

The Moura-Costa method doesn't set a starting and an ending point of the time horizon, it only considers its length. Thus, the impact of the emission is considered independently of when it occurred. This method considers as baseline the impact on radiative forcing caused by an emission at time zero of 1 t of CO_2 during a 100-year time period, which is the suggested reference time frame in the Kyoto Protocol (UNFCCC, 2008). This relation is presented in Figure 5. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Forster et al., 2007) data over this period, the atmospheric load curve integral during the 100-year period is approximately 48 ton-years (Figure 5a).

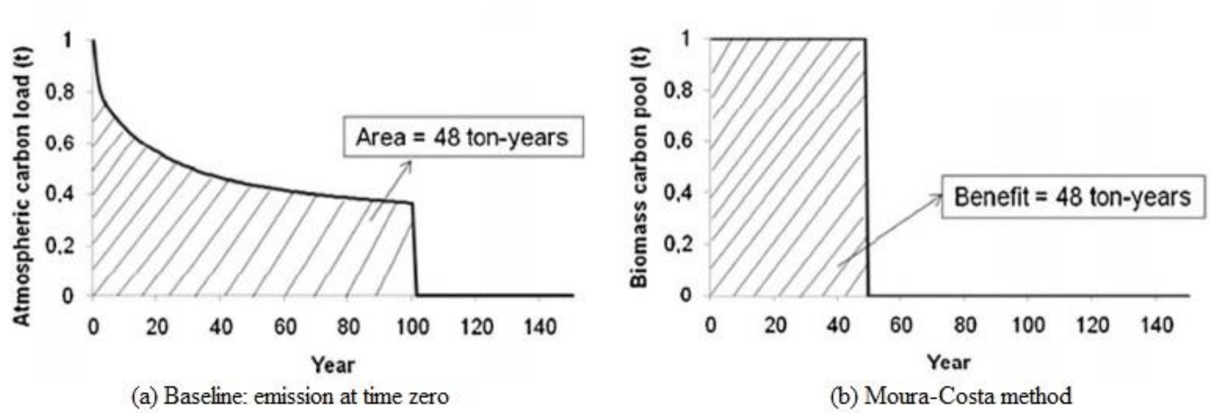

Figure 5: Representation of the Moura-Costa method (b) considering the cumulative radiative forcing of 1 t CO_2 (a) *(adapted from: Levasseur et al., 2012)*

The Moura-Costa method based on this value, considers an equivalency factor of 48 years. This means that removing 1 t of CO_2 from the atmosphere and storing it for 48 years is equivalent to avoiding a 1 t pulse emission of CO_2 when considering a 100-year integration and in terms of avoided radiative forcing. The credits are then distributed evenly, meaning that storing 1 t of CO_2 for 1 year compensates for a pulse emission of 1 ton-year/ 48 ton-years/t CO_2 = 0.02 t (Figure 5b).

In literature there are a few examples of studies considering the Moura-Costa method in comparison to other methods (e.g., Brandão et al., 2013; Levasseur et al., 2012). Additionally, this method is used for the calculation of delayed biogenic carbon emissions in the study of Garcia and Freire (2014) evaluating a particleboard's CF. The main issue with the Moura-Costa method is the consideration of a fixed length of time regardless of the specific time when the emission occurs (Brandão et al., 2013).

- **The Lashof method**

The Lashof method is another ton-year approach (Fearnside et al., 2000) under the Clean Development Mechanism in the context of Land Use, Land-Use Change and Forestry (LULUCF) of the Kyoto Protocol. This method considers a credit (in mass of CO_2-eq) for the removal and storing of CO_2 from the atmosphere (a credit for delaying an emission). More specifically, the Lashof method considers the same baseline as described in the Moura-Costa method. However, in this case the sequestration of 1 t of CO_2 during 48 years would result to a benefit of 19 ton-years. As presented in Figure 6, the result is obtained from the difference between the atmospheric load curve integral from an emission occurring at time zero (years 0 to 100) (Figure 6a) and the atmospheric load curve integral of the delayed emission (years 48 to 100) (Figure 6b). Consequently, the credit given for the sequestration of 1 t of CO_2 during 48 years is 19 ton-years / 48 ton-years/t CO_2 eq. = 0.4 t CO_2 eq. which is different than the result calculated with the Moura-Costa method.

Additionally, according to this method, the removal or storage of CO_2 for a period of 100 years or more is considered a neutral emission. When applying this method, the credit of a delayed emission never results in more than 100%. There are a few LCA studies found in literature applying the Lashof method such as Levasseur et al. (2012) for the assessment of a temporary carbon sequestration project by afforestation and Courchesne et al. (2010) for three biofuels (maize ethanol produced in the United States, sugar cane ethanol produced in Brazil and cellulosic ethanol made from willow plantation in the United States). As noted, the advantage of the Lashof method is its simplicity that facilitates its application.

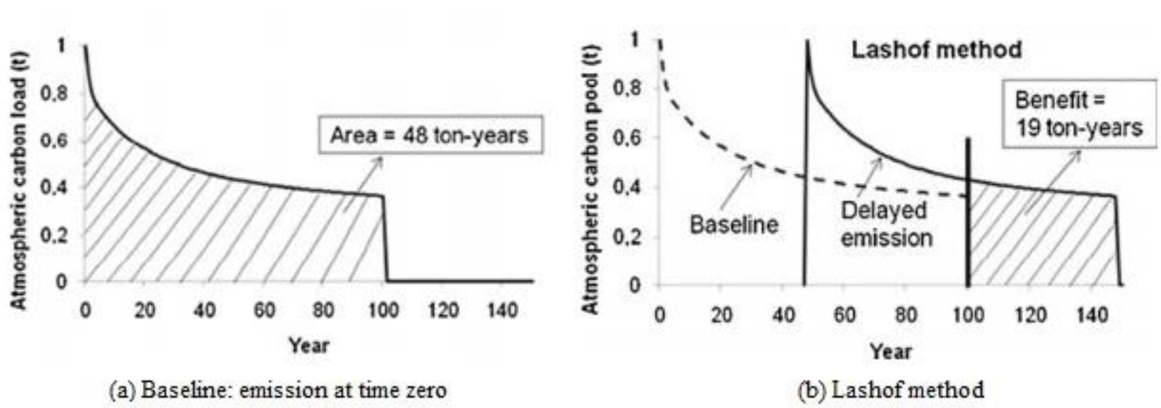

Figure 6: Representation of the Lashof method (b) considering the cumulative radiative forcing of 1 t CO_2 (a) *(adapted from: Levasseur et al., 2012)*

- **The Publicly Available Specification (PAS) 2050**

The first PAS 2050 was published by the British Standard Institution in 2008 in order to be used for the calculation of the CF of products and services with a credit given to temporary carbon storage and delayed emissions (BSI, 2008). The initial PAS 2050 accounted for temporary carbon storage in products considering the effect of delayed emissions on radiative forcing during the period from the product's manufacturing and up to 100 years. The specifications of the initial PAS 2050 (Section 5.4 of PAS 2050 document) considered carbon storage in products and also provided eligibility criteria for the products that could be assessed for carbon storage (1- not for human or animal ingestion, 2- more than 50% of the mass of carbon of biogenic origin in the product remains removed from the atmosphere for one year or more following production of the product and 3- the material containing the biogenic carbon is obtained from either human actions that cause its formation for the purpose of using it as an input to a process (e.g. managed forestry) or it is a recycled or re-use input).

PAS 2050 distinguished the storage periods in short and long. More specifically, this method for short storage periods uses a linear approach and for long storage periods uses the average amount of carbon stored over 100 years. Additionally, it notes that the emissions that occur after 100 years are not considered in the calculations. The published specification, in Annex C of PAS 2050 document, provides specific formulas for the calculation of the weighted average impact of delayed emissions depending of the delay period of the emissions.

More specifically, there is one formula for the calculation of the weighting factor, FW, when emissions from the use phase or the final disposal phase of a product occur as a single release within 25 years from the formation of the product (Equation 1):

$$\text{FW}= \frac{100-(0.76 * t_0)}{100} \quad \text{Equation 1}$$

Where, t_o is the number of years between formation of the product and the single release of the emissions. When the aforementioned case does not occur (there is not only a single release within 25 years from the formation of the product) for the weighted average time the emissions are in the atmosphere another formula is provided (Equation 2):

$$\text{FW}= \frac{\sum_{i=1}^{100} x_i * (100-i)}{100} \quad \text{Equation 2}$$

Where i is each year in which emissions occur and x is the proportion of total emissions occurring in any year i. The calculated FW is then multiplied by the biogenic carbon emissions during the end-of-life stage of the product under study.

The initial PAS 2050 was revised in 2011 (BSI, 2011) in order to include advances both in theoretical knowledge and in practical experience. The revised PAS 2050 continues to provide a framework both comprehensive and consistent for the calculation of the CF of goods and services with a credit given to temporary carbon storage and delayed emissions. The revised PAS 2050 (in Annex E of PAS 2050 document) considered the same formulas regarding carbon storage provided in the initial PAS 2050. However, it included some new aspects regarding biogenic carbon and CF. The most important changes included in the PAS 2050 revision related to biogenic carbon is the inclusion of CO_2 removals and emissions from biogenic sources in the calculations. This change was made considering that biogenic carbon can be important for certain products where there is long term carbon storage. In the revised version of PAS 2050 the previous requirement for applying a weighting factor for delayed emissions has been removed and is now optional with a requirement for separate reporting if a weighting factor is applied.

In literature, there is a number of studies mentioning the importance and input of this method in the general knowledge for the accounting of biogenic carbon, as for example in Brandão et al. (2013), Baldo et al. (2009) and Sinden (2009). Also there are other studies considering this method in the accounting of biogenic emissions in the evaluation of different products, such as Garcia and Freire (2014) for the CF evaluation of a particleboard and Vogtländer et al. (2014) for the CF evaluation of wood and bamboo.

- **International Reference Life Cycle Data System (ILCD)**

The ILCD handbook was published by the European Commission in order to provide a detailed technical guidance to the ISO standards on LCA (ISO, 2006a, b). The ILCD handbook suggests formulas for the accounting of GHG emissions considering a time horizon of 100 years (European Commission, 2010). According to ILCD, the consideration of temporary carbon storage and delayed emissions should be considered in the LCA only when stated by the goal of the study. In this case, equation 3 is used for the calculation of a weighting factor FW, which is then multiplied by the biogenic carbon emissions during the end-of-life stage of the product under study.

$$\mathrm{FW}=\frac{(100-(1*t))}{100} \quad \text{Equation 3}$$

Where *t* is the total of years when occurs biogenic carbon storage (equal to the use period and time at the landfill of the product). By subtracting the biogenic emissions during the end-of-life stage from the total biogenic carbon contained in the product, the stored emissions are calculated. In literature there are many studies considering this method, in some cases in comparison with other methods such as Vogtländer et al. (2014) for the CF evaluation of wood and bamboo and Brandão and Levasseur (2010), comparing ILCD, PAS 2050 and the Lashof method. From the comparison of the methods it is concluded that different results are obtained when applying the different methods and that the way that carbon sequestration in wood products is dealt within LCA needs further refinement.

- **ISO/TS 14067**

ISO/TS 14067 is one of the most recent standards considering the calculation of products CF (ISO, 2013). This standard is based on already existing ISO standards (ISO, 2006a, b; ISO, 2000c) and provides specific requirements and guidelines both for the quantification as well as the communication of products CF. Specifically, it provides guidelines on how to treat specific GHG emissions and removals (e.g. fossil and biogenic carbon, carbon storage in products, land-use change). In this standard, the use of a weighting factor to calculate the effect of delayed emissions is optional and there is no specific method recommended. However, it is mentioned that if the effect of delayed emissions is considered, it has to be documented separately. An example of an LCA study applying ISO/TS 14067 while highlighting the lack of a recommended method for the calculation of delayed emissions is the study of Garcia and Freire (2014). This study presents the evaluation of a particleboard through the application of various methods. However, when considering the delayed emissions it is mentioned that ISO/TS 14067 does not provide a specific formula for the evaluation of the delayed emissions as occurs for example in the case of PAS 2050 and thus, alternative methods were assessed.

- **Dynamic LCA**

Due to lack of temporal information, LCA mainly relies on steady-state models and this is considered to be an important limitation since it decreases LCA accuracy (Reap et al., 2008; Hauschild, 2005). In order to improve the precision of the tLCA, Pehnt (2006) considered the dynamics of time-related socioeconomic factors. This led to progress of the technical parameters, and then applied the proposed dLCA to different renewable energy systems. By incorporating time-dependent technical parameters of material inputs, this dLCA proposed by Pehnt (2006), focused on the improvement of the accuracy of LCI. In recent years, various methods were developed in order to deal with the temporal problem of LCA and in order to consider timing when evaluating global warming impacts in an LCA context (Levasseur et al., 2010; O'Hare et al., 2009; Kendall et al., 2009). The scientific community mainly accepts the dLCA approach developed by Levasseur et al. (2010) (Dyckhoff and Kasah, 2014; Matsumoto et al., 2011).

The dLCA approach of Levasseur et al. (2010) considers one-year time steps and was developed due to the exclusion of the albedo effect (i.e. the percentage of incoming solar radiation reflected off the Earth) in the existing methods, such as the Moura-Costa and Lashof methods. Additionally, this method considers more GHGs (e.g., methane - CH_4 and dinitrogen monoxide - N_2O) and not only CO_2. This approach firstly considers a dynamic characterization factor, DCF(t), (in watts per year per square meter [W/yr/m^2]) which expresses the radiative forcing occurring t years after a pulse emission calculated through equation 4:

$$\mathrm{DCF(t)}= \int_{t-1}^{1} a * C(t)dt \quad \text{Equation 4}$$

Where, a is the instantaneous radiative forcing per unit mass increase in the atmosphere for the given GHG (in W/m^2/kg), C(t) is the atmospheric load of the given GHG t years after the emission (in kg).

By using the DCF, this method also calculates the instantaneous impact on global warming $GWI_{inst}(t)$ in W/m^2 by using equation 5 for the various GHG considered (example of consideration of CO_2 and CH_4):

$$GWI_{inst}(t) = \sum_{i=0}^{i}[g_{CO2}(i) * DCF_{CO2}(t-i)] + \sum_{i=0}^{i}[g_{CH4}(i) * DCF_{CH4}(t-i)] \quad \text{Equation 5}$$

Where, *g(i)* is the inventory result (sum of the positive and negative emissions) of the given GHG for year *i* (in kg). Thus, $GWI_{inst}(t)$ is basically the sum of the radiative forcing occurring at time *t* caused by all the GHG emission occurring. By summing all the $GWI_{inst}(t)$, the cumulative global warming impact, $GWI_{cum}(t)$ in W/m^2, is calculated through equation 6:

$$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(i) \quad \text{Equation 6}$$

In order to enable the comparison of the results of GWI_{cum} with the traditional LCA, this method also considers one more formula for the calculation of CF (LCA_{dyn}) as presented in equation 7:

$$LCA_{dyn} = \frac{GWI_{cum}(TH)}{\int_0^{TH} a_{CO2} * C(t)_{CO2} dt} \quad \text{Equation 7}$$

Where, *TH* is a chosen time horizon. Through this equation, the GWI_{cum} for the chosen TH is divided by the cumulative radiative forcing of a 1 kg CO_2 pulse emission occurring at time zero and this results to the global warming impact, LCA_{dyn} (in kg CO_2 eq.). Based on Equations 4-7, there is a software tool DYNCO$_2$ which can be used in order to calculate the impact of GHG emissions over a time period developed by Levasseur et al. (CIRAIG, 2016). An excel spreadsheet, is used and the GHGs emitted along the life cycle under study are introduced in DYNCO$_2$ in order to obtain the GWI_{inst}, GWI_{cum} and LCA_{dyn} results.

Even though dLCA is a relatively new method, it is already applied in some LCA studies in order to show the significance of time horizon in the obtained results and the final conclusions. Some examples are the studies of Levasseur et al. (2013) that applied the dynamic LCA on the life cycle of a wooden chair and Yang and Chen (2014) that applied this method on a crop residue gasification project.

Both studies applied the equations presented above and they both concluded that dLCA represents in a more realistic way of GHG emissions representation along the life cycle of the products since the emissions do not occur in one specific moment (as considered in tLCA). Thus, it can be more appropriate than the other methods that do not have this advantage.

Even though there are several methods that can be applied for the accounting of biogenic carbon emissions, it has to be mentioned that there is no general accordance on the most appropriate one. In literature, a number of studies reviewing the existing methods can be found (Arzoumanidis et al., 2014; Vogtländer et al., 2014; Brandão et al, 2013; Levasseur et al., 2012; Finkbeiner, 2009).

Even though the aforementioned studies present the various biogenic carbon accounting methods, they do not identify the most appropriate one. However, some of them (e.g., Brandão et al. (2013) and Levasseur et al. (2012)), highlight the importance of time horizon choice in the climate change assessment and point out its influence on the final results and reached conclusions.

2.2.4 State-of-the-art of LCA application in the cork sector

Recently, scientific research on the cork sector from an environmental point of view is gaining attention. This is mainly due to the increasing economic and environmental importance of cork oak forests and cork as a material, as well as the environmental impact of the manufactured products due to sustainability reasons.

Currently, in literature, there is a small number of LCA studies addressing cork as a raw material or as a final product with Portugal and Spain as the main contributors of LCA studies on cork. The prevalence of Iberian countries in the area is reasonable due to the fact that the majority of the cork oak forests is located in Portugal and Spain.

Table 2 presents the LCA studies found in literature regarding cork. It can be noticed that the LCA studies focus on the production of raw cork and some of the most representative cork products (e.g., natural cork stoppers, champagne cork stoppers and construction materials).

Table 2: Literature revision of cork LCA studies

Product	Study	Country	Functional unit	Allocation	System boundaries	Impact assessment method	Hotspot stage	Hotspot process
Raw cork	Dias et al. (2014)	Portugal and Spain	1 t of each type of raw cork	Mass & economic	Forest stage	ILCD	Stand tending	Fertilization, pruning, and cleaning
	González-García et al. (2013)	Portugal	1 t of reproduction cork	Economic	Forest stage	CML 2001	Cork stripping	Pruning, cleaning of spontaneous vegetation
	Rives et al. (2012a)	Spain	1 t of raw cork material	Mass & economic	Forest stage	CML 2001	Cork stripping	Shrub clearance and road maintenance
Natural cork stoppers	Rives et al. (2011)	Spain	1 million of natural cork stoppers	100% to main product	Preparation, manufacturing, finishing, transport to distributors, transport to landfill, end-of-life	CML 2001	Manufacturing	Second boiling and punching
	Ecobilancio (2010)	Italy	1 natural cork stopper	100% to main product	Preparation, manufacturing, finishing, transport to distributors, transport to landfill, end-of-life	CML 1992, IPCC	Manufacturing	Thermal energy consumption for the process of boiling
	PwC/Ecobilan (2008)	Portugal	1 thousand natural cork stoppers	100% to main product	Preparation, manufacturing, finishing, bottling, transport to distributors, transport to landfill, end-of-life	CML 1992, IPCC, WMO, ETH	Manufacturing	Not specified
Champagne stoppers	Rives et al. (2012b)	Spain	1 million of champagne cork stoppers	Mass	Preparation, disc and granule manufacturing, champagne cork stoppers manufacturing and finishing	CML 2001	Champagne stopper manufacturing	Body agglomeration due to the consumption of electricity and the production of resins
Construction materials	Pargana et al. (2014)	Portugal	1 m^2 of cork slab (black cork)	Mass	Forest, manufacturing	CML 2001	Manufacturing	Use of electricity during the process of trituration
	Rives et al. (2012c)	Spain	1 t of final product (white/black cork granulate)	100% to main product	Forest, manufacturing (cork preparation, cork granulation)	CML 2001	Granulation	Use of electricity during the process of trituration
	Bribrian et al. (2010)	Spain	1 kg of cork (white cork)	100% to main product	Forest, manufacturing	IPPC 2007, CED	Manufacturing	Not specified
Integrated study	Rives et al. (2013)	Spain	1 t of raw cork material converted into the most representative cork products *	Mass & economic	Forest, manufacturing	CML 2001	Manufacturing of champagne cork stoppers	Body agglomeration due to the consumption of electricity and the production of resins

* the cork products considered are natural cork stoppers, champagne cork stoppers, white cork granulate and black cork granulate

As noticed in Table 2, the different studies apply different system boundaries, allocation criteria, impact assessment methods and FUs making the comparison of the results regarding the environmental impacts more difficult. It should be noted that the comparison of the results obtained in the various LCA studies revised here, is performed by product type in order to be easier to reach conclusions.

Raw cork production

There are three LCA studies focusing on the production of raw cork. Two of them are focusing on the production of raw cork including all the needed management activities (González-García et al. (2013) for Portugal and Rives et al. (2012a) for Spain), and one of them is a comparative LCA study of raw cork production in Portugal and Spain (Dias et al., 2014). Those three studies, take into account all the activities for the preparation and management of the cork oak forest during its entire life cycle in order to evaluate the total environmental impact of the forest stage and the processes that have the lowest environmental performance. It has to be noted that the life cycle length considered in the studies of González-García et al. (2013) and Dias et al. (2014) is the same, 170 years, while in the study of Rives et al. (2012a) the lifespan considered is 200 years. All three studies used primary data from cork producers in Portugal (regions of Alentejo and Tagus Valley) and Spain (region of Catalonia).

The FU considered in the three studies is 1 t of raw cork produced. However, attention should be given when comparing the obtained results since they consider different cork types. Additionally, the system boundaries in all three studies, consider only the forest stage which is divided in sub-stages consisting of various management processes. It has to be noted that the stages have different sub-stages and consider different processes, even if the number of sub-stages considered remains the same. Furthermore, the number of repetitions of each process are different since this is based on the characteristics of the management model applied to the cork stand. This aspect is important to mention since the frequency of the various processes as well as the differences among the sub-stages can influence the result and thus, it is important to be considered in their comparison.

Another difference noticed is the allocation method applied in each study. In the study of González-García et al. (2013), an economic allocation is applied while in the other two studies both mass and economic allocation was applied. When mass allocation is applied, the obtained results are the same per t of each cork type. It has to be noted that the choice of different allocation method can influence significantly the final environmental impact results and thus, it is important to be clarified in the LCA studies. Finally, as seen in Table 2, the studies consider different methods for the evaluation of the environmental impacts, namely González-García et al. (2013) and Rives et al. (2012a) used the CML 2001, while Dias et al. (2014) used the ILCD method. Thus, only one impact category can be compared, the climate change (CC) category since it considers the same unit (kg CO_2 eq.) and characterization method.

Figure 7 shows the CC results of the three studies per FU (1 t of each cork type). It has to be noted that in order to facilitate the comparison, the average results of the studies were considered in the case of González-García et al. (2013) where two different management approaches were considered in two different locations of Portugal and in the Dias et al. (2014) study where both plantation and natural regeneration were considered for the establishment of the cork stand.

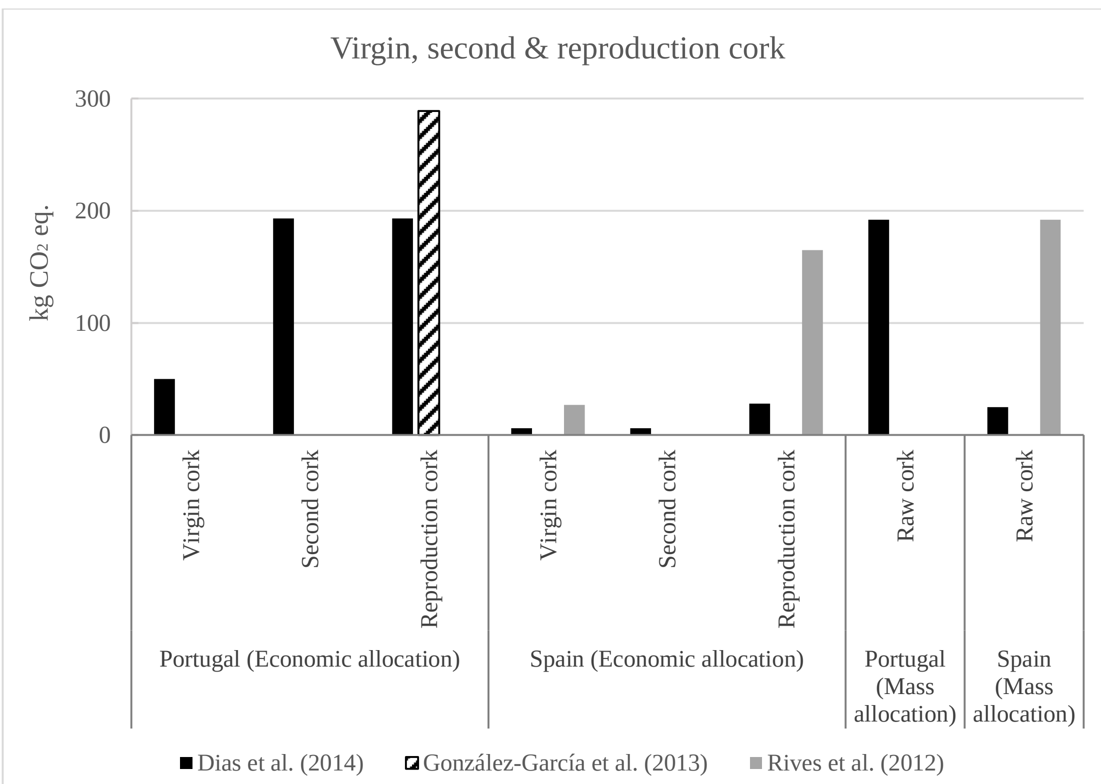

Figure 7: Comparison of climate change results regarding raw cork production (FU = 1 of each raw cork type)

It can be seen that the study of González-García et al. (2013) presents the highest CC result when economic allocation is applied for the reproduction cork type. Furthermore, it can be noticed that the results both for mass and economic allocation, for all three cork types, in Portugal are higher than in the case of Spain. However, this outcome was expected considering that the intensity and repetition of the management activities in Portugal is higher. Generally, in the case of Spain the environmental impact deriving from the preparation of the soil for the stand is lower than in the case of Portugal. Additionally, it can be noticed that the two studies considering both mass and economic allocation (Dias et al., 2014; Rives et al., 2012a) present different results (for all three cork types) when economic allocation is applied. Furthermore, the study of Dias et al. (2014) presents much lower CC results when economic allocation is applied for the case of Spain compared to the study of Rives et al. (2012a). However, this is expected since the former study considered much smaller transport distances.

According to the conclusions of the González-García et al. (2013) study, the intensity and repetitions of the management activities influences the total impact, nevertheless the highest emissions derive from the clearing of spontaneous vegetation and pruning processes. In the study of Rives et al. (2012a), the main influence derived from the cork extraction sub-stage due to the transport of the workers to the forest area. In the study of Dias et al. (2014), the results showed that the environmental impact of raw cork production in Portugal is higher than in Spain mainly due to the management model considered which consists of the application of mechanized processes more frequently. From the comparison of the three studies the importance of considering the same allocation method is highlighted since very different results are obtained. Even though the consideration of similar system boundaries facilitates the comparison of the studies, the FU considered is not the same in all three studies and thus, the CC results had to be converted to the same FU in order to obtain the comparison results.

It is important to mention that the studies of González-García et al. (2013) and Dias et al. (2014) did not consider biogenic carbon. More, specifically, in the study of Dias et al. (2014) it is mentioned that biogenic CO_2 is assumed to be neutral and thus, it is excluded from the calculation. The study of Rives et al. (2012a) is the only of the three studies that considers biogenic carbon and performs a CO_2 balance (where considers the sequestration of CO_2 at the cork oak forest) associated with 1 t of raw cork material. In this study it was considered that 2.9

t of CO_2 are sequestered per hectare of cork forest per year. This consideration shows that the quantity of CO_2 sequestered by cork oak forests is greater than the emission produced during their exploitation. However, it is highlighted that CO_2 fixation should be further studied and verified by experimental methods measuring the growth of the forest and the cork oak trees.

Natural cork stoppers production

There are three LCA studies for natural cork stoppers: Rives et al. (2011), Ecobilancio (2010) and PwC/Ecobilan (2008) focusing on the production of natural cork stoppers in Spain, Italy and Portugal, respectively. As the study of Ecobilancio (2010) was published in Italian, in order to avoid misunderstandings, it was only considered in the general comparison (Table 2). Thus, here only the other two studies are compared. The two studies considered different FU and thus, it was necessary to convert the FU (to 1 thousand natural cork stoppers) in order to obtain comparable results. More specifically, Rives et al. (2011) considered 1 million natural cork stoppers and PwC/Ecobilan (2008) 1 thousand natural cork stoppers. None of the studies considered allocation since in both cases all impacts were allocated to the main product (natural cork stoppers).

Another common aspect of the studies was the LCA approach considering the transport of raw cork to the preparation unit and then all the processes involved in the manufacturing of the natural cork stoppers, their distribution and their final destination. It has to be noted that both studies only considered landfilling as end-of-life destination, due to lack of information regarding the end-of-life aspect of cork and as noted in the studies, the behavior of cork in landfills was considered similar to that of wood. Additionally, in both studies the data were collected from natural cork stoppers producers. Concerning the choice of the impact assessment method, as seen in Table 2, the two studies considered different methods and thus, once again only the impact category of CC will be compared.

Figure 8 presents the results of the CC comparison of the two studies considering the FU of 1 thousand natural cork stoppers. It can be seen that the obtained results are different, with the study of Rives et al. (2011) presenting a greater CC total. According to the conclusions of the aforementioned studies, the hotspot sub-stages considered in the system boundary was the manufacturing stage. Moreover, in the study of Rives et al. (2011) it was specified that the process that mainly influenced the total CC was the second boiling due to the consumption of electricity. On the other hand, the PwC/Ecobilan (2008) does not specify the most influential process. Considering the results presented in Figure 8 and the conclusions of the studies, the difference between the two results can be mainly explained from the fuel used for the production of thermal energy needed for the processes. More specifically, in the study of Rives et al. (2011) diesel oil is consumed, while in the study of PwC/Ecobilan (2008) cork dust is burnt for the production of thermal energy resulting in lower GHG emissions and thus, lower CC impact. From this comparison, the importance and influence of the fuels to the impact of the products can be seen since by using cork dust, the CF decreased by 50%.

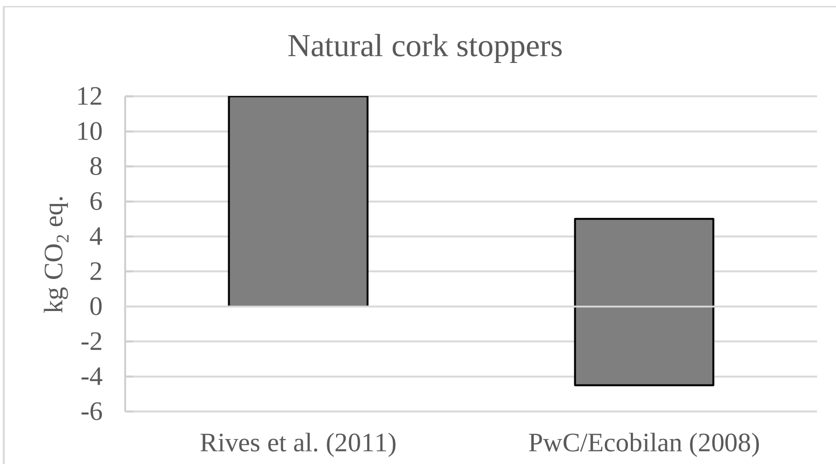

Figure 8: Comparison of climate change results regarding raw cork production (FU = 1,000 natural cork stoppers)

Only one of the two studies discusses the topic of biogenic carbon. The beneficial impact in terms of emission of GHG associated to cork stoppers is due to the carbon intake during cork growth (Figure 8). The study of Pwc/Ecobilan (2008) includes a section regarding the carbon sink associated to cork forestry. As mentioned in the study, it was considered that 6.56 t of CO_2 is sequestered per hectare of a Portuguese cork oak forest close to Évora (south-central region of Portugal). Using this value, the total amount of carbon sink corresponding to the cork oak forest and to each kg of cork was estimated. More specifically, it was found that for the production of 1 thousand natural cork stoppers 120 kg of CO_2 would be sequestered at the cork forest.

Champagne cork stoppers production

As seen in Table 2, for the product of champagne cork stoppers there is only one LCA study. This study is from Rives et al. (2012b) and considered the production of champagne cork stoppers in Spain. The FU used was 1 million of champagne cork stoppers and the allocation applied was mass allocation (for discs and cork waste). The boundaries of the system considered a gate-to-gate LCA approach and included the processes involved in the preparation of cork, the manufacturing of the discs and granules (that constitute the body of the stoppers), the manufacturing of the champagne cork stoppers and the finishing of the final product. The impact assessment method applied was the CML 2001. It is important to note that this study does not consider the biogenic carbon emissions.

According to the obtained results, the hotspot of the production of the champagne cork stoppers was the manufacturing stage due to the agglomeration process needed for producing the body of the stoppers. In this process, the granules of cork are glued together with resins. The high consumption of electricity as well as the production of the resins, result to the high environmental impact of this stage. Thus, regarding the manufacturing process of the champagne cork stoppers, attention should be given to this stage in order to decrease its impact. Alternative methods and equipment could be considered for the substitution/decrease of electricity consumption. Regarding the resins used, new materials could be tested in order to decrease the emissions from their production without however decreasing the quality of the final product.

Cork construction materials production

Another very common use of cork is for the production of agglomerated cork slab and granules to be used in construction, as building insulation and covering. In literature there are three studies focusing on the production of both black and white agglomerated cork slab. One of the studies, Pargana et al. (2014) presented a comparative environmental analysis among various insulation materials considering expanded cork slab (using ‘falca’) produced in Portugal. Another comparative study is that of Bribrian et al. (2010) but in this case agglomerated white cork slab produced in Spain was considered. The study of Rives et al. (2012c) presented the environmental impact for both black and white cork granulates produced in Spain.

As seen in Table 2, the FU of the studies is different. Rives et al. (2012c) considered 1 t of final product (black and white cork granulates), Bribrian et al. (2010) considered 1 kg of cork used for the production of white cork slab and Pargana et al. (2014) used 1 m^2 of cork slab, providing however that 1 m^2 of cork slab contains 4.4 kg of cork. Thus, it was necessary to convert the FU for the comparison of the obtained results. The allocation applied in the three studies is different. More specifically, in the study of Rives et al. (2012c) and Bribrian et al. (2010) the cut-off method was applied. Basically, the environmental burdens were assigned to the system directly responsible for them. The study of Pargana et al. (2014) considered mass allocation between the produced expanded cork slab and granules. Additionally, the three studies considered similar system boundaries applying a cradle-to-gate approach. This approach included the forest stage and the manufacturing of the cork slab (includes the cork preparation and cork trituration). However, as presented in Table 2, the studies considered different impact assessment methods and thus, only the CC impact category was compared. It is important to note that none of the mentioned studies considered the biogenic carbon in the CF calculations. Figure 9 presents the comparison of the aforementioned studies considering the CC impact category. Since the studies included different cork materials used in construction, the FU of 1 kg of final product was considered. The result for black and white cork granulate in the study of Rives et al. (2012c) was very similar and thus, they are represented in the same bar in the graph of Figure 9.

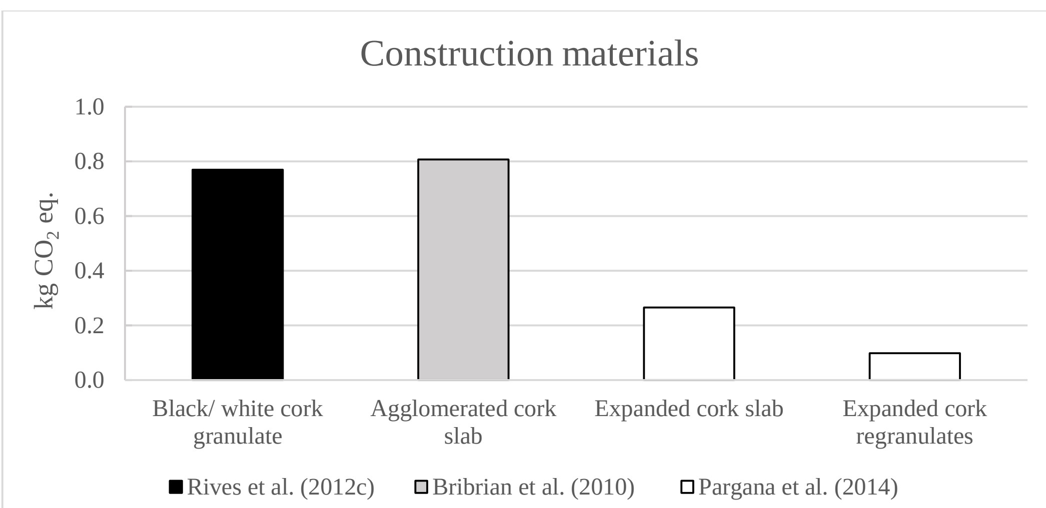

Figure 9: Comparison of climate change results regarding cork construction materials (FU = 1 kg of final product)

In the two Spanish studies, it can be seen that the total CC is very similar. The Rives et al. (2012c) study specifies that the manufacturing stage was the most influential due to the consumption of electricity during the process of trituration. The Bribrian et al. (2010) study agrees with the hotspot stage (manufacturing stage) but it does not specify the most influential process. Concerning the production of expanded cork slab and granules, it can be noticed that the CC total is much lower than in the two other studies (Rives et al., 2012c; Bribrian et al., 2010) since the manufacturing process mainly uses thermal energy deriving from burnt cork dust. Thus, the consumption of fossil fuels is much lower resulting to a lower CC total. As specified in the Pargana et al. (2014) study the stage hotspot is the manufacturing stage and the hotspot process is the consumption of electricity for trituration.

Integrated environmental analysis of the main cork products in Spain

One integrated Spanish LCA study considering the main cork products can be found in literature (Rives et al., 2013). This study assesses the production of four cork products (natural cork stoppers, champagne cork stoppers, black cork granulate and white cork granulate) considered to be the main cork products of the cork sector in Spain. The FU considered in the study is 1 t of raw cork material converted into the most representative cork products (186 kg of natural cork stoppers, 64 kg of white cork granulate, 74 kg of black cork granulate and 414 kg of champagne cork stoppers). The study considered both economic and mass allocation in order to evaluate their influence on the obtained results. The impact assessment method applied was the CML 2001.

Figure 10 presents the CC obtained results for the various cork products. As presented in the Rives et al. (2013) study, both when applying economic and mass allocation, the most influential cork product is the champagne cork stopper and the hotspot stage is the agglomeration stage. In this stage the main influence derives from the body agglomeration of the stoppers due to the consumption of electricity and the production of resins needed in the process. The second most influential product is the natural cork stopper. The greatest impact during the natural cork stoppers manufacturing process derives from the combustion of fossil fuels. However, the mass allocation is more favorable for the natural cork stopper since the CC total is lower than when applying economic allocation (due to the higher economic value of the natural cork stoppers).

The opposite occurs in the case of the champagne cork stoppers where the economic allocation is more favorable than mass allocation.

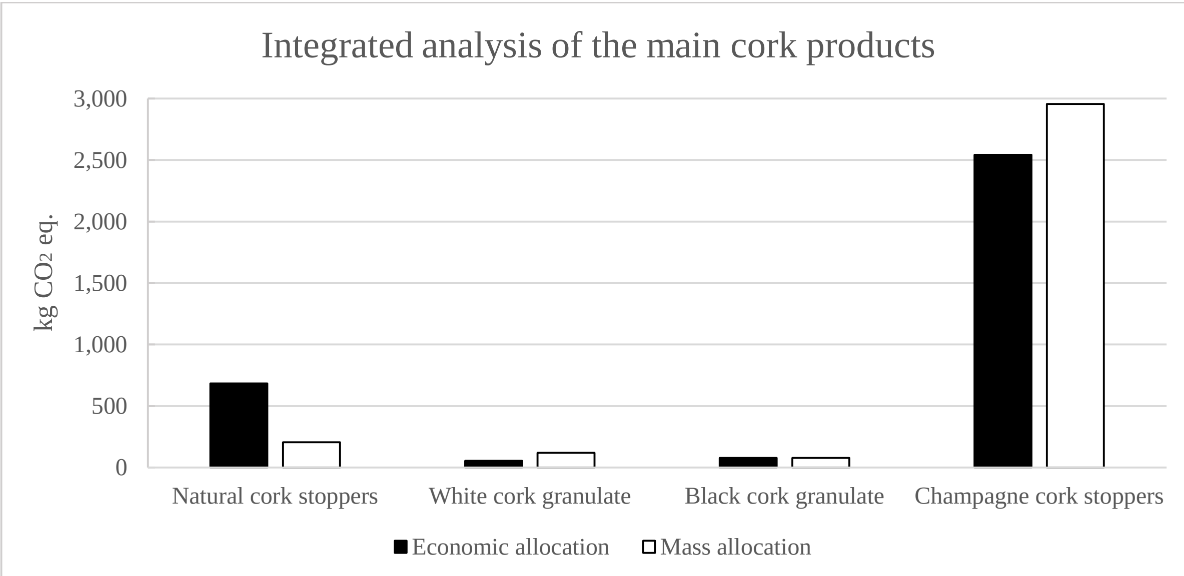

Figure 10: Comparison of climate change results of the main cork products (FU = 1 initial t of raw cork converted in the main cork products)

Rives et al. (2013) considered a CO_2 balance in order to include the sequestered CO_2 in the CC calculation. In this study it was found that during the manufacturing of the main cork products from 1 t of raw cork there is an emission of 3,359.4 kg of CO_2 eq. and there is sequestration of 18,000 kg CO_2 eq. Consequently, the sequestration of carbon is greater than the manufacturing emissions. Additionally, it was found that natural cork stoppers and champagne cork stoppers are the main cork products with the greatest carbon content. More specifically, it was calculated that 234 g of CO_2 would be stored in each natural cork stopper produced and 12 g of CO_2 would be stored in each champagne cork stopper.

From the literature review, it can be seen that there is only a limited number of LCA studies regarding the environmental impacts of cork products and that there is a need of enlarging this number and the primary data available. The main goal of the LCA studies is the evaluation of the environmental impacts due to the production of the various cork products and the identification of the hotspots both for the various stages as well as the processes considered in the system boundaries. It was found that the choice of FU does not cause great difficulties in the comparison of different studies as long as all needed data are provided for the ease of unit conversion (e.g. from 1 m^2 of product to kg of cork). The studies considered in the literature review applied different allocation procedure depending on the cork products under study (mass allocation, economic allocation and 100% impact to the main product). Additionally, it was found that the allocation procedure applied (e.g. mass allocation compared to economic allocation) is very influential for the final CC results and thus, this choice should be done carefully. The choice of methods for the impact assessment of the studies was the point that caused more difficulties in their comparison considering that the different methods consider different impact categories and/or different characterization factors.

Regarding the biogenic carbon sequestration and emissions, it was found that only a few of the studies considered carbon sequestration in the calculations (Rives et al., 2013, 2012a; PwC/Ecobilan, 2008). The inclusion of the carbon sequestered at the cork oak forest showed that the cork forest is a carbon sink since more CO_2 is sequestrated from the forest than it is emitted during the manufacturing of the cork products. Since the inclusion or exclusion of biogenic carbon can significantly influence the obtained CC results and since the existing LCA studies for cork products usually exclude it from the calculations, this aspect is important to be further studied.

The differences noticed among the various cork LCA studies could point to the consideration and evolution of Product Category Rules (PCR) for cork products. PCRs define the rules and requirements for the creation of Environmental Product Declarations (EPDs) and Product Environmental Footprint (PEF) of a certain product category of products (ISO, 2006c). Through the establishment of PCRs and the standardization of data collection methods, the comparison of different products of the same category would be easier.

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Chapter 3

Life cycle assessment of representative cork products

3.1 Introduction

This chapter consists of four published scientific papers. The main objective is to evaluate the environmental impacts from the production of different cork products in order to identify the hotspot of each product's life cycle. Additionally, the end-of-life of one cork product, namely natural cork stopper, is studied in order to evaluate the most efficient scenario. In all cases real data were considered from different Portuguese cork industries in order to achieve final results of better quality and with lower uncertainty.

This chapter presents the environmental assessment and results obtained for four representative cork products: natural cork stoppers (section 3.2), cork floating floor (section 3.3) and expanded cork slab and granules (section 3.4). Additionally, the end-of-life management alternatives are considered for the case of used natural cork stoppers (section 3.5) since currently there are running campaigns for the recycling of this commonly used cork product.

For the four representative cork products studied in this chapter, it was found that the main influence for the various environmental impact categories derives from the manufacturing stage (different processes were identified as hotspot for each cork product). In the case of natural cork stoppers and expanded cork slabs and granules it was found that except for the manufacturing stage, the forest stage had great contribution to some of the categories and thus, it was considered important as well.

Regarding the end-of-life alternatives for natural cork stoppers, the results showed that different alternatives can be more efficient depending on the environmental impact category under study. However, the alternatives of incineration and recycling were more effective than landfilling for all the environmental impact categories.

With the exception of section 3.2, the case studies introduce the consideration of biogenic carbon in the calculations. Considering that carbon is stored both in the cork products and in the landfills as well, it is important to consider this aspect which is usually considered neutral in LCA studies and thus, it is excluded from the calculations. Consequently, the CF was calculated both when considering and when excluding the biogenic carbon in order to compare the obtained results and to assess the CF change. Additionally, different methods for the consideration of biogenic carbon were applied in order to evaluate their influence as well. In the case of the cork floating floor (section 3.3) the methods of GHG Protocol, PAS 2050 and ILCD were applied considering 10 and 20 years of use in order to calculate the stored biogenic carbon and recalculate the CF of the product. This analysis showed that more biogenic CO_2 is stored in the case of landfilling when considering 20 years of use resulting to a decrease of the calculated CF. It was also found that the choice of method is not significant since the results of the two methods were very similar (slightly lower CF with PAS 2050 method).

In the case study of expanded cork slab and granules (section 3.4) apart from the biogenic carbon storage in the products, the biogenic carbon sequestration at the forest was considered as well. In this case 30 and 50 years of use were considered and the application of ILCD method was used for the accounting of biogenic carbon. The CF results showed that they are influenced by the use period choice but not significantly since the final CF were similar (slightly lower CF for 50 years than for 30 years). However, the consideration of the sequestration of biogenic carbon from the various components of the cork tree (foliage, roots, wood and cork) was found to be the most influential since it significantly decreases the CF results for both lifetimes and methods. The consideration of biogenic carbon delay in the CF calculation of the various end-of-life alternatives (section 3.5) showed that the obtained results could significantly change for the case of landfilling. More specifically, the ILCD method was chosen to be applied while considering biogenic carbon in the CF calculation and all landfilling scenarios showed a great decrease of their CF.

This chapter presents a great amount of primary data of the cork sector for the most representative cork products and their manufacturing processes. Thus, it enriches the existing literature regarding the cork sector. Furthermore, it highlights the importance of biogenic carbon consideration in the CF calculation since it was found that the inclusion of biogenic carbon sequestration and permanently stored biogenic carbon emissions can significantly decrease the calculated CF.

3.2 Cork stoppers supply chain: potential scenarios for environmental impact reduction

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Journal of Cleaner Production 112: 1985–1994 (2016)

Abstract

The purpose of the present study is to evaluate the environmental impacts deriving from the production of natural cork stoppers in Portugal, in order to identify the most significant stages and processes (hotspots) and to suggest improvement actions and alternative scenarios.

Life Cycle Assessment (LCA) methodology is used by applying a cradle-to-bottling approach. This approach includes the stages of forest management (not considered in related LCA studies), cork preparation, natural cork stoppers production, finishing and distribution to the bottling locations.

The results show that the forest management stage has the largest contribution to the environmental impact of natural cork stoppers in the majority of the impact categories. More specifically, the greatest influence derives from the operations of pruning and spontaneous vegetation cleaning. Additionally, the preparation stage and the production stage influence two impact categories each, while the finishing stage is the hotspot in one impact category. These contributions are mainly caused by the energy requirements of these stages.

The total environmental impacts may be decreased by 3% to 65% if maintenance pruning operations are not performed and simultaneously cleaning operations are undertaken by rotary mowers instead of disc harrows in the forest management stage. Changes in the production stage, such as decreasing the transport distance between the preparation and the production factory or the use of a combination of manual and mechanical punching, do not show great influence in the total environmental impact.

Keywords: environmental impact, hotspots, Life Cycle Assessment (LCA), natural cork stoppers, Portugal

1. Introduction

Cork oak (Quercus suber L.) forests cover an area of almost 2.1 million hectares, mainly extended in the Mediterranean region (South of Europe and North of Africa) (APCOR, 2014).

The countries in which cork oak forests are mostly located are Portugal, Spain, Italy, France, Algeria, Morocco and Tunisia. More than half of this cork oak area is located in Portugal and Spain (34% and 27% of the total cork oak area respectively) (APCOR, 2014).

Portugal produces about 100,000 tonnes of raw cork annually, which corresponds to 50% of the global raw cork production (APCOR, 2014). In this country, the cork sector has a high environmental, social and economic importance. Environmentally, cork oak forests can contribute to climate change mitigation since they absorb carbon dioxide (CO_2) from the atmosphere and store it in their perennial tissues and in the soil as organic matter and retain it for very long periods (Aronson et al., 2009). Consequently, cork products can also accumulate and store carbon for long periods (Demertzi et al., 2015; Dias and Arroja, 2014). Socially, the cork sector is important due to the employment of a great number of workers. More specifically, the Portuguese cork industry has almost 650 factories and around 20,000 workers (APCOR, 2014; INE, 2011). Economically, the importance of the cork sector is great, as Portugal is the largest exporter of cork products with a share of 64% of these goods world exports (835 million euros) (APCOR, 2014; ITC, 2011).

Moreover, due to its versatility, cork has application in a variety of uses in a wide range of sectors such as construction, aviation, sports, etc. However, the main sector for cork product use is the wine industry (APCOR, 2009). The Portuguese cork sector is responsible for producing approximately 40 million stoppers per day, placing them at the top (70%) of the total exports of the sector (APCOR, 2010a) with natural cork stoppers having the leading role (63% of the total number of stoppers export).

The natural cork stoppers are mainly exported to wine producing countries such as France, USA and Italy. Even though formerly concerns were raised for the adequacy of cork as wine stopper due to 2, 4, 6 trichloroanisole (TCA) contamination (Mazzoleni and Maggi, 2007; Prak et al., 2007), constant innovations, improvements and controls have managed to increase and guarantee quality of natural cork stoppers (Recio et al., 2011; Cabral, 2005; Ozhan et al., 2009). Due to the relevance of the cork sector, it is important to evaluate the environmental aspects and reduce the environmental impact resulting from its activities. A few Life Cycle Assessment (LCA) studies about cork and cork products can be found in literature, evaluating different environmental aspects and impacts. For example, Dias et al., (2014), González-García et al.

(2013) and Rives et al. (2012) applied LCA for the evaluation of the environmental impacts of raw cork production in Portugal and Spain. Moreover, LCA studies have also been carried out for cork products used as construction materials, such as flooring (Mahalle, 2011; Bowyer, 2009) and insulation material (Duijve et al., 2012; European Commission, 2011; DeBenedetti et al., 2007). However, there are not many LCA studies of natural cork stoppers either in Portugal or abroad. Examples are the studies of PwC/Ecobilan (2008) that assessed the environmental impacts of natural cork stoppers production in Portugal (comparatively to aluminum and plastic closures),

Rives et al. (2011) in Spain and Ecobilancio (2010) in Italy. However, none of the studies on natural cork stoppers have included the stage of forest management.

Thus, the present study further advances the state of the art in the area of LCA application to natural cork. A cradle-to-bottling approach is applied (including forest management, cork preparation, natural cork stoppers production, finishing and distribution to the bottling locations) to natural cork stoppers produced in Portugal. The main objective of this study is to identify the most influential stages and their dominant processes (hotspots) from an environmental point of view. Furthermore, improvement actions based on the results obtained, will be suggested.

2. Methodology

2.1 Functional unit

The functional unit (FU) used in this study is the production and delivery at bottling locations of 1,000 natural cork stoppers. The main physical characteristics of the natural cork stoppers were provided by the company CorkSupply Portugal SA and are the following:

- Average length ~ 45 mm
- Average diameter ~ 24 mm
- Density ~220 kg/m^3
- Average moisture ~ 6%

This kind of natural cork stoppers are mainly used for wine bottles with a neck diameter of 18 mm and a volume of 750 ml.

2.2 Boundaries of the system

The life cycle system is divided in five stages (Figure 11), each one including several processes. Stage 1 is the forest management stage which includes all the operations from the cork oak stand establishment up to the storage of the extracted cork in piles at the forest. For the stage of forest management, the data used were retrieved from González-García et al. (2013). As described in the mentioned paper, the stage under evaluation, consists of the following processes and operations: stand establishment (cut-over clearing, ripping, furrow-hillocking, planting, fertilization and dead plants substitution), stand management (spontaneous vegetation cleaning, pruning and thinning), cork stripping (manual cork extraction, transport of the slabs, cleaning of the spontaneous vegetation and pruning) and field recovery (cutting of the tree at the end of its life ~ 170 years). The transport of the workers is also included in the boundaries.

Stage 2 is the cork preparation stage and encloses five processes: planks pile establishment (the extracted cork is manually put into piles at the preparation unit), first stabilization (the cork piles are left at an open-air area for around six months until they achieve the required moisture content of 6-10%), planks boiling (immersion of cork planks in clean boiling water for one hour), second stabilization (resting of the planks for around three weeks in order to flatten) and scalding (similar to the boiling process, can be considered 2nd boiling, but for approximately 30 min). Additionally, there is a manual selection of the planks with the appropriate characteristics for the continuation of the manufacturing process, while the rejected planks are sent to the agglomeration industry. This stage also includes the transport of the raw cork from the forest to the preparation factory.

Stage 3 is the natural cork stoppers production stage and consists of eleven processes: slicing (cork planks are cut into strips), punching (perforation of the cork strips with a drill, it can be done manually or mechanically, in this case done mechanically), predrying (in a kiln to lower humidity ~11%), rectification/correction (to obtain final dimensions), aspiration (removal of cork dust), selection (both manual and automated), washing (using hydrogen peroxide or paracetic acid for disinfection), drying (in a kiln to lower humidity ~6%), deodorization (using water vapor and ethanol to clean the stopper's surface), coloring (with the use of waterborne coating) and packaging (storage in plastic bags of 500-1,000 stoppers). Moreover, this stage considers the transport of the prepared cork from the preparation factory to the manufacturer.

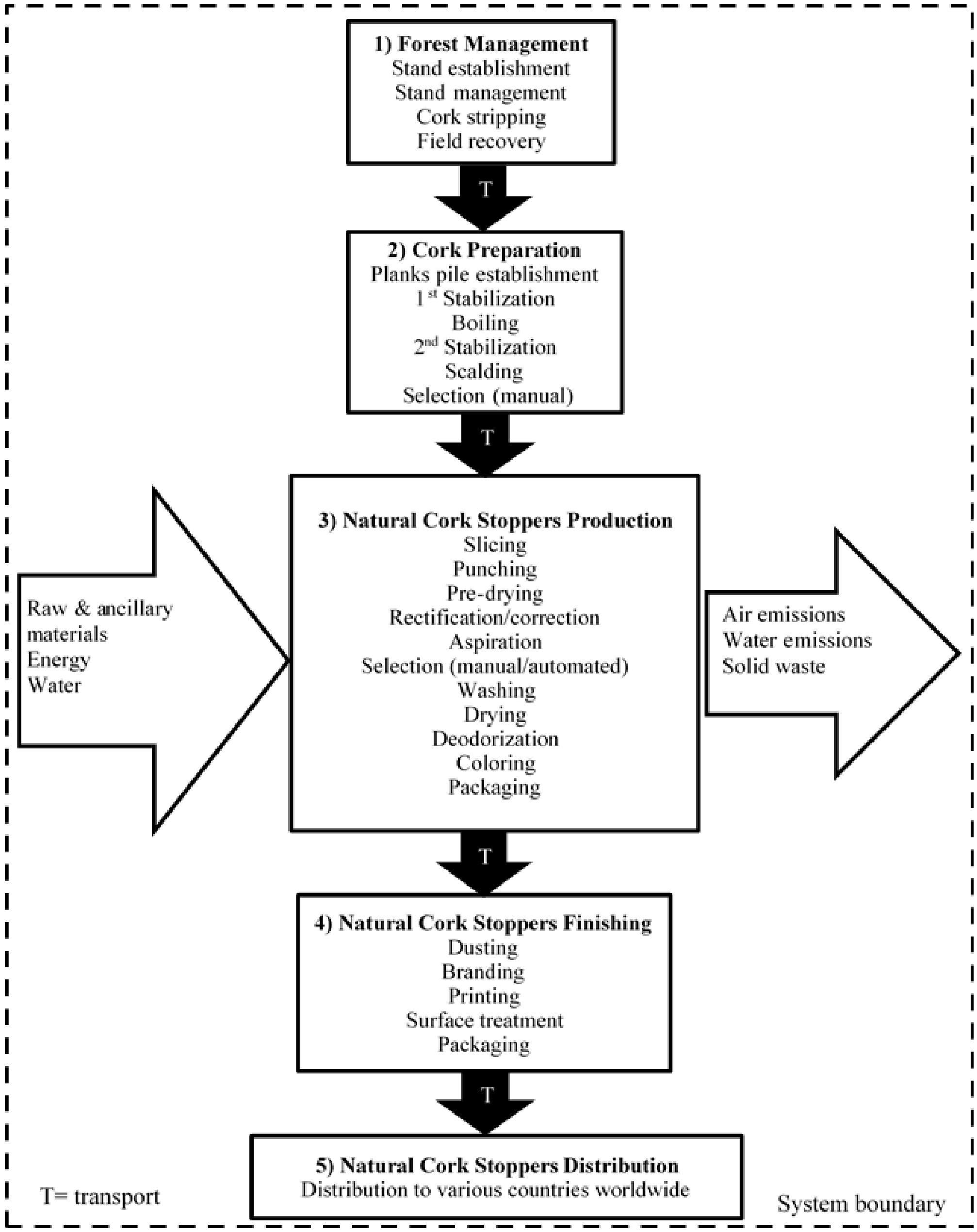

Figure 11: Boundaries of the system under study (the numbers represent the stage)

Stage 4 is the natural cork stoppers finishing and includes six processes: dusting (removal of dust), branding (using a heated metallic surface), printing (using food quality ink), surface treatment (to assure an easier insertion and extraction of the cork stoppers in the bottle) and packaging (in waterproof bags, containing sulphur dioxide to avoid contamination).

Additionally, this stage includes the transport of the cork stoppers from the manufacturer to the finishing factory.

Stage 5 represents the natural cork stoppers distribution from the finishing factory to the bottling centers worldwide for the year 2009.

2.3 Inventory data

Most of the information collected for the foreground industrial processes originated from the industrial activity of the company CorkSupply Portugal S.A. (preparation, production and finishing units) that is dedicated to the production of natural cork stoppers and was considered to be a representative unit of the industrial cork sector. The information collected was considered to be representative of the processes, materials and energy currently used in the different phases of the life cycle of natural cork stoppers.

The inventory of input and output flows of material and energy is based on a detailed analysis of the various processes of the life cycle. Tables 3-5 present the inventory data for stages 1-4.

Table 3: Inventory data for the stage of cork preparation expressed per FU

Input / Output	Quantity	Unit
Input [a]**:**		
Raw cork	20.0	Kg
Electricity	1.0321	kWh
Natural gas	0.9447	m^3
Water	0.0960	m^3
Output [b]**:**		
Cork planks	14.0	Kg
Cork residues [c]	6.0	Kg
Sludge	0.4890	Kg
Wastewater	0.0930	m^3

[a] The processes of Plank pile establishment, 1st Stabilization and 2nd Stabilization do not have neither inputs nor emissions

[b] Total on-site emissions associated with the production of cork planks include also emissions from natural gas combustion, which were calculated using emission factors from IPCC (2006) and EMEP/EEA (2013)

[c] The cork residues of this stage (e.g. thin planks or with defects) after being triturated are used in the production of agglomerates in other factories

For Stage 1, data were taken from González-García et al. (2013) that studied raw cork production in Portugal (data from cork oak stands located in Alentejo, South of Portugal) based on primary and site-specific data supplied by associations of Portuguese cork producers by means of surveys and interviews. These data are representative of cork oak woodlands in the South of Portugal.

Table 4: Inventory data for the stage of natural cork stoppers production expressed per FU

Input / Output	**Quantity**	**Unit**
Input:		
Cork planks	14.0	kg
Electricity	1.7510	kWh
Lubricating oil	0.0620	L
Natural gas	1.0630	m^3
Water	0.1224	m^3
NaOH	0.1400	kg
H_2O_2	0.3360	kg
$NaHSO_4$	0.0063	kg
Citric acid	0.0063	kg
Enzyme catalyst for H_2O_2	0.0004	kg
Antifouling mix	1.74E-04	kg
Anticorrosive	1.74E-04	kg
NaCl	0.0035	kg
Ethyl alcohol	0.0430	L
Water based coverings	0.2000	kg
Output [a]**:**		
Cork stoppers	4.2	kg
Cork residues [b]	9.8	kg
Sludge	0.0445	kg
Wastewater	0.0207	m^3

[a] Total on-site emissions associated with the production of cork stoppers include also emissions from natural gas combustion, which were calculated using emission factors from EMEP/EEA (2013) and IPCC (2006)
[b] The cork residues of this stage (e.g. cork stoppers with defects) after being triturated are used in the production of agglomerates in other factories

Table 5: Inventory data for the stage of natural cork stoppers finishing expressed per FU

Input / Output	Quantity	Unit
Input:		
Natural cork stoppers (unfinished)	4.2	kg
Electricity	2.1566	kWh
Paint	5.00E-04	kg
Silicone oil	0.0120	kg
Paraffin	0.0590	kg
SO_2	0.0040	kg
Output [a]:		
Natural cork stoppers	4.0	kg
Cork residues [b]	0.2	kg

[a] Total on-site emissions associated with the production of cork stoppers include also emissions from natural gas combustion, which were calculated using emission factors from EMEP/EEA (2013) and IPCC (2006)

[b] The cork residues of this stage (e.g. cork stoppers with defects) after being triturated are used in the production of agglomerates in other factories

For Stages 2, 3 and 4, primary and site-specific data were collected from the cork producer mentioned (CorkSupply Portugal S.A.) for the year of 2009. Due to the lack of measured data in the company, air emissions resulting from natural gas burning were calculated based on the emission factors of EMEP/ EEA (2013) and IPCC (2006). It should be noted that the factory that provided the raw data uses a specific patented deodorization method during the production stage, the Innocork® Process (CorkSupply, 2006), which uses a combination of water vapor and ethyl alcohol at controlled temperature to volatize TCA molecules and other unwanted aromas from the cell structure of cork. TCA remains the biggest obstacle to improved consistency in wine cork manufacturing and different anti-TCA strategies are being progressively integrated into the manufacturing process (APCOR, 2010c; Cabral, 2005).

Figure 12 presents the locations of the forest in Alentejo, the preparation unit in Montijo (located at about 58 km from the forest), the manufacturing unit in São Paio de Oleiros (about 308 km from Montijo) and the finishing unit in Rio Meão (at 6 km from São Paio de Oleiros).

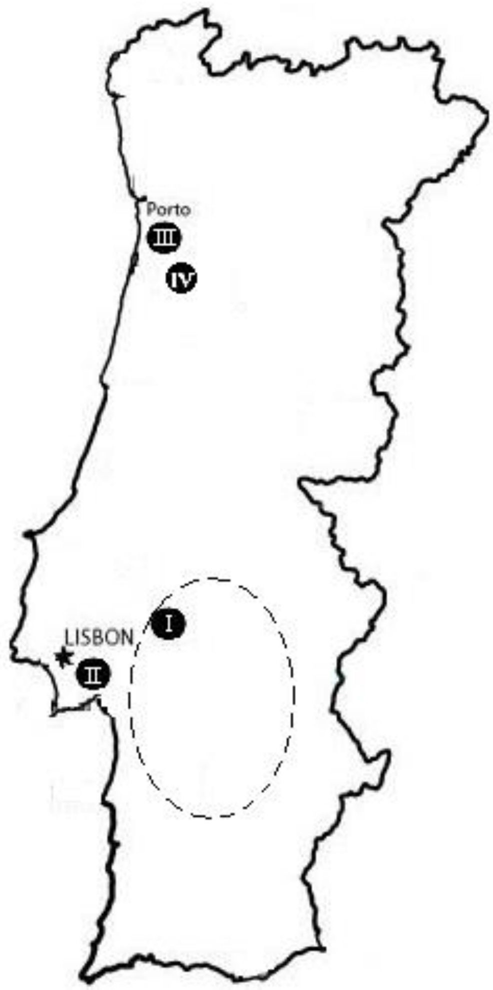

Figure 12: Map of the locations included in the study. I Coruche (forest), II Montijo (preparation unit), III São Paio de Oleiros (production unit), IV Rio Meão (finishing unit). The discontinuous line approximately shows the extension of the forest area.

For Stage 5 (Table 6) statistical data of the natural cork stoppers exports for 2009 (same year as the industrial processes) were used (UN Comtrade, 2009) to define the flows going to each country. Two different means of transport, namely, truck and ship were considered. In the former, the distances were based on existing road routes and in the latter they were based on existing sea harbors and real ship routes.

Secondary data concerning the production of electricity in the grid, chemicals, fuels and transport emission factors were taken from the Ecoinvent database (Ecoinvent, 2010).

Table 6: Distances for the natural cork stoppers distribution to the bottling locations

Country	Percentage of total natural cork stoppers	Distance by truck (km)	Distance by ship (km)
France	29	1,024	-
USA	13	124	14,005
Portugal	10	70	-
Spain	8	547	-
Others [a]	8	1,399	11,867
Italy	6	2,586	-
Argentina	5	1,224	10,155
Chile	5	1,729	10,155
Germany	4	1,632	-
UK	3	205	1,329
China	3	3,224	18,841
Russia	2	5,231	-
Switzerland	1	1,918	-
Australia	1	48	18,425
Mexico	1	505	8,682
South Africa	1	50	9,780

[a] This category represents the countries with a distribution flow lower than 1% of the total natural cork stoppers distributed

2.4 Allocation

The system under study is a multifunctional system since other products (co-products) are produced simultaneously with the main product (natural cork stoppers) along the supply chain. According to ISO:14040 (ISO, 2006) when allocation cannot be avoided and when there are no physical relationships to be used as a base for allocation, the economical values can be used for allocation. This was the case for the forest management stage. The allocation procedure for the forest stage is explained in more detail in the study of González-García et al. (2013). As mentioned there, different types of cork are produced, namely virgin, secondary and reproduction cork and economic allocation is applied in this case to obtain the environmental burdens of the reproduction cork used to produce natural cork stoppers. Moreover, as cork in the most important product of the cork oak forests and also due to lack of information, no burdens were allocated to wood (e.g., from pruning and thinning activities).

During the manufacturing process (preparation, production and finishing stages) of natural cork stoppers there is also the production of by-products (e.g., thin planks, planks or cork stoppers with defects) used in other industries (e.g., to produce agglomerates). In this study, all impacts are allocated to the natural cork stoppers, i.e., the cut-off method was applied. Following this method, each product must be assigned only the environmental impacts deriving directly from its production. In this case, the product made of primary materials (natural cork stoppers) carries the environmental impacts of those primary materials (e.g. raw cork from forest) and another product (e.g. cork agglomerates) made of secondary materials (e.g. cork stoppers residues) carries the environmental impacts of the secondary materials. The cut-off method is the easiest to apply since there is no need for data outside the life cycle of the studied product (Nicholson et al., 2009; Vogtlander et al., 2001; Ekvall and Tillman, 1997). This procedure was also adopted in the available LCA studies of natural cork stoppers (Rives et al., 2011; Ecobilancio, 2010; PwC/Ecobilan, 2008).

2.5 Impact assessment

The characterization factors reported by the International Reference Life Cycle Data System (ILCD) were considered (European Commission, 2012) for the impact assessment. The impact categories evaluated in this study and their units are: Climate Change (CC) in kg CO_2 eq, Ozone Depletion (OD) in kg CFC-11 eq, Human Toxicity Cancer Effects (HTC) in CTUh, Human Toxicity Non-cancer Effects (HTNC) in CTUh, Photochemical Ozone Formation (POF) in kg NMVOC eq, Acidification (A) in mol Hþ eq, Terrestrial Eutrophication (TE) in mol N eq, Freshwater Eutrophication (FEu) in kg P eq, Marine Eutrophication (ME) in kg N eq, Freshwater Ecotoxicity (FE) in CTUe and Mineral and Fossil Resource Depletion (MFRD) in kg Sb eq.

3. Results and discussion

3.1 Environmental impacts and hot spots for the baseline scenario

Table 7 presents for each impact category the total environmental impact of the defined life cycle for the production of natural cork stoppers produced in Portugal for the baseline scenario.

Table 7: Reduction of the total environmental impact of each category when applying the alternative scenarios in relation to the baseline

Category	Units	Baseline	Reduction (%)				
			Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
CC	kg CO_2 eq	1.62E+01	5	10	15	4	1
OD	kg CFC-1	2.20E -06	5	14	19	5	1
HTC	CTUh	2.48E -07	~0	12	12	~ 0	3
HTNC	CTUh	2.59E -06	-29[a]	24	-5[a]	1	1
POF	kg NMVOC eq	2.60E -01	4	61	65	1	~ 0
A	molc H+ eq	8.62E -02	9	10	19	3	3
TE	molc N eq	2.19E -01	18	8	25	4	1
FEu	kg P eq	1.851E -03	1	6	6	~ 0	4
ME	kg N eq	2.78E -02	13	18	31	3	1
FE	CTUe	7.50E+01	0	3	3	1	1
MFRD	kg Sb eq	1.76E -05	1	53	53	1	1

[a] In this case the percentage represents an increase of the final value and not a reduction

Figure 13 presents the contribution of each stage to the total environmental impact of each impact category, in order to identify the main hotspots.

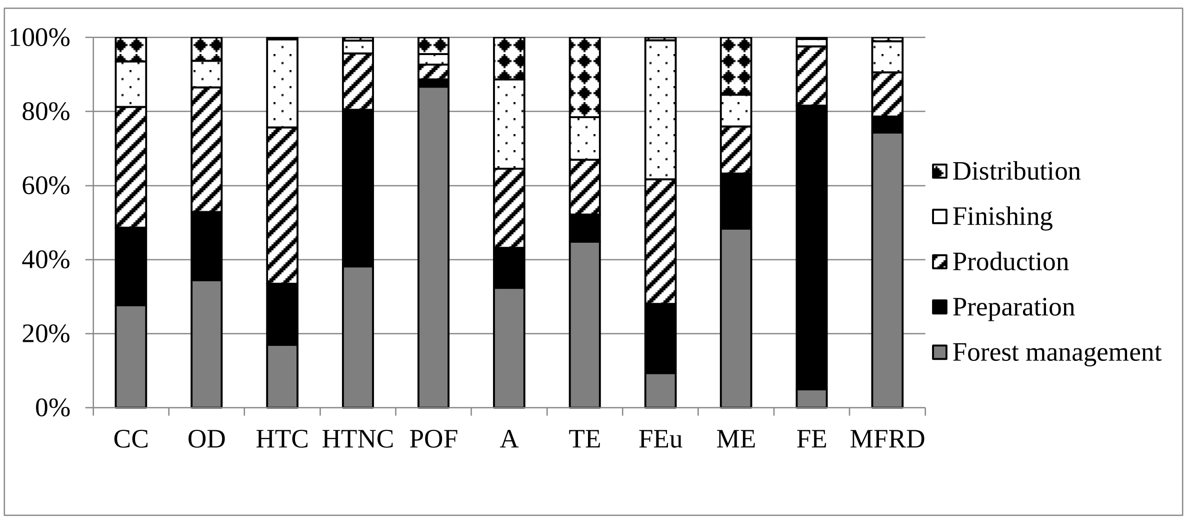

Figure 13: Contribution of each stage to the environmental impact of the manufacturing of natural cork stoppers

The forest management stage presents the greatest influence in the categories of OD, POF, A, TE, ME and MFRD (32%-87%) mainly due to emissions from fuel consumption during the forest machinery use and production. In the categories of CC and HTC, the stage of production presents the greatest influence (33% and 42% respectively) due to the consumption of natural gas and the use of chemicals for the washing of the cork planks. In HTNC and FE the influence mainly derives from the preparation stage (42% and 77% respectively) due to the disposal of sludge, generated during the treatment of the wastewater of this stage. Finally, in FEu the finishing stage has the greatest influence (38%) due to the emission of PO_4^{3-} during the production of electricity that is consumed in the processes of this stage.

The contribution of each process to the total environmental impact of each stage was also identified and analyzed. The following analysis, performed by stage, will allow the suggestion of improvement actions studied in Section 3.2 through the identification of alternative scenarios.

3.1.1 Forest management stage

The results obtained for the forest management stage are not presented in detail because they have already been analyzed and discussed in the study of González-García et al. (2013). However, it should be pointed out that the main influence in this stage derives from the cork stripping process (76%-99% of the total impact), due to various operations repeated several times throughout the life cycle of the cork oak tree, such as the operations of pruning (performed with chainsaw) and spontaneous vegetation cleaning (undertaken with disc/harrow).

3.1.2 Preparation stage

Figure 14 presents the relative contribution of the processes included in the cork preparation stage (transport of the raw cork from the forest to the preparation factory, cork boiling and cork scalding; the processes of 1st and 2nd stabilization were not included since they have no environmental burdens).

The main influence in all impact categories derives from the process of boiling (59%-79% of the total impact of the preparation stage). Even though the boiling process is very important, since it improves the mechanical properties of the raw cork and removes undesired water-soluble substances, it results in important environmental impacts for the majority of the impact categories (52%-94% of the total impact of the boiling process), mainly due to the consumption of electricity.

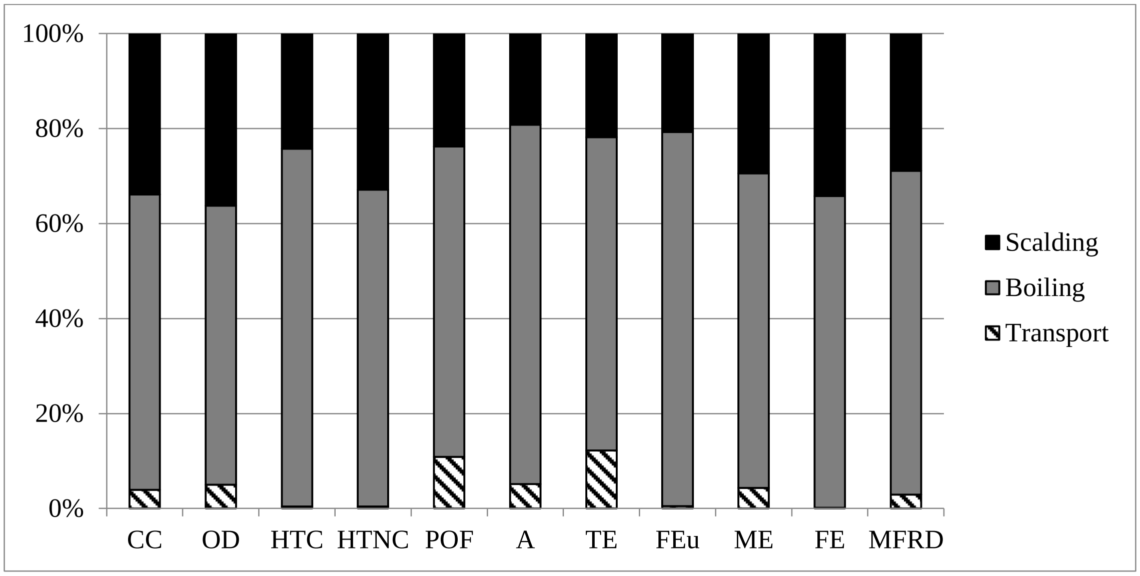

Figure 14: Contribution of the processes within the preparation stage.

However, for CC and OD, the emissions deriving from burning natural gas, for the production of the consumed heat, have the greatest influence (72% and 85% respectively). Moreover, for HTNC and FE, the main influence derived from the disposal of the sludge generated during the treatment of the wastewater from the boiling process (44% and 62% of the total impact of the boiling process), mainly due to the release of zinc and copper, respectively.

3.1.3 Production stage

Figure 15 presents the relative contributions of the various processes included in the production stage. Depending on the impact category, there are various processes highly influencing the impact of this stage, namely, washing, transport of cork planks from preparation to the manufacturer, punching and deodorization.

The process of washing the cork stoppers is the hotspot in four impact categories (HTC, HTNC, FE and MFRD) with contributions of 30%-66% of the total impact of the production stage. This process is important not only for the visual improvement of the cork stoppers but most importantly for its disinfection. However, the use of various chemicals (hydrogen peroxide, sodium hydroxide, sodium bisulfate and enzymes) leads to important contribution of this process to these impact categories (28%-94% of the total impact of the washing process).

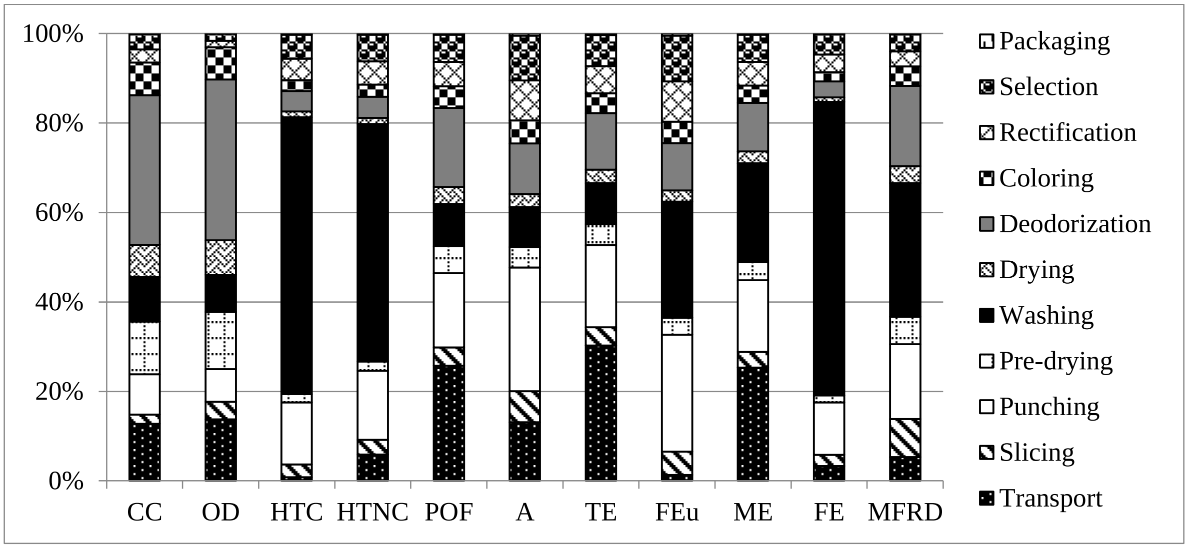

Figure 15: Contribution of the processes within the production stage

Another influential process for the production stage is the transport of the prepared cork planks to the cork production unit. The reason for this great influence is the fact that the preparation unit is located in the South of Portugal while the manufacturing unit is located in the North of Portugal. This results in an increased environmental impact in three impact categories, namely, POF, TE and ME (25%-30% of the total impact of the production stage) mainly from the emissions resulting from the consumption of diesel. CC and OD are dominated by the processes of deodorization (34% and 36% respectively) mainly resulting from natural gas burning for heat production (63%-98% of the total influence of deodorization).

Finally, another process with an important contribution to the environmental impact of the production stage is the punching process. This process is dominant in two impact categories, A and FEu (28% and 26%, respectively, of the total impact of the production stage) due to the consumption of electricity in the punching equipment (55%-99% of the total impact of the punching process).

3.1.4 Finishing stage

Figure 16 presents the relative contribution of the processes included in the finishing stage (transport of the manufactured natural cork stoppers, dusting, branding, printing, surface treatment and packaging). In this case, even though surface treatment has the highest contribution in all of the impact categories (33%-45% of the total environmental impact of the finishing stage) the processes of dusting and branding present similar results (19%-33% and 18%-32%, of the total environmental impact of the finishing stage respectively).

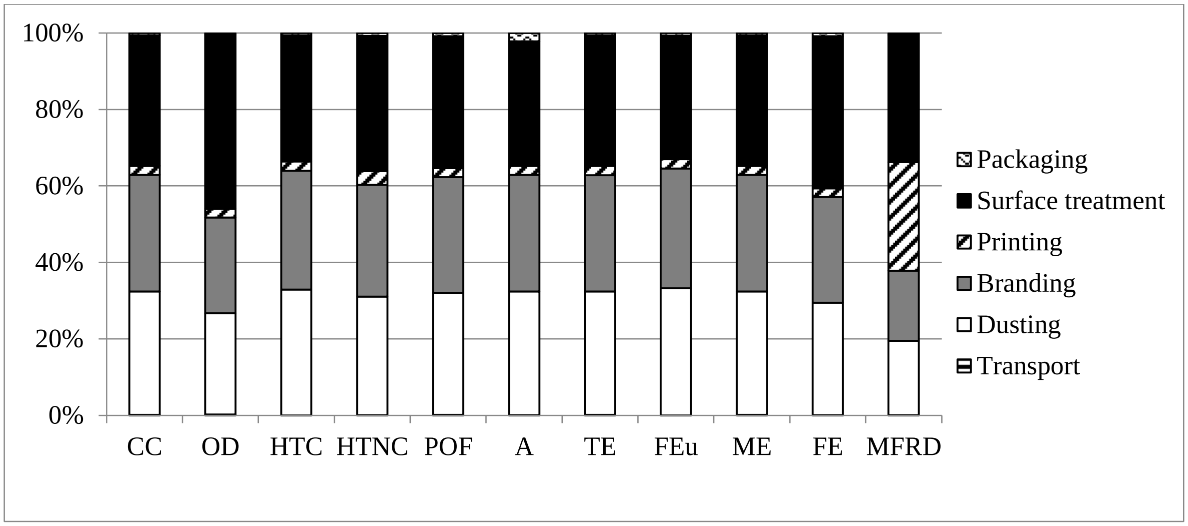

Figure 16: Contribution of the main processes of the finishing stage

As mentioned, the process of surface treatment is important since it helps sealing the pores of the cork and waterproofs it to absorb less wine, and additionally, this process helps the easier insertion and extraction of the cork stopper from the bottle. The two basic products used in this process are paraffin and silicone. Both products are applied in a similar way that consists of inserting the cork stoppers into a rotating machine in order to apply paraffin and then silicone homogenously. The main reason for the great contribution of surface treatment is the consumption of electricity by the equipment (55%-96% of the total environmental impact of the surface treatment process).

3.1.5 Distribution stage

Concerning the distribution stage the results show that the greatest influence in all the impact categories comes from the transport of the stoppers to the USA (20%-37%) with the exception of HTNC and FEu where France presented the greatest influence (12% and 25%, respectively). It should be mentioned that for the distribution to the USA two means of transport are necessary, namely, truck and ship. The greatest impact in all impact categories derived from the transport by ship (86%-99%) because the distances travelled are much bigger leading to higher consumption of fuel (diesel) and emissions.

3.2 Analysis of alternative scenarios

Taking into account the results obtained and the hotspots identified, this section defines and analyzes some alternative scenarios (quantitatively) and improvement actions (qualitatively) in order to decrease the environmental impact of the dominant stages (forest management, preparation, production and finishing).

The suggested scenarios show that the attention should be given to the forest management stage since it is the one that can contribute to decrease more effectively the total environmental impacts, mainly if changes are introduced in cleaning and pruning operations simultaneously.

3.2.1 Forest management stage scenarios

The forest management stage has an important contribution to the total environmental impacts mainly due to pruning and cleaning of spontaneous vegetation operations. Therefore, impact reduction scenarios should focus on those operations by reducing their frequency over the life cycle of the tree or/and by changing the machinery used. Three alternative scenarios were simulated, as follows:

- In Scenario 1, the spontaneous vegetation cleaning operation (during stand management and cork stripping processes) is performed with rotary mowers, instead of disc harrows (considered in the baseline scenario). The use of rotary mowers protects the superficial root system from damages and, thus, can be considered a better practice than disc harrowing, which can cause some root damage due to soil mobilization (Pereira, 2007).
- In Scenario 2, pruning operations during the cork stripping process (maintenance pruning) is not performed. According to recommended good practices (DGRF, 2006) maintenance pruning should be avoided as it can increase the predisposition of the tree to attacks by pests and diseases, and decrease the economic exploitation period of the cork oak trees. It should be noted that this scenario still considers the pruning operations performed during stand management.

- In Scenario 3, the two above mentioned scenarios were combined.

Table 7 presents the reduction of the environmental impacts of the life cycle when those three scenarios are applied in relation to the baseline. As expected, the total environmental impact decreased in both scenarios in all the categories, except in HTNC for Scenarios 1 and 3. Scenario 2 tends to present larger decreases (3%-61%) than Scenario 1 (0%-18%), and Scenario 3, which combines, Scenarios 1 and 2 presents the largest decreases (3%-65%). The increase in HTNC in Scenarios 1 and 3 is caused by the release of heavy metals emissions (zinc, lead and mercury) into the soil from the metal blades of the mowers.

3.2.2 Preparation and finishing stage improvement actions

As seen from the comparison of the relative contributions of the stages, the stage of preparation does not have a great influence in the final environmental impact (except for HTNC and FE due to the disposal of the sludge generated during the treatment of the wastewater from the boiling process) neither does the finishing stage (except for FEu due to electricity consumption during the surface treatment process) and because of that, no quantitative alternative scenarios were suggested for these stages. However, suggestions of some improvement actions are provided for the most influential process, cork boiling and surface treatment respectively. During cork boiling most of the impacts derive from the consumption of electricity and from the disposal of the sludge generated during the treatment of the wastewater produced.

Therefore, efforts should be attempted decreasing the consumption of electricity to improve the efficiency of the boiling technique. Additionally, in alternative techniques should be attempted for the decrease of the amount of sludge produced. For example, the cork stoppers manufacturer could consider and evaluate (both environmentally and economically) the installation of anaerobic digestion for the wastewater treatment deriving from the cork boiling process (Spinosa et al., 2011). Furthermore, the application of a catalytic ozonation process could also be helpful (Lee et al., 2010). The reduction of sludge production could be beneficial not only for the environment but also for the economic cost of its disposal (Serón et al., 2011). Concerning the finishing stage, the greatest influence derived from the consumption of electricity and this is where attention should be given.

3.2.3 Production stage scenarios

Concerning the production stage, there are several processes influencing the environmental impact (transport of prepared cork, washing, deodorization and punching). However, not all of them can afford alternative scenarios. For instance, the washing process that was dominated by the influence of the chemicals used cannot be altered because the manufacturers use specific amounts of chemicals depending on the quality of the cork. In the suggested alternative scenarios, two processes were altered (cork transportation and punching), as follows:

- In Scenario 4 is considered no transport distance (since the ideal situation would be the construction of the preparation and production factory in the same location, near the cork oak woodlands in the South of Portugal).
- In Scenario 5 both manual and mechanical punching is considered in equal parts (half of the electricity consumed in the baseline scenario).

Table 7 shows that the alternative scenarios of the production stage do not result in a great decrease of the environmental impact (up to 5%). However, Scenario 4 presents the highest decrease of the total impact (0%-5%) compared to Scenario 5 that presents a slightly lower decrease (0%-4%).

3.3 Comparison with previous studies

Only three LCA studies of natural cork stoppers were found in the literature and were compared with this study (Table 8). Regarding the methodological procedures, the four studies have various differences but also similarities, as follows:

- The FU used in all the studies is a certain amount of cork stoppers (the present study and the PwC/Ecobilan have the same). However, the FU can be converted easily in order to allow comparison of results.
- The impact categories studied are different in each study. The present study includes more impact categories that the previous ones. However, the most recent study, that of Rives et al. (2012) has included more impact categories and can be considered more informative and with more detailed results comparatively to the other two studies.

Table 8: Comparison of existing LCA studies for natural cork stoppers

Author	Present study	Rives et al. (2012)	PwC/Ecobilan (2008)	Ecobilancio (2010)
Country	Portugal	Spain	Portugal	Italy
LCA approach	Cradle-to-bottling	Gate-to-grave	Gate-to-grave	Gate-to-grave
Impact assessment method	ILCD [a]	CML [b] - 2001	WMO [c], CML [d] - 1992, ETH [e], IPCC [f]	CML [d] - 1992, IPCC [f]
FU	1,000 natural cork stoppers	1,000,000 natural cork stoppers	1,000 natural cork stoppers	1 natural cork stopper
Impact categories	– Climate Change – Ozone Depletion – Human Toxicity Cancer Effects – Human Toxicity Non-cancer Effects – Photochemical Ozone Formation – Acidification – Terrestrial Eutrophication – Freshwater Eutrophication – Marine Eutrophication – Freshwater Ecotoxicity and – Mineral and Fossil Resource Depletion	– Global Warming – Ozone Layer Depletion – Human Toxicity – Photochemical Ozone Formation – Acidification – Eutrophication – Terrestrial Ecotoxicity – Freshwater Aquatic Ecotoxicity – Marine Aquatic Ecotoxicity – Abiotic Depletion	– Global Warming – Photochemical Ozone Formation – Acidification – Eutrophication – Heavy metals	– Global Warming – Ozone Layer Depletion – Acidification – Eutrophication – Abiotic Depletion – Photochemical Ozone Formation – Heavy metals
Stages included	Forest Preparation Production Finishing Distribution to wineries	Preparation, Production, Finishing as Production Distribution to wineries End-of-life (as wood)	Preparation, Production, Finishing as Production Distribution to wineries End-of-life (as wood)	Preparation, Production, Finishing as Production Distribution to wineries End-of-life (as wood)
Stages excluded	End-of-life	Forest	Forest	Forest
Hotspot stage	Forest, preparation, production	Production	Production	Production
Hotspot process	– Fertilization – Boiling – Punching, washing, deodorization, transport of prepared cork planks – Surface treatment – Ship transport to USA	– Transport from the forest – Boiling – Punching – Rectification	Not specified	Not specified

[a] ILCD (2010) [b] Guinée et al. (2001) [c] WMO (1991) [d] Heijungs et al. (1992) [e] ETH (1995) [f] IPCC (1996)

- The boundaries of the system are different in the present study compared to the other three that have similar boundaries. More specifically, the present study includes the forest management stage while the other studies have excluded this stage. Moreover, in the present study the end-of-life stage was excluded while in the other three cases it was considered. However, in the other studies, cork was treated as wood since there are no inventory data for the incineration or landfilling of cork. This assumption increases uncertainty as cork and wood have different components (e.g. suberin, lignin, etc.) and chemical composition (e.g. carbon, oxygen, etc.) (Table 9). Consequently, some of the emissions that depend on the composition of the waste (e.g. SO_2 in waste incineration) present higher uncertainty, unlikely other mainly influenced by the technology and operational conditions used (e.g. NOx depend primarily on the combustion temperature).

Table 9: Composition of cork and wood

Composition	% in Cork	% in Wood [a]
Components [b, c]:		
Suberin	45	-
Lignin	27	22
Cellulose	12	40
Hemicellulose	-	30
Tannins	6	-
Ceroids	5	-
Resins	-	5
Minerals	5	3
Chemical compositions [c, d]:		
Carbon	67	50
Oxygen	23	44
Hydrogen	8	5
Nitrogen	2	1

[a] Average values for softwood and hardwood
[b] APCOR (2010b)
[c] Pereira (2013)
[d] Jianju et al. (2004)

The comparison of the results of the studies is qualitative because the studies applied different LCA approaches and because the processes considered in each stage were different. Thus, a comparison based on the identification of the hotspots (stages and processes) in each case is performed as follows:

- In the present study, the forest management stage presented the greatest influence for the majority of the impact categories considered. Even after the simulation of alternative scenarios, the forest management stage was still the main hotspot. When excluding the forest management stage, all four studies agree that for the majority of the impact categories, the production stage is the main hotspot throughout the natural cork stoppers life cycle.
- When focusing on the processes hotspots, the comparison cannot be very clear because in two of the studies, Ecobilancio (2010) and PwC/Ecobilan (2008), the process with the greatest impact is not specified. However, the present study has some common hotspots with the study of Rives et al. (2012) that also identified boiling and punching as hotspots. In the present study the identification of the most influential processes was clearer because the life cycle of the natural cork stoppers was divided in more processes.

4. Conclusions

The main conclusions of this study are as follows:

- The forest management stage plays the most important role in six impact categories, while the preparation and production stages were dominant in two impact categories and the finishing stage was the hotspot in one impact category.
- The stage of forest management was dominated by the cork stripping process mainly because of the spontaneous vegetation cleaning and pruning operations which are repeated several times over the life cycle of the cork oak tree.
- In the stage of preparation, the boiling process was the hotspot mainly because of electricity consumption and the disposal of the sludge generated from the boiling process.
- For the stage of production, the main hotspots were transport of the prepared cork planks, punching, washing and deodorization. This is mainly due to consumption of diesel,

consumption of electricity, use of chemicals and consumption of natural gas respectively.

- For the finishing stage, the surface treatment process was the main hotspot due to electricity consumption.
- For the stage of distribution, the hotspot was the transport of the natural cork stoppers to the USA mainly influenced by the emissions deriving from the transport by ship.
- Alternative Scenario 3 would lead to more effective reductions of the total environmental impact (3%-65%) by not performing prunings during the cork stripping process and, simultaneously, using rotary mowers instead of disc-harrows for cleaning operations.
- The adoption of these measures separately (Scenarios 1 and 2) were less efficient.
- The remaining alternative scenarios suggested did not present a great decrease of the total environmental impact (less than 5%) and can be considered insufficient.

Acknowledgements

The authors gratefully acknowledge the company CorkSupply Portugal S.A. for the collaboration in providing primary inventory data. This study has been supported by the project “Cork carbon footprint: from trees to products” (PTDC/AGR-FOR/4360/2012) funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program ‘Thematic Factors of Competitiveness’) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation e Portugal). Additional thanks to COMPETE (PEst-C/EME/UI0285/UI0285/2011).

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3.3 Environmental performance of a cork floating floor

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Materials and Design 82: 317- 325 (2015)

Abstract

The objective of this study is to evaluate the environmental impacts associated with the manufacturing process of a cork floating floor, produced in Portugal, in order to identify the most significant stages and processes (hotspots) with the aim of improving the manufacturing process and the sustainability of the product.

Life Cycle Assessment methodology is used by applying a cradle-to-gate approach. The results show that the stage with the highest environmental impact is the assembling stage (where all the product's components are assembled) mainly due to the production of high density fiberboard.

Additionally, the present study discusses the currently hot and controversial issue of biogenic carbon considering its storage in products and emission delay. For this part of the study a cradle-to-gate approach was adopted and three leading methods were compared, namely, Greenhouse Gas Protocol Product Standard, Publicly Available Specifications 2050 and the International Reference Life Cycle Data System. The results show that the choice of method has an important influence on the results obtained both for biogenic carbon dioxide emissions and carbon storage. This highlights the need for the establishment of a common methodology for the calculation of biogenic carbon, not only for the homogeneity of the guidelines but also for the ease of comparing results.

Keywords: biogenic carbon, cork flooring, environmental impact, life cycle assessment, Portugal

1. Introduction

Cork oak (Quercus suber L.) forests cover an area of 2,139,492 hectares, distributed in several European countries (Portugal, Spain, France and Italy), and Northern Africa countries (Algeria, Morocco and Tunisia). Portugal has the largest area of cork oak forest, about 736,000 hectares, representing about 34% of the total cork oak area. Cork oak is the second predominant tree species of the country, representing 23% of the total area of the national forest.

Portugal is also the world’s leader in raw cork production, contributing 100,000 tonnes of cork annually, corresponding to 50% of the global raw cork production (APCOR, 2013). The wine industry consumes the greatest part of the raw cork produced (70%) (APCOR, 2013) but due to its versatility, cork has application in a wide range of sectors, such as construction (e.g., for flooring, insulation, core material, coatings and decorative objects), aviation, sports and automotive components (Gil, 2013; Vilela et al., 2013; Castro et al., 2010; Farag, 2008).

The environmental importance of cork derives from the fact that cork oak forests can contribute to climate change mitigation since they absorb carbon dioxide (CO_2) from the atmosphere and store it in their perennial tissues and in the soil as organic matter. Carbon is thus retained for very long periods, as cork oaks are long living trees (up to 200–250 years) (Pereira and Bugalho, 2009). Part of the carbon sequestered by cork oak trees is transferred to cork products. Consequently, cork products have the potential to mitigate climate change as well since they can stay in use for long periods, storing part of the carbon contained in the cork harvested from the forest and delaying its return to the atmosphere. Even cork products with a relatively short lifetime (such as 10–20 years) can store carbon for long periods when disposed in landfills at the end of their life, because under anaerobic conditions their decay is slow and incomplete (Dias and Arroja, 2014; PwC/Ecobilan, 2008).

Because of the relevance of the cork sector, it is important to evaluate the environmental impact resulting from its activities. This can be accomplished through the application of Life Cycle Assessment (LCA), a technique addressing the environmental aspects and potential environmental impacts throughout the life cycle of a product, from raw material acquisition through manufacturing, use, recycling and handling at the end-of-life (e.g., incineration and landfilling) (ISO, 2006a, b). LCA can be useful in identifying opportunities to improve the environmental performance of products at various points in their life cycle; in transporting the information to decision makers in industry, government and non-governmental organizations (e.g., strategic planning, priority setting, design or redesign of products or processes); in promoting the selection of relevant indicators of environmental performance including measurement techniques; and in marketing, such as implementation of eco-labeling, conducting environmental claims, or preparation of environmental product declaration (EPD) schemes (ISO, 2006b).

A few LCA studies about cork and cork products can be found in the literature, evaluating different environmental aspects and impacts. There are examples of studies evaluating the environmental impact of raw cork production (Dias et al., 2014; González-García et al., 2013; Rives et al., 2012), cork stoppers (Rives et al., 2012, 2010; Ecobilancio, 2010; PwC/Ecobilan, 2008), cork used as construction material, such as flooring (Mahalle et al., 2011; Boyer et al., 2009) and insulation material (Pargana et al., 2014; Brito et al., 2010). However, most of these studies mentioned only present traditional LCA results and do not consider the biogenic CO_2 sequestration and emission.

There are some important issues to be considered when assessing the CO_2 balance of forest-based products. These products are mainly considered as potentially carbon–neutral materials since it is considered that the amount of carbon sequestrated by the forest is then emitted back to the atmosphere at the end-of-life of the product (Althaus et al., 2009; Guineé et al., 2002). Therefore, traditional LCA studies often treat biogenic CO_2 emissions (emissions of carbon temporarily stored in biomass) by excluding them from the assessment. However, according to a newer insight, biogenic CO_2 should be taken into account in order to avoid errors (Levasseur et al., 2013, 2010). On the other hand, even when carbon uptake during biomass growth is accounted for (as a negative emission) as well as the subsequent release (as a positive emission), the duration of storage is usually disregarded, i.e., the effect of delaying the emission of the temporarily stored carbon is not taken into account resulting in incomplete conclusions (Garcia and Freire, 2014; Brandão et al., 2012, 2010; Müller-Wenk, 2010). Even though there are various approaches to account for temporary storage and delayed emission of biogenic carbon (Garcia and Freire, 2014; Brandão et al., 2012, 2010), there is still no accordance on the most appropriate one.

The main objective of this study is to analyze, through LCA with a cradle-to-gate approach, the potential environmental impacts of a cork floating floor, used in construction, consisting of cork, high density fiberboard (HDF) and surface finishing. Furthermore, the present study aims to identify the most influential stages and processes (hotspots). Moreover, the biogenic carbon storage and emission delay during the product's use and end-of-life stages will be assessed by using different leading methods: the Greenhouse Gas (GHG) Protocol Product Standard (Bhatia et al., 2012), Publicly Available Specification (PAS) 2050 (BSI, 2011) and the International

Reference Life Cycle Data System (ILCD) (European Commission, 2010). In this way, the influence of those methods in the results obtained, for the impact category of climate change, will be evaluated.

2. Methodology

2.1 Product description and functional unit

The product studied is a cork floating floor, produced in Amorim Revestimentos in Portugal. It consists of five layers (presented from bottom to top): cork backing layer, HDF layer, cork base layer, optic image layer and finishing layer. The cork backing layer has a thickness of 1.2 mm (mm) and offers impact sound reduction and thermal reinforcement. The HDF layer with a thickness of 6.0 mm offers more resistance and stability to the product. The cork base layer with a thickness of 3.1 mm offers step sound reduction, warmth and comfort, while the optic image layer with a thickness of 0.1 mm, provides a variety of visuals (imitating marble, slate, stone, metal, various textile surfaces and wood grain). Finally, the finishing layer with a thickness of 0.1 mm offers easy maintenance and extra wear resistance. The functional unit (FU) used in this study is 1 square meter (m^2) of final product.

2.2 System boundaries

The life cycle system is divided in different stages (Figure 17), each one including several processes. Stage 1 represents the base layer manufacturing. This stage takes place in São Paio de Oleiros (northwest of Portugal). Firstly, the ‘‘broken’’ (cork resulting from the pre-trituration of ‘‘falca’’ that is low quality cork, extracted from the branches of the cork oak trees) arrives from the south of Portugal and it is separated from impurities, such as small stones. Then the ‘‘broken’’ is dried by heating it up to 60 ^oC (Celsius degrees) (depending on its moisture) in a dryer consuming thermal energy, and it is sent for trituration. The granules are then divided by granulometry and the granules of different sizes are stored in silos. The agglomeration process involves the blending of the cork with a resin. The mixture is placed on a conveyor and is pressed (applying high temperature and pressure) in order to be cut in slabs of the desired dimensions. After pre-sanding, the slabs are placed in an oven with controlled humidity and temperature for 255 min. After this operation, the slabs are put in stock (ambient conditions, not controlled) to

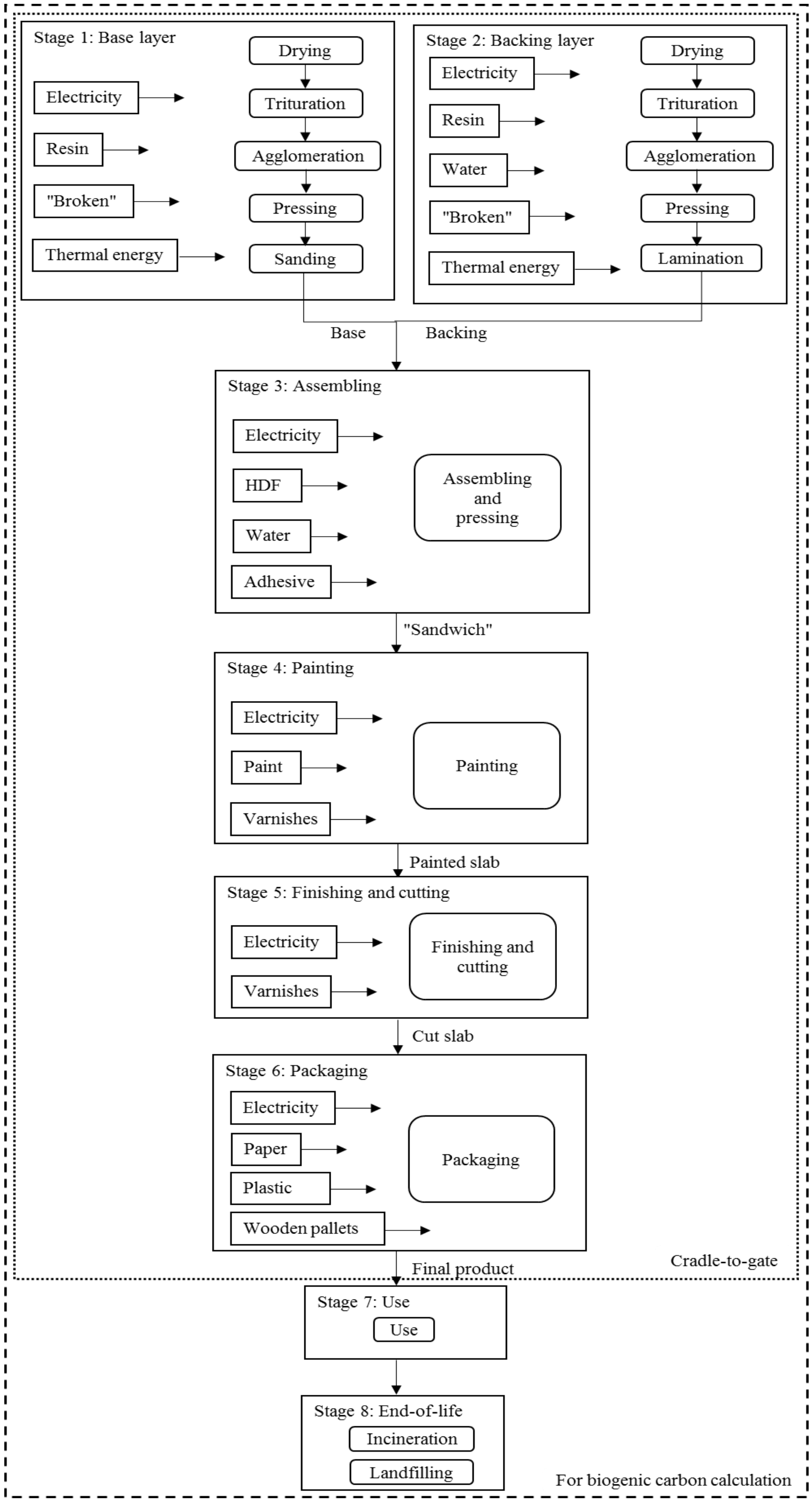

Figure 17: Boundaries of the system (the rectangles represent the inputs and the rounded rectangles the processes)

stabilize for 10 days (minimum). After stabilization, the slabs pass through a sanding process. During this stage, electric and thermal energy are consumed. The thermal energy is produced by cork dust burning in an industrial biomass boiler (with natural gas as an ancillary fuel) and the electric energy comes from the national grid. The surplus cork dust produced at this stage is sold or given to other manufacturing units of the cork sector and other sectors (such as the ceramic sector) and it is not considered waste because it reaches the end-of-waste state (when a certain waste ceases to be waste and obtains a status of a product or a secondary raw material). The wastes associated with this process are stones, scrap, plastic and waste electrical and electronic equipment (WEEE) that only reach the end-of-waste state at the management operator. Thus, their transport is considered.

Stage 2 represents the backing layer manufacturing. The processes at this stage are similar to those of stage 1 but this stage takes place in a different industrial unit located in Lourosa (northwest of Portugal). In this stage, the agglomeration technology is different. The mixture of cork with the resin is placed in a metallic mold and by pressing and heating for some time, a slab is formed. Next occurs the bonding of two slabs in order to obtain the desired length that is then laminated to obtain a backing sheet of the desired thickness (1.2 mm). During this stage, there is use of electric energy (from the national grid) and thermal energy (from cork dust) as well. Moreover, there is water consumption for the cleaning of the equipment. The effluent generated in this process is sent for treatment in a waste water treatment plant (WWTP). The wastes produced in this stage are stones, raffia and scrap and their transport is considered, as referred above for stage 1.

Stage 3 represents the assembling of the product. This is the stage in which the assembling of all the main components of the product occurs through gluing and cold pressing. The glued and pressed component consisting of the base layer, the HDF layer and the backing layer is called ‘‘sandwich’’. For the assembling and pressing, electricity (again through the national grid) is used. This process requires water for the equipment cleaning and the water after use ends up at the WWTP.

Stage 4 represents the painting of the product. During this process varnish is applied to the product, in order to prepare the surface for printing, and also the printing operation occurs. All layers of varnish and printing are cured in ultraviolet (UV) tunnels.

Stage 5 represents the finishing and cutting of the product. This stage starts with the application of several layers of varnishes that are cured by UV tunnels. After finishing the application of varnish, the material goes to stabilization for at least 24 h and then moves on to the cutting process. In this process, the product is pre-cut and then cut according to the cutting profile of the fitting.

Stage 6 represents the packaging of the final product. This process includes the use of plastic, paper and wooden pallets. The product is put in paper boxes, stacked on a wooden pallet and then strapped together with a plastic film/coat.

For the painting, finishing and cutting and packaging stages, electricity is consumed from the national grid, and the painting process results in liquid effluents that are treated at a WWTP.

It should be mentioned that the internal transport of materials, pre-products and finished product at the industrial units, is also included in the inventory, because of the consumption of diesel fuel for the operation of forklifts. Moreover, it should be noted that the manufacturing and maintenance of the used equipment and building is excluded from the boundaries of this study.

2.3 Inventory data and impact assessment

Data collection and calculation procedures follow the recommendations of the International Organization for Standardization (ISO) included in ISO 14044 (ISO, 2006a). All data for the foreground processes are primary data obtained from the Amorim Revestimentos manufacturing units of the product and the data used in the calculations refer to the year 2013. The information collected was considered to be representative of the processes, materials and energy currently used in the different stages of the life cycle of the product. Table 10 presents the inventory data for the manufacturing stages expressed per FU. Additionally, Table 11 provides information regarding the transportation profiles as provided by Amorim Revestimentos. Furthermore, the fuel consumption and related emissions from transport were obtained from the Ecoinvent database (Weidema et al., 2013).

The Ecoinvent database (Weidema et al., 2013) was used for processes for which the manufacturer has no specific influence or information (e.g., electricity production and raw material production). Moreover, it should be noted that the specific data concerning the production of ‘‘broken’’ used for the manufacturing of the studied product was obtained from

Amorim Florestal and data for the raw cork production was taken from a study by Dias et al. (2013).

Table 10: Inventory data for stages 1 to 6 expressed per FU

Input / Output	**Quantity**	**Unit**
Input:		
“Falca” [a]	3.50E+00	kg
HDF	1.15 E+00	m^2
Cork dust (thermal energy)[b]	2.34E+00	MJ
Natural gas (thermal energy)	1.09E-01	MJ
Diesel	5.57E-03	L
Electricity	1.87E+00	kWh
Water	5.27E-05	m^3
Resins	2.84E-01	kg
Adhesive	2.22E-01	kg
Varnishes	2.71E-01	kg
Paint	1.00E-03	kg
Paper	1.07E+02	g
Plastic	4.97E+00	g
Wooden pallets	1.27E-02	p [c]
Output:		
Cork dust	1.00E+00	kg
Wastewater [d]	5.89E-05	m^3
Solid waste	5.75E-02	kg
Air emissions [e]*:*		
NOx	1.02E-03	kg
NMVOC	1.62E-04	kg
Particulate matter	3.22E-04	kg

[a] Quantity needed for the production of “broken” used for the production of both base and backing layers

[b] Produced internally

[c] Stands for pieces

[d] The quantity of water leaving the system as wastewater is bigger than the quantity of water entering the system because it also includes the used resin that contains water

[e] The air emissions presented are those measured at the manufacturing units. However, in the calculations other emissions were considered as well (e.g. CO_2 and CH_4,) based on emission factors from EEA (2013) and IPCC (2006)

Table 11: Transport profiles

Material transport	Distance (km)	Type of transport	Maximum load (t)	Return journey
Raw materials				
"Broken"	338	Freight lorry, EURO 3	16	Empty
HDF	122	Freight lorry, EURO 3	16	Empty
Backing layer	7	Freight lorry, EURO 3	16	Full
Resin	50	Freight lorry, EURO 3	24	Empty
Adhesive	183	Freight lorry, EURO 3	24	Empty
Paint	2,100	Freight lorry, EURO 3	16	Empty
Varnish	2,200	Freight lorry, EURO 3	16	Empty
Paper (for packaging)	2	Freight lorry, EURO 3	16	Empty
Plastic (for packaging)	112	Freight lorry, EURO 3	16	Empty
Wooden pallets (for packaging)	42	Freight lorry, EURO 3	16	Empty
Residues				
Stones	40.6	Freight lorry, EURO 3	16	Empty
Various waste	40.6	Freight lorry, EURO 3	16	Empty
Scrap	40.6	Freight lorry, EURO 3	16	Empty
Plastic waste	40.6	Freight lorry, EURO 3	16	Empty
Waste electrical and electronic equipment	9.8	Freight lorry, EURO 3	16	Empty
For the sensitivity analysis				
"Broken"	365	Freight train	N.A.	Full
"Broken"	10	Freight lorry, EURO 3	16	Empty
"Broken"	338	Freight lorry, EURO 3, biodiesel	16	Empty

N.A.: Not applicable

For the impact assessment the characterization factors recommended by the ILCD were considered (European Commission, 2010). The impact categories evaluated in this study are: Climate Change (CC), Ozone Depletion (OD), Human Toxicity Cancer Effects (HTC), Human Toxicity Noncancer Effects (HTNC), Photochemical Ozone Formation (POF), Acidification (A), Terrestrial Eutrophication (TEu), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Freshwater Ecotoxicity (FE) and Mineral and Fossil Resource Depletion (MFRD).

2.4 Allocation

At the manufacturing units of São Paio de Oleiros and Lourosa, where the cork floating floor is produced, the production of other products takes place as well. Thus, it was necessary to perform allocation procedures (co-product allocation) to identify which inputs and outputs correspond to the manufacturing process of the studied product. The data of both plants were treated separately, since the production is independent.

When possible, allocation was avoided by dividing the unit processes and therefore, only the operations linked to the production of the studied product were considered. Furthermore, since various products are subjected to these operations, it was necessary to perform an allocation of environmental burdens considering that the environmental burdens per 1 m^2 of produced product in each operation are equivalent for all the products.

No environmental loads were assigned to residues that reach the end-of-waste state, such as cork dust, due to their low economic value compared to the main product. Thus, all environmental loads were allocated to the main product of each process.

2.5 Biogenic carbon

As previously mentioned, forest-based products during their life cycle store a certain amount of biogenic carbon that is then released into the atmosphere at the end-of-life of the product. For the evaluation of the biogenic CO_2 emissions, two more stages were added to the system's boundaries, in order to calculate the amount of biogenic carbon [in kilograms (kg) of CO_2] emitted in the case of 10 and 20 years life span in use (commercial and domestic use, respectively) and also in the case of incineration and landfilling since they are considered the most common end-of-life destinations for municipal solid waste (OECD, 2010).

This way, the amount of biogenic CO_2 temporarily and permanently stored in the product is calculated. This study applies three leading methods (GHG Protocol, PAS 2050 and ILCD), with different approaches on biogenic carbon accounting, in order to evaluate if they have an influence on the results of the CC impact category.

A partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) released the Product Life Cycle Greenhouse Gas Accounting Standard (Bhatia et al. 2012), also known as the GHG Protocol. It provides a framework for GHG accounting based on a life cycle and attributional approach and builds on the ISO standards for LCA (ISO, 2006a, b). The British Standard Institution published another method, namely the PAS 2050 (BSI, 2011) that also builds on the existing ISO standards (ISO, 2006a, b) and further specifies them for the assessment of the life cycle GHG emissions of goods and services. The European Commission developed the ILCD handbook (European Commission, 2010), according to which temporary carbon storage and delayed emissions should not be considered in the LCA, unless included in the goal of the study.

In all the methods, in order to calculate the biogenic CO_2 storage and emission, the content of carbon in the product (equal to the amount of carbon sequestrated/stored in that product) has to be known. The product under study consists of HDF (4.94 kg/ m^2) and cork for the base and the backing layer (2.11 kg/m^2 and 0.26 kg/m^2 respectively). Each of these components has a different content of carbon that is 40% and 60% respectively for HDF and cork (dry basis) (Dias et al., 2007; Gil and Pereira, 2007). By using the information previously mentioned and by considering 5% of moisture in the product, the biogenic CO_2 in 1 m^2 of the final product, equal to 11.836 kg of CO_2 (58% from HDF and 42% from cork) was calculated. This was then multiplied by a correction factor (different in each method), in order to calculate the biogenic CO_2 emissions during the end-of-life scenarios, namely incineration and landfilling. Even though the amount of carbon incorporated in 1 m^2 of final product is the same in all methods, the correction factor (expressing the weighted average time the emission is present in the atmosphere during a 100-year assessment period) by which it was multiplied, is not the same. According to the GHG Protocol, correction factors for delayed carbon emissions should not be included when quantifying inventory results and consequently, it adopts the fixed global warming potential (GWP – corresponds to the impact of emissions on the heat radiation absorption of the atmosphere) that is equal to 1 for CO_2. The other two methods do not adopt the same correction factor as will be presented in the next section. More details on the above mentioned methods can be found in literature (Garcia and Freire, 2014; Levasseur et al., 2013; Brandão et al., 2012).

Concerning the two end-of-life scenarios, in the case of landfilling it was considered that 98% of biogenic CO_2 will remain in the product, since it does not completely decompose in a landfill

(EPA, 2014; Garcia and Freire, 2014; Freed et al., 2004; Micales and Skog, 1997). Furthermore, the product will emit biogenic CO_2 at a constant rate during 20 years (0.012 kg CO_2/year) after disposal (EPA, 2014; Garcia and Freire, 2014; Freed et al., 2004) between the 10th and 30th year (when considering 10 years in use) and between the 20th and 40th year (when considering 20 years in use) following the formation of the product. In the case of incineration, the biogenic CO_2 was obtained for a delay (use period only) of 10 and 20 years while for the landfill scenario the biogenic CO_2 was obtained for the same delay plus the 20 years at the landfill (both for use and end-of-life stages).

3. Results and discussions

3.1 Environmental impacts and hotspots of the cradle-to-gate approach

Table 12 presents each stage's environmental impact and the total environmental impact during the product's life cycle. Moreover, Figure 18 shows the relative contribution of each stage to the environmental impact of the product's manufacturing. There are three stages that influence the total environmental impact (representing 30%, or more, of the total environmental impact), namely, the assembling stage, the base manufacturing stage and the painting stage. They will be presented in this section in more detail.

Table 12: Each stage's contribution and total environmental impact during the life cycle (cradle-to-gate) of 1m^2 of the final product

Impact category	Unit	Base	Backing	Assembling	Painting	Finishing & cutting	Packaging	Total
CC	kg CO_2 eq	1.63E+00	2.38E-01	3.36E+00	4.20E-01	3.61E-01	2.35E-01	6.23E+00
OD	kg CFC-11 eq	9.62E-08	1.44E-08	2.26E-07	3.06E-08	2.72E-08	1.55E-08	4.10E-07
HTC	CTUh	2.61E-08	4.30E-09	5.67E-08	4.97E-08	4.03E-08	1.35E-08	1.91E-07
HTNC	CTUh	2.13E-07	4.21E-08	5.83E-07	1.31E-07	7.55E-08	2.12E-07	1.26E-06
POF	kg NMVOC eq	7.86E-03	1.23E-03	1.40E-02	1.93E-03	1.60E-03	1.62E-03	2.82E-02
A	molc H+ eq	1.73E-02	2.53E-03	1.71E-02	3.56E-03	3.07E-03	1.84E-03	4.54E-02
TEu	molc N eq	4.99E-02	7.23E-03	4.12E-02	6.48E-03	5.39E-03	4.69E-03	1.15E-01
FEu	kg P eq	2.26E-04	3.57E-05	6.82E-04	9.30E-05	8.27E-05	1.07E-04	1.23E-03
MEu	kg N eq	4.16E-03	5.78E-04	3.86E-03	7.07E-04	5.39E-04	4.70E-04	1.03E-02
FE	CTUe	3.26E+00	4.71E-01	6.49E+00	7.50E+00	3.38E+00	1.17E+00	2.23E+01
MFRD	kg Sb eq	2.10E-05	2.94E-06	6.93E-06	5.85E-05	4.66E-05	3.56E-05	1.72E-04

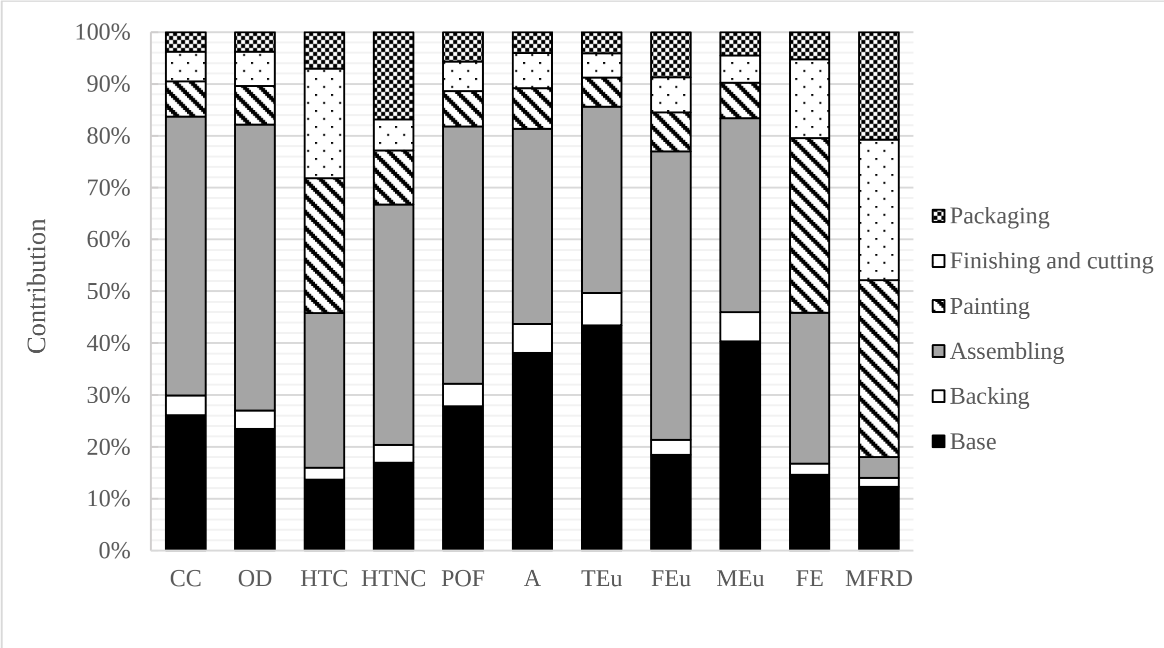

Figure 18: Contribution of each stage to the environmental impact of the manufacturing of 1m^2 of the final product

The most influential stage for the majority of the environmental impact categories is the assembling stage accounting for 30–56% of the total environmental impact in the categories of CC, OD, HTC, HTNC, POF, FE and MFRD. The impact category of A is equally influenced by the assembling stage and the base manufacturing stage (38% each). Figure 19 presents the relative contribution of the processes included in the assembling stage to the total environmental impact in each impact category. It can be seen that this stage is dominated by the process of HDF production in all impact categories representing 83–95% of the stages’ total environmental impact. The main influence for the great impact of the HDF production derived from the consumption of natural gas and electricity during its production. The second most influential stage is that of base manufacturing, dominating the categories of TEu and MEu with 43% and 40%, respectively.

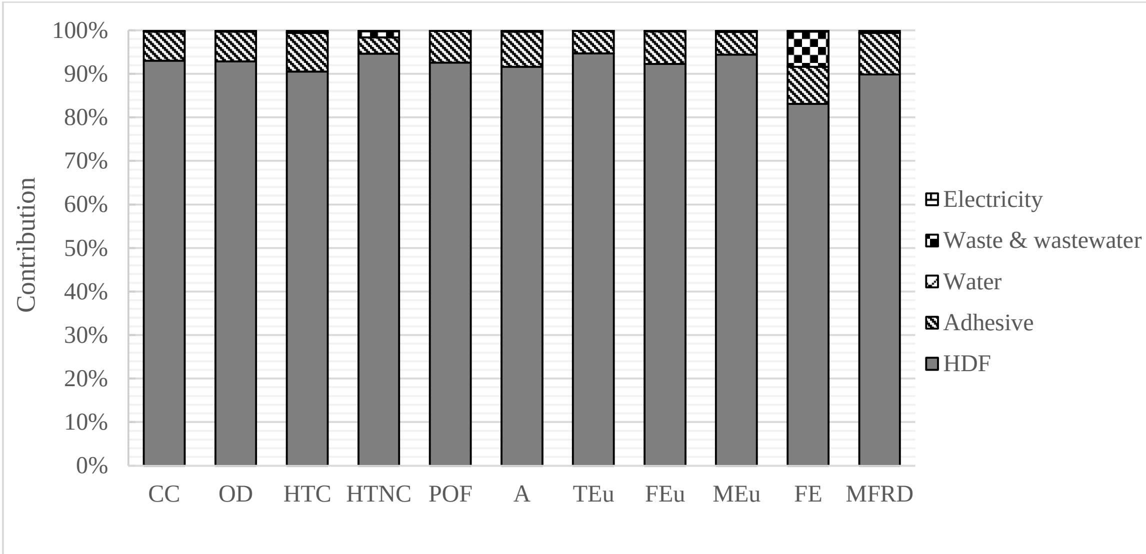

Figure 19: Contribution of each process within the assembling stage to the environmental impact

Figure 20 presents the relative contribution of the processes included in this stage. The two processes dominating this stage are the transport of ‘‘broken’’ to the manufacturing unit and the production of resins. More specifically, the resin production influences the categories of CC, OD, HTC, A, TEu and FE representing 47–64%. The ‘‘broken’’ transport dominates the rest of the categories with 41–84%. The great influence of the resin derives from its production (mainly due to the emission of nitrogen), while in the case of the ‘‘broken’’ the major influence derives from its transport (diesel consumption) to the manufacturing unit of São Paio de Oleiros (a distance of ~340 km was considered). The third most influential stage is that of painting. It dominates the impact categories of FE and MFRD, representing 34% in both cases.

Figure 21 presents the relative contribution of the processes included in the painting stage to the total environmental impact in each impact category. It can be seen that this stage is dominated by the production and transport of the applied varnishes and also the waste and wastewater treatment. More specifically, in the categories of CC, OD, HTC, POF, A, TEu, FEu, MEu and MFRD the use of the varnishes represents 85–99% of this stage’s environmental impact. In these categories, the emissions derived from the production of the varnishes and also from their transport by truck to the manufacturing unit (2000 km), resulted in increased air emissions due to the consumption of fuel. For HTNC and FE categories, the major influence derived from the waste treatment (48% and 62%, respectively) and it was mainly due to the disposal of solid waste in the landfill.

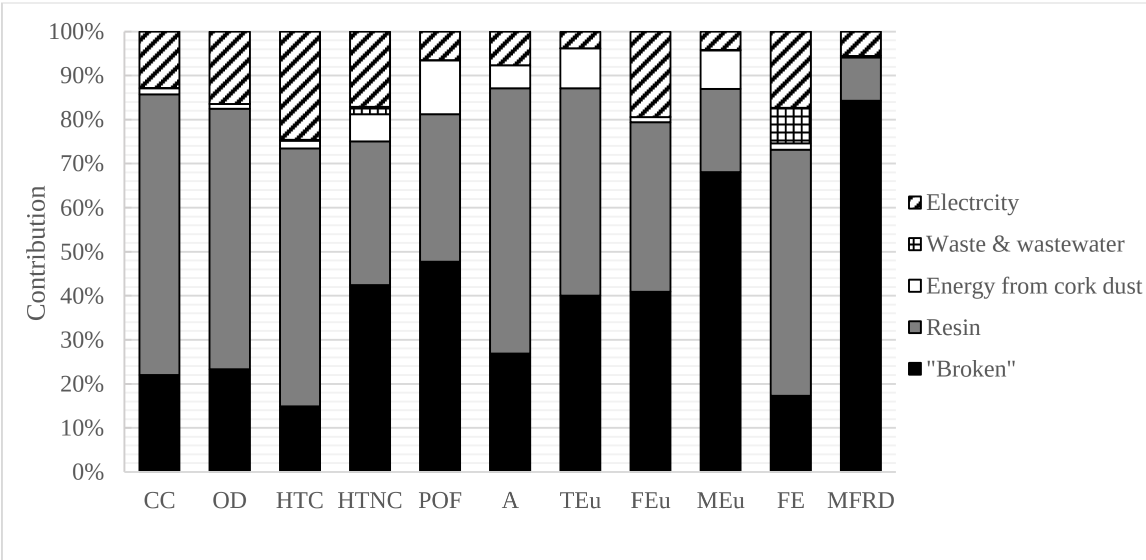

Figure 20: Contribution of each process within the base manufacturing stage to the environmental impact

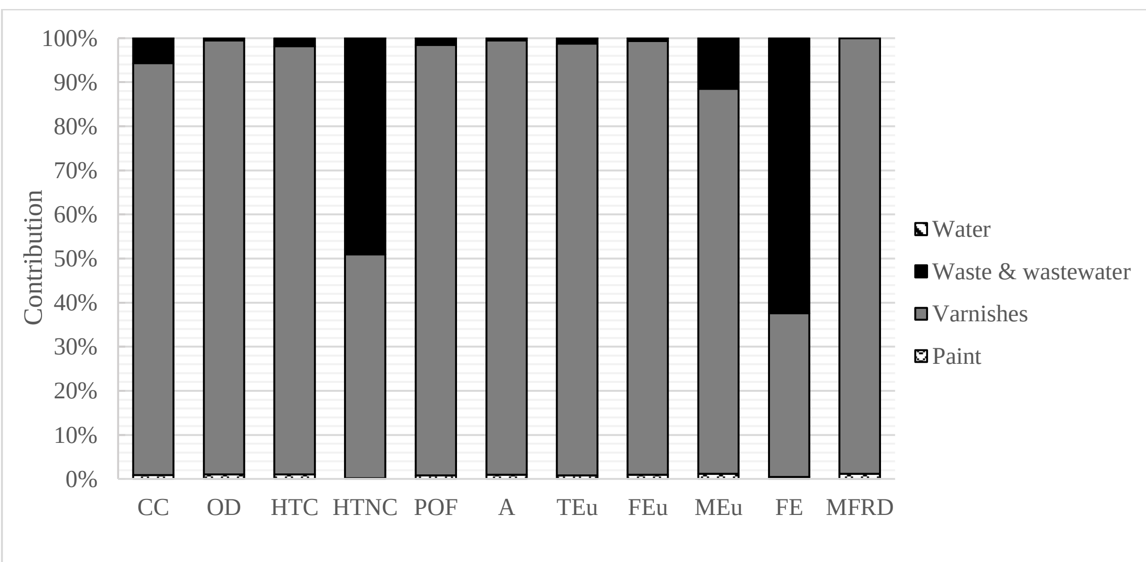

Figure 21: Contribution of each process within the painting stage to the environmental impact

The rest of the stages have a lower environmental impact, namely, the backing stage represents 2–6% of the total environmental impact, the finishing and cutting stage 5–27% and the packaging stage 4–21%.

In order to decrease the environmental impact of the product, the identified hotspots can point to the strategies the company should follow. One of the most influential processes was found to be the HDF production because of the natural gas and electricity consumption. Consequently, attention should be given to the equipment used during its production and a change to less consuming equipment could be attempted. Concerning the stage of the base manufacturing that was also found to have an important impact, care should be given to the transport of ‘‘broken’’ to the manufacturing unit.

A sensitivity analysis was performed in order to assess the influence of changing the means of transport. Transport by train combined with trucks (for the transport from and to the train station) and transport by biodiesel trucks were compared to the baseline (transport by truck). The distances considered in each case are presented in Table 11 (under sensitivity analysis). The change of transport was evaluated for the transport of ‘‘broken’’ (from the forest to the manufacturing unit) for the manufacturing of both the base and the backing layers. The results obtained showed that the use of a train and truck combination would be more effective than the use of biodiesel trucks for both cases. More specifically, in the case of the base ‘‘broken’’, the use of train and truck would decrease the environmental impact of the base manufacturing stage in all the categories by 8–23%. On the other hand, the use of biodiesel truck would decrease the impact of the base manufacturing by 2–15% for the categories of CC, OD, POF, A and MFRD, while it would cause an increase of 2–33% in the categories of HTC, HTNC, TEu, FEu, MEu and FE. Likewise, in the case of the backing ‘‘broken’’, the use of train and truck would decrease the environmental impact of the backing manufacturing stage in all the impact categories by 1–14%. The use of biodiesel truck would decrease the impact of the base manufacturing by 1–15% for the categories of CC, OD, POF, A and MFRD, while it would increase by 6–41% the rest of the categories.

Furthermore, when considering the use of a train and truck combination for the base ‘‘broken’’ transport, the total environmental impact (Table 12) would present a decrease of 1–7% while by applying the use of train and truck combination for the transport of both base and backing ‘‘broken’’, the total impact would decrease by 1–8%. Consequently, the company could contemplate the change in means of transport in the aforementioned cases in order to obtain a lower environmental impact.

Even though there is no significant research on LCA of cork floating floors, there are some studies including this product in LCA comparisons with other types of floors. However, it should be mentioned that the comparison of this kind of product, is hampered by the differences in the components of the final product, the processes included in each stage, the life span given to the product, the impact assessment methodology and even the functional unit.

More specifically, a study (Boyer at al., 2009) comparing different types of flooring (such as cork floating floor, vinyl or wood carpet and linoleum) considered the production of a cork floating floor with a service time of 50 years, produced with cork stoppers waste (for the cork components). The cradle-to-gate evaluation was carried out through BEES (building for environmental and economic sustainability) and even though the results of that study were not presented in detail (the results are provided for the whole life cycle and the relative contribution of each stage is not specified) the study mentioned that the floating floor has substantially greater impacts than a fixed (glued down) cork floor due to the HDF that triples the weight of the flooring. Another study (Mahalle et al., 2011), evaluated the environmental impact of various floor materials (such as cork, vinyl and linoleum) through the application of TRACI (tool for the reduction and assessment of chemical and other environmental impacts). In this case, the life span assumed was 25 years, the impact categories studied and the impact assessment methodology were different from those of the current study. However, in this case credit was given to the accumulation of carbon during the cork growth and this was done by modifying the impact assessment method used (TRACI) by adding carbon dioxide from the air as a negative emission, to include carbon dioxide sequestration by forests. The total value for the CC category (cradle-to-grave approach) was negative [-1.14 kg CO_2 equivalent (eq) per 1 m^2].

However, it cannot be compared to the CC value of the present study because the life span of the products and the impact assessment methodologies were not the same and the conclusions could be biased.

3.2 Carbon storage and delayed emissions

Table 13 presents the correction factors, calculated according to the different methods, used for the quantification of the biogenic CO_2 emitted. By multiplying these correction factors by the total biogenic CO_2 content of the final product, the biogenic CO_2 emission is obtained for each end-of-life scenario. These emissions, as well as the biogenic CO_2 stored in the final product in each scenario, are presented in Table 13.

Table 13: Emission factor, biogenic CO_2 emitted, stored and considered in the CC impact category (per FU) according to the three methods, for a life time for the product of 10 and 20 years in use and for the scenarios of incineration and landfilling

		10 years use		**20 years use**	
		Incineration	**Landfill**	**Incineration**	**Landfill**
Correction factors (fraction)	GHG protocol	1.000	1.000	1.000	1.000
	PAS 2050	0.924	0.202	0.848	0.176
	ILCD	0.900	0.700	0.800	0.600
Biogenic CO_2 emitted (in kg CO_2)	GHG protocol	11.836	11.836	11.836	11.836
	PAS 2050	10.936	0.047	10.037	0.042
	ILCD	10.652	0.166	9.469	0.142
Biogenic CO_2 stored (in kg CO_2)	GHG protocol	0.000	0.000	0.000	0.000
	PAS 2050	0.900	11.789	1.799	11.794
	ILCD	1.184	11.670	2.367	11.694
CC impact category considering biogenic CO_2 (in kg CO_2eq)	GHG protocol	6.230	6.230	6.230	6.230
	PAS 2050	5.330	-5.559	4.431	-5.564
	ILCD	5.046	-5.440	3.863	-5.464

The GHG Protocol considers that the entire amount of biogenic CO_2 will be emitted at the end-of-life. Consequently, the GHG Protocol results in zero biogenic CO_2 storage because it considers that the amount of biogenic CO_2 that will be emitted is equal to the amount of biogenic CO_2 accumulated in the product due to carbon sequestration from the forest (11.836 kg of CO_2). For the other two methods, in all cases, the amount of biogenic CO_2 emitted is more for incineration (both when considering 10 and 20 years of use) compared to the landfilling at the end-of-life. The total of biogenic CO_2 emitted in the landfilling scenario is much lower because the emission factor considers the time that the product stays in use and the time in the landfill as well. Furthermore, in landfilling, the biggest part of the carbon in the product (98%) is never released back into the atmosphere (remains permanently stored) since the product is not completely decomposed. In the scenario of incineration, both for 10 and 20 years of use, ILCD accounts for the most stored biogenic CO_2 in the product while in the landfilling scenario, PAS 2050, is the method that accounts for the most stored biogenic CO_2 in the product both for 10 and 20 years (higher for 20 years).

Additionally, Table 13 shows the results of the CC impact category when considering the effect of biogenic CO_2 storage and delayed emissions. When the method of the GHG Protocol is used, there are no changes. However, for the other two methods a decrease can be noticed in the CC impact category. The decrease, in the case of incineration ranges from 14% to 38% (for the three methods) with the ILCD method resulting in the greatest decrease (both for 10 and 20 years). For landfilling, the decrease is much greater ranging from 186% to 189% (for the three methods), with PAS 2050 method resulting in the greatest decrease (both for 10 and 20 years). It is also noticed that for the CC category when accounting for the biogenic CO_2 the result is a negative value for landfilling (both for ILCD and PAS 2050). A negative value means that the amount of CO_2 sequestered and stored in the product is bigger than the amount of GHG emissions (other than biogenic CO_2) throughout the product's life cycle. That shows the importance of considering the biogenic carbon in the LCA results.

Table 13 points out that the choice of method for accounting biogenic CO_2 can lead to different results and subsequently to different conclusions. Thus, the choice of method is an important part of the evaluation and in order to facilitate the comparison of different studies, a common methodology should be established in order to avoid miscalculations.

4. Conclusions

The main conclusions of this study are as follows:

- The assembling stage is the most dominant stage in the majority of the environmental impact categories, while the base manufacturing and painting stages are the most influential in two categories each.
- The production of the HDF layer is the most environmentally influential process in the assembling stage, mainly due to the consumption of natural gas and electricity.

- The process with the greatest impact in the painting stage is the production and transportation of the varnishes that are imported from abroad. This results in higher diesel consumption during transportation.
- The processes with the greatest impact in the base manufacturing stage are the transport of ‘‘broken’’ and the production and transport of resin.
- The amount of biogenic CO_2 emitted and stored in the product depends not only on the life span assumed for the product but also on the chosen end-of-life scenario. In all methods, the landfill scenario presented greater biogenic CO_2 eq. storage than the incineration. The scenario with the biggest biogenic CO_2 permanent storage is that of landfilling after 20 years of use calculated according to the PAS 2050 method. This is the method that results in the biggest decrease of the CC impact category of the product.
- The choice of method can lead to different results thus, the accounting of biogenic carbon should be done carefully. The establishment of a common methodology for the calculation of the delayed and stored biogenic emissions should be attempted for more homogeneity in the calculations and for more validity in the results comparisons.

Acknowledgements

The authors gratefully acknowledge the company Amorim Revestimentos S.A. for the collaboration in providing primary inventory data. This study has been supported by the project ‘‘Cork carbon footprint: from trees to products’’ (PTDC/AGR-FOR/4360/2012) funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal). Additional thanks to COMPETE (PEst-C/EME/UI0285/UI0285/2011).

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3.4 Environmental performance of expanded cork slab and granules through life cycle assessment

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(*Submitted*)

Abstract

The great quantities of raw materials used in the construction sector, involve high energy consumption in their production resulting to a high energy use in this sector. One of the ways to improve the energy efficiency of buildings is through the use of more environmentally friendly materials such as forest-based materials. In the present study, the environmental impacts associated with the production of expanded cork slab and granules used in construction for insulation are evaluated from a life cycle perspective with the aim of identifying the most influential stages and processes. The obtained results show that the process with the greatest environmental impact derives from the boiler process due to the production of thermal energy used for the agglomeration of the slabs and also the production of 'falca' used as raw material at the manufacturing process. It was also observed that the choice of mass or economic allocation has a significant impact on the results. The present study also considered the accounting of biogenic carbon in the climate change impact category which is usually considered neutral and excluded. The final results of climate change were recalculated by applying the International Reference Life Cycle Data System method for the stages of the forest, use and end-of-life. The consideration of biogenic carbon sequestration at the forest influenced significantly the environmental impact of the two products under study. The present study shows the importance of biogenic carbon inclusion in the environmental assessment of forest-based products. Additionally, the obtained results highlight the need for establishment of a common methodology for the calculation of the environmental impacts of cork products in order to apply common guidelines and facilitate the comparison of the obtained results.

Keywords: biogenic carbon, building materials, environmental impact, expanded cork granules, expanded cork slab, life cycle assessment

1. Introduction

The construction industry consumes great quantities of raw materials involving high energy consumption in their production (Sieffert et al., 2014). The energy use of this sector accounts for a significant part of the world's total energy use (up to 40%) and the energy requirement for space heating and cooling of a building reaches 60% of the total energy consumed in buildings, representing the largest percentage of energy usage (Kaynakli, 2012; Jelle 2011). Consequently, the need to improve the energy efficiency of buildings could be achieved through proper design and material choice for the insulation of the buildings in order to decrease the energy demands of the entire sector (Wright and Wilton, 2012; Zheng, 2012).

Considering the current increase of the environmental consciousness and general interest, the construction sector has shifted to the use of more environmentally friendly materials, such as natural materials, for various parts of the buildings, namely their thermal insulation, in order to decrease the environmental impact of the entire sector. Natural materials can be renewable (if they can be extracted more than once) or non-renewable (if they can be extracted only once) and they can potentially result in a more efficient building construction.

Natural materials include forest-based materials, such as wood and cork. One of the main advantages of using forest-based materials in construction is the carbon stored in them. More specifically, trees are known for their capacity to sequester carbon dioxide (CO_2) from the atmosphere and store it in their perennial tissues and in the soil as organic matter where it can be stored for very long periods (Linkosalmi, 2015; Martínez-Alonso and Berdasco, 2015). Thus, forest-based products contain part of the carbon that remains stored during their use period before being released at the end-of-life of the product (Dias and Arroja, 2014; Dias et al., 2012). When assessing the biogenic CO_2 balance (CO_2 emissions and removals resulting from biogenic sources) in life cycle assessment (LCA) studies, the forest-based products are mainly treated as potentially carbon-neutral materials since it is considered that the amount of CO_2 sequestrated by the forest is then emitted into the atmosphere at the end-of-life stage of the product (Althaus et al., 2009; Guinée et al., 2002). Therefore, biogenic CO_2 sequestration and emissions are usually excluded from LCA studies, for example in the study of González-García et al. (2013) and Dias et al. (2014) for the production of raw cork. However, recent studies suggest that biogenic CO_2 should be taken into account in order to have a more complete view of the system under study and in order to avoid partial conclusions (Demertzi et al., 2015; Levasseur at al., 2013; Müller-Wenk and Brandão, 2010). Currently, there are several approaches to account for temporary storage and delayed emission of biogenic carbon, however there is still no accordance on the most appropriate (Garcia and Freire, 2014; Brandão et al., 2012, 2010).

In the present study, two renewable natural construction materials are studied in order to evaluate their environmental performance through the use of LCA. This is a technique accounting for the environmental aspects and impacts of a product along its life cycle (i.e., raw material acquisition, manufacturing, use and end-of-life) (ISO, 2006a, b). More specifically, the materials under study are an expanded cork slab used in construction for thermal and acoustic insulation (main material) and expanded cork granules with acoustic insulation properties for use in screeds, flooring and interior cavity walls (coproduct). The main objective of the present study is to analyze the potential environmental impacts and identify the most influential stages and processes (hotspots) during the production of the two materials (used for insulation in construction).

A few LCA studies regarding the use of cork as a construction material can be found in literature. For example, Boyer et al. (2009) and Mahalle et al. (2011) that studied agglomerated cork slab as flooring and Brito et al. (2010) and Pargana et al. (2014) studied expanded cork slab as insulation material. Additionally, there is a study focusing on the production of Iberian cork from an economic and environmental point of view, presenting statistical information regarding this topic (Sierra-Pérez et al., 2015). However, most of the mentioned studies only present traditional LCA results and do not consider the biogenic CO_2 sequestration and emission. Thus, as a second objective, the biogenic carbon storage and emission delay at the forest (not only in cork but also in wood, roots and foliage), during the product's use and end-of-life stages is assessed by using a biogenic carbon accounting method, the International Reference Life Cycle Data System (ILCD) (European Commission, 2010), in order to evaluate its influence on the results obtained for the climate change impact category.

2. Methods

In this study, a cradle-to-gate approach is applied in order to assess the environmental impacts of the expanded cork slab and granules. Thus, the stages considering the extraction of raw materials up to the packaging of the final product ready to be sold are included in the assessment. Concerning the accounting of the biogenic CO_2 emissions, two additional stages are considered in the calculations, namely the use stage (considering 30 and 50 years of use) and end-of-life stage (considering incineration, landfilling and recycling as end-of-life destinations).

2.1 Product description and functional unit

The main product studied is an expanded cork slab, produced in Amorim Isolamentos S.A. in Portugal, used in construction for thermal, acoustic and anti-vibration insulation. Expanded cork slab is a 100% natural product since it only contains cork and no additional chemicals such as resins. Furthermore, it is a renewable and recyclable product with a very low waste generating manufacturing process. During the manufacturing process of the expanded cork slab, there is also the production of a coproduct that is studied as well, the expanded cork granules. This is also a 100% natural and recyclable product used as a solution of lightweight filling with thermal, acoustic and anti-vibration insulation properties. Some of the possible applications of this coproduct are for pitched roof with loose fill insulation between joists, filling of the internal double walls, rustic decorative floor, between joists loose fill, lightweight concrete-screed filling.

The functional unit (FU) is defined as 1 m^2 of insulation material with a thickness that gives a design thermal resistance (R) of 1 (m^2.ºC)/W. Thus, based on the above definition of FU, the amount of insulation material (expanded cork slab and granules) that needs to be installed can be determined. Table 14 presents the specific characteristics of the expanded cork slab and granules (per FU) (as provided by the Amorim Isolamentos S.A. Company).

2.2 System boundaries

Figure 22 presents the system boundaries for the production of the expanded cork slab and granules. The raw material, called 'falca', refers to fractions/pieces of 'virgin cork' (first bark grown in cork oak trees) that are extracted from the pruned branches of the living cork oak trees and/or from thinned trees (Pereira, 2007). This cork type, which is of low quality and cannot be used for the production of cork stoppers and thus, it is used mainly for the manufacturing of construction materials such as expanded cork slabs and granules for insulation. During 'falca' production, the cork oak forest management processes such as fertilization, thinning and pruning, are considered. Furthermore, the transport of the pruned branches to the separation location (50 km) is also considered. At the separation location, the ‘falca’ is separated from the wood and then the clean ‘falca’ is transported to the manufacturing industry (30 km) in order to be naturally dried in the open air.

Table 14: Specific characteristics of the expanded cork slab and granules (per FU)

Parameter	**Quantity [a]**	**Unit**
Expanded cork slab		
Mass	4.40	kg
Volume	0.04	m^3
Width	1,000.00	mm
Thickness	40.00	mm
Length	1,000	mm
Density	110.00	kg/m^3
Thermal conductivity	0.04	W/(m.ºC)
Thermal resistance	1.00	$(m^2.^{o}C)/W$
Expanded cork granules [b]		
Mass	2.80	kg
Volume	0.04	m^3
Width	1,000.00	mm
Thickness	40.00	mm
Length	1,000.00	mm
Size of granules	0-15.00	mm
Density	70.00	kg/m^3
Thermal conductivity	0.04	W/(m.ºC)
Thermal resistance	1.00	$(m^2.^{o}C)/W$

[a] Data provided by provided by the Amorim Isolamentos S.A. Company in Portugal
[b] It refers to the application of the granules as insulation

After an average period of at least 6 months, the dried ‘falca’ is transported internally by a machinery to the trituration area. There the ‘falca’ passes through a trituration machine, consuming electricity, and producing ‘falca’ granules. Furthermore, in this stage, occurs a separation of the ‘falca’ granules from impurities, such as small stones (moved to the landfill of the industrial area) and soil (transported for 30 km for agricultural valorization). In the trituration stage there is also production of cork dust which is aspirated and stored in silos in order to be burned for the production of thermal energy used in a following process. During the cork dust combustion there is production of ashes (transported for 30 km for agricultural valorization).

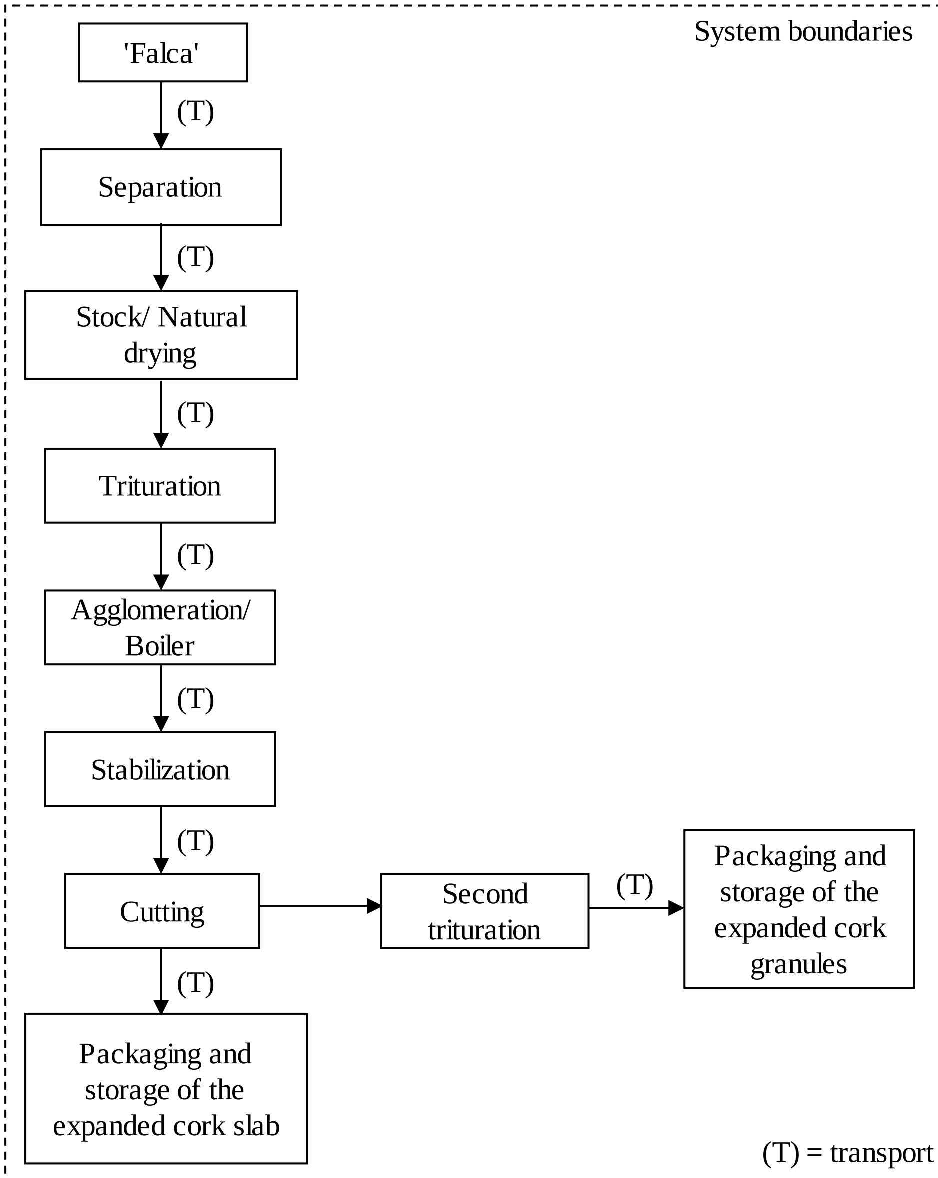

Figure 22: System boundaries for the production of the expanded cork slab and granules

The 'falca' granules are internally transported (though suction) to the stock silos and from there to the agglomeration stage. There, the granules are heated up to 350 ºC-370 ºC (through vapor heated by the thermal energy of cork dust's combustion) for approximately 20 minutes, and transformed into blocks of specific dimensions (1,000x500x320 mm). During this period of time the ‘falca’ granules expand up to 30% of their initial size and their natural resins are heated resulting to their agglomeration in the form of blocks. It should be noted that there are no additional resins or adhesives added in the agglomeration process, turning this stage and final product, 100% natural. In order to cool the cork blocks, metallic perforated needles are inserted in them and water passes through their center. The used water is recirculated and reused in this stage of production. During the agglomeration process there is production of sludge that is collected and burnt in the boiler.

The produced blocks are transported by forklifts to the stabilization area where they stay during at least 7 days in order to cool down and naturally obtain their final size. After the stabilization period, the blocks are sent to the cutting stage. In this stage, the blocks are placed in line in order to pass through a rectification machine in order to be cut (by automatic chainsaw) into the desired dimensions and electricity is consumed. The cork dust resulting from the chainsaw cutting of the cork blocks, is aspirated and sent to the cork dust silos to be used for thermal energy production. Furthermore, the cork slabs, before being sent to the packaging stage, are visually controlled in order to reject the ones of lower quality. The selected slabs are sent to the packaging stage where they are stacked on wooden pallets, wrapped with a plastic film and stored in the stock area.

The rejected slabs and the cork residues from the cutting of the blocks (cut edges) are sent to another trituration machine (second trituration) which produces the coproduct, expanded cork granules. This is packaged in raffia bags and stored in order to be ready for expedition.

It should be mentioned that the internal transport of raw materials, intermediate and finished products at the industrial units was also included in the inventory because of the consumption of diesel for the operation of the small machinery. On the other hand, the energy consumption in laboratories and infrastructure as well as the manufacturing of the used equipment was excluded due to the low contribution in the total environmental impact.

2.3 Inventory data

Table 15 presents the inventory data expressed per FU of expanded cork slab. Data collection and calculation procedures followed the recommendations included in ISO 14044 (ISO, 2006b).

Concerning the foreground processes, the data were obtained from the Amorim Isolamentos S.A. manufacturing unit of the product for the reference year 2014.

Table 15: Inventory data expressed per FU of expanded cork slab

Input/ Output	Quantity	Unit
Inputs		
Stock/ Natural drying		
Clean 'falca'	1.60E+01	kg
Trituration		
Electricity	4.20E-01	kWh
Boiler		
Water	4.00E-02	m^3
Burnt cork dust [a, b]	1.02E+02	MJ
Sludge [c]	5.48E-05	kg
Agglomeration	6.95E+00	kg
Water	2.00E-03	m^3
Electricity	1.19E-01	kWh
Cutting		
Electricity	2.00E-01	kWh
Packaging (expanded cork slab)		
Wood pallets	1.10E-01	kg
Plastic film	5.00E-02	kg
Paper	1.00E-03	kg
Second trituration (expanded cork granules)		
Electricity	1.00E-01	kWh
Packaging (expanded cork granules)		
Raffia	1.70E-02	kg
Internal transport		
Diesel	2.40E-02	kg
Outputs		
Trituration		
Stones	6.00E-01	kg
Soil	6.00E-01	kg
Boiler		
CH_4 [d]	3.06E-03	kg
CO [e]	5.81E-02	kg
N_2O [d]	4.08E-04	kg
NH_3 [e]	3.77E-03	kg
NMVOC [f]	2.43E-03	kg
NOx [g]	3.20E-02	kg
Particulate matter [f]	2.46E-02	kg
SO_2 [e]	1.12E-03	kg
Ashes [f]	7.20E-02	kg

Table 15: Inventory data expressed per FU of expanded cork slab (continuation)

Input/ Output	Quantity	Unit
Internal transport [e]		
CH_4	1.32E-06	kg
CO	2.65E-04	kg
N_2O	5.04E-06	kg
NH_3	6.72E-07	kg
NMVOC	5.26E-05	kg
NO_X	5.77E-04	kg
Particulate matter	4.38E-05	kg
SO_2	4.80E-08	kg
CO_2	2.60E-04	kg
Pb	2.34E-09	kg
Cutting		
Expanded cork slab (final product)	1.00E+00	m^2
Second trituration (expanded cork granules)		
Expanded cork granules (final product)	1.49E+00	kg

[a] calorific value considered 14.65 MJ/kg
[b] The burnt cork dust for energy production considers the cork dust brought from another cork company of the same group (0.58 kg), the cork dust produced during the trituration process (6.01 kg) and the cutting process (0.36 kg)
[c] Internal flux
[d] IPCC (2006)
[e] EMEP/EEA (2013)
[f] Demertzi et al. (2015)
[g] Measured value

Table 16 presents the transport profiles considered in the assessment (distances and load of truck), also provided by the aforementioned company.

For the background processes, the Ecoinvent database v.3 (Weidema et al., 2013) was used since the manufacturer has no specific influence or information (e.g. electricity production, raw material production, etc.). The inventory data for the production of ‘falca’ used for the manufacturing of the expanded cork slab and granules, derived from the combination of data of a previous study concerning the production of raw cork in Portugal considering virgin, second and reproduction cork (Dias et al., 2014), and by performing an economic allocation of the environmental impacts to ‘falca’ by using data on ‘falca’ production and price provided by industrial unpublished statistics.

Table 16: Transport profiles considered in the assessment

Material	**Distance (km)**	**Type of transport**	**Maximum load (t)**	**Return journey**
Pruned branches	50 km	Freight lorry, EURO 3	16	Empty
Clean 'falca' [a]	30 km	Freight lorry, EURO 3	16	Empty
Soil separated from 'falca' [b]	30 km	Freight lorry, EURO 3	16	Empty
Cork dust from another industry of the group	30 km	Freight lorry, EURO 3	16	Empty
Ashes from cork combustion	30 km	Freight lorry, EURO 3	16	Empty
Plastic (for packaging)	180 km	Freight lorry, EURO 3	16	Empty
Pallets (for packaging)	180 km	Freight lorry, EURO 3	16	Empty
Paper (for packaging)	180 km	Freight lorry, EURO 3	16	Empty
Raffia (for packaging)	180 km	Freight lorry, EURO 3	16	Empty

[a] from the separation location to the industrial unit
[b] during the trituration process

2.4 Allocation

As mentioned in the description of the manufacturing process, apart from the expanded cork slab there is another product produced as well (expanded cork granules). Thus, it is necessary to perform allocation procedures (coproduct allocation) to identify which inputs and outputs correspond to the manufacturing process of the main product and which to the coproduct. Both mass and economic allocation were performed for the main and coproduct in order to assess the difference in the obtained results of each case. The economic allocation was performed based on the market prices of the two studied products, expanded cork slab (220€/m^3) and expanded cork granules (90€/m^3). The allocation factors considered in the case of the economic allocation were 82% for the cork slab and 18% for the cork granules. The mass allocation was performed based on the mass values provided in the inventory (Table 15). In this case of the mass allocation, the allocation factors considered were 75% for the cork slab and 25% for the cork granules. The allocation procedure was applied to all operations except for the packaging processes and the second trituration process that were allocated to the specific products.

2.5 Impact assessment

For the impact assessment, the characterization factors recommended by the ILCD were used (European Commission, 2010). The impact categories considered to be relevant in this study are: Climate Change (CC), Ozone Depletion (OD), Human Toxicity Cancer Effects (HTC), Human Toxicity Non-cancer Effects (HTNC), Photochemical Ozone Formation (POF), Acidification (A), Terrestrial Eutrophication (TEu), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Freshwater Ecotoxicity (FE) and Mineral and Fossil Resource Depletion (MFRD).

2.6 Biogenic carbon

The expanded cork products under study store biogenic carbon during their life cycle that is then released into the atmosphere during its end-of-life. In the present study, the amount of biogenic carbon (in kg of CO_2) emitted after 30 and 50 years of use lifespan (according to the product manufacturer indications) was accounted for the cases of incineration, landfilling and recycling. In this way, the amount of biogenic CO_2 temporarily and/or permanently stored in the product was calculated. A leading method for the accounting of biogenic carbon is used (ILCD) in order to evaluate the influence of biogenic carbon inclusion in the results of the CC impact category. The ILCD handbook was developed by the European Commission (European Commission, 2010). In this method, temporary carbon storage and delayed emissions should not be considered in LCA per default, unless required in the goal of the study. In such case, equation 8 should be applied.

$$\text{FW}= \frac{(100-(1*t))}{100} \quad \text{(Equation 8)}$$

where *t* is the total of years when occurs biogenic carbon storage (equal to the use period and time at the landfill of the product).

For all the end-of-life alternatives the assessment period is 100 years. In order to calculate the emissions of CO_2, it is needed to know the content of carbon in the product (equal to the amount of carbon sequestrated/stored in that product). The expanded cork slab, considering the FU used in the present study, contains 4.4 kg of ‘falca’ cork and has a carbon content of 65% (dry basis) and 2% of moisture (Dias and Arroja, 2014). Consequently, there is a content of 2.826 kg of biogenic carbon (equivalent to 10.277 kg of biogenic CO_2) per FU of expanded cork slab (1 m^2). In the case of the expanded cork granules there is a content of 1.780 kg of biogenic carbon (equivalent to 6.540 kg of biogenic CO_2) per FU of expanded cork granules (1 m^2), considering the same carbon and moisture content as for the expanded cork slab.

Table 17 presents the correction factor, biogenic CO_2 emitted and stored and CC impact category accounting for biogenic CO_2 (per FU) according to the ILCD method. In the case of incineration, there is an immediate release of the total biogenic carbon content of the products after 30 or 50 years, depending on the lifespan. In the case of landfilling it is considered that 98% of biogenic carbon permanently remains in the product since cork does not entirely decompose in landfill (EPA, 2014; IEC, 2013; Freed et al., 2004). Thus, only 2% of the biogenic carbon will be emitted. The lifespan in the landfill facility is considered to be 20 years (Garcia and Freire, 2014; Micales and Skog, 1997). The 2% of the biogenic CO_2 is considered as a single release at years 50 and 70 respectively for 30 and 50 years of use period.

In the alternative of recycling, two products (initial and recycled) are produced consecutively since the cork contained in the manufactured product (initial product) is recycled to be used for the partial manufacturing of the new product (recycled product). It should be noted that a closed-loop is considered (cork slab is used for the production of the recycled cork slab and cork granules are used of the production of the recycled cork granules). In the present study, it is considered that the products are recycled only once and that after their new use period (addition of 30 and 50 years) they will end up at an incineration or landfill facility where the biogenic CO_2 will be released.

Thus, in the recycling alternative the use period will increase to 60 and 100 years (for the second lifespan). According to the ILCD method, carbon stored for more than 100 years is considered permanently stored. Consequently, only in the case of 60 years use, there will be a release of biogenic emissions while in the case of 100 years use, the biogenic CO_2 will be permanently stored and will not return into the atmosphere. The FW calculated is multiplied with the biogenic carbon emissions occurring during the initial and recycled product. Specifically, after the first use period, it is considered that the contained carbon in the product is released during the recycling process due to cork dust production and combustion (72.5% and 82.5% of the contained biogenic carbon is released from the cork slab and granules respectively). The recycled product contains less biogenic carbon since 27.5% and 17.5% of the initial carbon content (for the cork slab and the granules, respectively) remains in the product.

Table 17: Correction factor, biogenic CO_2 emitted and stored during use and end-of-life stages, and CC impact category accounting for sequestration of biogenic CO_2 in cork and rest biomass (per FU) according to the ILCD method

	Correction factors (fraction)		**Biogenic CO_2 emitted at the end-of-life (in kg CO_2)**		**Biogenic CO_2 stored during use and end-of-life (in kg CO_2)**		**CC impact category considering biogenic CO_2 sequestration only in cork (in kg CO_2eq)**		**CC impact category considering biogenic CO_2 sequestration in cork and rest biomass (in kg CO_2eq) [a]**	
	30 years	**50 years**	**30 years**	**50 years**	**30 years**	**50 years**	**30 years**	**50 years**	**30 years**	**50 years**
Expanded cork slab										
Incineration	0.700	0.500	7.194	5.138	3.083	5.138	-2.183	-4.238	-452.260	-454.316
Landfilling	0.500	0.300	0.103	0.062	10.174	10.215	-9.274	-9.315	-459.352	-459.393
Recycling followed by incineration	-	-	6.346	3.725	3.931	6.551	-3.031	-5.652	-453.108	-455.729
Recycling followed by landfilling	-	-	5.227	3.725	5.050	6.551	-4.150	-5.652	-454.227	-455.729
Expanded cork granules										
Incineration	0.700	0.500	4.578	3.270	1.962	3.270	-1.362	-2.670	-80.140	-81.448
Landfilling	0.500	0.300	0.065	0.039	6.474	6.501	-5.874	-5.901	-84.652	-84.678
Recycling followed by incineration	-	-	4.235	2.698	2.306	3.842	-1.705	-3.242	-80.483	-82.020
Recycling followed by landfilling	-	-	3.782	2.698	2.759	3.842	-2.159	-3.242	-80.936	-82.020

[a] the rest of the biomass considers the wood that remains on the cork oak tree after the extraction of the cork as well as the roots and foliage

The sequestration of biogenic carbon at the forest stage was also included by considering the sequestration of carbon in the wood, roots and foliage of the tree. Due to the cork oak tree ability for regenerating the bark tissue, after the extraction of cork, the tree remains at the forest and continues to contribute to the sequestration of carbon of the forest for more than 100 years (cork oak trees are long-lived trees that can live for up to 200-250 years), which leads to permanent carbon storage. The quantity of wood produced, was calculated based on the proportions of wood and cork (reproduction, virgin and second cork) presented in Dias et al. (2014) and on the proportion of 'falca' provided by unpublished industrial statistics. The proportions (dry basis) are 63.10% for wood, 27.50% for reproduction cork, 0.68% for second cork, 0.24% for virgin cork and 8.48% for 'falca'. The calculations for roots and foliage biomass were based on the average proportions of biomass. These were computed as a ratio (dry basis) between wood biomass and roots and foliage that presented a value equal to 0.99 and 14.75, respectively (Palma et al., 2014; Paulo, 2011; Paulo and Tomé, 2006). The values obtained were then converted to kg of CO_2 eq. (Oubrahim et al., 2015). Table 18 presents the production of wood, roots and foliage and their respective carbon content (per FU).

Table 18: Production of wood, roots and foliage and their carbon content per (FU)

Produced	**Quantity (kg)** [a]	**Carbon (%)** [b]
Expanded cork slab		
Wood [c]	109.53	54
Roots [d, e, f]	110.64	54
Foliage [d, e, f]	7.43	52
Expanded cork granules		
Wood [c]	19.17	54
Roots [d, e, f]	19.36	54
Foliage [d, e, f]	1.30	52

[a] Dry mass
[b] Oubrahim et al. (2015)
[c] Dias et al (2014)
[d] Palma et al. (2014)
[e] Paulo (2011)
[f] Paulo and Tomé (2006)

3. Results and discussion

In this section, the environmental impacts deriving from the manufacturing of the expanded cork slab and granules are evaluated and the main hotspots, both stages and processes, are identified. Additionally, the obtained results of the present study, are compared with those of previous studies in order to verify their accordance or discordance. The influence of biogenic carbon consideration in the calculation of the CC impact category, for the stages of forest, use and end-of-life, is also evaluated.

3.1 Environmental impacts and hotspots

Figure 23 shows the relative contribution of each stage to the environmental impact of the manufacturing of the expanded cork slab (a) and granules (b) per FU. It should be noted that in those cases, mass allocation is considered but the economic allocation showed the same trend for the various process. It can be observed that for the majority of the impact categories, the main influence derives from the boiler process that is needed for the production of heat used for the agglomeration of the product (47%-95% of the total impact). The only exception is presented for the categories of CC, OD and MFRD where the main influence derives from the 'falca' preparation that is used as raw material (50%, 71% and 91% of the total impact, respectively).

In the case of the boiler process, two sub-processes were considered namely the combustion of cork dust and sludge for energy. It was found that for all the impact categories the main influence derived from the combustion of cork dust (99% of the total process). In the case of 'falca' preparation, all the management processes were considered as well as the transport of the 'falca' to the manufacturing unit. The main impact in the majority of the impact categories derived from the management processes at the forest (63%-100% of the total process) with the exception of the CC, OD, POF and FE categories where the main influence derived from the transport of the 'falca' (52%-70%). The same trend is observed for the expanded cork granules environmental impacts.

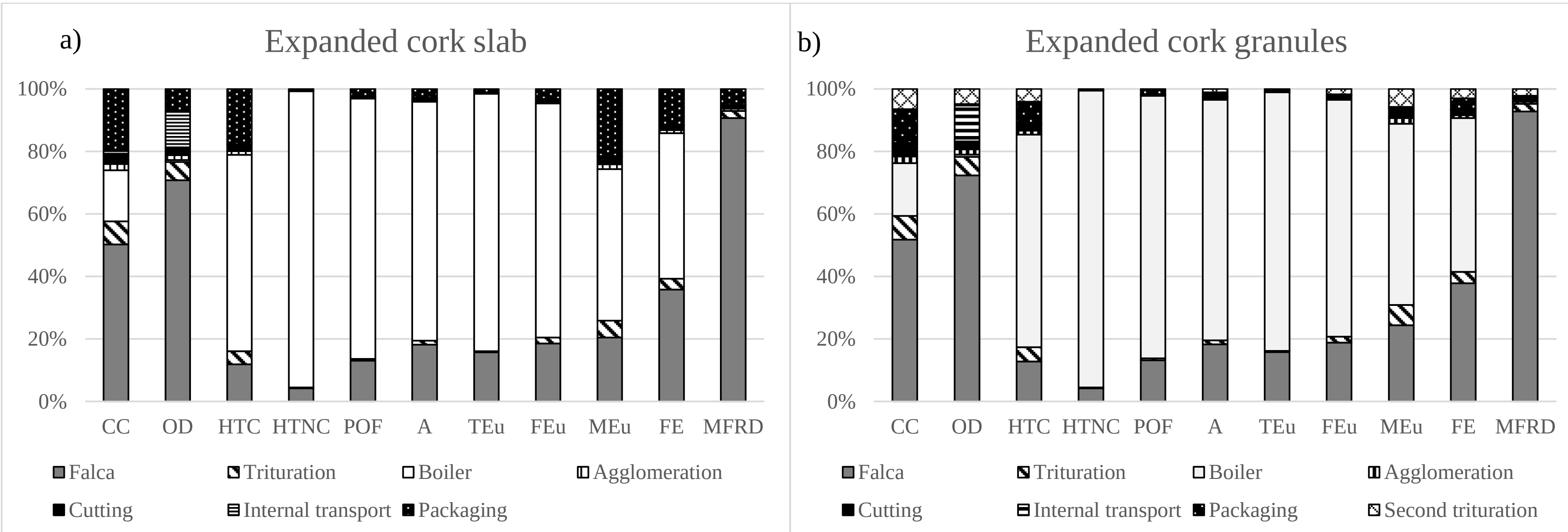

Figure 23: Contribution of each stage to the environmental impact of the manufacturing of the expanded cork slab (a) and granules (b) per FU

Table 19 presents the total environmental impact of the two products under study when considering mass and economic allocation (per FU). It can be noticed that in both allocation approaches, the expanded cork slab presented higher environmental impact than the expanded cork granule, considering that in both allocation approaches, the expanded cork slab has greater share than the expanded cork granules (more mass and economic value). In the case of the economic allocation, the environmental impact of the expanded cork slab increased by 10%, considering that the allocation percentage was higher than in the case of mass allocation. On the other hand, when changed from mass to economic allocation, the expanded cork granules presented lower environmental impact by 49% considering that their lower economic value decreases their impact.

Table 19: Total environmental impact with mass and economic allocation of expanded cork slab and granules per FU

Impact category	Unit	Expanded cork slab		Expanded cork granules	
		Mass allocation	**Economic allocation**	**Mass allocation**	**Economic allocation**
CC*	kg CO_2 eq	9.19E-01	1.01E+00	5.89E-01	4.20E-01
OD	kg CFC-11 eq	1.08E-07	1.20E-07	6.96E-08	4.68E-08
HTC	CTUh	4.67E-08	5.14E-08	2.85E-08	1.97E-08
HTNC	CTUh	4.29E-06	4.81E-06	2.82E-06	1.85E-06
POF	kg NMVOC eq	3.32E-02	3.71E-02	2.17E-02	1.43E-02
A	molc H+ eq	3.54E-02	3.96E-02	2.33E-02	1.54E-02
TEu	molc N eq	1.69E-01	1.89E-01	1.11E-01	7.27E-02
FEu	kg P eq	6.98E-04	7.80E-04	4.55E-04	3.01E-04
MEu	kg N eq	1.95E-02	2.14E-02	1.08E-02	7.30E-03
FE	CTUe	5.53E+00	6.12E+00	3.46E+00	2.34E+00
MFRD	kg Sb eq	1.59E-05	1.78E-05	1.03E-05	6.83E-06

*Excluding biogenic carbon sequestration and emissions

The present study shows the importance of the LCA to improve the environmental performance of expanded cork slab and granules. Through the application of LCA it is possible to consider all the materials used, the fossil and renewable fuels consumed and all the emissions occurring in order to identify the most influential stages that could be improved in order to decrease the total environmental impact for the production of expanded cork slab and granules. The results regarding the main hotspots of the manufacturing process (boiler and forest management) could be considered by the industry in order to apply improvement actions and decrease the final environmental impacts. Since those two specific process are the most influential in all the impact categories considered, the cork industry by focusing on those two aspects could achieve a better environmental performance. For example, in the case of forest management, an alternative approach could be applied by changing the frequency of activities such as clearing of the spontaneous vegetation or fertilization (Dias et al., 2014) or the application of slow-release fertilizers (Trenkel, 2010).

Thus, through the application of LCA and the improvement of the identified hotspots, the environmental impacts deriving from the production of expanded cork slab and granules could be achieved. This, in a larger scale could also help decrease the environmental impacts of the entire cork sector. However, various barriers could be confronted in the application of the LCA improvement actions for the decrease of the sector’s CF. For example, considering the great number of cork producers it could be challenging to communicate the improvement actions regarding the forest management. Furthermore, in the case of the forest stage it is difficult to generalize actions since the application and frequency of the management activities depends on the climatological and edaphological conditions of each region and thus, could vary significantly. Another possible barrier could be the economic aspect of the application of the improvement actions since they could result to additional costs.

Apart from the evaluation of the environmental impacts during the manufacturing of the studied products, it is important to point out the fact that most of the produced wastes are valorized. For example, the cork dust (produced at the granulation process and the cutting of the blocks) and the sludge (produced at the agglomeration stage of the product) are used for on-site thermal energy production, while the cork wastes (produced at the cutting of the blocks and the rejected slabs) are used for the production of the expanded cork granules. Thus, this manufacturing process can be considered an important example of circular economy where the objective is to keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life. Consequently, this is another advantage of the expanded cork slabs and granules over the conventional insulation materials (e.g. extruded and expanded polystyrene and polyurethane).

3.2 Comparison with previous studies

Currently, there are not many studies in literature regarding the environmental impact of cork slab used as insulation in buildings (Pargana et al., 2014; Bribrián et al., 2010). Besides, only the Pargana et al. (2014) study considered the same product as the present study (expanded cork slab from 'falca' and not white cork slab). More specifically, the study of Pargana et al. (2014), compared various insulation materials for buildings (extruded and expanded polystyrene, polyurethane, expanded cork agglomerate and expanded clay lightweight aggregates) through LCA in order to find the most environmentally efficient. Even though the study considered the same product, a different impact assessment method, CML (Guinée et al., 2002), was applied. Thus, only the CC category can be directly compared since they have the same unit (kg CO_2 eq.) and characterization method. It should be mentioned that in both studies the FU used was the same and this facilitates the comparison of the CC total value. Also the considered processes in the system boundaries were similar considering the extraction of the raw materials ('falca'), their transport and storage and the manufacturing process of the expanded cork slab. The allocation procedure considered in the study of Pargana et al. (2014) was mass allocation. The obtained results for the CC impact category were higher than in the present study (1.61 kg CO_2 eq. and 0.92 kg CO_2 eq., respectively).

Furthermore, the two studies agree on the main hotspot of the life cycle that was found to be the manufacturing process mainly due to the direct emissions from the boiler. The differences between the two studies can be explained by the fact that the Pargana et al. (2014) study considered the production of 'falca' according to the Ecoinvent database, while the present study used real data for the production of 'falca' according to Portuguese cork producers. Considering the total CC impact for the expanded cork slab, the value remains lower than the rest of the products studied in the Pargana et al. (2014) study concluding that both the expanded cork slab and granules presented better environmental performances than the conventional insulation materials (e.g., extruded and expanded polystyrene and polyurethane). Thus, their use for the insulation of a building can result to a lower environmental impact of the entire construction.

3.3 Considering biogenic carbon in the CC category

Table 17 presents the results of the CC category when considering the biogenic carbon emissions. It is important to mention that when the biogenic CO_2 is considered, the product instead of a source is considered a sink of CO_2 since more biogenic carbon is sequestered than emitted along the life cycle. It can be noticed that both for the lifespan of 30 and 50 years, the expanded cork slab presented greater amount of biogenic CO_2 storage (-2.183 kg CO_2 and -9.315 kg CO_2) compared to the expanded cork granules (-1.362 kg CO_2 to -5.901 kg CO_2) considering that per FU the slab contains more carbon than the granules.

Both for the expanded cork slab and granules, in the alternative of incineration, the FW is the same. As explained previously, the FW is influenced by the use period of the product. It can be noticed that in the case of 50 years use period, there is a lower CC total impact when biogenic CO_2 is considered in the calculations than in the 30 years use period. This occurs due to the longer storage period of the biogenic CO_2. In the case of landfilling (both for the expanded cork slab and granules), the FW for the two use periods is the same. It can be noticed that the CC result for the two use periods are similar but slightly lower for the 50 years use period where there is a higher amount of biogenic CO_2 stored in the products. For the alternative of recycling even though different percentages of the initial product end up to the recycled product, the trend is the same both for the expanded cork slab and granules. The CC results are lower when considering landfilling as the final destination for a 30 years use period. In the case of the 50 years use period, the results of the CC are the same for both final destinations, since in those cases the entire amount of biogenic CO_2 contained in the products is considered to be permanently stored.

From the comparison of the tree alternatives, the alternative of landfilling is followed by the recycling alternative (the recycled product ends up in a landfill) and then by the incineration alternative. It can be noticed that there is an influence of the use period considered in each case. However, it can be observed that both when considering the 30 and 50 years use period, the most environmentally efficient alternative is landfilling, due to the great percentage of the contained carbon that remains in the landfill. Nevertheless, it should be noticed that landfilling can be preferable from a greenhouse gas (GHG) point of view in this case, but a GHG-only assessment cannot be considered a full environmental assessment.

Regarding the alternative of recycling, it was observed that it is an important alternative since there is a longer delay of the carbon emission and also there is a part of it that remains permanently stored (after 100 years). Furthermore, the recycling alternative has an advantage that the two other alternatives don't have. The initial products are used to partially produce the new recycled products. Thus, there will be a decrease of the raw material needed for the production of the cork slab and granules. Consequently, except for the biogenic carbon storage there will be a decrease of the fossil emissions. Furthermore, it could also help to avoid the production of other insulation materials with higher environmental impacts (Pargana et al., 2014).

The development and application of Product Category Rules (PCR) could be useful for the case of cork products since it would facilitate the comparison of different studies and to avoid miscalculations by establishing a common methodology. It is important to highlight that the most influential aspect when considering the biogenic CO_2 emissions and storage is the choice of the end-of-life destination, since the results can change significantly.

Table 17 presents the results of CC impact category when considering the use and end-of-life stages in the accounting of the biogenic CO_2 emissions, as well as the sequestration of biogenic CO_2 at the forest stage (wood, roots and foliage of the tree). It can be seen that for both studied products, the results of CC decreased dramatically. When the forest stage biogenic carbon sequestration is considered, the consideration of different use periods and the choice of different end-of-life destinations, do not change significantly (-451.413 kg CO_2 to -459.393 kg CO_2 for expanded cork slab, -79.796 kg CO_2 to -84.678 kg CO_2 for expanded cork granules). This occur because the biogenic CO_2 sequestration is much greater than the biogenic CO_2 emissions. Nevertheless, the various CC results obtained show the consideration or exclusion of biogenic CO_2 in the calculations has to be clearly mentioned in the LCA studies since very different results are obtained in the different cases and considering that currently biogenic carbon is considered neutral and excluded from the calculations.

Even though the present study considered the sequestration of carbon by the above and below ground forest biomass, a suggestion for future studies is the consideration of carbon storage in the soil. This aspect was not considered in the present study since currently there is no specific information.

4. Conclusions

The present study has concluded that the production of thermal energy used in the agglomeration process and the production of the raw material 'falca' used for the manufacturing of the expanded cork slab and granules are the most influential processes and stages during the production of the two products under study (expanded cork slab and granules). Consequently, more attention should be paid on this aspect in order to decrease the total environmental impact of those products.

The comparison of the environmental impact results when applying mass and economic allocation, showed that this choice is very influential since the allocation percentages are different. It should be noted that the influence of the allocation procedure is more noticeable in the case of the cork granules where there was noticed a great decrease of the final environmental impact when changing from mass to economic allocation due to the economic value of the two products under study.

When considering the biogenic carbon contained in a product, it changes the product from a source of carbon to a sink. The consideration of biogenic carbon in various stages has different influence in the total result of the CC impact category. It was found that with the inclusion of the use and end-of-life stages, the results change slightly depending on the lifespan in use considered (lower CC for 50 years use). However, the consideration of the biogenic carbon sequestration at the forest stage, leads to a significant decrease of the CC results. The previous LCA studies regarding cork products, usually do not include biogenic carbon in the calculations or the consideration of biogenic carbon delayed emissions.

Thus, the outcome of the present study is considered significant and proves that the accounting of biogenic carbon (both sequestered at the forest and contained in the products) should be done carefully. The choice of lifespan and end-of-life destination can lead to different results since it influences the delayed emissions calculated. The establishment of a common methodology for the environmental evaluation of cork products could be important since it could facilitate the comparison of different studies.

Acknowledgements

The authors gratefully acknowledge the company Amorim Isolamentos S.A. (Portugal) for the collaboration in providing primary inventory data. This study was supported by the project 'Cork carbon footprint: from trees to products' (PTDC/AGR-FOR/4360/2012), funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal).

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3.5 Evaluation of different end-of-life management alternatives for used natural cork stoppers through life cycle assessment

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Waste Management 46: 668-680 (2015)

Abstract

An important aspect of sustainable development is the implementation of effective and sustainable waste management strategies. The present study focuses on a Life Cycle Assessment (LCA) approach to different waste management strategies for natural cork stoppers, namely incineration at a municipal solid waste incinerator, landfilling in a sanitary landfill, and recycling. In the literature, there are no LCA studies analyzing in detail the end-of-life stage of natural cork stoppers as well as other cork products. In addition, cork is usually treated as wood at the end-of-life stage. Thus, the outcome of this study can provide an important insight into this matter.

The results showed that different management alternatives, namely incineration and recycling, could be chosen depending on the impact category considered. The former alternative presented the best environmental results in the impact categories of climate change, ozone depletion and acidification, while the latter for photochemical ozone formation and mineral and fossil resource depletion. The landfilling alternative did not present the best environmental performance in any of the impact categories. However, when the biogenic carbon dioxide emission was assessed for the climate change category, the landfilling alternative was found to be the most effective since most of the biogenic carbon would be permanently stored in the cork products and not emitted into the atmosphere.

A sensitivity analysis was performed and the results showed that there are various parameters that can significantly influence the results (e.g., carbon content in cork and decay rate of cork in the landfill). Thus, LCA studies should include a detailed description concerning their assumptions when the end-of-life stage is included in the boundaries since they can influence the results, and furthermore, to facilitate the comparison of different end-of-life scenarios. The present study and the obtained results could be useful for the decision-making process concerning public solid waste policies and industrial strategies.

Keywords: biogenic carbon, incineration, landfilling, life cycle assessment, natural cork stoppers, recycling

1. Introduction

Cork is the bark of the cork oak (Quercus suber L.), a long-lived tree (~170 years) located in different Mediterranean countries and northern regions of Africa. Most cork oak forests are found in Portugal and Spain (34% and 27% of the total cork oak area, respectively) resulting in a considerable cork industry of great economic importance (APCOR, 2014).

Cork is used for the production of various products in a wide range of sectors due to its versatility. However, the main sector of cork use is the wine industry due to the need for cork stoppers to seal wine bottles. In Portugal, cork stoppers represent 70% of the total exports of the sector (in value), with natural cork stoppers having the leading role with 42% (APCOR, 2014). Due to the relevance of the natural cork stopper production to the economy of the country, an increasing interest in the evaluation of its environmental impacts is observed. This evaluation can be done through Life Cycle Assessment (LCA), a useful tool for the environmental assessment of a product throughout its life cycle according to specific guidelines recommended by the International Organization for Standardization (ISO), such as ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). According to the aforementioned standards, four phases are included in a LCA study, namely goal and scope definition (determining the depth and direction that the study will have), inventory analysis (the unit processes of the system are analyzed for the identification and quantification of energy, water, materials use and environmental releases), impact assessment (evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the previous stage) and interpretation (the results of the inventory analysis and the impact assessment are evaluated and validated before making and reporting conclusions, with a clear understanding of the assumptions used to generate the results).

A few examples of LCA studies focusing on natural cork stoppers can be found in the literature, both in Portugal (e.g., Demertzi et al., 2016; PwC/Ecobilan, 2008) and abroad (e.g., Rives et al., 2011). However, none of these studies performed an in depth analysis of the end-of-life stage. More specifically, Demertzi et al. (2016) excluded the end-of-life stage due to lack of information, while Rives et al. (2011) and PwC/Ecobilan (2008) only considered one option for the final disposal of the natural cork stoppers, namely landfilling. Furthermore, in these studies, cork was assumed to have the same emissions as wood. This assumption may increase uncertainty since cork and wood have different components (e.g., suberin and lignin) and different chemical compositions (e.g., carbon and oxygen) (Pereira, 2013; Jianju et al., 2004). Cork mainly consists of four chemical components – carbon (55%), oxygen (35%), hydrogen (8%) and nitrogen (2%) (Pereira, 2013, 2007). Furthermore, it should be noted that the existing studies regarding LCA of waste management systems do not tackle cork since they consider other waste fractions (Laurent et al., 2014; Turconi et al., 2011; Cherubini et al., 2009).

At the end-of-life stage, natural cork stoppers are, at the moment, considered municipal solid waste (MSW), and as such they are traditionally sent for incineration and/or landfilling (OECD, 2010). However, apart from these traditional final disposal options and in line with the Directive 2008/98/EC that sets a waste management hierarchy (European Commission, 2008), there is a recent alternative concerning the selective collection and recycling of used natural cork stoppers. In fact, there are various running campaigns worldwide (e.g., ‘‘Greencork” in Portugal, ‘‘ReCORK” in USA and ‘‘Cork Recycling Program” in Australia), aimed at the collection and recycling of used natural cork stoppers. Even though the recycled cork stoppers cannot be used for the production of new cork stoppers (due to low quality), they can be harnessed for their reentrance to the manufacturing of cork granules and agglomerated cork products such as coverings, cork fabrics and decorative products (Amorim, 2014). However, there are rising doubts about the environmental benefits of the recycling procedure since it requires the transportation of the natural cork stoppers to the transformation industry (Garcia, 2011).

The aim of this study is to evaluate and compare three waste management alternatives for the final disposal of used natural cork stoppers, namely, incineration at a MSW incinerator, landfilling and recycling. Several scenarios are included in each management alternative and LCA is applied in order to identify the most environmentally efficient alternative and scenario for the end-of-life of natural cork stoppers.

2. Methodology

2.1 Goal definition

The goal of this study is to evaluate the different environmental impacts of different management alternatives in order to be used in the future decision-making process of the natural cork stoppers' end-of-life destinations. Thus, it is considered that fits in Situation A (micro-level decision support) as suggested by the ILCD Handbook (European Commission, 2010). In LCA there are two modeling principles that can be applied, namely the attributional and the consequential approaches (European Commission, 2010). The attributional approach was considered to be more appropriate for the present study, based on the objective established and thus, attributional LCA will be used.

2.2 Functional unit and multi-functionality

The functional unit (FU) provides a reference to which the inputs and outputs are related. The FU used in all of the alternative scenarios evaluated in this study is the disposal/valorization of one tonne of used natural cork stoppers. When comparing the different systems, the attributional modeling principle was chosen for this comparative LCA, and the system expansion by substitution approach was considered for solving multi-functionality (Situation A). In the case of system expansion, the multi-functional processes lead to the inclusion of further products into the functional unit. Thus, the initially-defined product system is expanded into a whole system model, including different functions (Werner, 2006). The alternatives and associated scenarios under study are as follows:

A. Incineration at a MSW incinerator:
   - Scenario 1: with electricity generation (substituting electricity generation from the Portuguese electricity mix).
   - Scenario 2: with electricity generation (substituting electricity generation from natural gas).
   - Scenario 3: with electricity generation (substituting electricity generation from hard coal).
   - Scenario 4: with combined heat and power generation (CHP) (substituting cogeneration of energy from natural gas).

B. Landfilling in a sanitary landfill:
   - Scenario 5: without landfill gas recovery.
   - Scenario 6: with landfill gas recovery for flaring.
   - Scenario 7: with landfill gas recovery for electricity generation (substituting electricity generation from the Portuguese electricity mix).
   - Scenario 8: with landfill gas recovery for electricity generation (substituting electricity generation from natural gas).
   - Scenario 9: with landfill gas recovery for electricity generation (substituting electricity generation from hard coal).

C. Recycling:
   - Scenario 10: for the production of agglomerated cork used for agglomerated cork products. In this scenario, the production of cork slab used as covering material in construction is considered, avoiding the use of raw cork (namely, 'falca' that is the cork from the branches of the cork oak tree).
   - Scenario 11: for the production of cork slab (as in Scenario 8) but in this scenario avoiding the use of industrial cork waste resulting from the production of natural cork stoppers (e.g., punched planks). Currently, those residues are exclusively used for the production of cork agglomerates. Thus, in practice, recycled cork stoppers cannot substitute for the industrial residues. However, this scenario will quantitatively show if it is actually more efficient or not to use the industrial waste or the recycled stoppers.

Even though not all of the above-mentioned technologies are currently applied in Portugal, they were all considered in order to be evaluated for future consideration for the final disposal of natural cork stoppers. This could be useful for decision-making concerning public solid waste policies and industrial strategies.

2.3 Boundaries of the system

In the present study, in all of the alternatives, a consumer-to-grave approach was applied. This approach included the transport of the used natural cork stoppers from the consumer to their final destination (MSW incineration facility, landfilling or recycling), the on-site processes and the production of materials/energy consumed in each case. Furthermore, in the scenarios producing energy (Scenarios 1–4, 7–9) and in the recycling scenarios (Scenarios 10 and 11) the avoided burdens were considered as well.

For the management alternative of incineration (Figure 24), it was considered that the used cork stoppers are transported to the incineration facility where they are completely incinerated at a fixed grate incinerator.

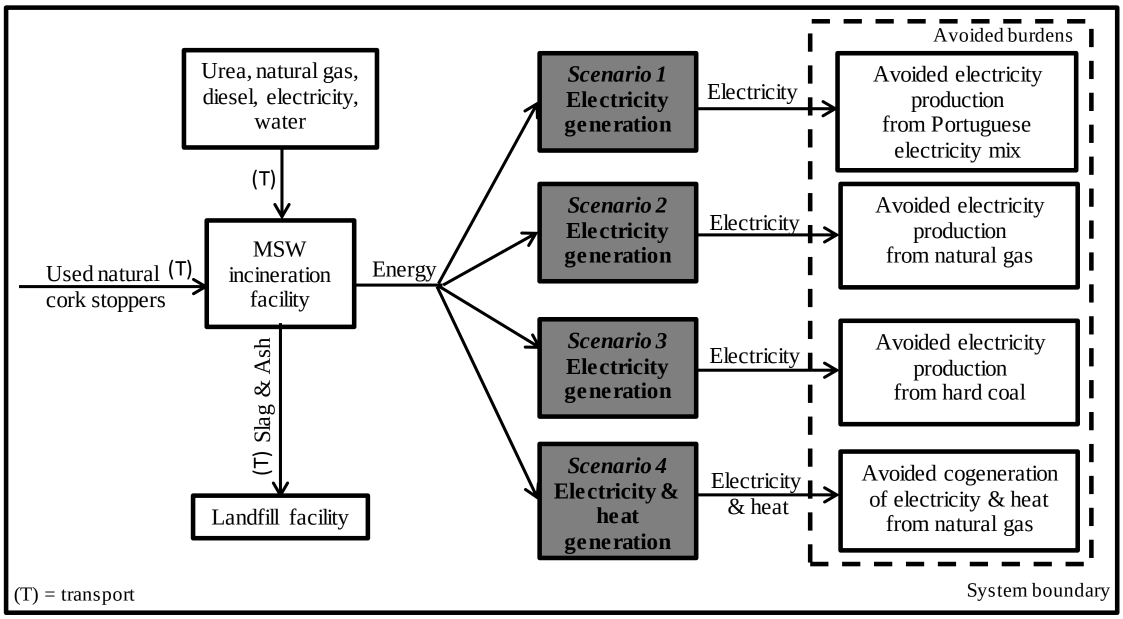

Figure 24: System boundaries for incineration at a MSW incineration (Scenarios 1, 2, 3 and 4)

The chemical production (urea for the control of nitrogen oxides), the fuels consumed (diesel for the machinery and natural gas as auxiliary fuel for starting the equipment), and the water and electricity consumed, also made part of the system. The slag and inert ashes produced during the incineration process and their transport to a nearby landfill were also considered. In Scenario 1, it was considered that the incineration process results in electrical energy generation. The avoided burdens were considered to be an equivalent amount of energy generated from the Portuguese electricity mix. Likewise, in Scenario 2, the incineration process resulted in electrical energy generation and the avoided burdens were considered to be an equivalent amount of energy generated from natural gas. For Scenario 3, the same components were included in the system, with the differentiation that the avoided burdens consider an avoided amount of electricity produced from hard coal. In Scenario 4, a typical CHP was considered. In this case, heat derived from the incineration was used for the generation of both electricity and heat. In this scenario, the avoided burdens represented the avoided cogeneration of electricity and heat from natural gas.

During landfilling, there are two main pollutant flows – landfill gas and leachate. Landfill gas (also called biogas) is produced by bacterial decomposition occurring when the landfilled residues are broken down by bacteria naturally present in the waste and soils (EPA, 2008, 2005). Leachate is any liquid material containing elevated concentrations of undesirable matter derived from the residues that it penetrated while draining from land or stockpiled material. In this study, leachate and leachate treatment are not being included in the boundaries since cork is considered to be a slowly degrading and highly impermeable material. Thus, the amount of leachate and the emissions from its treatment were expected to be insignificant (Manfredi et al., 2009). Furthermore, a 10% methane oxidation was considered according to the value recommended by IPCC (IPCC, 2006).

For the management alternative of landfilling (Figure 25), all scenarios considered the production of diesel (for machinery used for the compaction of the waste) and electricity in the boundaries.

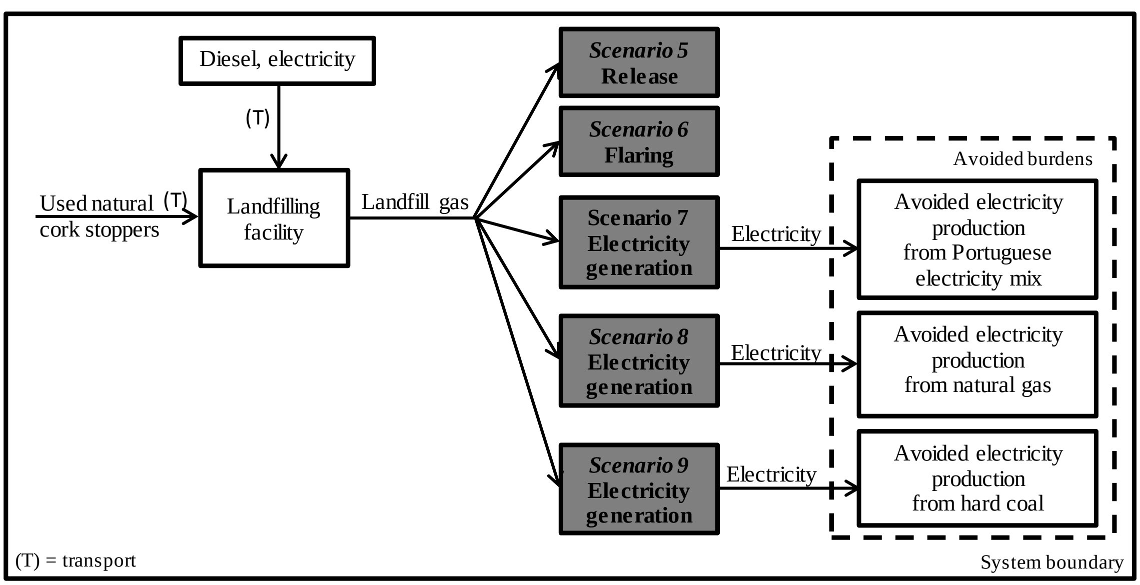

Figure 25: System boundaries for landfilling (Scenarios 5, 6, 7, 8 and 9)

However, the produced landfill gas had different uses in each case. More specifically, Scenario 5 represents the case of landfilling with no landfill gas recovery. In this scenario, there was neither recovery nor use of the emitted landfill gas considered to be released into the atmosphere. Scenario 6 is the case of landfilling with landfill gas recovery for flaring. In this case, part of the landfill gas was captured (through vertical pipes/wells penetrating the deposited waste) in order to be flared resulting in a decrease of air emissions at the landfill site (EPA, 2012a). Scenarios 7, 8 and 9 are cases of landfilling with landfill gas recovery for electricity generation. Those scenarios are similar to Scenario 6, with the difference being that in this case, the recovered landfill gas was burned in a combustion unit, driving a generator for the production of electricity. In those scenarios, the avoided burdens were considered to be an equivalent amount of electricity produced from the Portuguese electricity mix (Scenario 7), natural gas (Scenario 8) and hard coal (Scenario 9).

Currently, the cork industry uses two ways for the production of the agglomerated cork used for manufacturing agglomerated cork products, namely the use of raw cork and the use of industrial cork waste (residues from the production of natural cork stoppers – punched planks). Thus, for the management alternative of recycling, two scenarios were considered (Figure 26).

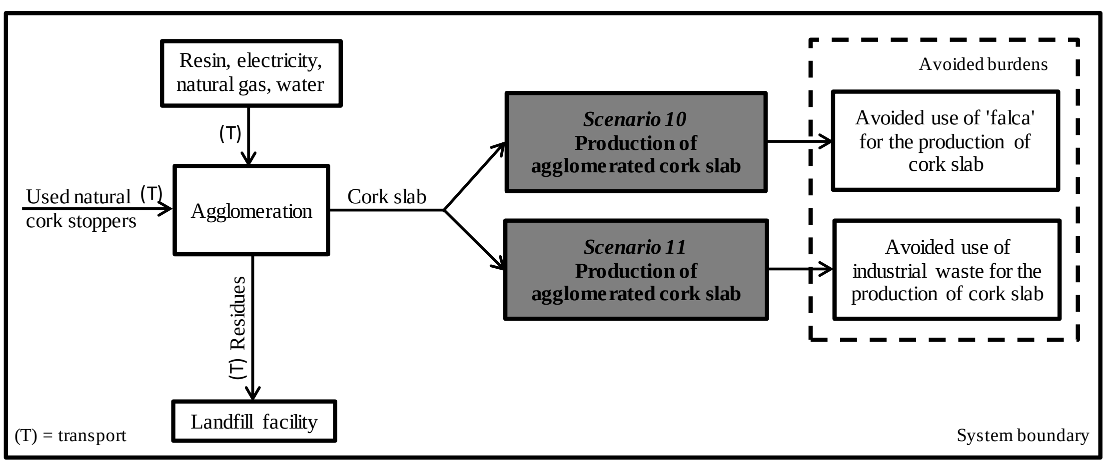

Figure 26: System boundaries for recycling (Scenarios 10 and 11)

Recycling used natural cork stoppers was evaluated for the substitution of the utilization of both raw cork 'falca' (Scenario 10) and industrial cork waste (Scenario 11). In both scenarios, the environmental impact considered the collection and transport of the used cork stoppers to the transformation unit and the impact from the trituration and agglomeration processes (including the consumption of electricity, resin, water, natural gas and cork dust for energy) for the production of cork slabs used in construction. In Scenario 10, the avoided burdens included the production and transport of 'falca' from the forest and its trituration and agglomeration for the production of cork slab. Likewise, in Scenario 11, the avoided burdens included the transport of the industrial cork waste (from the natural cork stopper production unit to the transformation unit) and the impact from its trituration and agglomeration.

It should be mentioned that in all scenarios, the impact from the infrastructure was excluded from the system since it represented less than 1% of the total environmental impact based on a preliminary assessment.

2.4 Life cycle inventory and data quality

Table 20 presents the life cycle inventory data for the alternatives of incineration at a MSW and landfilling in a sanitary landfill including their different scenarios. The information for the foreground processes for Scenarios 1–9, originated from the activity of the LIPOR Company (average for the years 2009–2011) that is responsible for the management, recovery and treatment of MSW produced by eight municipalities in Portugal (LIPOR, 2012, 2009). Moreover, the data were complemented by data on air emissions collected from various sources, as noted in Table 20, such as Herva et al. (2014), EMEP/EEA (2013), IPCC (2006) and McDougall et al. (2001).

It should be noted that the information collected was considered to be representative of the processes, materials and energy currently used in the different end-of-life scenarios under evaluation. Additionally, the information for the background processes, such as the production of chemicals, was derived from the Ecoinvent database v.3.1 (Weidema et al., 2013). Furthermore, Table 21 presents the transport profiles considered in the three alternatives.

Table 20: Inventory data for the management scenarios 1 to 11 under evaluation

Input/output	Unit	MSW incineration facility: Scenarios 1 & 2	MSW incineration facility: Scenario 3	Landfilling at a sanitary landfill: Scenario 4	Landfilling at a sanitary landfill: Scenario 5	Landfilling at a sanitary landfill: Scenarios 6 & 7
Input						
Natural cork stoppers	t	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Electricity [a]	kWh	1.67E+00	1.67E+00	1.03E+01	1.03E+01	1.03E+01
Diesel [a]	GJ	3.00E-04	3.00E-04	3.07E-02	3.07E-02	3.07E-02
Natural gas [a]	GJ	1.42E-02	1.42E-02	-	-	-
Water [a]	m^3	5.13E-01	5.13E-01	-	-	-
Urea [a]	kg	4.10E+00	4.10E+00	-	-	-
Output						
Air emissions (product)						
CO_2 biogenic [b]	kg	1.92E+03	1.92E+03	1.92E+01	1.92E+01	1.92E+01
CH_4 biogenic [b]	kg	1.65E-01	1.65E-01	6.97E+00	6.97E+00	6.97E+00
CO [c, d]	kg	3.00E-02	3.00E-02	-	4.65E-04	3.25E-03
NO_x [c, d]	kg	7.00E-01	7.00E-01	-	6.20E-04	1.69E-04
NMVOC [d]	kg	2.25E+00	2.25E+00	5.82E-02	3.54E-02	3.54E-02
N_2O [d]	kg	1.05E-01	1.05E-01	-	-	-
Air emissions (diesel)						
CO_2 fossil [e]	kg	1.90E-02	1.90E-02	1.90E-02	1.90E-02	1.90E-02
CH_4 fossil [e]	g	3.30E-04	3.30E-04	3.30E-04	3.30E-04	3.30E-04
CO [f]	g	6.43E-02	6.43E-02	6.43E-02	6.43E-02	6.43E-02
NO_x [f]	g	1.97E-01	1.97E-01	1.97E-01	1.97E-01	1.97E-01
NMVOC [f]	g	2.03E-02	2.03E-02	2.03E-02	2.03E-02	2.03E-02
N_2O [f]	g	8.10E-04	8.10E-04	8.10E-04	8.10E-04	8.10E-04
NH_3 [f]	g	4.80E-05	4.80E-05	4.80E-05	4.80E-05	4.80E-05
SO_2 [g]	mg	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01
Particulate matter [f]	g	1.30E-02	1.30E-02	1.30E-02	1.30E-02	
Air emissions (natural gas)						
CO_2 fossil [e]	kg	7.97E-01	7.97E-01	-	-	-
CO [h]	g	5.54E-01	5.54E-01	-	-	-
NO_x [h]	g	1.26E+00	1.26E+00	-	-	-
NMVOC [h]	g	3.69E-02	3.69E-02	-	-	-
N_2O [h]	g	1.42E-03	1.42E-03	-	-	-
SO_x [h]	g	3.99E-03	3.99E-03	-	-	-
Particulate matter [h]						
Waste [i]						
Slag and ashes	kg	5.00E+01	5.00E+01	-	-	-
Energy [j]						
Electricity	MJ	3.75E+03	2.81E+03	-	-	4.97E+01
Heat	MJ	-	8.44E+03	-	-	-

[a] Calculated based on the sustainability report of LIPOR (2012, 2009) for the FU considered in the present study (for the alternatives of MSW incinerator and landfilling)
[b] Demertzi et al. (2015) (for the alternative of recycling)
[c] Calculated based on the IPCC default method for biogenic CO_2 (also applied for CH_4) according to IPCC (2006) and the specific percentages mentioned in the text (for the alternatives of MSW incinerator and landfilling)
[d] Herva et al. (2014) (for the alternative of MSW incinerator)
[e] For the landfilling alternative, the emissions were based on emission factors from McDougall et al. (2001)
[f] Calculated based on emission factors for diesel and natural gas according to IPCC (2006)
[g] Non-road mobile sources and machinery emissions according to EMEP/EEA (2013)
[h] Calculated based on the maximum permitted content of sulfur in the fuels according to the Ministry of Economic Activity and Labor of Portugal (2004)
[i] Calculated based on the emission factors for natural gas consumption according to EMEP/EEA (2013)
[j] Calculated based of the calorific value of 15 MJ/kg of cork and the equipment efficiency of each scenario as mentioned in the text

The quantity of waste produced (slag and ashes) was based on the waste production from industries burning cork dust for energy production (Demertzi et al., 2015). Furthermore, it was considered that they are landfilled and their impact calculation was derived from the Ecoinvent database (Weidema et al., 2013). Additionally, the energy exported from the MSW incineration process was calculated by considering a calorific value of 15 MJ/kg of cork stoppers and an average efficiency of 25% (for Scenarios 1, 2 and 3) was considered for its transformation to electricity (ERSE, 2003). For Scenario 4, a typical CHP was considered with a typical total system efficiency of 75%. It was considered that 25% of the produced energy is transformed into electrical energy and 75% into heat (EPA, 2012b).

Concerning the alternative of landfilling, data were obtained from the LIPOR sustainability report (LIPOR, 2012, 2009). For the calculation of the biogenic carbon dioxide (CO_2) and methane (CH_4), the IPCC default method for emissions from solid waste disposal in landfills was applied (IPCC, 2006). More specifically, for the application of the IPCC formula, it was considered that the cork landfilled had a moisture content of 5% and a carbon content of 55% in dry mass (Dias and Arroja, 2014). In the case of landfilling the emissions for 100 years are considered. Furthermore, 98% of carbon was considered to effectively decay under anaerobic conditions and only 2% of carbon was considered to be released back to the atmosphere (Garcia and Freire, 2014; EPA, 2014a; Freed et al., 2004; Micales and Skog, 1997). Additionally, a 50–50 content of CO_2 and CH_4 was considered in the landfill gas. By using their density – 1.977 kg of CO_2/m^3 of landfill gas and 0.717 kg of CH_4/m^3 of landfill gas (Pillai, 2008) – the amount of landfill gas produced was calculated. For Scenario 6, it was considered that the landfill gas recovery reaches 40% while the burner's efficiency during flaring reaches 98% (IPCC, 2006; ERSE, 2003). Furthermore, the flaring equipment (Scenario 6) and the internal combustion engine's (Scenarios 7, 8 and 9) emission factors were considered according to McDougall et al. (2001). In Scenarios 7, 8 and 9, the landfill gas recovery was the same as in Scenario 6 (40%) and the equipment efficiency was 35% (Wilson et al., 2012; World Bank, 1999).

Table 21: Transport profiles

Material transport	Distance (km)	Type of transport	Load (t)	Return journey
MSW incineration facility				
Used natural cork stoppers	40	Freight lorry, EURO 3	16-32	Empty
Urea	400	Freight lorry, EURO 3	16-32	Empty
Diesel	16	Freight lorry, EURO 3	16-32	Empty
Landfilling at a sanitary landfill				
Used natural cork stoppers	40	Freight lorry, EURO 3	16-32	Empty
Diesel	16	Freight lorry, EURO 3	16-32	Empty
Recycling [a]				
Used natural cork stoppers	217	Freight lorry, EURO 3	16-32	Empty
'Falca'	300	Freight lorry, EURO 3	16-32	Empty
Industrial cork waste	10	Freight lorry, EURO 3	16-32	Empty

[a] The transport of the resin used in the agglomeration process as well as the transport of the residues to the landfill facility, are also considered as indicated in Demertzi et al. (2015)

In the case of the recycling alternative, for the collection of the used cork stoppers, the distance considered (217 km) was calculated based on the average distances between the municipalities of the eight most populated districts of Portugal and Santa Maria de Lamas (northwest of Portugal), where the majority of the transformation units are located. Moreover, the transport of 'falca' to the manufacturing unit was accounted for based on the average distance of the cork oak forests in Portugal to the transformation units (300 km). For industrial residues, the transport distance was based on average distances of existing manufacturing units (10 km). For the emissions from the production of ‘falca’, data were taken from Dias et al. (2014), considering economic allocation to determine the impacts of this raw cork type (virgin). For the consumptions and emissions of the trituration and agglomeration processes (e.g., electricity, resin, natural gas and water), data were adopted from Demertzi et al. (2015), considering the average values of two industrial units (producing the base and backing layers of a cork covering product). The trituration and agglomeration data were equal in all cases of recycling (of used cork stoppers, ‘falca’ and industrial cork waste). In Scenarios 10 and 11, the impacts and benefits from the natural cork stopper recycling relative to agglomeration cancel each other out. Thus, the environmental impacts were mainly related to the stopper transport and the avoided burdens were related to the production of ‘falca’ and its transport (in the case of Scenario 10). Furthermore, the electricity mix used in the processes was for Portugal during the year 2013 according to the Portuguese electricity operator (EDP, 2013).

2.5 Allocation

As previously mentioned, the multi-functionality of the system was resolved through the system expansion by substitution. Furthermore, in this study, different allocation types were applied. More specifically, mass allocation was applied for the consumption of fuel (diesel for Scenarios 1–9) and natural gas, urea, electricity and water (Scenarios 1–4). Furthermore, allocation based on the chemical composition of natural cork stoppers landfilled was applied in the case of landfill gas production (Scenarios 5–9).

Concerning the recycling scenarios, it was considered that the recycled used natural cork stoppers will be used for a 100% replacement of the virgin material and the industrial cork waste (Scenarios 10 and 11, respectively). Furthermore, it was considered that the residues from the production of natural cork stoppers (Scenario 11) would have no environmental burden allocation from previous processes (according to the cut-off allocation method) since they are considered waste from other activities.

2.6 Impact assessment

For the impact assessment, the characterization factors recommended by the International Reference Life Cycle Data System (ILCD) were considered (European Commission, 2010). The impact categories evaluated in this study were: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Acidification (A) and Mineral and Fossil Resource Depletion (MFRD), since they were considered the most relevant for the present study.

In addition, since temporary biogenic carbon storage and CO_2 delayed emissions were expected to vary in the different scenarios and alternatives analyzed, the CC impact category was recalculated, taking into account the biogenic carbon storage, as recommended in the ILCD Handbook (European Commission, 2010).

The emissions of biogenic CO_2 are defined as CO_2 emissions related to the natural carbon cycle and also those resulting from the combustion, harvest, digestion, fermentation, decomposition, or processing of biologically based materials (EPA, 2014b). According to recent studies, biogenic carbon storage should be considered in the calculations (Demertzi et al., 2015; Levasseur et al., 2013, 2010; Brandão et al., 2012). One of the reasons for its accounting is the extra time provided for climate change mitigation while technologies and knowledge are evolving (Dornburg and Marland, 2008; Noble and Scholes, 2001).

The ILCD Handbook (European Commission, 2010) provides formulas for the calculation of the correction factors used for the accounting of biogenic CO_2 adopted in this study. Those factors were multiplied by the biogenic carbon contained in the natural cork stoppers that will be released into the atmosphere in order to obtain the biogenic CO_2 emitted from the product.

In the case of incineration at a MSW incinerator, there was no carbon storage in the product. The emission factor in those alternatives was equal to 1, since there was no time delay for the biogenic carbon emissions. All of the contained carbon (522.5 kg of biogenic carbon) was instantly released at the moment of incineration. On the other hand, the landfilling alternative considered that 98% of the biogenic carbon contained in the product would remain permanently stored in the landfill. Furthermore, the rest 2% of the emissions was assumed to be released at a constant rate during the first 20 years after landfill disposal (Micales and Skog, 1997). Thus, the correction factor of 0.8 (as calculated based on the formulas provided in the ILCD handbook) had to be multiplied by the amount of biogenic carbon released during this time (10.45 kg of carbon) in order to calculate the amount emitted and the amount stored (by subtraction from the initial biogenic carbon amount). Finally, in the recycling alternative it was considered that the cork slab produced by recycled natural cork stoppers contained the same amount of biogenic carbon as the cork slab produced by ‘falca’ or by the industrial cork waste (avoided burdens considered in Scenarios 10 and 11 respectively). Thus, in this alternative, there was a self-annulation of the biogenic carbon and there was no final biogenic carbon storage.

2.7 Sensitivity analysis

The sensitivity analysis is an important method tool for the evaluation of the various assumptions influence. The assessed parameters were considered to be the most uncertain and thus, they were changed in order to evaluate their influence on the environmental impact results. Table 22 presents the various parameters that were included in the sensitivity analysis:

- For the alternative of incineration at a MSW incinerator, the equipment efficiency was changed to 20% and 30% (Scenarios 1, 2 and 3) and 70% and 80% (Scenario 4) (DEFRA, 2013).
- For the landfilling alternative, the carbon content of cork (in Scenarios 5–9) was changed to 50% and 67% (Dias and Arroja, 2014; Pereira, 2013); the decay rate of cork (in Scenarios 5–9) was changed to 50% as suggested by IPCC (2006) for wood; the landfill gas recovery percentage (in Scenarios 6–9) was changed to 50% (EPA, 2012b); the equipment efficiency (in Scenarios 7, 8 and 9) was changed to 30% and 40% (Wilson et al., 2012; World Bank, 1999).
- For the recycling alternative, the transport distances were changed to half and double the baseline distance. For the biogenic carbon emissions, the carbon content of cork and the decay rate of cork in the landfill (Scenarios 5–9) were changed as mentioned above.

Table 22: List of parameters and respective changes considered in the sensitivity analysis

Scenario	Parameter description	Minimum and maximum considered	Change of final environmental impact (decrease/ increase)
1	Equipment efficiency [a]	30% and 20%	(-9% to -24%) and (+18% to +31%)
2	Equipment efficiency [a]	30% and 20%	(-18% to -69%) and (+14 to +37%)
3	Equipment efficiency [a]	80% and 70%	(-5% to -8%) and (+5% to +8%)
4	Cork carbon content [b, c]	50% and 67%	(0% to -8%) and (0% to +16%)
4	Decay rate of cork [d]	Baseline and 50%	(0% to +96%)
4	Considering both parameters		(0% to -8%) and (0% to +96%)
5	Cork carbon content [b, c]	50% and 67%	(0% to -3%) and (0% to +15%)
5	Decay rate of cork [d]	Baseline and 50%	(0% to +96%)
5	Landfill gas recovery percentage [e]	Baseline and 50%	(0% to -14%)
5	Considering all parameters		(0% to -8%) and (0% to +96%)
6	Cork carbon content [b, c]	50% and 67%	(0% to -8%) and (0% to +17%)
6	Decay rate of cork [d]	Baseline and 50%	(+14% to +96%)
6	Landfill gas recovery percentage [e]	Baseline and 50%	(0% to -15%)
6	Landfill gas use equipment efficiency [f, g]	40% and 30%	(-2% to -79%) and (+1% to +43%)
6	Considering all parameters		(-1% to -43%) and (+9% to +96%)
7	Cork carbon content [b, c]	50% and 67%	(0% to -9%) and (0% to +17%)
7	Decay rate of cork [d]	Baseline and 50%	(+14% to +96%)
7	Landfill gas recovery percentage [e]	Baseline and 50%	(0% to -16%)
7	Landfill gas use equipment efficiency [f, g]	40% and 30%	(0% to -76%) and (0% to +54%)
7	Considering all parameters		(0% to -54%) and (0% to +96%)
8	Transport distance	50% and 100%	(0% to -66%) and (0% to +57%)
9	Transport distance	50% and 100%	(-60% and +4%)
Biogenic carbon [h]	Cork carbon content [b, c]	50% and 67%	(+10% and -19%) in CC for landfilling
Biogenic carbon [h]	Decay rate of cork [d]	Baseline and 50%	(+41% to +43%) in CC for landfilling
Biogenic carbon [h]	Considering all parameters		(-19% to +43%) in CC for landfilling

[a] DEFRA (2013)
[b] Pereira (2013)
[c] Dias and Arroja (2014)
[d] IPCC (2006)
[e] EPA (2012b)
[f] Wilson et al. (2012)
[g] World Band (1999)
[h] The sensitivity analysis for biogenic carbon does not include the recycling alternative for the reasons explained in the text. Moreover, the result of the incineration and biomass combustion alternative is not influenced since the whole biogenic carbon quantity is always emitted and none is stored.

3. Results and discussion

3.1 Environmental impact of the various management alternatives

Table 23 presents the total environmental impact obtained for the various end-of-life scenarios. Moreover, Figure 27 presents the same results in terms of environmental impact (on positive axis) and avoided burdens (on negative axis). It can be seen that there is not only one scenario presenting the best performance in all of the impact categories.

Table 23: Total environmental impact of the various scenarios (considering both the environmental impact and the avoided burdens)

	MSW incineration facility			**Landfilling at sanitary landfill**				**Recycling**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
CC (kg CO_2 eq)	-5.49E+02	-1.05E+03	-8.09E+02	1.75E+02	1.14E+02	1.03E+02	9.91E+01	-1.24E+02	5.77E+01
OD (kg CFC-11 eq)	-1.06E-05	1.42E-06	-1.22E-04	2.88E-06	2.88E-06	4.46E-07	2.83E-06	-1.20E-05	1.08E-05
POF (kg NMVOC eq)	2.13E+00	-3.13E-01	1.65E+00	2.60E-01	2.11E-01	1.75E-01	1.65E-01	-8.73E-01	4.60E-01
A (molc H+ eq)	-1.95E+00	-9.19E+00	-3.31E+00	1.47E-01	1.48E-01	1.04E-01	1.54E-02	-1.61E+00	3.90E-01
MFRD (kg Sb eq)	-7.18E-05	-1.30E-04	-1.57E-04	5.89E-06	5.89E-06	2.94E-06	3.96E-06	-4.61E+03	1.18E-05

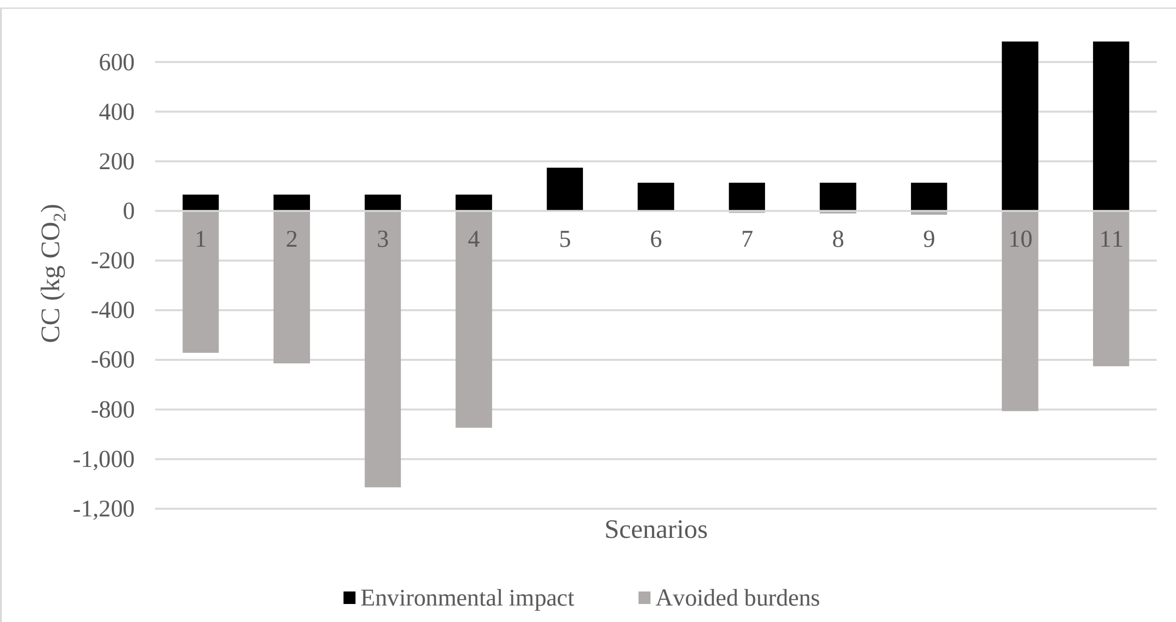

Figure 27: Environmental impact of the various waste management scenarios (1–11) per FU

3.1.1 Climate change

More specifically, Scenario 3 presented the best environmental performance in the CC category. The result in this category was mainly influenced by the avoided burdens of this scenario. This result can be explained from the avoided emission of GHGs for the production of electricity by coal that is higher than in the case of natural gas use (1.1 kg CO_2 eq/kWh and 0.6 kg CO_2 eq/kWh, respectively). Furthermore, considering that the avoided electricity generation was the main influence, the CHP scenario (Scenario 4) presented lower avoided burdens since less electricity was produced (0.2 kg CO_2 eq/kWh), and furthermore, the avoided heat production did not significantly influence this impact category, presenting lower GHGs emissions (0.1 kg CO_2 eq/kWh) than did the electricity production. The recycling alternative presented both high impact and avoided burdens. The differences were due to the emissions from the diesel combustion for the transport of the used cork stoppers, the 'falca' and the industrial cork waste (since impact and avoided burdens from the agglomeration process are equal and thus self-annulated), resulting in a higher total environmental impact compared to the incineration alternative. Additionally, the landfilling alternative also had low performance because it mainly presented environmental impact and when it presented avoided burdens (Scenarios 7, 8 and 9), they were low. In this category, the worst environmental performance was noticed for Scenario 5 where the produced landfill gas from the landfilling process was all released into the atmosphere.

3.1.2 Ozone depletion

In the OD category, the total environmental impact was influenced by the avoided burdens as well. In this case, Scenario 4 presented the greatest avoided burdens due to the production of both electricity and heat from natural gas, and had the best environmental performance. The landfilling alternative presented similar results in all scenarios but both the environmental impact and the avoided burdens were low resulting in worse performance compared to the aforementioned alternatives. Furthermore, the recycling alternative presented both high impact and avoided burdens (mainly due to the resins used in the agglomeration process), resulting in a low environmental performance. Scenario 11 presented the worst environmental behavior in this impact category because the impact from the cork slab production from recycled natural cork stoppers was higher compared to the cork slab production from industrial cork waste, resulting in a higher total environmental impact.

3.1.3 Photochemical ozone formation

In the POF category, Scenario 10 showed the lowest total environmental impact due to the avoided burdens that were higher than the environmental impact. In this category, the incineration at a MSW incinerator presented a higher environmental impact than did the recycling alternative due to the emission of NMVOCs from the combustion of the cork. Even though the landfilling alternative had the lowest environmental impact, it did not have significant avoided burdens (in the case of Scenarios 7, 8 and 9) and thus, this alternative presented low environmental performance. In this impact category, Scenario 2 presented the worst performance because of the high environmental impact from the NMVOC emissions and the low avoided burdens from the production of electricity from natural gas.

3.1.4 Acidification

In the A impact category, Scenario 3 presented the lowest total environmental impact. This scenario had higher avoided burdens than did the other scenarios due to the generation of electricity from hard coal since it would avoid more air emissions than do the other scenarios. Once again, the landfilling alternative did not present neither high environmental impact nor avoided burdens. In this category, the greatest total environmental impact was noticed in Scenario 11 where the environmental impact was higher than were the avoided burdens due to the longer transport distance in the case of the natural cork stopper recycling compared to the industrial cork waste transport.

3.1.5 Mineral and fossil resource depletion

Finally, in the MFRD category, Scenario 10 presented the best performance mainly due to the avoided burdens from the substitution of raw cork used in the production of agglomerated cork. As previously mentioned, the distance between the cork oak forest and the agglomeration units is usually long (300 km) and, as a result of the substitution of this raw material, significant air emissions from the transport will be avoided. The other alternatives did not present significant impact or avoided burdens because the emissions from diesel consumption for the equipment or for the cork stopper collection were low. In this category, the highest environmental impact was noticed in Scenario 11. Once again, the environmental impact was higher than were the avoided burdens because in one case the transport distance of the used natural cork stoppers was 217 km, while in the other (industrial cork waste), it was 2 km, resulting in much lower levels of air emissions, resulting in a higher total environmental impact in this category.

Concerning the recycling alternative, in all of the impact categories, the environmental impact for the production of the cork slab by 'falca' presents the highest environmental impact, followed by its production by recycled natural cork stoppers and then by industrial cork waste. In this way, the transport distance of the raw material used would change from 300 km to 2 km and not 217 km, and the total air emissions would decrease. Thus, it can be concluded that for the production of cork slab, the substitution of 'falca' by industrial cork waste would be a more efficient option compared to the substitution of 'falca' by recycled natural cork stoppers. However, regardless of the slightly higher environmental impact, it should be pointed out that the recycling of used natural cork stoppers could result in two different advantages. Firstly, the utilization of recycled used natural cork stoppers could decrease the need for the use of raw cork, which has the greatest environmental impact. Secondly, the recycling of used natural cork stoppers could further increase the amount of agglomerated cork products produced, which could help avoid the production and use of more energy-intensive construction materials (e.g., polyvinyl chloride (PVC)), resulting in a lower environmental impact of a building.

3.2 Storage of biogenic carbon

As previously mentioned in Section 2.6, only the alternative of landfilling was influenced by the consideration of the biogenic carbon contained in the product (natural cork stopper). Table 24 presents the calculated correction factors and the amount of the biogenic CO_2 emitted and stored in each scenario of the landfilling alternative. Additionally, the obtained results for the CC category were recalculated considering the biogenic carbon stored in the product. Those results show that the inclusion of biogenic CO_2 delayed emissions in the calculations can significantly change the results. Namely, the landfilling alternative presented the best results in the CC category compared to the other three alternatives (that were not influenced by the consideration of the biogenic carbon accounting). That occurred because only 2% of the total biogenic carbon of the product will be emitted into the atmosphere (linear decay during 20 years) while the rest 98% will be permanently stored in the landfill. On the other hand, in the incineration alternative, there is no carbon storage and all of the biogenic carbon contained in the stoppers will be emitted at the moment of the burning.

Table 24: Emission factor, biogenic CO_2 emitted, stored and considered in the CC impact category (per FU) for the scenarios considered in the landfilling alternative.

	Landfilling			
	4	**5**	**6**	**7**
Correction factors (fraction)	0.800	0.800	0.800	0.800
Biogenic CO_2 emitted (in kg CO_2)	30.653	30.653	30.653	30.653
Biogenic CO_2 stored (in kg CO_2)	1,885.180	1,885.180	1,885.180	1,885.180
CC impact category without biogenic CO_2 (in kg CO_2 eq.)	174.744	113.865	103.159	99.099
CC impact category considering biogenic CO_2 (in kg CO_2 eq.)	-1,710.436	-1,771.315	-1,782.021	-1,786.081

Thus, when considering the biogenic CO_2, the most environmentally efficient alternative for the CC category is landfilling. Nonetheless, it should be noticed that landfilling can be preferable from a greenhouse gas (GHG) point of view in this case, but a GHG-only assessment cannot be considered a full environmental assessment, since the landfilling alternative is not environmentally efficient when considering other impact categories.

3.3 Sensitivity analysis results

The results obtained showed that the most influential parameter is the decay rate of cork in the landfilling alternative since there is a great variation in the environmental impact in all of the impact categories. In more detail, the results of the sensitivity analysis, presented in Table 22 showed that:

- The change of the equipment efficiency in the alternative of the incineration at a MSW incineration would mainly influence Scenario 3, and specifically, the POF and OD categories (-69% to +14% and -61% to +14%, respectively), while the rest of the categories would be less influenced. The lowest influence would be presented in Scenario 4, with a total change of -8% to +8%.

- For the landfilling alternative, more parameters were evaluated. However, the most influential parameter was the carbon decay rate that, when changed to 50% could increase the environmental impact up to 96% for all of the landfilling scenarios (Scenarios 5–9) in the categories of CC and POF. Furthermore, when changing all of the parameters considered in the sensitivity analysis, the greatest influence was observed in Scenario 9, where a decrease of the environmental impact by -54% to +96% was observed.
- For the biogenic CO_2 accounted for the CC category, only the landfilling alternative was influenced. By changing the carbon content to 50% in the natural cork stoppers, the environmental impact would increase by 10%, and to 67%, it would decrease by 19% (Scenarios 5–9). The change of the decay rate could increase the CC category by +41% to +43% (Scenarios 5–9). The combination of those two parameters would mostly influence Scenario 9. It has to be mentioned that all scenarios followed the same trend, but Scenario 9 showed the greatest influence when changing the parameters.
- For the recycling alternative, the doubling of the transport distance could decrease the environmental impact by up to 66% (Scenario 10) and up to 60% in all categories (Scenario 11). On the other hand, the change of the transport distance to half could increase the environmental impact up to 57% (Scenario 10) and up to 4% in all categories (Scenario 11). Consequently, the distance change of the 'falca' transport (Scenario 10) could be of great influence in the case of recycling.

Additionally, Figure 28 presents the results of the impact categories for the various scenarios when considering all of the evaluated parameters mentioned above in order to obtain the maximum and minimum estimates. In this way, it is easier to notice if the consideration of the different parameters would change the final results.

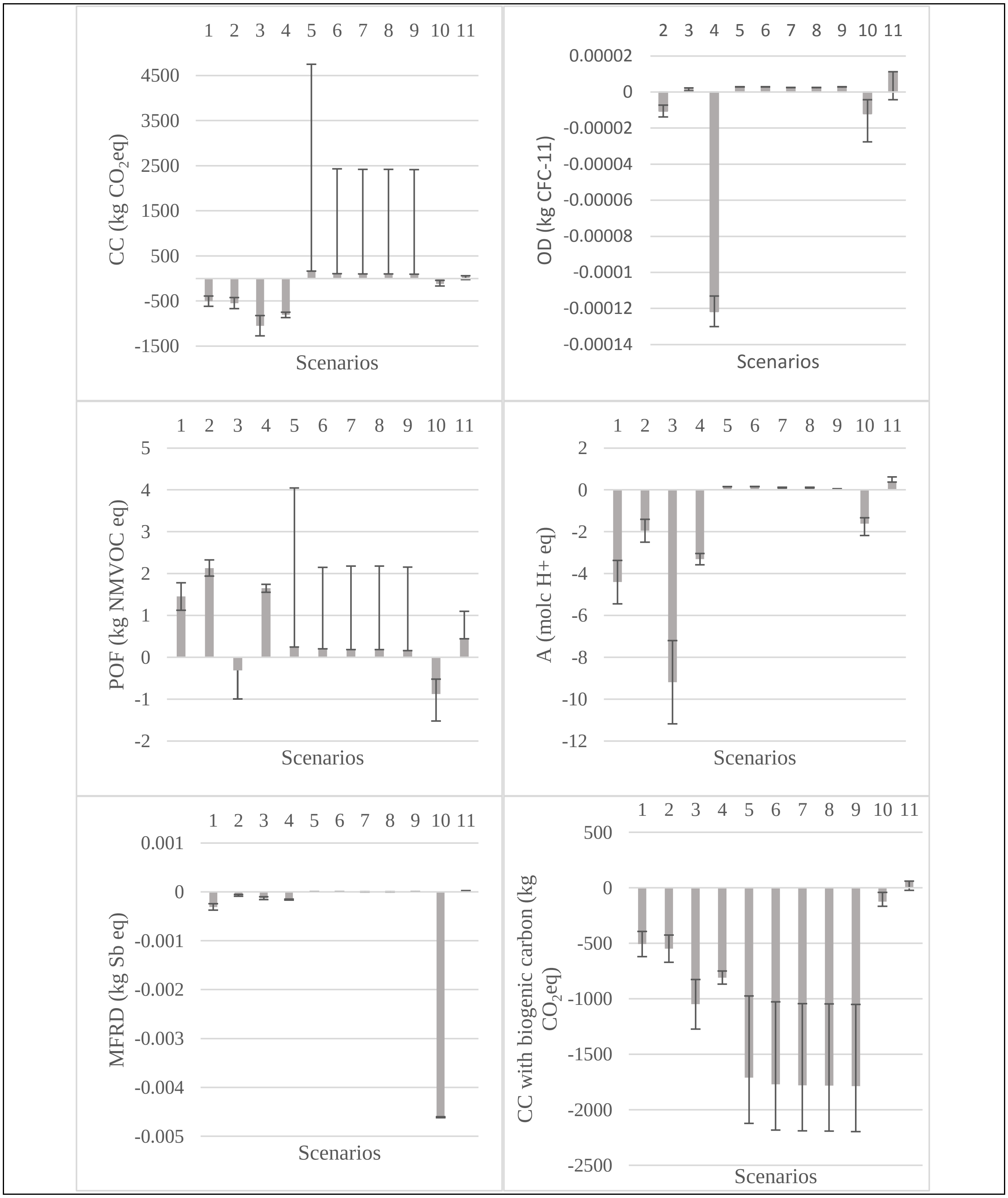

Figure 28: Sensitivity analysis of the environmental impact of the various waste management scenarios (1 to 11) per FU

It can be concluded that only for the impact categories of CC, when accounting for the biogenic carbon and the POF category, the final ranking of the most efficient scenario would change. In more detail, when considering the biogenic carbon in the CC category, the landfilling alternative presented the best results. However, the sensitivity analysis showed that by considering a better efficiency for the equipment at a MSW incinerator (30%) when producing electricity (Scenario 3) and a lower decay rate and carbon content (50%) in the case of landfilling, the ranking of the most efficient alternative would change and the burning alternatives would be the most effective. Additionally, in the POF category, it was found that Scenario 10 presented the best environmental performance. However, by considering a better efficiency for the equipment at a MSW incinerator (30%) and a different transport distance for the 'falca' to the agglomeration unit (150 km), then the result would be different with Scenario 3 presenting the best environmental performance.

3.4 Comparison with previous studies

As previously mentioned there is not a great number of LCA studies in the literature concerning the life cycle of natural cork stoppers. Moreover, the results comparison of the present and the previous studies is not easy due the lack of information concerning the used data (i.e., cork carbon content, cork decay rate, landfill gas recovery percentage and the efficiency of the equipment used). Moreover, both of the LCA studies for natural cork stoppers (Rives et al., 2011; PwC/Ecobilan, 2008), applied a different assessment method, CML, while here the ILCD method was applied. For this reason, only the CC category can be directly compared since they have the same unit (kg CO_2 eq) and characterization method.

In Rives et al. (2011) LCA study, cork was assumed to behave as wood in the landfill. Additionally, it is mentioned that the final disposal represented 3% of the total environmental impact – approximately 328 kg CO_2 eq – which is more than double the quantity calculated in the present study for the landfilling baseline scenario (namely, Scenario 6 that is common in the two studies). However, by comparing the results of Rives et al. (2011) with the results of the sensitivity analysis (Section 3.3), by considering the IPCC default decay rate of cork (50%), the CC category for Scenario 6 would change to 2,383 kg CO_2 eq and would be much higher than the result obtained in the study of Rives et al. (2011) study. Thus, it can be considered that the result of the previous study falls within the range of the present study.

On the other hand, PwC/Ecobilan's (2008) study provided more details on the assumptions made. It was mentioned that the landfill gas production was 0.05 kg per kg of cork with an alternative of 0.15 kg of landfill gas per kg of cork and 50% of landfill gas was recovered for flaring. The amount of landfill gas production in the present study was 0.03 kg of landfill gas/kg of natural cork stoppers, which is lower by 58% and 86%, respectively. However, a more complete comparison of the results is not possible since the environmental impact of the various stages considered in the study of PwC/Ecobilan (2008) was provided in relative values (percentage of contribution of the environmental impact of each life cycle stage to the total environmental impact). Therefore, absolute values are not available.

From the difficulties faced in the comparison of the results of the various studies it was concluded that the results in the case of the landfilling alternative are highly dependent on the assumptions made, which is why the authors of LCA studies should provide specifications in order to guarantee the transparency of the results.

3.5 Recommendations based on the results

The management of MSW in Portugal is continuously gaining importance as an environmental preservation factor on which political concerns should focus. Even though the landfill facilities are still the main final destination of the MSW in Portugal, the numbers have improved and the future targets of the country are encouraging. Currently, the main final destinations of MSW are as follows: 60% landfilling, 21% incineration and 19% recycling (Eurostat, 2010; INE, 2010).

According to the national Strategic Plan for MSW (PERSU 2020) a set of actions targeting among others, the reduction of MSW deposition in landfills, their economic valorization and the increase of the effectiveness and operational capacity of the sector, are being implemented for the improvement of the MSW management by 2020 (MAOPE, 2014). The results obtained in the present study confirm and strengthen these future targets since it was found that the landfilling alternative does not have an environmentally efficient performance and thus, should be avoided.

Moreover, as seen in the results obtained, recycling the used natural cork stoppers does not necessarily improve the environmental impact of the end-of-life stage because it is highly dependent on the transport distance from the collection point to the agglomeration unit. Additionally, it should be noted that there is not only one management alternative that could be recommended, since the results showed that different alternatives presented the best performance in different impact categories. Thus, depending on the impact category focus on a particular time, different management alternatives can be suggested.

Furthermore, apart from the management alternatives presented in this study, considering both separate or undifferentiated collection, different solutions could be suggested for their reuse at home for the creation of products in various domains, for example, in gardening (mixed with soil, cork allows for the better aeration and hydration of the planted area, helping the plants grow) and decoration (e.g. for the creation of doormats, baseboards and doorstops). By reusing cork stoppers at home, the air emissions from their collection for recycling can be avoided.

4. Conclusions

The main conclusions of this study are as follows:

- Different scenarios presented the best performance in the various impact categories under study. The alternative of incineration at a MSW incinerator with electricity generation, avoiding the electricity generation from hard coal (Scenario 3), had the best environmental result in the CC and A impact categories.
- The same alternative, while considering CHP generation (Scenario 4), presented the best performance in the OD impact category. The recycling alternative, considering the avoided production of cork slab using raw cork 'falca' (Scenario 10), presented the best results in the POF and MFRD impact categories.
- The utilization of recycled used natural cork stoppers for the production of agglomerated cork materials, such as cork slab used in construction, could further increase the amount of cork materials produced and decrease the need for raw cork use, in addition to helping avoid the production of more energy-intensive construction materials.

- The inclusion of biogenic CO_2 in the calculation of the CC category can change the results due to the time delay of the carbon emissions. In the present study, its inclusion resulted in a significant improvement of the landfilling performance.
- The sensitivity analysis that was performed showed that the most influential parameter in the assessment of the end-of-life stage is the decay rate of cork in landfills. The ranking of the most efficient scenario would change only in the POF category. If considering the largest equipment efficiency in the incineration alternative and decreased transport distance of the raw cork 'falca', the incineration scenario with electricity generation, avoiding the equivalent energy production from hard coal (Scenario 3) would present the best environmental impact (only for POF). In the other categories the ranking of the alternative would remain the same.
- The end-of-life behavior of cork should be further studied, considering different parameters, since it can be an important aspect of the cork products. For example, since the decay rate was found to be the most influential parameter in the landfilling alternative, different ranges for different countries could be evaluated because this parameter is influenced by the climate conditions of each country.
- The management alternatives of incineration with energy recovery and the used natural cork stopper recycling presented the most environmentally efficient results and thus, can be considered in future decision-making process.

Acknowledgements

This study was supported by the project, Cork carbon footprint: from trees to products (PTDC/AGR-FOR/4360/2012), funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal).

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Chapter 4

Carbon footprint of the entire cork sector

4.1 Introduction

This chapter is an integration of the obtained results for the case studies of the most representative cork products. More specifically, the obtained results from the previously presented case studies are used for the evaluation of the entire cork sector's CF.

In section 4.2 a CF simulation model for the cork sector (CCFM) is developed and presented for the first time (also see supplementary material). The application of CCFM can provide an important insight of the cork sector since it calculates the mass output of cork products as well as the CF per stage/ industry and cork product as well as for the entire cork sector. The user is allowed to introduce and choose different quantities of various cork types (virgin, second, 'falca' and reproduction) and to specify the characteristics of the system (transport distances, end-of-life destination and percentage of cork waste treated in each destination). This fact allows the application of CCFM in different countries with different characteristics.

In section 4.2 the model was applied to the Portuguese cork sector (considering a cork production approach) due to its importance for the global cork sector, in order to obtain quantitative results and identify the most influential stages and cork products of the sector. The results showed that the agglomeration industry is the most influential for the CF of the cork sector mainly due to the emissions from the production of the resins used for the agglomeration process. The reproduction cork type was the most influential since it represents the greatest percentage of cork production (almost 50% of the total cork production) and the champagne cork stoppers were found to be the most influential product. This product represents the greatest cork flow distribution of reproduction cork type (14% of the total reproduction cork) but the main influence derives from the agglomeration of the stoppers body. Furthermore, by applying a sensitivity analysis it was concluded that with a 10% decrease of agglomeration's stage impact a total 6% decrease of the entire cork sector CF can be achieved. Additionally, by combining various improvement actions (decrease of agglomeration and transformation stages CF by 10%, use of newer trucks (EURO 6) and the change of the end-of-life destination percentages) a 10% decrease of the cork sector’s CF can be achieved (excluding the biogenic emissions and sequestration).

In section 4.3 of this chapter, the recent LCA approach of dLCA is presented and applied in order to calculate the CF of the entire cork sector and compare it with the results obtained by using the tLCA approach. As presented in Chapter 2, the approach of dLCA considers one year intervals in the emissions of the life cycle of a product and thus, it is a more realistic representation of the CF. In general, section 4.3 provides useful information for the dLCA approach, the formulas applied and the obtained results in comparison to tLCA. It was found that by applying the two LCA approaches different results are obtained. For the 20-year time horizon, tLCA presents greater CF than dLCA, while the opposite occurs for the 100-year time horizon. In the case of tLCA, the results only represent a specific moment (20 or 100 years) considering all the emissions during the life cycle of the cork oak forest and cork products. Additionally, it was found that the inclusion or exclusion of the biogenic carbon sequestration and emission is also very influential since much lower CF is obtained when including biogenic carbon sequestration and emissions.

It is important to highlight that in both studies of sections 4.2 and 4.3 the inclusion and exclusion of biogenic carbon sequestration and emissions was considered. It was found that this choice is very influential since when excluding biogenic carbon emissions the cork sector is considered a carbon source. On the contrary, when biogenic carbon sequestration and emission are included in the calculations, the cork sector is considered a carbon sink since the biogenic carbon sequestrated is greater than the GHGs emitted along the entire life cycle.

4.2 A carbon footprint simulation model for the cork oak sector

Martha Demertzi, Joana Amaral Paulo, Luís Arroja, Ana Cláudia Dias

Science of the Total Environment 566–567: 499–511 (2016)

Abstract

In the present study, a simulation model for the calculation of the carbon footprint of the cork oak sector (CCFM) is developed for the first time. A life cycle approach is adopted including the forest management, manufacturing, use and end-of-life stages. CCFM allows the user to insert the cork type used as raw material and its respective quantity and the distances in-between the various stages. The user can choose among different end-of-life destination options for the used cork products. The option of inserting different inputs, allows the use of the present simulation model for different cork oak systems, in different countries and with different conditions. CCFM allows the identification of the stages and products with the greatest carbon footprint and thus, a better management of the sector from an environmental perspective. The Portuguese cork oak sector is used as an application example of the model. The results obtained showed that the agglomeration industry is the hotspot for the carbon footprint of the cork sector mainly due to the production of the resins that are mixed with the cork granules for the production of agglomerated cork products. The consideration of the biogenic carbon emissions and sequestration of carbon at the forest in the carbon footprint, resulted to a great decrease of the sector's carbon footprint. Future actions for improvement are suggested in order to decrease the carbon footprint of the entire cork sector. It was found that by decreasing by 10% the emission factor of the agglomeration and transformation industries, substituting the transport trucks by more recent ones and by decreasing by 10% the cork products reaching the landfilling end-of-life destinations (while increasing the quantities reaching incineration and recycling), a decrease of the total CF (excluding the biogenic emissions and sequestration) of the entire cork industry by 10% can be achieved.

Keywords: biogenic carbon, carbon footprint, cork oak sector, cork products, life cycle assessment, simulation model

1. Introduction

Cork oak (Quercus Suber L.) is an evergreen tree, native to the western and central Mediterranean region. The most important product deriving from the cork oak tree is cork, which is the outer bark of the cork oak tree and it is extracted for commercial use. Due to the ability of the tree in regenerating the cork layer after its extraction and due to the versatility and unique characteristics of cork as a material (e.g. elasticity, durability and impermeability), cork can be used in a variety of sectors for the manufacturing of various products (e.g. wine industry, construction and sports).

The cork oak forests are very interesting systems since they are the result of previous long term management activities. From an environmental point of view, cork oak forests can contribute to climate change mitigation since they can sequester carbon dioxide (CO_2) from the atmosphere and store it in their perennial tissues and in the soil as organic matter (Palma et al., 2014). Since the cork oaks are long-living trees, they can retain carbon for very long periods. The same stands for the cork products because they can stay in use or at a landfill facility for long periods, storing part of the carbon contained in the cork harvested from the forest and delaying its return to the atmosphere (Dias and Arroja, 2014; Aronson et al., 2009). In literature, there are a few life cycle assessment (LCA) studies focusing on the environmental impact of the cork oak forest management processes such as Dias et al. (2014), González-García et al. (2013) and Rives et al. (2012a), which studied the environmental impact of the raw cork production in Portugal and Spain (Catalonia). A few LCA studies focusing on the environmental impact of different products of the cork sector can also be found in literature. For example, for natural cork stoppers (Demertzi et al., 2016a, 2015a; Rives et al., 2011; PwC/Ecobilan, 2008), for champagne cork stoppers (Rives et al., 2012b) and for cork floating floor (Demertzi et al., 2015b). Additionally, there is a study considering an integrated environmental analysis of the main cork products in Catalonia (Spain) (Rives et al., 2013). However, there is no LCA-based model considering the greenhouse gas (GHG) emissions of the whole cork sector from the forest to the produced cork products and their final disposal.

The main objective of the present study is to develop a cork carbon footprint model (CCFM) that calculates the carbon footprint (CF) and tracks the flows of different cork types along the entire cork sector. Thus, CCFM can provide useful insights and be utilized for the environmental management of the entire cork oak sector and be used in the decision-making process for the decrease of the sectors' CF. In this study, CCFM is applied to the Portuguese cork oak sector (using a production approach) in order to obtain quantitative results and evaluate the sectors' stages and products with the greatest influence on the total CF of the sector. Cork oak forests in Portugal (called montados) represent 34% (736,775 hectares) of the total cork oak forest area (2,139,942 hectares) (APCOR, 2014). Portugal is also the leader in raw cork production with about 50% of the global raw cork production. Additionally, Portugal has a leading role in cork processing, having a 68% share of the global production of cork products (Pestana and Tinoco, 2009).

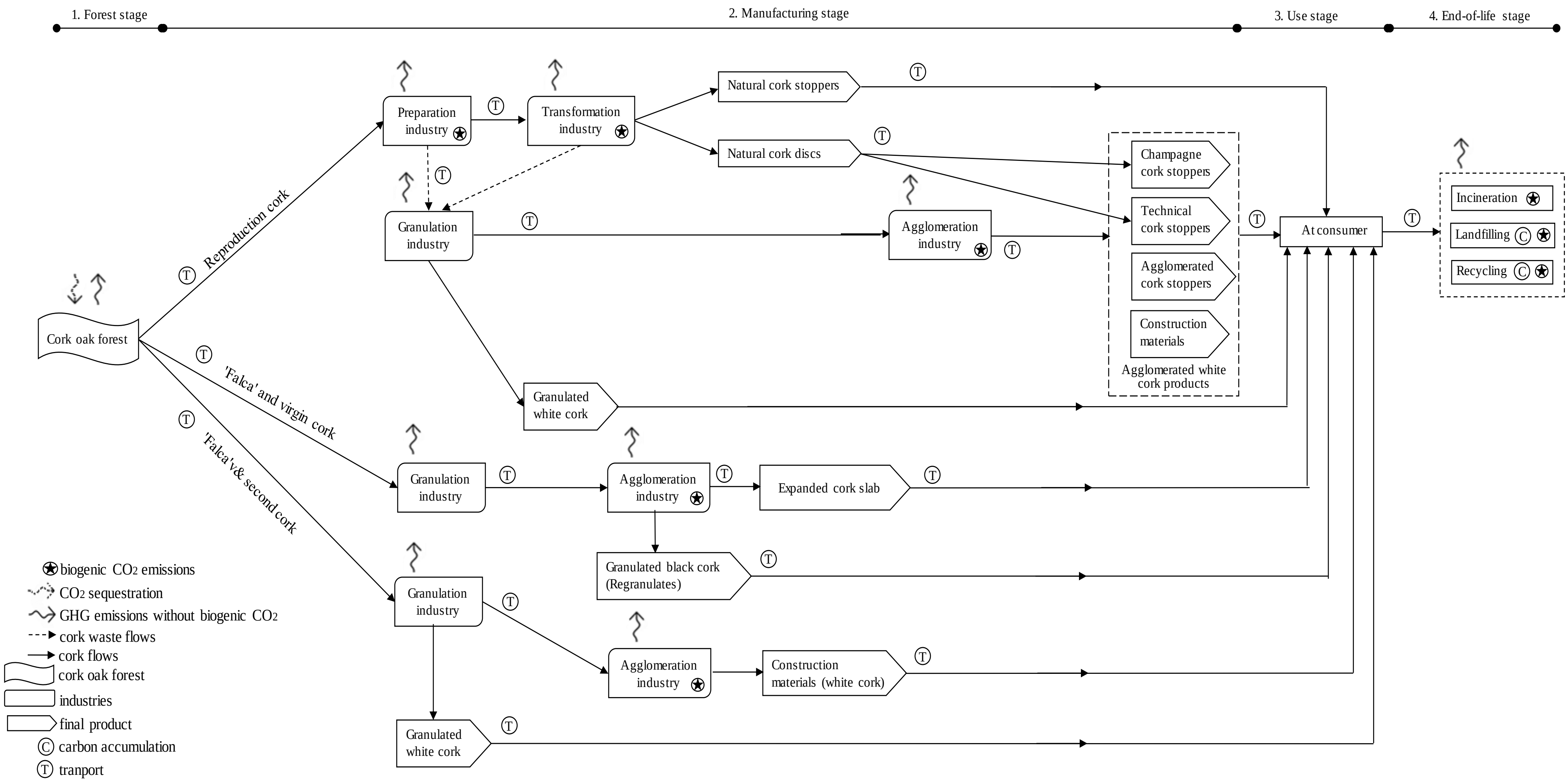
2. Methodology

2.1 Presentation of the Cork Carbon Footprint Model (CCFM)

CCFM aims the calculation of the flows of different cork types along the cork sector and the assessment of the CF of the most representative cork products through a life cycle perspective. A cradle-to-grave approach is applied, considering four different stages, namely the forest stage, the manufacturing stage, the use stage and the end-of-life stage. The model takes into consideration the different cork types used as raw material for the cork products considered. The biogenic carbon is also accounted for in the model in order to enable the evaluation of its impact on the total CF when it is included in the calculations. Usually, forest-based products are considered as potentially carbon-neutral materials considering that the amount of carbon sequestrated by the forest will be then emitted into the atmosphere during the manufacturing and the end-of-life stages of the products' life cycle. Thus, biogenic carbon emissions are usually excluded from the calculations. Consequently, the present study can provide another important output regarding this aspect of the forest-based products.

2.1.1 Description of the cork sector and the different cork types considered in the model

Figure 29 presents the stages of the cork oak sector that release GHG emissions into the atmosphere. Those are the forest stage (including the cork oak management activities), the manufacturing stage (including the various processes for the production of the cork products under study), the use stage (considering the transport of the used cork products to the distribution



Note: the different cork types and their distribution were adapted from: Rives et al., 2013; Marques and Gil, 2012; Autoridade da Concorrência, 2012; Fortes et al., 2004

Figure 29: Boundaries of the system and representation of the most important GHG fluxes throughout the cork sector

locations) and the end-of-life stage (including the management strategies of incineration, landfilling and recycling). Additionally, Figure 29 presents the processes included in each stage, considered in the simulation model CCFM for the calculation of the CF of the sector. Figure 29 also presents the sequestration of CO_2 at the forest stage (during the growth of the cork oak trees). As previously mentioned, the sequestered carbon remains in the biomass of the cork oak tree and then in the cork products produced until it is released into the atmosphere by combustion or decay. Figure 29 also introduces the four different cork types considered in CCFM and the corresponding products manufactured with each cork type.

The harvesting period of cork takes place in the summer (May to August) and is carried out after the tree has reached 0.7 meters in perimeter at 1.3 meters from the ground. In the same tree, two consecutive debarkings are separated by a minimum 9-year interval. The first debarking usually takes place between 20 and 30 years after the trees plantation. The first extracted is called virgin cork and it is considered of low quality because of the irregularities noticed on the exterior surface. In the model, this cork type is considered to be destined to the granulation industry for the production of cork granules, used in the agglomeration industry for the production of black cork products (expanded cork slab and granulated black cork/ regranulates) used in construction. After 9 years, the second extraction of cork takes place. This type of cork is called second (or secondary) cork and since its quality is still low it is sent to the granulation industry for the production of white granulated cork and then to the agglomeration industry for the production of agglomerated cork products (such as agglomerated cork panels used in construction). The third cork extraction and the ones following result to the best cork quality. This cork type is called reproduction cork and it is mainly used for the production of the natural cork stoppers used in the wine industry for the sealing of wine bottles and natural cork discs used at the assembling of the agglomerated cork stoppers (in order to seal the bottle more effectively). Finally, the pruning of the cork tree branches results to a cork by-product called ‘falca’ that is a mixture of virgin cork, inner bark and wood. This cork type, after its separation from the wood, enters the streams of low quality cork (virgin and second cork types) and is used for the production of construction materials.

The cork sector is characterized by a great variety of cork products. Thus, in order to decrease the complexity of the present study, only the most representative cork products produced from the different cork types are considered. More specifically, the present study considers the manufacturing of black agglomerated cork construction products and granules (from 'falca' and virgin cork), white agglomerated cork construction products and granules (from 'falca' and second cork), natural cork stoppers and discs, agglomerated cork stoppers and construction materials (from reproduction cork). These products represent more than 92% of the total cork products produced in Portugal (APCOR, 2014). The remaining 8% includes mainly decoration products as well as cork sheets used in fashion products and since there are no available data regarding the GHG emissions during their manufacturing, they are not considered in the present study.

2.1.2 Boundaries of the system

Figure 29 presents the stages considered in the system boundaries of the cork sector under study. The manufacturing stage was divided into three smaller systems, based on the different types of cork used as raw material. This categorization was made in order to facilitate the representation of the different cork types used for the production of different cork products, as well as due to the complexity of the stage itself. The three systems under study have different processes as presented in this section.

In the case of the lower quality cork types ('falca', virgin and second cork), two separate systems were created and 'falca' was divided between them for the manufacturing of different cork products. Figure 30 presents in more detail the processes of System 1 concerning the 'falca' and virgin cork types. Additionally, it presents the default quantified flows of this cork type along the sector. It should be noted that the simulation model considers different input quantities for each type. Firstly, the extracted cork is transported from the cork oak forest to the granulation industry where it is triturated. The cork dust produced during the trituration process is considered to be an intermediate product since it is used internally for energy generation through its combustion in boilers in order to avoid the use of fossil fuels. This fact increases the sustainability of the cork sector considering that a smaller amount of fossil fuels is used. The agglomeration of the granulated cork is also considered in this system. During the agglomeration process, the triturated cork is sent to an autoclave to be used for the production of expanded black cork construction materials.

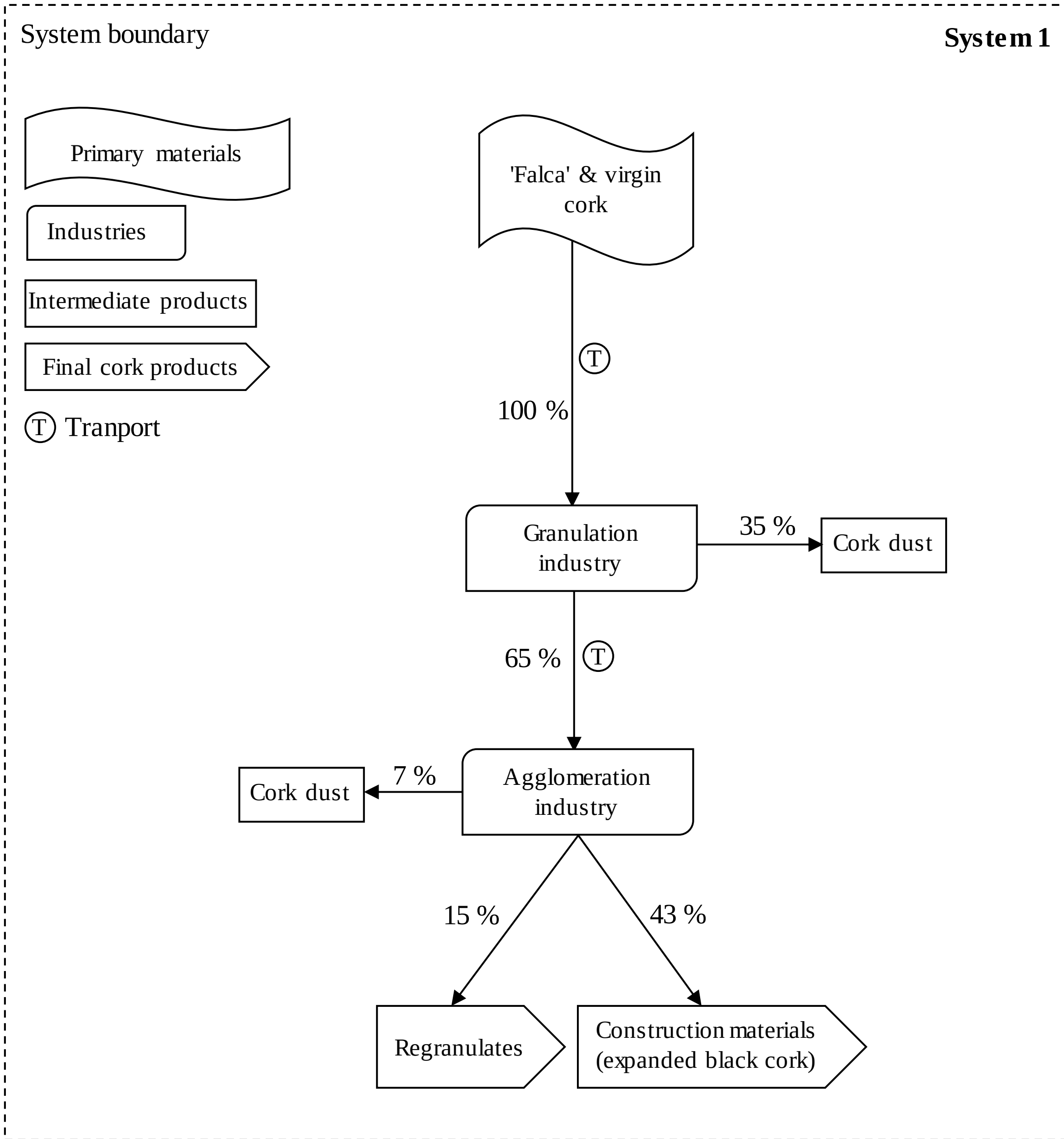


Figure 30: Processes considered in System 1 (representing the 'falca' and virgin cork and the products manufactured using those types as primary materials) and default distribution percentages of the model (cork distribution flows for Portugal)

For this process, cork dust deriving from the trituration process is burnt in a boiler in order to heat water. The steam produced passes through the cork granules at high temperatures (350ºC – 370ºC) and cork's natural resins are released and work as a natural glue for the cork granules. In this way, the cork granules obtain the shape of the autoclave (squared blocks) and are then transported to the stabilization area for approximately 7 days to decrease their temperature and obtain their final dimensions naturally. Those blocks are then cut in slabs (with the desired dimensions) in order to be used in construction as insulation materials (both acoustic and thermic). During the cutting of the expanded cork slabs, there is cork waste produced (e.g., cork strips from the cutting). The cork wastes, along with the rejected cork slabs, are sent to a second trituration for the manufacturing of a coproduct called regranulates. This coproduct is also used in construction as insulation material.

Figure 31 presents in more detail the processes of System 2 concerning the ‘falca’ and second cork types. The harvested cork is transported to the granulation industry to be triturated. Once again, the cork dust produced during the trituration process is considered an intermediate product since it is consumed internally. In the granulation industry, granulated white cork is produced and sold as a final product to be used in construction. The rest of the cork is sent to the agglomeration industry in order to be used for the production of construction materials from agglomerated white cork. In this system, the agglomeration process involves the blending of cork with resins which act as a glue resulting in the production of cork construction products such as cork slabs used in buildings. The cork and resin mixture is placed on a conveyor and is pressed (applying high temperature and pressure) in order to be cut in slabs of specific dimensions. The slabs are then placed in an oven with controlled humidity and temperature for a specific amount of time. After that, the slabs are put in stock (ambient conditions, not controlled) to stabilize for a minimum of 10 days. After stabilization, the slabs pass through a sanding process in order to improve the visual aspect of the final product.

Figure 32 presents in more detail the processes of System 3 (reproduction cork type) and also the default quantified flows of this cork type and its main products in the cork sector considered in CCFM. The boundaries include the transport of the reproduction cork from the cork oak forest to the preparation industry. There, the cork planks follow a specific procedure (planks pile establishment, first stabilization, planks boiling, second stabilization and scalding) and after a manual selection, the prepared planks with the appropriate characteristics are sent to the transformation industry where they are used for the natural cork stoppers and discs production. The planks of higher quality, are separated in two streams based on their thickness.

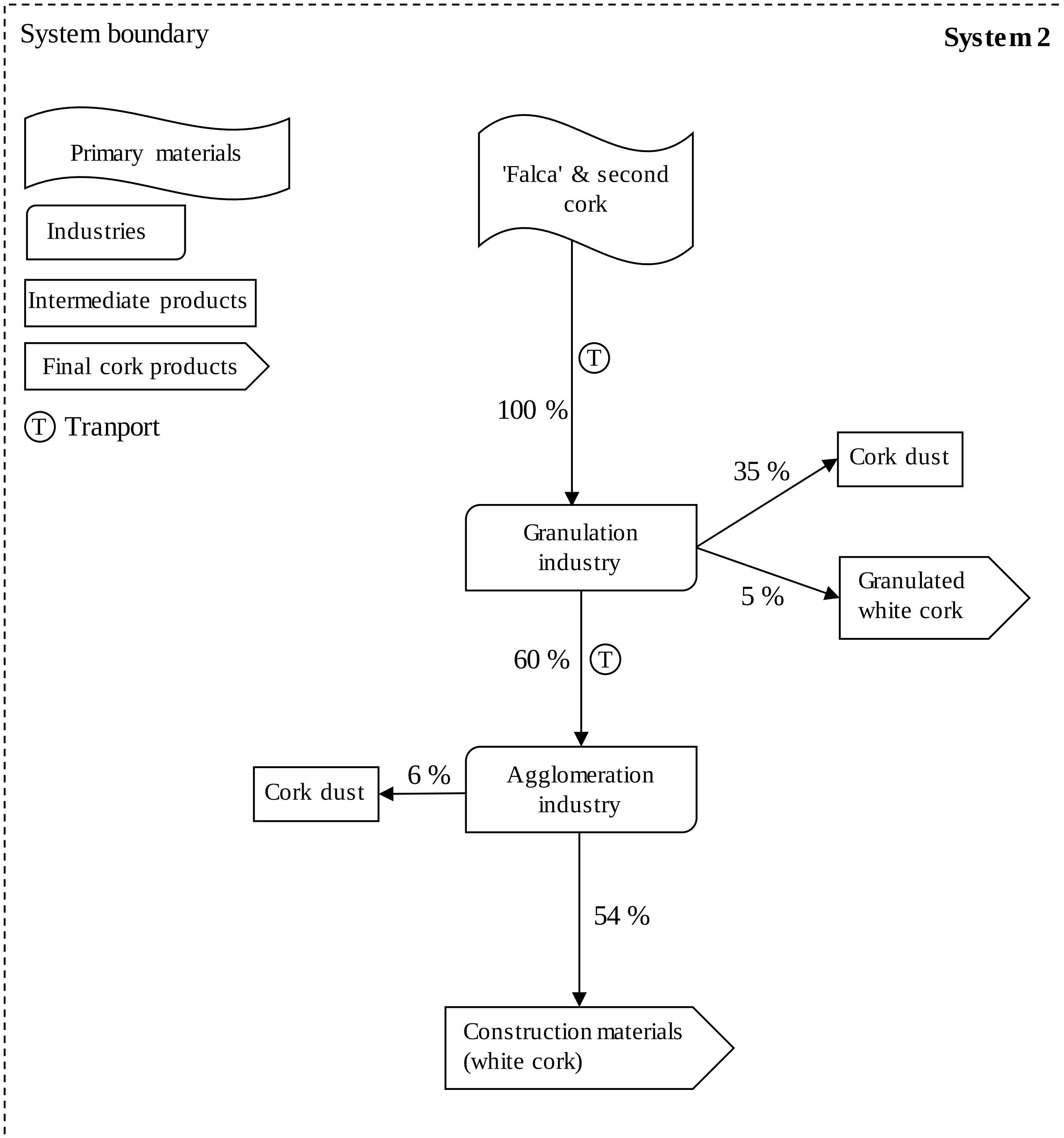


Figure 31: Processes considered in System 2 (representing the ‘falca’ and second cork and the products manufactured using those types as primary materials) and default distribution percentages of the model (cork distribution flows for Portugal)

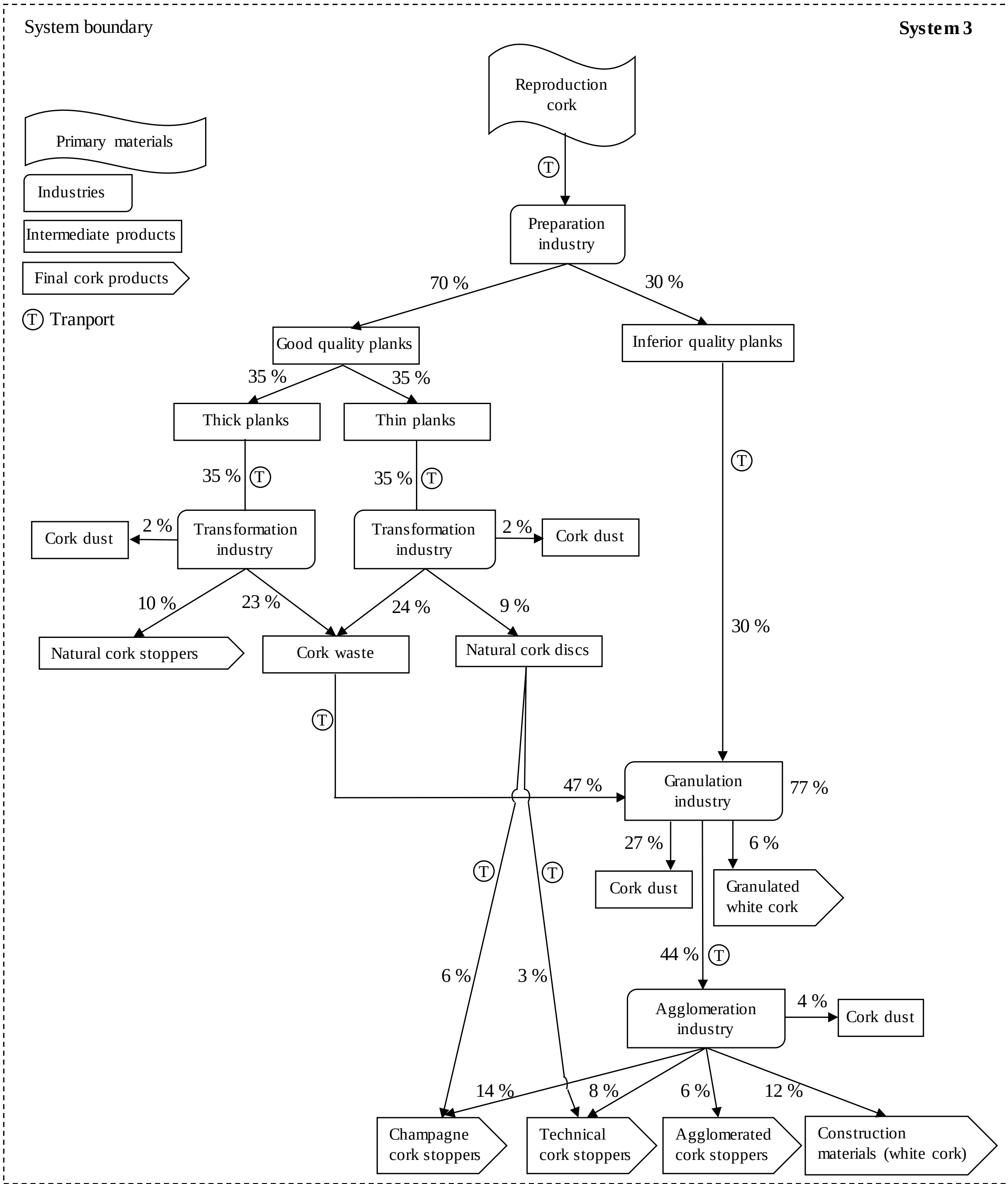


Figure 32: Processes considered in System 3 (representing the reproduction cork and the products manufactured using this type as primary material) and default distribution percentages of the model (cork distribution flows for Portugal)

The thicker planks (thickness of 27 to 54 mm) are destined for natural cork stoppers and thinner planks (thickness of 9 to 27 mm) for natural cork discs. The production of the natural cork stoppers considers all the processes involved in this stage (slicing, punching, pre-drying, rectification/correction, aspiration, selection, washing, drying, deodorization, coloring, dusting, branding, printing, surface treatment and packaging). The thinner planks are used for the production of natural cork discs. The production of natural cork discs considers all the processes involved (slicing, trimming, punching, sanding, selection and packaging). Once again, the cork waste produced is destined to the agglomeration industry for the production of agglomerated cork products. The cork waste resulting from the natural cork stoppers and discs production (e.g., perforated cork planks) is destined to the granulation industry, together with the lower quality planks (not appropriate for natural cork stoppers and discs) for the production of granulated white cork. The cork granules are then sent to the agglomeration industry for the production of agglomerated cork products. During agglomeration, cork is mixed with resins (approved for food contact when used for stoppers) and with the use of different molds, different agglomerated products are produced. In this study, four streams have been considered including champagne cork stoppers (for sparkling and champagne wines), technical cork stoppers (for wines that are consumed within 2-3 years), agglomerated cork stoppers (for wine sealing that does not exceed 1 year) and agglomerated cork materials used in construction. It should be mentioned that in the case of the champagne and the technical cork stoppers, after the molding of the product, natural cork disks are glued on one (in the case of the champagne cork stoppers) or both ends (in the case of the technical cork stoppers), to provide a closure that is chemically very stable and mechanically very strong.

The use stage is considered in order to include the transport of the final cork products to the distribution locations where they will be sold to the final consumer. Thus, the use stage only considers the GHG emissions from the products transport. For the end-of-life stage, three alternatives are considered: incineration with energy recovery for the production of electricity, landfilling with landfill gas recovery for flaring and recycling (only in the case of the natural cork stoppers). In the case of incineration with recovery of energy, three different cases were considered as avoided burdens. Namely, the recovery of energy for the production of electricity substituting the electricity production from natural gas, hard coal and electricity mix. For the used natural cork stoppers, the alternative of recycling is considered as well, since some of the used stoppers can be sent back to the trituration and agglomeration processes for the production of agglomerated cork products. In all three end-of-life alternatives, the different transport distances are considered in the boundaries as well.

2.1.3 Flows and emission factors

In order to obtain the cork flows and the cork products along the entire cork sector, different ‘distribution factors’ and ‘conversion factors’ were considered. Firstly, ‘distribution factors’ were used for the distinction of the main cork types and their distribution along the cork sector, based on a number of studies and reports (Rives et al., 2013; Marques and Gil, 2012; Autoridade da Concorrência, 2012; Fortes et al., 2004). The same was done with the different ‘conversion factors’ in order to account for the transformation of the different cork types into the cork products under study (in percentage) (Demertzi et al., 2016a, 2015b; APCOR, 2014; Rives et al., 2013, 2011; UNAC, 2013; Pereira, 2007). For the distribution of the thick and thin planks used for the production of natural cork stoppers and naturals cork discs respectively, the empirical distributions available in the SUBER growth and yield model (Faias et al., 2012; Paulo, 2011; Paulo et al., 2011; Almeida et al., 2010; Paulo and Tomé, 2010) were used and confirmed by the cork industry. These distributions consider the following cork thickness classes (<18-23 mm used for natural cork discs, 23-41 mm used for natural cork stoppers and >41 sent to trituration industry).

Table 25 presents the default emission factors used for the calculation of the CF of the cork sector and the respective sources (Demertzi et al., 2016a, b; 2015a, b; Dias et al., 2014; Weidema et al., 2013, Rives et al., 2012b). For the calculation of the emission factors both the direct and indirect emissions (from the processes and the production of the secondary materials such as chemicals and fuels) were considered. The emission factors are used for the calculation of the CF of the various cork products since the model multiplies those emissions factors with the quantities of cork products. It should be noted that the emission factors, presented in Table 25, are the default values of the model but the user is able to change them, if desired.

Table 25: Default emission factors used for the calculation of the carbon footprint along the cork sector and their sources

Stage / material	Quantity	Unit
Reproduction cork [a]	148.0	kg CO_2 eq./ t of cork (extracted)
Virgin cork [a]	40.0	kg CO_2 eq./ t of cork (extracted)
Second cork [a]	148.0	kg CO_2 eq./ t of cork (extracted)
'Falca' cork [a]	14.8	kg CO_2 eq./ t of cork (extracted)
Prepared planks [b]	241.0	kg CO_2 eq./ t of cork (prepared)
Natural cork stoppers [b, c]	1,330.0	kg CO_2 eq./ t of natural cork stoppers
Natural cork discs [d]	3,102.5	kg CO_2 eq./ t of natural cork discs
Champagne cork stoppers [d]	4,364.8	kg CO_2 eq./ t of champagne stoppers
Technical cork stoppers [d]	4,364.8	kg CO_2 eq./ t of technical stoppers
Agglomerated cork stoppers [d]	4,364.8	kg CO_2 eq./ t of agglomerated stoppers
Construction materials (white cork) [e]	661.0	kg CO_2 eq./ t of final material
Construction materials (black cork) [f]	209.1	kg CO_2 eq./ t of final material
Granulated black cork/ regranulates [f]	210.4	kg CO_2 eq./ t of granulated black cork
Granulated white cork [e, f]	11.5	kg CO_2 eq./ t of granulated white cork
Landfilling [g]	114.0	kg CO_2 eq./ t of cork (for landfill)
Incineration (avoiding electricity production from natural gas) [g]	-614.0	kg CO_2 eq./ t of cork (for incineration)
Incineration (avoiding electricity production from hard coal) [g]	-1,115.0	kg CO_2 eq./ t of cork (for incineration)
Incineration (avoiding electricity production from electricity mix) [g]	-572.0	kg CO_2 eq./ t of cork (for incineration)
Recycling [g]	-124.0	kg CO_2 eq./ t of cork (for recycling)
Transport by freight lorry, EURO 3 [h]	0.139	kg CO_2/ t*km (transported)

[a] Dias et al. (2014)
[b] Demertzi et al. (2016a)
[c] PwC/Ecobilan (2008)
[d] Rives et al. (2012b)
[e] Demertzi et al. (2015b)
[f] Demertzi et al. (2016b)
[g] Demertzi et al. (2015a)
[h] Weidema et al. (2013)

Figure 33 presents a simplified scheme of the developed simulation model. The model calculates the CF of the cork sector both with and without the accounting of biogenic carbon in the calculations. The biogenic carbon is stored both at the forest biomass and in the cork products and is released, entirely or partially, at the end-of-life of the products. For the calculation of the biogenic carbon emissions along the entire life cycle of the cork products, each stage was considered separately. The assessment period is 100 years and the long-term emissions are not considered.

For the forest stage the sequestration of biogenic carbon by all the components of the cork tree were considered (cork, wood, foliage and roots). For the calculation of the sequestered carbon each components' quantity was multiplied by the carbon content in dry basis. In the case of cork, each cork type quantity derived from the user input, while the carbon content and dry basis derived from the study of Dias and Arroja (2014). The quantity of wood was calculated based on the proportion (dry basis) of cork and wood (63.10% for wood, 27.50% for reproduction cork, 0.68% for second cork, 0.24% for virgin cork and 8.48% for 'falca') derived from the studies of Demertzi et al. (2016b) and Dias et al. (2014). For the rest of the components, the quantities were calculated as a ratio (dry basis) between wood biomass and roots and foliage that presented a value equal to 0.99 and 14.75, respectively (Palma et al. 2014; Paulo 2011; Paulo and Tomé, 2006). The content of carbon (dry basis) for the cork wood, roots and foliage derived from the study of Oubrahim et al. (2015). The sum of the above mentioned components provides the biogenic carbon sequestration in the forest stage (presented as a negative value since it represents a removal). It has to be noted that the sequestration of biogenic carbon in the soil was not considered due to lack of data.

The biogenic carbon released from the manufacturing stage was calculated from a mass balance. Specifically, it was the difference between the carbon contained in the raw cork and the carbon contained in the cork products. The carbon content in dry basis (both for raw cork and cork products) derived from the study of Dias and Arroja (2014). The calculated biogenic carbon was then converted to CO_2 in order to provide the biogenic CO_2 emissions of the manufacturing stage.

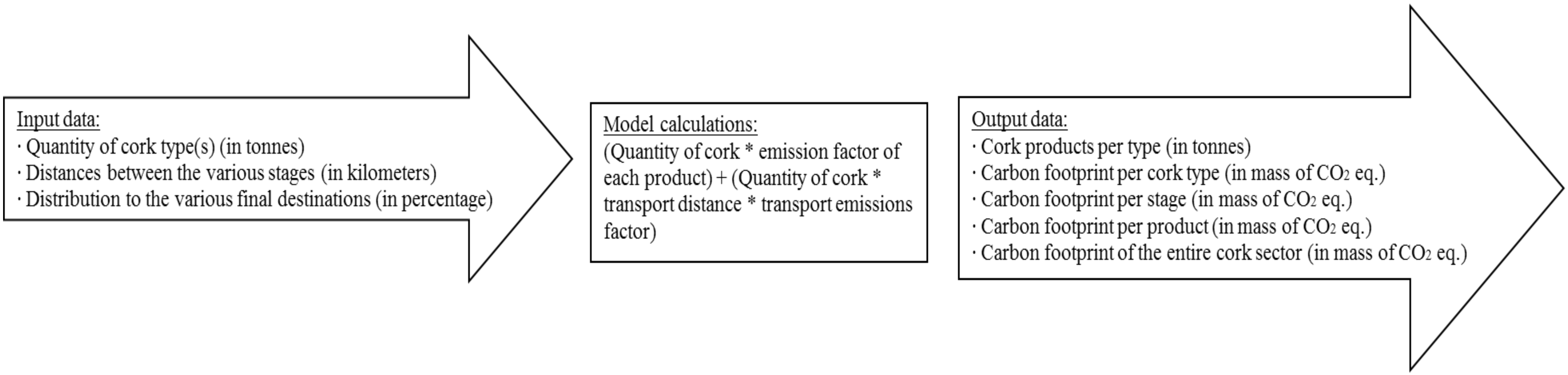


Figure 33: Scheme of the developed simulation model

In the use stage, the transport of the final products from the respective industries to the distributions locations was considered. Since there are no specific data for the distribution of cork products in Portugal, the 10 most populated districts were assumed to be the final destinations and the average distance was used as the transport distance of the cork products.

In the end-of-life stage, the total biogenic carbon emissions of the stage were the sum of the biogenic carbon released by the three considered end-of-life destinations. During the incineration process, there is an immediate release of the entire carbon contained in the cork products. In the case of landfilling, there is only a partial release of the carbon contained in the cork products back into the atmosphere. More specifically, there is a great amount of biogenic carbon that is permanently stored in the landfill facility (98%) while only a small amount (2%) is considered to be emitted (Demertzi et al., 2015a). In the case of recycling, the recycled product is not sufficient for the production of the needed quantity of new products and thus it is not possible to consider that 100% of the contained biogenic carbon remains in the system loop. Considering that the recycled cork stoppers will be used for the production of agglomerated cork products used in construction, a previous study was used (Demertzi et al., 2016a) according to which 30% of the raw material reaches the final product. Thus, in the case of recycling 30% of the amount of carbon contained in the natural cork stoppers is considered to stay in the system without reaching the atmosphere and 70% of the biogenic carbon contained in the natural cork stoppers is emitted (due to cork dust combustion).

2.1.4 Allocation

In general, the application of allocation is necessary in the case of multiple products production. In the present study, considering that during the production of all the considered cork products there is the production of co-products as well, the application of allocation procedures is important. The calculated emission factors (presented in Table 25) consider the allocated emissions of each product.

In the case of the forest stage, the considered allocation derived from the study of Dias et al. (2014). As mentioned there, since different types of cork are produced (virgin, second and reproduction cork), economic allocation was applied in order to obtain the environmental burdens of the different cork types. Additional data was considered in order to consider in the allocation the ‘falca’ produced in the forest stage (Demertzi et al., 2016b). For the cork products considered in System 1 (expanded cork slab and granules), the mass allocation presented in the study of Demertzi et al. (2016b) was considered. Regarding the products of System 2, mass allocation was applied as presented in the study of Demertzi et al. (2015b). In System 3, the allocation procedure applied in the case of the natural cork stoppers is presented in the study of Demertzi et al. (2016a). In this case, the cut-off method was applied according to which all impacts are allocated to the main product. Similarly, in the case of the natural cork discs, all impacts were allocated to the manufacturing of discs as presented in the study of Rives et al. (2012b). Consequently, the products made of primary materials (such as natural cork stoppers and discs) carry the environmental impacts of those primary materials (e.g. raw cork from forest), while the products (such as agglomerated cork products) deriving from secondary materials (e.g. cork stoppers waste) have no environmental burden since they are considered wastes from other activities.

2.1.5 Impact assessment

For the CF calculation, the global warming potentials for a time horizon of 100 years recommended by the Intergovernmental Panel on Climate Change (IPCC) was used (IPCC, 2013). The CF was calculated in mass [kilograms (kg) or tonnes (t)] of CO_2 equivalent (CO_2 eq.).

2.2 Application of CCFM to Portugal

In this section, the inputs of the model for Portugal are presented. Table 26 presents the input data used for the calculation of the CF by the developed model.

Regarding the forest stage, a representative cork oak forest in Portugal (called montado) was considered. Montados are agro-forestry systems and currently, there are two types of management practices for the establishment of the cork stand, plantation and natural regeneration. Those two practices consider slightly different operations (Dias et al., 2014) and in the case of plantation the environmental impact is higher due to the mechanized preparation of the soil and plantation of the cork plants which is natural in the case of regeneration.

Table 26: Input quantities of raw cork and transport distances introduced

Input	Quantity	Unit
Raw cork quantities		
Virgin cork [a]	11,400	t
Second cork [a]	14,250	t
Reproduction cork [a]	69,350	t
'Falca' cork [b]	50,000	t
'Falca' to System 1	22,500	t
'Falca' to System 2	27,500	t
Transport distances [c]		
For System 1 (virgin/ 'falca' cork):		
From forest to granulation unit	160	km
From granulation unit to agglomeration unit	0	km
From the agglomeration unit to the distribution location	200	km
For System 2 (second/ 'falca' cork):		
From forest to granulation unit	600	km
From granulation unit to agglomeration unit	0	km
From the granulation unit to the distribution location	200	km
From the agglomeration unit to the distribution location	200	km
For System 3 (reproduction cork):		
From forest to preparation unit	116	km
From preparation unit to transformation unit	300	km
From preparation unit to granulation unit	300	km
From transformation unit to granulation unit	2	km
From transformation unit to agglomeration unit	2	km
From granulation unit to agglomeration unit	0	km
From transformation unit to distribution location	200	km
From granulation unit to distribution location	200	km
From agglomeration unit to distribution location	200	km
For end-of-life destinations:		
Incineration	40	km
Landfilling	40	km
Recycling	217	km
End-of-life destinations [d]		
For agglomerated products:		
Incineration [e]	32	%
Landfilling	68	%
For natural cork stoppers:		
Incineration [e]	31	%
Landfilling	66	%
Recycling	3	%

[a] Average quantities for 2006-2014 from SUBER simulation model (Faias et al., 2012; Paulo, 2011)
[b] Personal communication from Portuguese cork industries considering average annual production
[c] Demertzi et al., 2016a, b, 2015b (the distance between the forest and the industry is doubled since it considers that the trucks return to the forest empty)
[d] Demertzi et al., 2015a; Eurostat, 2013; Green Cork, 2013
[e] Incineration with energy recovery for production of electricity avoiding electricity production by electricity mix

An average emission factor was considered in order to obtain an average behavior for the entire country. An average lifespan of 170 years was considered for the cork forest. Furthermore, since the tree density of a cork forest has a wide range (50-150 trees per hectare) an average density of 100 trees per hectare was considered (in the cork production phase of the trees) with an approximate 150 kg total raw cork production per hectare. Those assumptions were necessary to be made since the raw cork production can vary significantly depending on the tree density of the cork forest, size of the cork trees (diameter) and the cork stripping intensity (Paulo et al., 2016). Considering that there are no specific statistical data for the different cork types produced, the total cork produced considers the average of 9 years cork production in Portugal for 2003-2011 (APCOR, 2011). However, the distribution of the total cork among the different cork types (virgin, second and reproduction cork types) was done through the SUBER simulator (Faias et al., 2012; Paulo, 2011). Additionally, the specific quantity of 'falca' cork was provided by unpublished industrial data (personal communication). Regarding the 'falca' cork, it was considered that 46% ends up in System 1 and that 54% of the total input of this cork type ends up in System 2. Figures 31, 32 and 33 provide the distribution percentages of the different cork types along the cork sector (default model values). In all cases, the cork products produced only consider the country's cork production and no imported cork (production approach).

The transport distances of cork as raw material and intermediate product are average distances between the different stages (Demertzi et al., 2016a, b, 2015b). Additionally, the transport distances of the used natural cork stoppers to the incineration facility, the landfill facility and the recycling unit were based on a study for the end-of-life of natural cork stoppers (Demertzi et al., 2015a).

The percentages used for the final destinations of the various cork products were based on the actual main final destinations of municipal solid waste (MSW) in Portugal. More specifically, it was considered that 68% of the agglomerated cork products is destined to a landfilling facility and that 32% to an incineration facility (Eurostat, 2013). In the case of the natural cork stoppers that also consider the recycling destination, according to the recycling campaign in Portugal for 2013, there is a 3% of used natural cork stoppers sent to recycling (Green Cork, 2013). Thus, the mentioned end-of-life percentages in the case of the natural cork stoppers were recalculated, considering that 66% is sent to landfilling, 31% to incineration and 3% to recycling.

3. Results and discussion

3.1 Carbon footprint of each system

In this section, the outputs of the model applied to Portugal are presented. The results consist of the cork flows along the cork sector (in tonnes) as well as the CF of each cork type (in tonnes of CO_2 eq.) considering the entire life cycle of the cork sector (stages of forest, manufacturing, use and end-of-life) both when accounting for and excluding the biogenic carbon emissions and sequestration. Considering that the biogenic carbon emissions deriving from forest-based products are usually excluded since they are considered neutral, their consideration will evaluate their influence.

3.1.1 Carbon footprint when excluding the biogenic carbon emissions and sequestration

Table 27 presents the flows of cork products calculated by CCFM based on the initial cork quantity (145,000 tonnes of raw cork).

Table 27: Flows of the model for each cork type under study

Intermediate & final cork products	Mass (t)
System 1 ('Falca' & virgin cork)	
Final products	
Expanded cork slab	14,763
Granulated black cork (Regranulates)	5,068
System 2 ('Falca' & second cork)	
Final products	
Granulated white cork	2,088
Construction materials (white cork)	22,545
System 3 (Reproduction cork)	
Final products	
Natural cork stoppers	6,935
Granulated white cork	4,272
Champagne cork stoppers [a]	13,901
Technical cork stoppers [a]	7,560
Agglomerated cork stoppers	4,261
Construction materials	8,218

[a] The flow of the natural cork discs is included (4,161 t of discs to champagne cork stoppers and 2,081 t of discs to technical cork stoppers)

It can be observed that the main flow of cork for the manufacturing of the final products, in the case of System 1 ('falca' and virgin cork) ends up at the expanded cork slab used as construction material and in System 2 ('falca' and second cork), also ends up at the construction materials (in this case from white cork). On the other hand, in System 3 (reproduction cork), the main flow of cork end ups at the different types of agglomerated cork stoppers (champagne cork stoppers, technical cork stoppers and agglomerated cork stoppers), followed by the construction materials, the natural cork stoppers and the granulated white cork.

Figure 34 presents the total CF per cork type for the 3 systems, both per stage (the manufacturing stage consists of the preparation, transformation, granulation and agglomeration industries) and in total. In this figure, the CF presented only considers the fossil emissions. By comparing the total CF of each system, it can be noticed that System 3 represents the greatest percentage of the total CF of the sector (86%). This can be explained by the additional industries considered in this System (preparation and transformation industries for the manufacturing of natural cork stoppers and discs) and also by the greatest amount of cork as an input to this system.

It can be noticed that in all three systems the end-of-life stage is negative since it considers the use of the energy recovered for the production of electricity (in the case of incineration), flaring (in the case of landfilling) and production of agglomerated white cork construction materials (in the case of recycling). For the rest of the stages (which have positive values) it can be noticed that the agglomeration industry presented the greatest influence of the CF of all three systems.

More specifically, in the case of System 1, the agglomeration industry represents 64% of the total CF of System 1. The granulation industry is the second most influential source of GHG emissions (16% of the total CF of System 1) due to the consumption of electricity for the trituration of cork. Then follows the forest stage (12% of the total CF of System 1) due to the processes from the management of the cork oak stand (e.g., cleaning of spontaneous vegetation). The use stage was found to be the less influential for System 1 (8% of the total CF of System 1) due to the transport of the final products to the distribution locations.

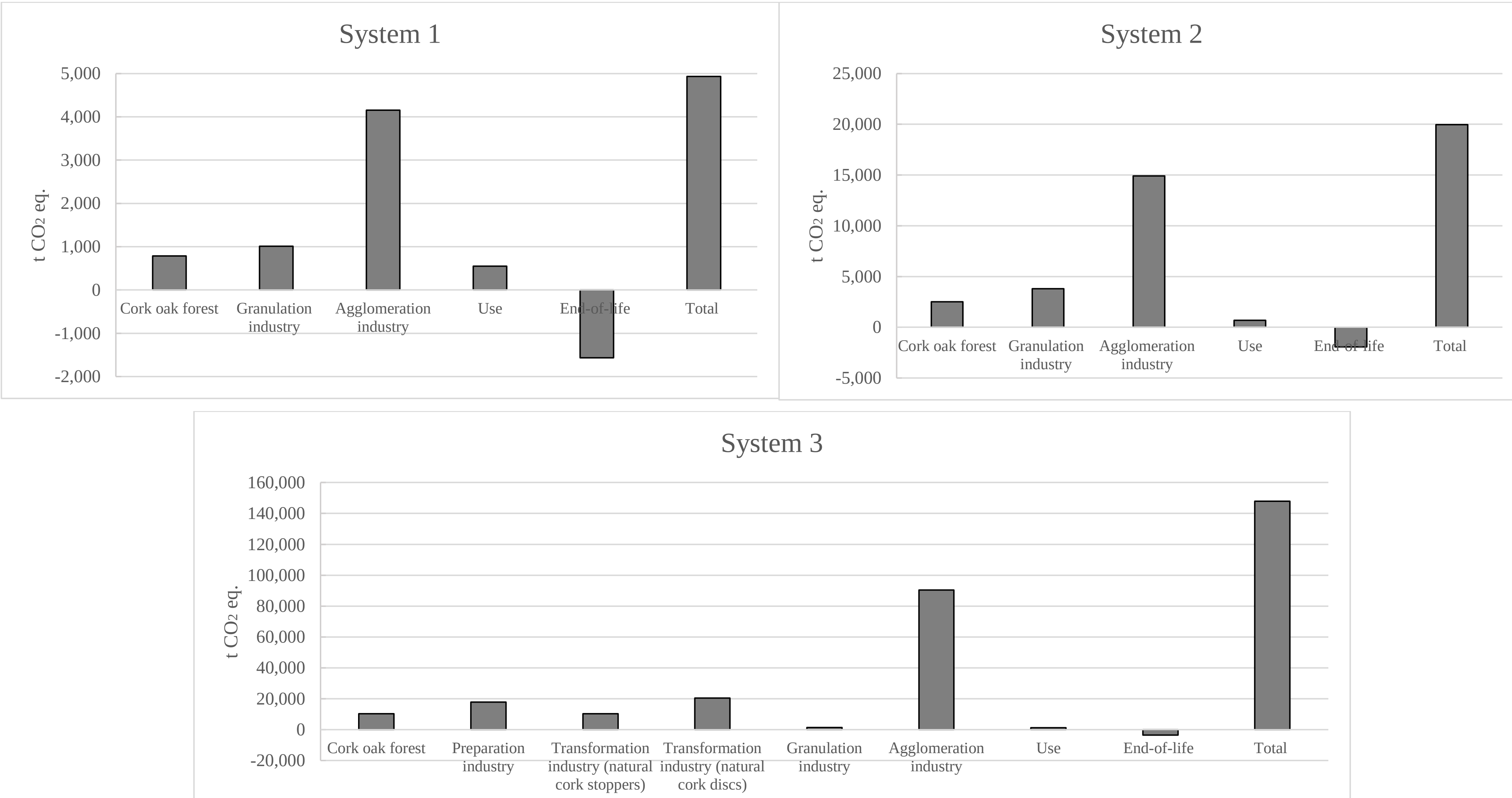


Figure 34: Carbon footprint output of the model (excluding biogenic carbon sequestration and emissions) for the various stages of the cork industry (System 1 - ‘falca’ and virgin cork, System 2 - ‘falca’ and second cork, System 3 – reproduction cork)

In System 2, the agglomeration industry is by far the most influential (68% of the total CC of System 2). The main GHG emissions in the agglomeration industry, derive from the consumption of electricity and adhesives used for the agglomeration of the white cork granules for the manufacturing of the main body of the agglomerated cork products. The second most influential industry is the granulation industry (17% of the total CC of System 2) and the source of the GHG emissions is the consumption of electricity for the trituration of cork. Then follows the forest stage (11% of the total CC of System 2). The less influential stage of System 2 is the use stage (3% of the total CF of System 2) where the GHG emissions derive from the fuel consumption for the transport of the final cork products to the distribution locations.

The main influence in System 3 also derives from the agglomeration industry (60% of the total CC of System 3), followed by the transformation industry (20% of the total CC of System 3) mainly due to the fuel consumption for the deodorization of natural cork stoppers and due to electricity consumption for the punching of natural cork discs. The third most influential industry was the preparation of the cork planks (12% of the total CC of System 3) due to the consumption of fuel for the planks boiling process (for the disinfection of the planks). The forest stage, the granulation industry and the use stage were the less influential (7%, 1% and 1% of the total CC of System 3, respectively).

Figure 35 presents the specific CF of the representative cork products under study. The influence of each stage to the total CF during the entire life cycle of each product is presented as well. It can be noticed that the cork products with the greatest CF derive from System 3 and are the champagne cork stoppers, followed by the technical cork stoppers and the agglomerated cork stoppers. Then follow the construction materials from System 2 and the rest of the cork products. In all those cases, the most influential stage is the agglomeration stage (for the aforementioned reasons). It has to be noted that both the champagne and the technical cork stoppers also consider the CF deriving from the production of the natural cork discs since they make part of their final body.

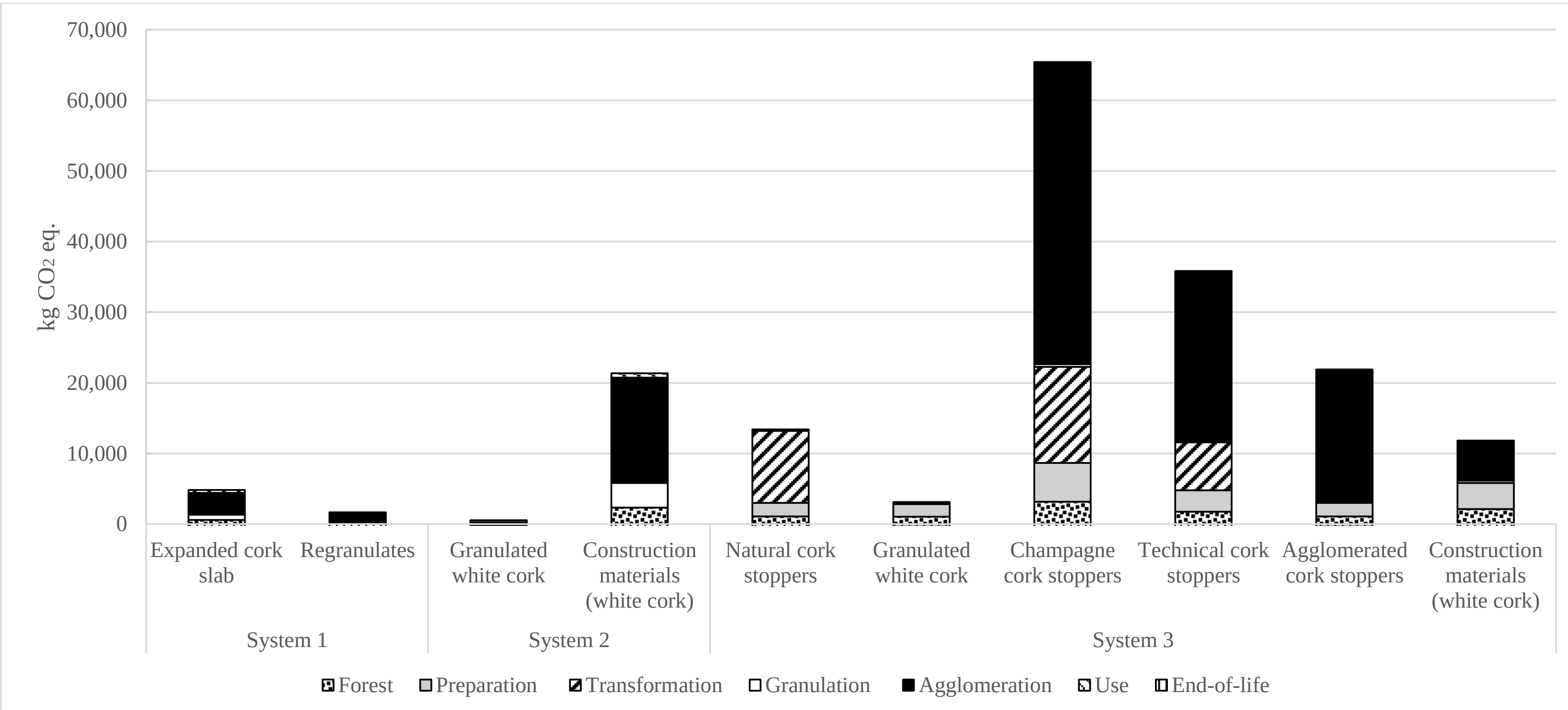


Figure 35: Carbon footprint output of the model for the most representative final products of the cork industry

3.1.2 Carbon footprint when accounting for the biogenic carbon emissions and sequestration

Figure 36 presents the results for the CF when excluding biogenic CO_2 from the calculation (172,844 t CO_2 eq.) and when considering biogenic CO_2 sequestration and emissions in the calculations (-956,042 t CO_2 eq.). As seen in Figure 36, the total CF of the cork sector is highly influenced by the consideration or exclusion of the biogenic carbon especially in the case of the forest stage.

The forest stage has a positive CF when the biogenic carbon is excluded from the calculations due to the GHG emissions from the stand management processes occurring along the production of raw cork. However, when biogenic carbon is considered, the CF of the forest stage becomes negative due to the sequestration of carbon by the different components of the cork tree which remain alive for more than 100 years. The consideration of biogenic carbon for the rest of the stages also results in different final results (as seen in Figure 36).

It was found that 79% of the total carbon sequestered in the forest stage, is stored in the wood, roots and foliage of the cork tree, while the rest 21% in raw cork. Considering that cork oak trees can live many more years than the 100-year assessment period of the global warming potentials considered in the calculations (IPCC, 2013), there is a long-term carbon storage. Additionally, a part of the carbon stored in raw cork is permanently stored in the landfill facilities where the cork products end-up after use (38% of the total carbon stored in raw cork). The rest of the carbon sequestered will be released mostly through the burning of the cork dust (manufacturing stage) or through the incineration of the cork products (end-of-life stage).

The manufacturing stage was responsible for 90% of the total GHG emissions, 66% of which were biogenic CO_2 emissions deriving from the burning of cork dust for the production of thermal energy. The great decrease of the CF due to CO_2 sequestration shows the importance of the cork forest for the mitigation of climate change, considering that the sequestered carbon is not emitted into the atmosphere during the 100-year time horizon considered.

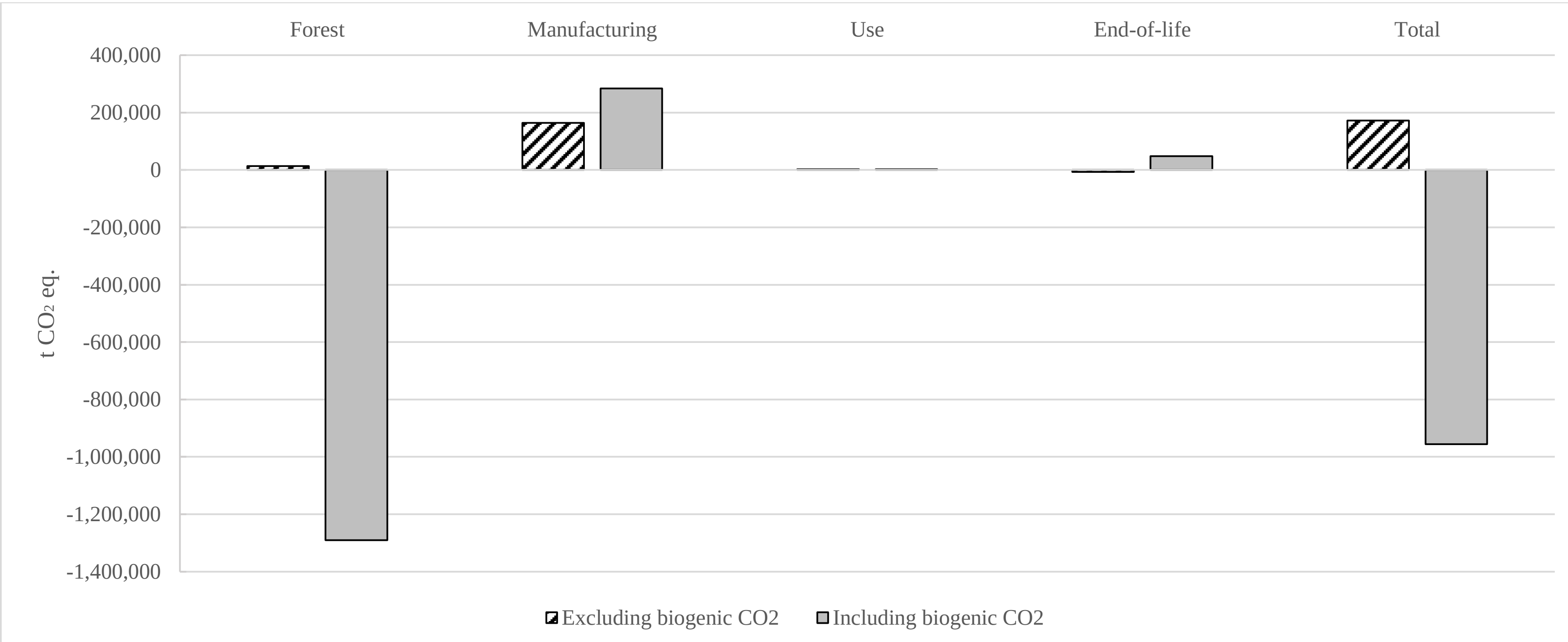


Figure 36: Calculation of the carbon footprint of the cork oak sector when including and excluding the biogenic carbon emissions and the sequestration of carbon at the forest stage

3.2 Data limitations

In order to apply CCFM in the case of Portugal, some assumptions and simplifications had to be done. For the calculations of the emission factors considered in the study, an average CF for each cork product was used based on published studies. Considering the limited number of cork LCA studies in Portugal the emission factors used can bias the actual impact in each case. For example, not all cork companies use the same technology for the different manufacturing processes and by considering primary data of a small range of companies could introduce uncertainty in the study.

The emission factors considered for the production of champagne, technical and agglomerated cork stoppers, derived from a case study performed in Spain since there is no such study for Portugal. Thus, the primary data considered the specifications and characteristics of the Spanish cork sector and not the Portuguese. Considering that the manufacturing processes are not the same in the two countries (e.g. use of diesel oil instead on natural gas and different electricity mix of the countries) the emission factors used for those products could also be limiting the final output of the model for the case of Portugal. Regarding the end-of-life stage, it is important to mention that the study used for the emission factors (Demertzi et al., 2015a), highlights the influence of some parameters in the final CF of this stage (e.g. decay rate of cork in landfills). A sensitivity analysis performed quantifies the influence of each one of the parameters in the final CF from the final disposal of the natural cork stoppers. However, considering that the influence of the end-of-life stage is very low compared to the rest of the stages, its influence is not significant on the total CF of the cork sector.

The limitations acknowledged in this study can be considered in future studies in order to improve and enrich the knowledge regarding the CF of the cork sector.

3.3 Actions for improvement

Various scenarios were considered in a sensitivity analysis in order to evaluate the CF of the cork sector when attempting improvement actions to decrease the total CF of the cork sector. As seen in the previous section, the most influential stage for the cork oak sector is the agglomeration industry. Thus, a decrease of 10% of the emissions factor of the agglomeration industry was assumed as a possible improvement (Scenario 1). Considering that the second most influential industry for the total CF of the sector was the transformation industry, a 10% decrease was considered for the transformation industry in addition to the 10% decrease of the agglomeration industry (Scenario 2). The decrease of the emission factors of those two industries could be achieved through the decrease of the energy consumption (e.g. electricity and fuel) and the use of different materials (e.g. resins) in order to decrease the emissions from their production (consumption of fossil fuels and electricity) and consequently the GHG emissions. Another possible improvement action could be the use of trucks achieving the exhaust emission limits of more recent European standards in order to decrease the emissions from the transportation of cork between the different stages of the cork sector. Thus, instead of the use of trucks of EURO 3, trucks of EURO 6 (lower exhaust emission limits) were considered (Scenario 3). Furthermore, since there is an attempt to decrease the amount of residues ending up at the landfill sites (according to the Strategic Plan for Urban Waste - PERSU 2020 (MAOPE, 2014)), a conservative decrease of 10% of the landfill alternative percentages was assumed (Scenario 4). Thus, instead of considering 32% to incineration and 68% to landfilling (for the agglomerated products) and 31% to incineration, 66% to landfilling and 3% to recycling (for natural cork stoppers), new percentages were adopted. Namely, 39% to incineration and 61% to landfilling (for the agglomerated products) and 34% to incineration, 59% to landfilling and 7% to recycling (for natural cork stoppers). Finally, two combination scenarios were considered. Firstly, the improvement of the existing conditions was attempted by combining Scenarios 2 and 4 (Scenario 5). Then, the consideration of all the suggested improvements, Scenarios 2, 3 and 4 were considered (Scenario 6).

Table 28 shows the changes in the CF (without biogenic carbon) of the sector when considering the various improvement scenarios. It can be seen that the improvement scenarios can result to a 0.1%-10% decrease of the total CF (excluding the biogenic emissions and sequestration) of the cork sector. By comparing the various scenarios, it can be noticed that the two combination scenarios considering different aspects influencing the cork sector (Scenarios 5 and 6) can result in the greatest decrease of the CF of the sector (by 9% and 10%, respectively). From the rest of the scenarios it was found that Scenario 2 considering the decrease of the agglomeration and transformation industries would result in the greatest decrease of the sector's CF (8%).

Table 28: Sensitivity analysis for possible improvements of the cork sector's carbon footprint

	Baseline CF (t CO_2 eq.)		Decrease of the CF when excluding the biogenic emissions and sequestration (%)					
Stages	**Including***	**Excluding***	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Forest	-1,290,969	13,566	0	0	0	0	0	0
Manufacturing	284,510	164,038	-6	-8	-0.1	0	-9	-8
Use	2,318	2,318	0	0	-2.2	0	0	-2
End-of-life	48,099	-7,078	0	0	-0.2	-29	-29	-29
Total	-956,042	172,844	-6	-8	-0.1	-2	-9	-10

* *biogenic emissions and sequestration*
Scenario 1: 10% agglomeration emission factor decrease
Scenario 2: 10% agglomeration & transformation emission factors decrease
Scenario 3: more recent trucks (EURO 6 instead of EURO 3)
Scenario 4: change of the percentages considered for the end-of-life destinations
Scenario 5: combination of Scenarios 2 & 4
Scenario 6: combination of Scenarios 2, 3 & 4

Considering a 10% decrease of the most influential industry, the agglomeration industry, a 6% decrease the total CF of the sector can be noticed. The decrease of the percentage of cork products reaching the landfill facility (Scenario 4) would result to a 2% decrease of the sector's CF. The scenario resulting in the lowest decrease of the sector's CF was Scenario 3 which considers the use of transport trucks with lower emissions (0.1% decrease of the total CF). Consequently, the obtained results show that only by focusing on the specific aspects of the cork sector that are the most influential (agglomeration and transformation industries) and end-of-life destinations, a significant decrease of the CF of the entire cork sector can be achieved (up to -10% of the cork sector's total CF when excluding the biogenic emissions and sequestration).

4. Conclusions

The objective of the present study was the development of a CF simulation model for the entire cork sector, CCFM. By applying CCFM to Portugal, which is considered a leader in the cork sector, quantitative results were obtained for the evaluation of the hotspots of the sector. The developed simulation model can be used for the calculation of the mass and CF output of different cork types (virgin, second, reproduction and 'falca' cork) for the most representative cork products. The user is allowed to manually introduce the quantity of each cork type, distances between the different stages of the cork industry and end-of-life destinations (incineration, landfilling and recycling and their respective percentages). Even though CCFM considers default values for the emission factors of the various industries and the cork contribution along the entire cork sector, they can be changed by the user if desired. In this way, CCFM developed for the present study, can be applied to different countries since there are no limitations in the inputs that the user introduces. Considering its capability to be adapted in different conditions, the application of CCFM can be useful for the decision-making process of the cork sector of different countries in order to achieve a decrease of the global CF of the entire sector.

The application of CCFM to Portugal showed that the most influential stage for all the cork types is the agglomeration industry mainly due to the emissions from the production of the materials used for the agglomeration process (e.g. resins). The consideration of different scenarios concerning possible improvements for the cork sector showed that a combination of the agglomeration and transformation emission factors decrease (by 10%), the use of newer trucks (EURO 6) and the change of the end-of-life destination percentages (10% decrease of the landfilling percentage) can result in a 10% decrease of the cork sector's CF (excluding the biogenic emissions and sequestration).

Regarding the consideration of biogenic carbon emissions and sequestration in the calculation of CF of the cork sector, it was found to be very influential. More specifically, the consideration of biogenic carbon results in a great decrease of the total CF of the cork sector mainly due to the carbon sequestration by the various components of the cork tree. The obtained results show that the cork sector is a carbon sink and that the quantity of CO_2 sequestered is much greater than the quantity of the GHG emissions of the sector. Furthermore, this fact highlights the importance of the cork oak forests for the mitigation of climate change since the sequestered carbon is not released into the atmosphere and remains stored for a long time considering that cork oaks are long-lived trees. Future studies could also consider the sequestration of carbon by the soil of the cork forest since it could be important and it was excluded from the present study due to current lack of data regarding this aspect.

Acknowledgements

The authors gratefully acknowledge the company Corticeira Amorim S.G.P.S. for the collaboration in providing unpublished data. This study was supported by the project "Cork carbon footprint: from trees to products" (PTDC/AGR-FOR/4360/2012) funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal).

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4.3 Evaluating cork sector's carbon footprint through traditional and dynamic life cycle assessment

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Abstract

The aim of the present study is to assess the influence of two different life cycle assessment (LCA) approaches, namely traditional LCA (tLCA) and dynamic LCA (dLCA), through their application to the calculation of the carbon footprint of the entire cork sector in Portugal. The inclusion and exclusion of biogenic carbon sequestration and emissions is considered as well.

tLCA is often described as a static tool since all the emissions are accounted for as if occurring at the same time which may not be the case in reality for greenhouse gases. Currently, another LCA approach, dLCA, aims to evaluate the impact of life cycle greenhouse gas emissions on radiative forcing considering the specific moment when these emissions occur.

The results show that there is a difference between the final carbon footprint values depending on the approach and time horizon chosen. However, the greater it is the time horizon chosen, the smaller the difference between the CF results of the two approaches. Additionally, the exclusion or inclusion of biogenic carbon sequestration and emissions also influences the CF result. Cork sector is considered a carbon source when biogenic carbon is excluded from the calculations and a carbon sink when biogenic carbon is included in the calculations since more carbon is sequestered than emitted along the sector. Both when including and excluding the biogenic carbon sequestration and emissions from the calculation of the cork sector's CF, for the 20-year time horizon, tLCA presents greater CF than dLCA, while the opposite occurs for the 100-year time horizon. dLCA allows an overview of greenhouse gas emissions along the time, face to tLCA (static). This is an advantage as it will be possible to identify and plan different management approaches for the cork sector. Even though dLCA is a more realistic approach, it is a more time-consuming and complex approach for long life cycles. The choice of time horizon was found to be another important aspect for CF assessment.

Keywords: biogenic carbon, carbon footprint, cork products, cork sector, dynamic life cycle assessment, traditional life cycle assessment

1. Introduction

Cork is a natural material deriving from the outer bark of the cork oak tree (Quercus Suber L.). Cork oak forests are mainly located in the western Mediterranean basin, covering a total area of 2,139,942 hectares (APCOR, 2014). The majority of this area is distributed along Portugal (730,000 hectares according the last national forest inventory (ICNF 2013)), representing 34% of the cork oak forests global area and 23% of the country's forest area (second most dominant tree species). Portugal is the leader in raw cork production with a 50% quota of the global raw cork production (APCOR, 2014). Due to the unique characteristics of cork as a material, it can be used in many industrial sectors (e.g. wine industry and construction) for the manufacturing of various products (e.g. stoppers and insulation slabs) resulting in a high economic value for the country (APCOR, 2014).

The environmental evaluation of cork, considering the forest management and manufacturing processes for the production of cork products, can be done through the application of life cycle assessment (LCA). A few LCA studies about raw cork and cork products can be found in literature, evaluating raw cork (Dias et al., 2014; González-García et al., 2013; Rives et al., 2012a), natural cork stoppers (Demertzi et al., 2016a, 2015b; Rives et al., 2011; PwC/Ecobilan, 2008), champagne cork stoppers (Rives et al., 2012b) and cork construction materials (Sierra-Pérez, 2016; Demertzi et al., 2016b, 2015a; Pargana et al., 2014; Rives et al., 2013, 2012c; Bribrian et al., 2010).

In the case of the forest-based products, besides the fossil emissions, there are also the biogenic carbon emissions. Those are defined as emissions resulting from the combustion or decomposition of biologically-based materials other than fossil fuels (EPA, 2011). Cork, as a forest-based material, can store carbon in its tissue up to almost 200 years (for cork oak tree) or as long as it remains in use or at landfills (for products). This occurs because cork oak forests can sequester carbon from the atmosphere and store it in their perennial tissues and in the soil as organic matter for very long periods (Pereira and Bugalho, 2009). Due to the periodic cork debarking of the cork tree, a fraction of the carbon is transferred to cork products delaying its return to the atmosphere (Dias and Arroja, 2014). Additionally, the carbon contained in the cork products can be permanently stored in the landfill facilities since only a small part is released into the atmosphere (Demertzi et al., 2015b). Thus, both cork forests and cork products have the potential to mitigate climate change for long periods.

It is known that LCA techniques often do not consider the biogenic carbon emissions (e.g., study of González-García et al., 2013) or biogenic carbon is considered to be neutral (e.g., in the study of Dias et al., (2014)), excluding an important aspect of cork. Only a few recent studies have considered this aspect in the carbon footprint (CF) results, namely in the environmental analysis of raw cork extraction in cork oak forests in southern Europe (Rives et al., 2012a) and the integrated environmental analysis of the main cork products in southern Europe (Rives et al., 2013). It should be noted that an increasing number of studies suggest that biogenic carbon emissions should be accounted for in order to have a more complete view of the system under study (Levasseur at al., 2013, 2010a,b) and in order to avoid partial conclusions (Garcia & Freire, 2014; Brandão et al., 2012; 2010; Müller-Wenk & Brandão, 2010).

Traditional LCA (tLCA) is often described as a static tool, where all the emissions are accounted for as if occurring at the same time (Helin et al., 2013). A different approach, called dynamic LCA (dLCA), aims the evaluation of life cycle greenhouse gas (GHG) emissions impact on radiative forcing while considering the exact moment when these emissions occur (Pehnt, 2006). Even though dLCA is a newer approach compared to tLCA, in literature there are a few studies with its application to forest-based products such as Fouquet et al. (2014) that applied dLCA for the LCA of a timber house and Levasseur et al. (2012) for a wooden chair. Currently, there is no dLCA application for the case of cork as a material or for the entire cork sector. However, its application to the cork sector can be relevant since it is a more realistic approach which provides more detailed information regarding GHG emissions per year of occurrence.

The aim of the present study is to assess the influence of two different life cycle assessment (LCA) approaches, namely tLCA (static) and dLCA, through their application to the calculation of the carbon footprint of the entire cork sector in Portugal. The inclusion and exclusion of biogenic carbon sequestration and emissions is considered as well. For the application of dLCA, a software tool (dynamic carbon footprinter, $DYNCO_2$) developed for the calculation of the impact of GHG emissions over a time period is used (Levasseur et al. 2010a, b). In order to obtain quantitative results, specific data from the cork sector of Portugal is applied.

2. Methodology

2.1 Traditional and dynamic life cycle assessment

The two applied approaches for the calculation of cork sector's CF have several differences, namely the time horizon and the characterization factors considered. The main issue with tLCA (static) is that it considers that all GHG emissions occur at a specific time (reference year). Thus, for the calculation of the CF of a process, the emission of GHG from the various sources considered (e.g., diesel combustion for transport and natural gas combustion for heat production) are multiplied by a characterization factor (global warming potential - GWP) for a given time horizon (20, 100 or 500 years) in order to calculate the CF of the process (in mass of CO_2 eq.). The life cycle's CF is calculated by the sum of the CF of all the processes making part of the system under study. Since tLCA does not consider time distribution of GHG emissions and uses GWPs for a fixed time horizon (usually 100 years) it has a main issue with inconsistency in temporal boundaries (Levasseur et al., 2010a, b).

The approach of dLCA takes into account the distribution of the emissions along a determined time horizon. The whole life cycle of the system under study is subdivided in yearly steps and the amount of pollutant released into the atmosphere is correspondent to each year and each GHG. Regarding the dLCA, the software tool DYNCO$_2$ is used in order to calculate the impact of GHG emissions over a time period. Through the help of an excel spreadsheet, this dynamic approach allows taking into account the temporal distribution of the emissions by using a dynamic inventory. The respective quantities of carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O), emitted when performing the various processes considered in the system under study, are introduced in DYNCO$_2$ in order to obtain the CF results for the cork oak sector.

In the case of tLCA, GWPs have been proposed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013). The GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas according to equation (9):

$$GWP_i^{TH} = \frac{\int_0^{TH} a_i \bullet [C(t)]dt}{\int_0^{TH} a_r \bullet [C(t)]dt} \qquad \text{Equation (9)}$$

Where *TH* is the time horizon over which the calculation is considered, *a* is the instantaneous radiative forcing per unit mass increase in the atmosphere, *C(t)* is the time-dependent atmospheric load of the released gas, *i* is the released gas, and *r* is the reference gas, carbon dioxide.

In dLCA, instead of GWP, a dynamic characterization factor (DFC) is used according to equation (10) (Levasseur et al., 2010a):

$$\mathrm{DCF(t)} = \int_{t-1}^{t} a \times C(t)dt \qquad \text{Equation (10)}$$

where, α is the instantaneous radiative forcing per unit mass increase in the atmosphere for the given GHG ($W.m^{-2}.kg^{-1}$) and *C(t)* is the atmospheric load of the given GHG *t* years after the emission ($kg.kg^{-1}$). Based on equations 9 and 10, Table 29 shows the GWP and DCF values considered in the calculation of the CF in the two LCA approaches for the three GHGs (CO_2, CH_4 and N_2O) for three time horizons (20, 100 and 500 years). In the case of the tLCA, the characterization factors recommended by the IPCC are used for three time horizons (20, 100 and 500 years) (IPCC, 2013). Both for tLCA and dLCA, the CF is calculated in kilograms of CO_2 equivalent (kg CO_2 eq.).

In the case of the dLCA, all the emissions of the three main GHGs (CO_2, CH_4 and N_2O) in kilograms during each life cycle year must be added for all the processes considered in the system under study in order to be introduced in the DYNCO$_2$ model. This model returns three types of results:

- The instantaneous impact (GWI_{inst}) that is the radiative forcing caused by the life cycle GHG emissions at any specific time along the studied life-cycle (Levasseur et al., 2010a). The instantaneous impact is calculated according to equation (11) and shows changes over time in radiative forcing, which is not possible when using GWP.

$$\mathrm{GWI(t)_{inst}} = \sum_{i=0}^{i} g(t) \times DCF(t-i) \qquad \text{equation (11)}$$

  where, *g(t)* is the dynamic inventory (in this study the three main GHGs in kg) multiplied by the dynamic characterization factors for global warming *DCF (t)* (as presented in equation (10) in $W.m^{-2}.kg^{-1}$).

Table 29: Global warming potential (GWP) and dynamic characterization factor (DCF), respectively in traditional and dynamic LCA for the main three greenhouse gases (CO_2, CH_4 and N_2O) for three time horizons (20, 100 and 500 years)

	20 years			**100 years**			**500 years**		
	CO_2	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**
GWP (kg CO_2 eq.kg^{-1}) [a]	1	84	264	1	28	265	N/A	N/A	N/A
DCF (W. m^{-2}.kg^{-1}) [b]	2.47E-14	1.78E-12	7.14E-12	8.69E-14	2.39E-12	2.59E-11	2.86E-13	2.95E-12	4.38E-11

N/A: not available (IPCC (2013) does not consider 500-year GWP due to the uncertainty involved)
[a] IPCC (2013)
[b] CIRAIG (2016)

- The cumulative impact (GWI_{inst}) that is the sum of the instantaneous impacts from time zero to a specific time (Levasseur et al., 2010a). Basically, it is the total amount of additional radiative forcing caused by GHGs along the studied life cycle. The cumulative impact is calculated according to equation (12):

$$GWI(t)_{cum} = \sum_{i=0}^{i} GWI(t)_{inst} \qquad \text{Equation (12)}$$

- The relative impact (GWI_{rel}) that is the ratio of the life cycle cumulative impact over the cumulative impact of a 1 kg CO_2 pulse-emission. The relative impact transforms the dLCA result into the same units (kg CO_2 eq.) as the tLCA, while taking into account the timing of the emissions which cannot be done while using GWPs. The relative impact can be calculated according to equation (13):

$$GWI(t)_{rel} = \sum_i \sum_{j=0}^{t} [g(i)]_j \times [DCF_i]_{t-j} \qquad \text{Equation (13)}$$

where, *g* is the inventory result, DCF is the instantaneous dynamic characterization factor and *i* stands for every GHG present in the inventory. As explained in Levasseur et al. (2010a), equation 13 signifies that to calculate the impact of a given GHG *i* on global warming at a given time *t*, the total emission occurring at time *t* has to be multiplied by the DCF at time 0 (since this amount of GHG has just been released). Then the total emission occurring at time t-1 multiplied by the DCF at time 1 (since it has been released one time step ago) is added and so on, until the addition of the total emission occurring at time 0, multiplied by the DCF at time *t*. The result provides the increase in radiative forcing at time t caused by every GHG emission over the course of all the life cycle processes since the beginning of the life cycle.

2.2 Functional unit and system boundaries

Figure 37 presents the system boundaries considered in the present study. Both in the tLCA and dLCA, the system boundaries are the same and the functional unit (FU) considered is cork production of 1 hectare of cork oak forest assessed throughout its entire life cycle of 170 years (average life of cork oak trees in Portugal) excluding ‘falca’ cork type. Consequently, the GHG emissions for the management of 1 hectare of forest, the raw cork produced and the emissions from the manufacturing of the cork products using it as raw material and finally the end-of-life management of the different cork products are considered in the boundaries of the system.

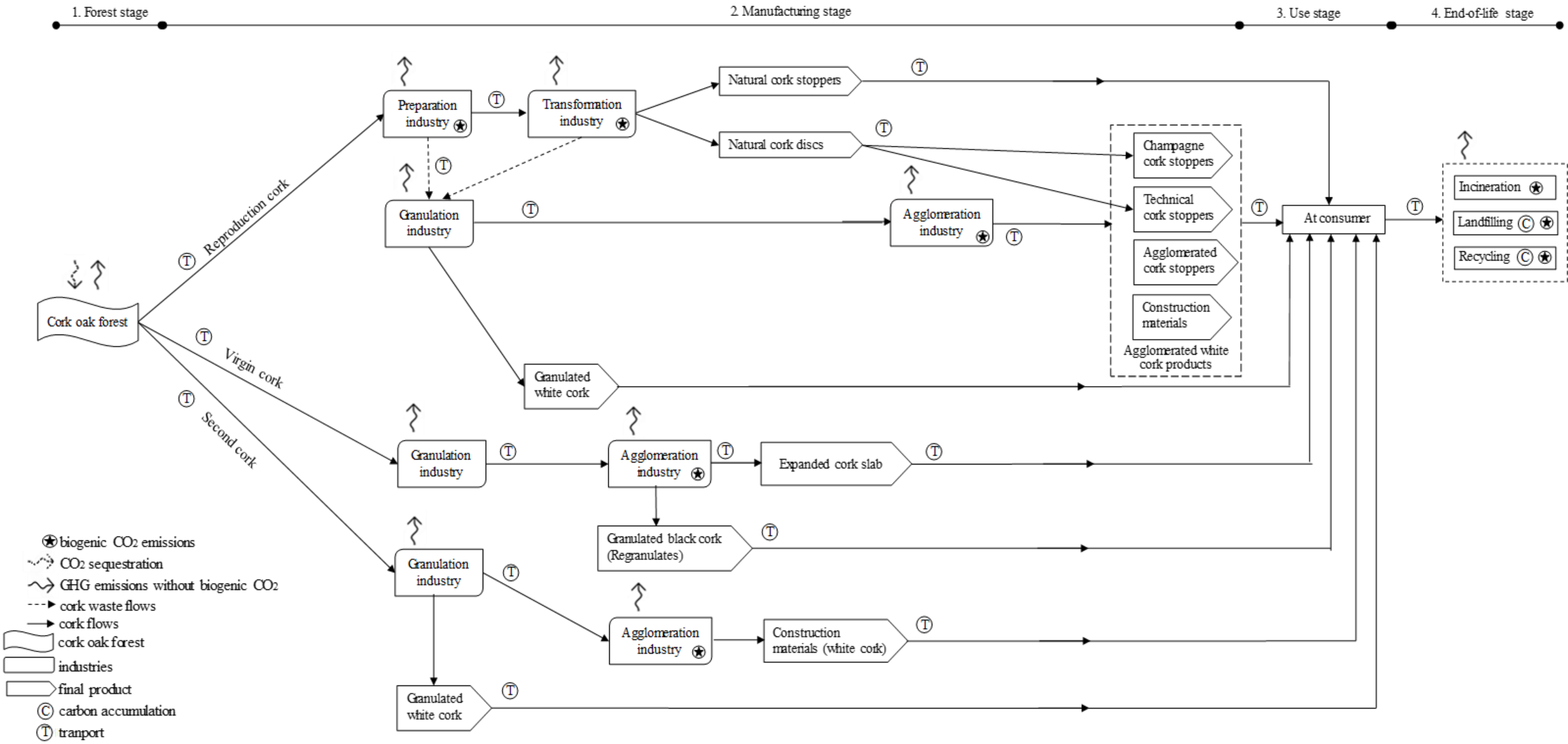

Figure 37: Boundaries of the system

Concerning the inclusion of biogenic carbon in the CF of the sector, both its sequestration at the forest stage (from the different tree components, namely cork, wood, roots and foliage) and its storage in the cork products during their use period and at the landfill facility is considered. Carbon sequestration in soil was excluded from the calculations due to lack of data regarding this aspect. It should be noted that the transport emissions were also considered for all the stages where transport of cork or auxiliary materials (e.g., resins) is needed.

2.2.1 Forest stage

In the forest stage all the activities performed for the establishment of the cork oak stand and for its management throughout its entire life cycle are included in the boundaries of the system under study. Two management approaches were considered: 50% plantation and 50% natural regeneration. When considering the plantation approach soil preparation (previous to trees plantation) was considered, which requires clearing of spontaneous vegetation and pit-opening. The plantation of the cork oak trees occurs together with a first fertilization operation. In the case of natural regeneration the stand preparation activities do not occur since it is a natural procedure. However, the following management activities (after plantation) are the same. Furthermore, in the case of natural regeneration the tree density is assumed to be similar to that of plantation. The number of the trees of the cork oak stand does not stay constant throughout the entire life cycle due to natural mortality that occurs in some trees and due to thinning activities occurring along the life cycle of the cork oak forest. These thinning activities are performed close to the year of the first debarking for the reduction of tree density and tree competition. Sanitary thinning occurs in order to remove dead trees from the stand. The operations of fertilization, removal of spontaneous vegetation, pruning and thinning are included in the forest stage since they are repeated various times along the life cycle of the cork oak forest (34, 56, 5 and 2 times, respectively) their frequency is also accounted for in the calculations. When the cork oak stand trees obtain the minimum trunk diameter of 17 cm measured over bark (between 20 and 35 years of age depending on the stand conditions), the extraction of cork occurs for the first time. This is a manual process that is repeated every 9 years along the life cycle. The extracted cork is transported from the cork forest to the designated cork industries.

2.2.2 Manufacturing stage

In the manufacturing stage, all the production processes for the main cork products are included. As seen in Figure 37, different cork types are used for the manufacturing of different cork products, depending on the quality of the cork used as raw material. In the same figure the stages along the cork sector where GHG emissions occur can be seen. The first and second cork extracted, called virgin and second cork respectively, are of low quality due to the cracks and irregularities on their exterior surface. These cork types are destined to the granulation industry (trituration of cork in granules) and then to the agglomeration industry. In the case of virgin cork, through the use of high temperatures the natural resins of cork are used as glue for the production of expanded cork slabs and granules. In the case of the second cork, at the agglomeration industry the cork granules are mixed with resins for the production of agglomerated cork products used in construction (e.g., for insulation and coverings).

The third and following extractions provide the reproduction cork. This cork type has the appropriate quality to be used for the production of natural cork stoppers and discs for which the manufacturing process is different than the aforementioned processes for the virgin and second cork types. In this case, cork is sent to the preparation industry where various processes occur (planks pile establishment, first stabilization, planks boiling, second stabilization and scalding), in order to remove organic compounds embedded in the pores and enable the cork to reach the ideal moisture content for processing (around 20%). After a manual selection, the prepared planks with the appropriate thickness (27 to 55 mm) are sent to the transformation industry where they are used for the production of natural cork stoppers. Their manufacturing includes various processes, namely slicing, punching, pre-drying, rectification/correction, aspiration, selection, washing, drying, deodorization, coloring, dusting, branding, printing, surface treatment and packaging. The prepared cork planks that are thinner, are sent to the transformation industry for the production of natural cork discs. Their manufacturing process is different than the process of the natural cork stoppers and includes trimming, punching, drying, sanding, selection and packaging. More details regarding the manufacturing processes of the aforementioned cork products can be found in literature (Demertzi et al., 2016a, 2015a; Rives et al., 2012b, 2011; Pereira, 2007).

2.2.3 Use stage

The use stage considers the transport of the final cork products to the distribution locations. Since there are no specific data, an average distance between the cork industries and the ten most populated Portuguese districts was considered. For the dLCA approach, the use stage was considered in order to account for the elapsed time between the manufacturing of the cork products and their end-of-life.

2.2.4 End-of-life stage

The final stage included in the boundaries of the system is the end-of-life stage. For all the cork products considered in this study, with the exception of the natural cork stoppers, two final destinations were considered: incineration at a municipal waste incineration facility with energy recovery for the production of electricity (avoiding the use of the country’s electricity mix) and landfilling at a sanitary landfill with landfill gas recovery for flaring. In the case of the natural cork stoppers, the two aforementioned final destinations as well as the option of recycling were considered. The used natural cork stoppers are recycled in order to be used for the production of agglomerated cork products used in the construction sector (e.g. insulation slabs and coverings) avoiding the use of raw cork for their production.

2.3 Inventory analysis

Table 30 presents the GHGs emission factors for the various stages considered in the system boundaries of the study. The emission factors were based on previous studies (Demertzi et al., 2016a, 2015a, b; Dias et al., 2014; Weidema et al., 2013; Rives et al., 2012b; PwC/Ecobilan, 2008) as well as the transport distances considered (Demertzi et al., 2016a, b, 2015a, b). For the use stage an average of 200 km was considered based on the distance between the industries and the most populated districts of Portugal. The cork distribution percentages along the cork sector derived from a study considering the evaluation of the entire cork sector’s CF (Demertzi et al., 2016c).

Table 30: Emission factors of the three main greenhouse gases for the processes considered for the calculation of the carbon footprint along the cork sector and their sources

Stage / material	Fossil emissions			Biogenic emissions		Reference unit
	kg CO_2	kg CH_4	kg N_2O	kg CO_2	kg CH_4	
Virgin cork [a]	28.60	0.07	0.03			per t of cork (extracted)
Second cork [a]	105.00	0.27	0.12			per t of cork (extracted)
Reproduction cork [a]	105.00	0.27	0.12			per t of cork (extracted)
Preparation industry [b]	207.00	1.20	0.01			per t of cork (prepared)
Transformation industry (natural cork stoppers) [b, c]	1,200.00	4.0	0.05			per t of natural cork stoppers
Transformation industry (natural cork discs) [d]	3,102.50	0.00	0.00			per t of natural cork discs
Granulation industry [e]	11.00	0.01	0.00			per t of cork (to be triturated)
Agglomeration industry (stoppers) [d]	4,364.80	0.00	0.00			per t not natural cork stoppers
Agglomeration industry (construction materials) [e]	607.50	1.55	0.03	150.94		per t of construction materials
Agglomeration industry (expanded cork slab) [f]	209.10	0.00	0.00	45.45		per t of expanded cork slab
Agglomeration industry (expanded cork granules) [f]	210.40	0.00	0.00	45.45		per t of expanded cork granules
Landfilling [g]	8.00	3.75	0.00	20.68.00	7.52	per t of cork (for landfilling)
Incineration [g]	-565.00	-1.00	0.08	2,068.00		per t of cork (for incineration)
Recycling [g]	-99.00	-0.41	-0.05	1,327.00		per t of cork (for recycling)
Transport [h]	0.139	0.00	0.00			per t*km (transported)

[a] Dias et al. (2014)
[b] Demertzi et al. (2016a)
[c] PwC/Ecobilan (2008)
[d] Rives et al. (2012b)
[e] Demertzi et al. (2015a)
[f] Demertzi et al. (2016b)
[g] Demertzi et al. (2015b)
[h] Weidema et al. (2013)

Table 31 presents the quantities of cork extracted per hectare during the 170 years of the forest's life cycle using the SUBER growth and yield simulation model (Faias et al., 2012; Paulo, 2011; Paulo and Tomé, 2010). On these years, the extracted cork continues to the granulation, agglomeration and transformation industries for the manufacturing of the cork products and after the use periods (2, 10 and 30 years for the agglomerated cork stoppers, the natural cork stoppers and the construction material, respectively) they end up to the final destinations. It should be noted that there is another cork type, called 'falca' that is the cork deriving from the tree branches during the pruning and thinning of the trees. This cork type is usually used for the manufacturing of products used in construction (e.g., expanded cork slab used for thermos-acoustic insulation). However, the 'falca' cork type is not included in the SUBER model outputs and consequently, this cork type was excluded from the system boundaries.

Table 31: Quantities of cork extracted (based on the results from the SUBER simulation)

Number of extraction	**Year of extraction**	**Quantity of cork extracted (t/ha)** [a]
1	35	0.441
2	44	0.668
3	53	1.215
4	62	1.457
5	71	1.641
6	80	1.702
7	89	1.664
8	98	1.807
9	107	1.903
10	116	1.971
11	125	1.733
12	134	1.660
13	143	1.258
14	152	1.159
15	161	1.093
16	170	0.810
	Total	22.181

[a] dry basis

When biogenic carbon is included in the calculations sequestration of CO_2 in the forest stage is treated as a negative emission since it reduces the amount of atmospheric CO_2, leading to a negative radiative forcing. The quantity of CO_2 sequestered during the growth of the cork oak forest was calculated by the SUBER model. The model simulates, for an annual time step, the tree diameter growth at a reference height of 1.3 m (Tomé et al., 2006). The model then uses this value for the determination of the tree biomass by the application of an allometric system of equations (Paulo and Tomé, 2010, 2006; Paulo et al., 2003). The system of equations considers the stem, branches, leaves, roots and cork components. The total biomass estimates result from the sum of the tree component biomass estimates, since the system of equations was simultaneously adjusted in order to guarantee additivity properties. The carbon content is then estimated considering a 50% fraction of the biomass dry weight. The dLCA approach considers the sequestered CO_2 per year (as calculated by SUBER), while tLCA considers the total CO_2 sequestered by the cork forest during the 170-years life cycle.

The carbon contained in the cork products that will remain stored during the use period of the products. Specifically, the use period for the cork products that are considered in the present study are: two years for the agglomerated cork stoppers, thirty years for the agglomerated cork construction materials (Dias and Arroja, 2014) and ten years for the natural cork stoppers (personal communication from the Portuguese Cork Association in 2015). The temporary stored carbon will be released at the end-of-life stage and this is also considered in the calculations. In the end-of-life stage, the biogenic carbon emissions were considered as well. More specifically, in the case of incineration all biogenic carbon contained in the cork products was considered to be released back into the atmosphere (after the use period or the cork products). In the case of landfilling, only a small part (2%) of the biogenic carbon contained in the products was considered to be released while the rest remained permanently stored in the landfill facility (Demertzi et al., 2015b; Micales and Skog, 1997). In the case of dLCA 20-year delay of the emissions was considered after the landfilling of the product. Finally, in the case of recycling (for natural cork stoppers) 30% of the carbon contained in the stoppers is considered to remain in the production loop while the rest is emitted during the recycling process and returns into the atmosphere. The biogenic carbon contained in the various cork products was calculated by multiplying the quantity of the cork products by the quantity of carbon contained (per dry basis) in them (Dias and Arroja, 2014) in order to obtain the biogenic CO_2 emissions after the use and end-of-life stages.

Finally, based on the percentage of the various cork products ending up in the different end-of-life disposal destinations the final biogenic carbon emissions and permanent carbon storage (in the case of landfilling) was calculated. In the case of dLCA the respective year when those emissions occur was considered, while for tLCA the emissions were considered to occur on two specific years (20 and 100 years). The percentages used for the distribution of the cork products to the various end-of-life destinations derived from the actual main final destinations of municipal solid waste (MSW) in Portugal. A 68% of the agglomerated cork products was considered to end-up in a landfill facility and the rest 32% to an incineration facility (Eurostat, 2013). For the natural cork stoppers apart from the incineration and landfill alternatives, the recycling alternative was considered as well. According to the recycling campaign in Portugal for 2013, there is a 3% of used natural cork stoppers sent to recycling (Green Cork, 2013). Thus, the mentioned end-of-life percentages in the case of the natural cork stoppers were recalculated, considering that 66% is sent to landfilling, 31% to incineration and 3% to recycling.

3. Results and discussion

3.1 Carbon footprint assessment excluding biogenic carbon sequestration and emissions

Figures 38, 39 and 40 (black line) present the obtained results for GWI_{inst}, GWI_{cum} and GWI_{rel} when excluding biogenic carbon sequestration and emissions from the calculation of the cork sector's CF (over a time horizon of 500 years).

In the case of GWI_{inst} (Figure 38) the GHG emissions start increasing around the 35th year when the manufacturing processes begin and continue up to year 170 when the last cork is extracted and sent to the transformation industry for the manufacturing of the last cork products. In the following years, the GHG emissions are decreasing since there is no more cork to be extracted and consequently there are no emissions from the manufacturing processes. During the following years there are only GHG emissions from the end-of-life treatment of the cork products. Furthermore, in the same graph for GWI_{inst} there are a lot of picks and lows regarding the GHG emissions, representing the years with and without cork products manufacturing. In the years when the manufacturing stage takes place for the production of cork materials made by the extracted raw cork material, an increase of the air emissions is observed due to the emission of GHGs. During the years when there are no manufacturing processes, the total emissions are lower since there are only emissions deriving from the end-of-life stage which are lower considering the recovery of energy for the production of electricity avoiding the use of the country's electricity mix.

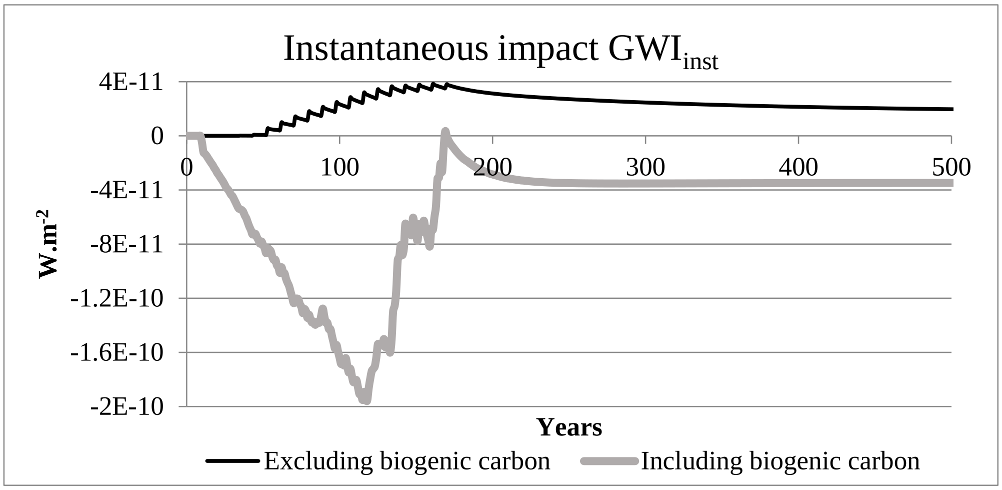

Figure 38: Instantaneous (GWI_{inst}) impact calculated using the dynamic life cycle assessment approach when excluding (black line) and including (grey line) biogenic carbon sequestration and emissions

Figure 39 presents the GWI_{cum}, which considers the sum of the instantaneous impact of all the previous years, shows a continuously increasing impact. This is due to the GHG emissions from the various stages involved in the production of the various cork products.

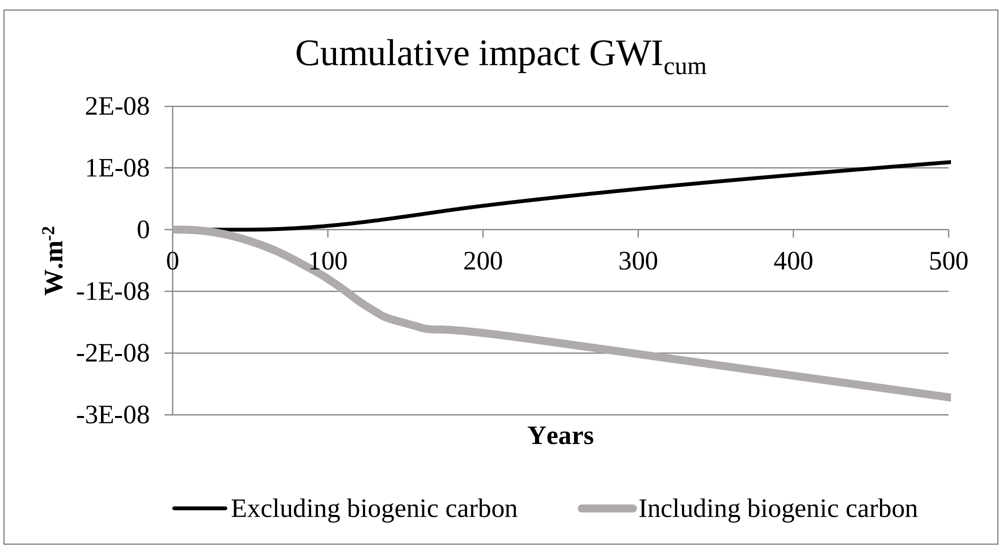

Figure 39: Instantaneous (GWI_{inst}) impact calculated using the dynamic life cycle assessment approach when excluding (black line) and including (grey line) biogenic carbon sequestration and emissions

In Figure 40 the CF of the cork sector, or the impact relative to a 1 kg CO_2 pulse emission at time zero as called in dLCA (GWI_{rel}), is presented. During the first years the environmental impact is zero and it increases throughout time due to the additional GHG emissions from the manufacturing process and the end-of-life disposal. Through the dLCA approach it is possible to obtain the specific CF of the sector along its entire life cycle.

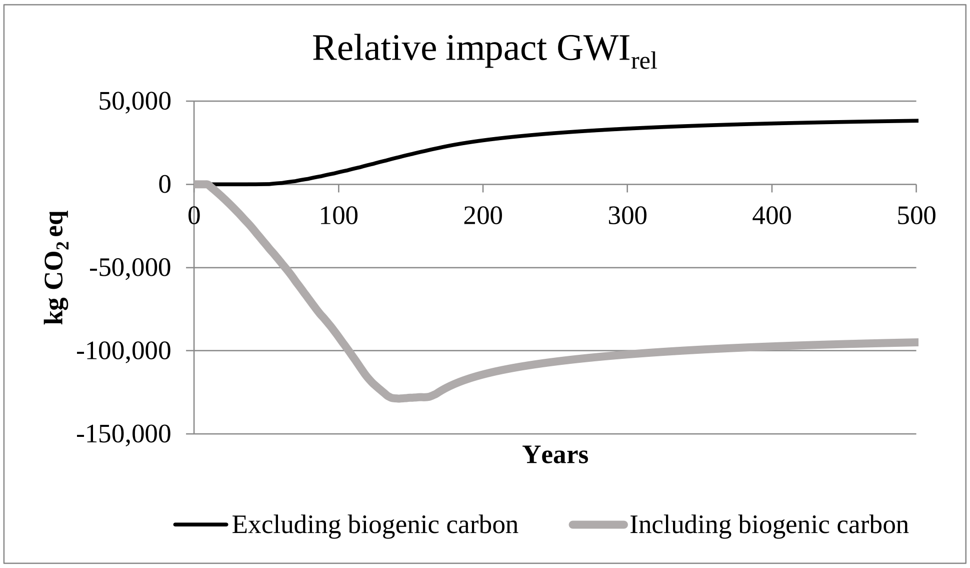

Figure 40: Relative impact (GWI_{rel}) calculated using the dynamic life cycle assessment approach when excluding (black line) and including (grey line) biogenic carbon sequestration and emissions

Table 32 presents the comparison between the CF results for the two LCA approaches (tLCA and dLCA) considering three time horizons (20, 100 and 500 years). The results of the two approaches are different for all three time horizons. When excluding biogenic carbon from the calculations, the CF obtained for the tLCA approach is higher than for the dLCA both for the 20 and 100-year time horizons. In the case of the 500-year time horizon, tLCA does not provide a CF since in the last IPCC report (IPCC, 2013) there are no GWPs provided for this time horizon due to the high uncertainty involved. The total CF of the sector, in the case of tLCA, even though it decreases when a greater time horizon is considered, it does not change significantly (54,000 kg CO_2 eq. for 20 years to 49,000 kg CO_2 eq. for 100 years). In the case of dLCA the difference noticed when different time horizons are considered is significant and an increasing tendency is noticed since in this case the emissions from all the previous years are summed as the time horizon increases (0 kg CO_2 eq. for 20 years, 7,235 kg CO_2 eq. for 100 years and 38,211 kg CO_2 eq. for 500 years).

Table 32: Comparison of the tLCA and dLCA results, with and without biogenic carbon accounting, for three time horizons (20, 100 and 500 years)

	Excluding *		**Including ***		
Time horizon	**tLCA**	**dLCA**	**tLCA**	**dLCA**	**Units**
20	54,000	0	-48,530	-8,027	kg CO_2
100	49,000	7,235	-53,530	-91,609	kg CO_2
500	N/A	38,211	N/A	-73,373	kg CO_2

**Biogenic carbon sequestration and emissions*
N/A: not available, (in the most recent report, IPCC (2013) does not consider 500-year GWP due to the uncertainty involved)

The CF when applying the tLCA approach decreases with time while with the dLCA approach the CF increases with time. This occurs because according to tLCA the GWP declines as the time horizon increases (except for CO_2 that remains the same) since the GHG is gradually removed from the atmosphere through natural removal mechanisms and its influence on the GHG effect declines. On the other hand, dLCA considers different DCF for each year of the life cycle and the CF of the three specific time horizons is the sum of the CF of all the previous years, resulting to a higher CF with the increase of the time horizon. Thus, it can be considered that dLCA is more realistic and advantageous, considering the possibility of providing the CF throughout the entire life cycle of the studied system, while in the case of tLCA the same information is provided for only two specific time horizons (20 and 100 years).

3.2 Carbon footprint assessment including biogenic carbon sequestration and emissions

Figures 38, 39 and 40 (grey line) present the obtained results for GWI_{inst}, GWI_{cum} and GWI_{rel} when including carbon sequestration and emissions in the calculations. These graphs are very different from the previous case when the biogenic carbon was excluded from the calculations. In the forest stage, where sequestration occurs, the emissions were represented with a negative value since carbon is removed from the atmosphere. In Figure 38 (GWI_{inst}) up to around year 120 of the cork oak forest growth, there is a greater carbon sequestration per year considering that there is a higher tree density (greater number of trees per hectare) resulting to a greater carbon sequestration. After year 120 of the forest, a decrease of the cork oak trees population is noticed resulting to a lower carbon sequestration per year during the final years of the forest.

When there is growth of a greater number of cork trees at the cork oak forest there is more carbon accumulation which then decreases due to the mortality of the trees. Then, there are only the biogenic emissions occurring after the end of the use period at the end-of-life stage when the cork products have reached their final destination (incineration, landfill or recycling) and released the stored carbon. Consequently, during the 100-year time horizon there are more cork trees resulting to a greater sequestration of biogenic carbon which then decreases since there are less trees. The main influence of CF presented in this graph derives from the sequestration of carbon in the forest stage and thus when the tree density decreases and sequesters less carbon, the emissions represented in the graph start increasing. The influence from the biogenic carbon emissions during the end-of-life stage is lower since the quantity of cork products (where carbon is contained) is much less than the forest biomass (where cork is contained in the forest stage).

Concerning GWI_{cum} (Figure 39), the trend line is decreasing (on the contrary of the case excluding biogenic carbon sequestration) due to the addition of all the previous years of the instantaneous impact. This means that the sequestration of carbon is greater that the GHG emissions from the manufacturing processes.

The same decrease of the trend line occurs in the graph for the GWI_{rel} (Figure 40). In this graph the lowest value of CF is reached around the 170th year of the life cycle which is when the cork oak forest accumulates the greatest amount of biogenic carbon. After that period, the cork oak forest reaches the end of its cycle and stops accumulating carbon from the atmosphere. Furthermore, there is an amount of biogenic carbon (98%) contained in the cork products which is stored permanently at the landfill facility when those cork products are considered to be landfilled at the end of their use period.

Table 32 shows the CF results of the two approaches for three time horizons (20, 100 and 500 years) when considering the biogenic carbon in the calculations. The CF results of the two approaches are different. However, in both cases the CF is negative which means that the cork sector is a carbon sink since more carbon is sequestered than emitted along the entire life cycle.

In the case of tLCA, the CF does not change significantly when changing the chosen time horizon (-62,570 kg CO_2 eq. for 20 years and -65,570 kg CO_2 eq. for 100 years). In the case of dLCA the CF changes significantly depending on the time horizon (-8,027 kg CO_2 eq. for 20 years, -91,609 kg CO_2 eq. for 100 years and -94,971 CO_2 eq. for 500 years).

For the 20-year time horizon, tLCA presents greater CF than dLCA, while the opposite occurs for the 100-year time horizon. In the case of tLCA, the results only represent a specific moment (20 or 100 years) considering all the emissions during the life cycle of the cork oak forest and cork products. In dLCA there are variations of the CF depending on the time horizon considered since it corresponds to different year of the life cycle considering different processes performed.

4. Conclusions

In the present study the CF of the cork sector obtained from the two studied LCA approaches, tLCA and dLCA, was different and showed the influence of time horizon preferences. For the 20-year time horizon, tLCA presents greater CF than dLCA, while the opposite occurs for the 100-year time horizon. Moreover, it was concluded that the inclusion or exclusion of biogenic carbon sequestration and emissions is very influential for the CF. Cork sector is considered a carbon source when biogenic carbon is excluded from the calculations and a carbon sink when biogenic carbon is included in the calculations since more carbon is sequestered than emitted along the sector.

However, both when including and excluding biogenic carbon from the calculation of CF, the bigger the time horizon the smaller the difference between the CF results of the two LCA approaches. When excluding biogenic carbon sequestration and emissions, tLCA presented greater CF for the cork sector and dLCA presented greater CF when including biogenic carbon in the calculations mainly due to the sequestration of biogenic carbon at the forest stage. Even though the use of dLCA for the calculation of CF is more realistic and it allows a more detailed analysis of the GHG emissions along the entire life cycle compared to the tLCA approach, it is more time-consuming and complex to apply. The complexity of this approach derives from the need to distribute along the life cycle the various processes and their emissions resulting to a great complexity when the life cycle is long and considers various products like in the case of the cork sector.

Thus, decision-makers should consider the differences between the two LCA approaches and also the importance of time horizon when assessing the CF of a product. In order to choose the most appropriate LCA approach and time horizon, the decision-makers should consider: (1) the lifetime of the GHG studied (if long-living, then greater time horizon should be considered), (2) the life cycle of the system under study (e.g., the life cycle of the cork oak tree is more than 100 years so this time horizon could result to biased conclusions) and (3) the involved difficulties in each approach considering that dLCA is more time consuming and more complex in its application. Consequently, the choice of approach and time horizon can be made depending on various criteria in order to obtain more realistic and correct results/conclusions.

Acknowledgements

This study was supported by the project ‘Cork carbon footprint: from trees to products’ (PTDC/AGR-FOR/4360/2012) funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal). Thanks are due, for the financial support to CESAM (UID/AMB/50017), to FCT/MEC through national funds, and the co-funding by the FEDER, within the PT2020 Partnership Agreement and Compete 2020.

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Chapter 5

General conclusions and future perspectives

5.1 General conclusions

Having a focus on the cork sector, the present thesis aimed the enrichment of the general knowledge on this sector through the use of LCA. The outcome of the various scientific papers shows the relevance of this sector from an environmental point of view. The obtained results point to specific stages and products along the entire sector and can be used in the future decision-making in order to improve the CF of the cork sector. The general conclusions that can be drawn from the present thesis are as follows:

- LCA was found to be an appropriate and useful technique for the evaluation of the environmental impacts deriving from the most representative cork products as well as the entire cork sector. Through the application of LCA it was possible to evaluate the life cycle of each product in order to identify the hotspots in terms of stages and processes. For the four representative cork products studied, it was found that the manufacturing stage was the stage hotspot (different process hotspot for each cork product). Furthermore, in the case of natural cork stoppers and expanded cork slabs and granules together with the manufacturing stage, the forest stage had great contribution to some of the categories as well. This identification enabled the suggestion of future improvement actions, such as decrease of electricity consumption during the process of boiling for the case of natural cork stoppers, decrease of natural gas and electricity consumption during HDF production in the case of cork floating floor and change of forest management activities frequency in the case of expanded cork slab and granules. The decrease of the products environmental impacts can result to the improvement of the entire cork sector’s CF.
- Considering that there is not a great number of LCA studies on cork products, this thesis adds an important amount of primary data from the cork industry. Additionally, the

detailed description of the different processes along the product life cycles also enriches the knowledge of the sector and enables the better understanding of the reader. Consequently, through this thesis, valuable information can be collected and used for future studies in order to compare the obtained results regarding the hotspot stages and processes of the life cycle of the different cork products.

- Another innovative and important part of the present thesis is the consideration of the biogenic carbon sequestration and emissions in the CF calculation. Instead of considering those emissions neutral, as commonly occurs in most LCA cork studies found in literature, here they were studied separately. By considering the use period of the various cork products and the different end-of-life destinations as well, the carbon storage was calculated (both temporary and permanent in the case of landfilling) and it was considered in the calculation of the CF. The comparison of different biogenic carbon accounting methods, showed that the choice of method as well as the use period influences the results but not significantly. The greatest influence resulted from the consideration of biogenic carbon sequestration at the forest stage from the various components of the cork tree (roots, foliage, cork and wood). Additionally, this influence on the CF results shows the importance of establishing common guidelines for the environmental evaluation of cork products. In this way, the comparison of different cork products and studies would be easier and more accurate.
- Section 3.5, focused on the end-of-life of cork products and specifically of natural cork stoppers. Currently, there are many campaigns running globally, aiming the recycling of used natural cork stoppers for the production of agglomerated cork products used in construction. Though this published study it was possible to evaluate the CF of different end-of-life destinations, such as incineration, landfilling and recycling. For the different alternatives considered (incineration, landfilling and recycling), different scenarios were also studied including the use of the energy produced (in the case of incineration and landfilling) for the production of electricity. The choice of different end-of-life alternatives showed that the inclusion of biogenic carbon emissions storage/ delay is one of the aspects significantly influencing the CF results since there is a great decrease of the CF. Specifically, this is more noticeable in the case of landfilling since there is a

great amount of biogenic carbon (98%) permanently stored in the landfills. This aspect is also identified in section 3.3 and 3.4 where the decrease of the CF results was greater in the case of landfilling than in the case of incineration and recycling. This component of the thesis adds new information for cork products since until now, the end-of-life of cork was treated as wood and additionally, only one end-of-life destination was considered in the LCA studies, namely landfilling. Consequently, the obtained results of the thesis can be used for the enrichment of this aspects' knowledge.

- Another important outcome of the present thesis is the development of a CF simulation model for the entire cork sector. Its development facilitates both the industrial as well as the scientific community that is interested in the cork sector. Through the use of this model, one can introduce specific data of a cork system (cork type, cork quantity, distances, etc.) and obtain both the mass quantity of each cork product and its CF as well. The application of this model can return to the user an important insight of the hotspots of the sector and can be used for the decision-making in order to improve the environmental impact of the entire sector. The model's capability of accepting different characteristics for the system, increases its potential for wider use in different countries with different conditions. The application of the developed model in the case of Portugal considering a cork production approach showed that the most influential product of the cork sector is the champagne cork stopper. More specifically, it was found that the agglomeration stage has the greatest influence on the CF of the sector mainly due to the production of resins used for the agglomeration of the stopper's body. The consideration and improvement of only this aspect (10% decrease of the CF impact of the agglomeration stage) in the future could be useful for the decrease of the sector's CF by 6%. Additionally, by improving various hotspots of the cork sector (decrease of agglomeration and transformation stages CF by 10%, use of newer trucks (EURO 6) and the change of the end-of-life destination percentages) a 10% decrease of the cork sector's CF can be achieved (excluding the biogenic emissions and sequestration).
- Through the inclusion and exclusion of biogenic carbon sequestration and emissions in the CF calculations, it was found that the results change significantly. The exclusion of biogenic carbon from the calculations identifies the cork sector as a carbon source. On

the other hand, the inclusion of biogenic carbon in the calculation of the sector's CF identifies the cork sector as a carbon sink (carbon sequestration greater than GHGs emission). More specifically, for the production of raw cork in Portugal (145,000 t of raw cork) it was found that when excluding biogenic CO_2 from the CF calculation the result would be 172,844 t CO_2 eq. and when including biogenic CO_2 sequestration and emissions in the CF calculation the result would be -956,042 t CO_2 eq. The greatest amount of sequestered carbon in the forest stage is stored in the wood, roots and foliage of the cork tree (79% of the total carbon sequestered), while raw cork sequesters a smaller amount of biogenic carbon (21% of the total carbon sequestered).

- The consideration of a more recent LCA approach also consists an important innovation of the present thesis. The application of dLCA has never been attempted for the cork sector and thus, the outcome of this part of the thesis can provide new information for the evaluation of the sector. The dLCA approach has an important advantage against the tLCA approach since it has a one-year step evaluation of the GHG emissions and thus, it is more realistic since the GHG emissions do not occur on specific time periods as it is considered in tLCA. By applying dLCA and tLCA and comparing the obtained results a new aspect, that of the time horizon considered, is introduced in LCA studies of cork products. Additionally, the inclusion and exclusion of biogenic carbon sequestration and emissions also influences the CF results. When excluding biogenic carbon from the CF calculations for the life cycle of 1 hectare of cork oak forest, the total CF of the sector in the case of tLCA changes from 54,000 kg CO_2 eq. for 20 years to 49,000 kg CO_2 eq. for 100 years, while for dLCA changes from 0 kg CO_2 eq. for 20 years, to 7,235 kg CO_2 eq. for 100 years and 38,211 kg CO_2 eq. for 500 years. When including biogenic carbon in the calculations the results are significantly different for both approaches since for tLCA the CF is -62,570 kg CO_2 eq. for 20 years and -65,570 kg CO_2 eq. for 100 years and for dLCA the CF is -8,027 kg CO_2 eq. for 20 years, -91,609 kg CO_2 eq. for 100 years and -94,971 CO_2 eq. for 500 years. Those results show the influence both of the chosen LCA approach as well as the chosen time horizon on the obtained CF results. Nevertheless, it is important to mention that the application of dLCA is more time consuming since all the different processes included in each stage of the sector's life cycle have to be distributed in each specific year of the life cycle. On the other hand, when applying tLCA, the inventory consists of the same processes but it is not necessary to distribute them along the entire life cycle.

5.2 Future perspectives

Even though the present thesis attempted to consider topics not widely covered in literature, some suggestions for future studies can be made. As presented in the published scientific papers, some aspects can be further studied.

- Considering the LCA studies of cork products found in literature, it is important to enrich even more the cork products included. For example, the consideration of agglomerated cork stoppers, such as champagne cork stoppers, can be further studied in the future since currently, only one study from Spain covers this cork product. The evaluation of more products can result to more primary data. Those data could then be used for the consideration of average values for the cork industry in order to decrease the uncertainty and increase even more the quality of the results, since a wider range of technologies should be included.
- Regarding the end-of-life aspect of cork products, it is important to further study the influential characteristics. From the sensitivity analysis performed while studying this aspect, it was found that one of the most influential characteristics is the decomposition rate considered for the cork products. By keeping that in mind, as well as the rest of the mentioned characteristics, future studies in different countries with different conditions can increase the knowledge for this specific part of the cork products life cycle.
- Future studies could focus on the identified hotspots of the cork sector. For example, the agglomeration industry that was found to be the most influential for the entire sector could be considered and studied in detail in order to find and suggest future improvements. Additionally, since the present thesis has suggested some future actions that could be attempted in order to decrease the CF of the specific industry, future studies could apply them in order to quantify the exact decrease of CF and in order to verify their applicability on the sector.

- The model developed in the present thesis can be a useful tool to further study the cork sector. Since the input data can be introduced by the user, this new simulation model can be applied to other countries with strong cork industry, such as Spain, in order to obtain even more quantitative data. Additionally, the results of the different countries could be compared in order to identify the differences between the hotspots of the stages and processes considered.
- Regarding the considerations of the simulation model developed in this thesis, the raw cork and cork products imported from other countries could be included as well as the export of raw cork and final cork products to various countries (since the present thesis followed a cork production approach).
- Based on the outcome of the present thesis, the consideration of dLCA for the evaluation of the cork sector can also be important for future studies. Since this approach specifically for the cork sector was applied in this thesis for the first time, it could be attempted in the future on study cases for different cork products as well as for the entire cork sector of different countries. The obtained results could point out the differences or similarities between the results of the present thesis and the future studies in order to better understand the importance of the applied LCA approach in the CF calculation.

Supplementary material (CCFM as seen from the user before the introduction of the needed data)

Cork Carbon Footprint Model (CCFM)

CCFM is a model developed for the calculation of the cork sector carbon footprint by considering the main stages, processes and products of the sector.

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The development of this model was supported by the project 'Cork carbon footprint: from trees to products' (PTDC/AGR-FOR/4360/2012) funded by FEDER (European Regional Development Fund) through COMPETE (Operational Program Thematic Factors of Competitiveness) (FCOMP-01-0124-FEDER027982) and by FCT (Science and Technology Foundation – Portugal).

For the user:

The user is able to insert values in specific cells (Input tab) in order to obtain the cork distribution throughout the sector and also its total carbon footprint depending on the chosen cork type.

The user can chose the cork type used as raw material and introduce the quantity and its transport distance. In this way, the present model allows its use for different spatial and temporal scales.

Information needed:

The user should introduce the quantity of each cork type(s) that will be used and the transport distance of the cork along the various stages (Input tab). Additionally, the user can choose both the end-of-life destination and percentage of the cork product ending-up to the chosen final destination (Input tab).

NOTICE: If the user does not want to include transport in the calculation **MUST** introduce **0 (zero)** in the indicated cells.
For the emission factors, the user can use the default values or change them.

The user should insert the data asked in this tab:

Note:

System 1 (virgin & 'falca' cork used for black agglomerated cork products)
System 2 (second & 'falca' cork used for white agglomerated cork products)
System 3 (reproduction cork used for natural cork stoppers/discs and white agglomerated cork products)

Introduce one or more cork type quantity in tons:

Virgin cork quantity		t			
Second cork quantity		t			
Reproduction cork quantity		t	*Percentage of falca destined to System 1		%
'Falca' cork quantity *		t	*Percentage of falca destined to System 2		%
Total	0	t	(MUST add up to 100)	**ERROR**	

Introduce transport distance in kilometers for System 1:

From the cork oak forest to the granulation unit		km
From the granulation unit to the agglomeration unit		km
From the agglomeration unit to the distribution location		km

Introduce transport distance in kilometers for System 2:

From the cork oak forest to the granulation unit		km
From the granulation unit to the agglomeration unit		km
From the granulation unit to the distribution location		km
From the agglomeration unit to the distribution location		km

Introduce transport distance in kilometers for System 3:

From the cork oak forest to the preparation unit		km
From the preparation unit to the tranformation unit		km
From the preparation unit to the granulation unit		km
From the transformation unit to the granulation unit		km
From the transformation unit to the agglomeration unit		km
From the granulation unit to the agglomeration unit		km
From the transformation unit to the distribution location		km
From the granulation unit to the distribution location		km
From the agglomeration unit to the distribution location		km

Introduce the end-of-life destination (in percentage) for the natural cork stoppers:

Incineration		%	Choose the use of energy recovered from incineration:	To subsitute electricity produced by natural gas	NO
Landfilling with landfill gas recovery for flaring		%	(one cell must be YES and the others NO):	To subsitute electricity produced by hard coal	NO
Recycling		%	**OK**	To subsitute electricity mix	YES
(MUST add up to 100) **ERROR**					

Introduce the distance to the final destination unit (in kilometers) for the used natural cork stoppers:

From user to incineration facility		km
From user to landfill facility		km
From user to recycling unit		km

Introduce the end-of-life destination (in percentage) for the agglomerated black cork products:

Incineration		%	Choose the use of energy recovered from incineration:	To subsitute electricity produced by natural gas	NO
Landfilling with landfill gas recovery for flaring		%	(one cell must be YES and the others NO):	To subsitute electricity produced by hard coal	NO
(MUST add up to 100) **ERROR**			**OK**	To subsitute electricity mix	YES

Introduce the distance to the final destination unit (in kilometers) for the the agglomerated black cork products:

From user to incineration facility		km
From user to landfill facility		km

Emission factors used for the calculatin of the carbon footprint

Stage / material	**Quantity**	**Unit**
Reproduction cork	148.0	kg CO_2 eq. / ton of cork (extracted)
Virgin cork	40.0	kg CO_2 eq. / ton of cork (extracted)
Second	148.0	kg CO_2 eq. / ton of cork (extracted)
'Falca'	14.8	kg CO_2 eq. / ton of cork (extracted)
Preparation industry	241.0	kg CO_2 eq. / ton of cork (to be prepared)
Transformation industry (stoppers)	380.0	kg CO_2 eq. / ton of cork (to be transformed)
Natural cork stoppers	1330.0	kg CO_2 eq. / ton of cork (final natural cork stoppers)
Transformation industry (discs)	797.8	kg CO_2 eq. / ton of cork (to be transformed)
Natural cork discs	3102.5	kg CO_2 eq. / ton of cork (final natural cork discs)
Agglomeration industry (white cork) (System 2)	594.9	kg CO_2 eq. / ton of cork (to be agglomerated)
Agglomeration industry (white cork) (System 3)	2971.9	kg CO_2 eq. / ton of cork (to be agglomeration)
Champagne cork stoppers	4364.8	kg CO_2 eq. / ton of cork (final champagne cork stoppers)
Technical cork stoppers	4364.8	kg CO_2 eq. / ton of cork (final technical cork stoppers)
Agglomerated cork stoppers	4364.8	kg CO_2 eq. / ton of cork (final agglomerated cork stoppers)
Construction materials (white cork)	661.0	kg CO_2 eq. / ton of cork (final material)
Agglomeration industry (black cork)	188.5	kg CO_2 eq. / ton of cork (to be agglomeration)
Construction materials (black cork)	209.1	kg CO_2 eq. / ton of cork (final material)
Black cork regranulates	210.4	kg CO_2 eq. / ton of cork (triturated)
Granulation industry (systems 1 & 2)	7.5	kg CO_2 eq. / ton of cork (to be triturated)
Granulation industry (system 3)	7.5	kg CO_2 eq. / ton of cork (to be triturated)
Granulated white cork	11.5	kg CO_2 eq. / ton of cork (triturated)
Landfilling	114.0	kg CO_2 eq. / ton of cork (for landfill)
Incineration (impact)	65.6	kg CO_2 eq. / ton of cork (for incineration)
Incineration (three cases depending on the input)		kg CO_2 eq. / ton of cork (for incineration)
Incineration (avoided when considering natural gas)	-614.0	kg CO_2 eq. / ton of cork (for incineration)
Incineration (avoided when considering hard coal)	-1115.0	kg CO_2 eq. / ton of cork (for incineration)
Incineration (avoided when considering electricty mix)	-572.0	kg CO_2 eq. / ton of cork (for incineration)
Recycling (for natural cork stoppers)	-124.0	kg CO_2 eq. / ton of cork (for recycling)
Transport	0.139	kg CO_2 /ton*km (transported)

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Distribution of the cork (in percentage) in the entire cork sector for the production of the most representative cork products

SYSTEM 1
VIRGIN, & 'FALCA' CORK

Stage	Quantity	Unit
Cork oak forest	100	%
Granulation industry	100	%
Cork dust	35	%
Agglomeration industry (black cork)	65	%
Construction materials	44	%
Regranulates	15	%
Cork dust	7	%
Balance	100	%

SYSTEM 2
SECOND & 'FALCA' CORK

Stage	Quantity	Unit
Cork oak forest	100	%
Granulation industry	100	%
Granulated white cork	5	%
Cork dust	35	%
Agglomeration industry (white cork)	60	%
Construction materials	54	%
Cork dust	6	%
Balance	100	%

SYSTEM 3
REPRODUCTION CORK

Stage	Quantity	Unit
Cork oak forest	100	%
Preparation industry	100	%
Good quality planks	70	%
Thick palnks	35	%
Thin planks	35	%
Transformation industry (natural cork stoppers)	35	%
Natural cork stoppers	10	%
Residues (from natural cork stoppers)	23	%
Cork dust (from natural cork stoppers)	2	%
Transformation industry (natural cork discs)	35	%
Natural cork discs	9	%
Residues (from natural cork discs)	24	%
Cork dust (from natural cork discs)	2	%
Inferior quality planks	30	%
Granulation industry	77	%
Granulated white cork	6	%
Cork dust	27	%
Agglomeration industry	44	%
Champagne cork stoppers	14	%
Technical cork stoppers	8	%
Agglomerated cork stoppers	6	%
Construction materials	12	%
Cork dust	4	%
Balance	100	%

Mass distribution of the cork types along the cork sector based on the quantities introduced by the user

SYSTEM 1
VIRGIN, & 'FALCA' CORK

Stage	Quantity	Unit
Cork oak forest	0	t
Granulation industry	0	t
Cork dust	0	t
Agglomeration industry (black cork)	0	t
Expanded cork slab	0	t
Granulated black cork (Regranulates)	0	t
Cork dust	0	t
Balance	0	t

SYSTEM 2
SECOND & 'FALCA' CORK

Stage	Quantity	Unit
Cork oak forest	0	t
Granulation industry	0	t
Granulated white cork	0	t
Cork dust	0	t
Agglomeration industry (white cork)	0	t
Construction materials	0	t
Cork dust	0	t
Balance	0	t

SYSTEM 3
REPRODUCTION CORK

Stage	Quantity	Unit
Cork oak forest	0	t
Preparation industry	0	t
Good quality planks	0	t
Thick palnks	0	t
Thin planks	0	t
Transformation industry (natural cork stoppers)	0	t
Natural cork stoppers	0	t
Residues (from natural cork stoppers)	0	t
Cork dust (from natural cork stoppers)	0	t
Transformation industry (natural cork discs)	0	t
Natural cork discs	0	t
Residues (from natural cork discs)	0	t
Cork dust (from natural cork discs)	0	t
Inferior quality planks	0	t
Granulation industry	0	t
Granulated white cork	0	t
Cork dust	0	t
Agglomeration industry	0	t
Champagne cork stoppers	0	t
Technical cork stoppers	0	t
Agglomerated cork stoppers	0	t
Construction materials	0	t
Cork dust	0	t
Balance	0	t

Carbon footprint (CF) of the most representative products of the cork sector and the various cork industries

SYSTEM 1
VIRGIN, & 'FALCA' CORK

Stage	Quantity			Unit
	From processes	From transport	Total	
Cork oak forest	0	0	0	t CO_2 eq.
Granulation industry	0	0	0	t CO_2 eq.
Agglomeration industry (black cork)	0	0	0	t CO_2 eq.
Expanded cork slab	0	0	0	t CO_2 eq.
Granulated black cork (Regranulates)	0	0	0	t CO_2 eq.
To the user	0	0	0	t CO_2 eq.
From the agglomeration industry	0	0	0	t CO_2 eq.
End-of-life (black cork)	0	0	0	t CO_2 eq.
Incineration (impact)	0	0	0	t CO_2 eq.
Incineration (avoided burdens)	0	0	0	t CO_2 eq.
Incineration (total)	0	0	0	t CO_2 eq.
Landfilling	0	0	0	t CO_2 eq.
Total carbon footprint	0	0	0	t CO_2 eq.

SYSTEM 2
SECOND & 'FALCA' CORK

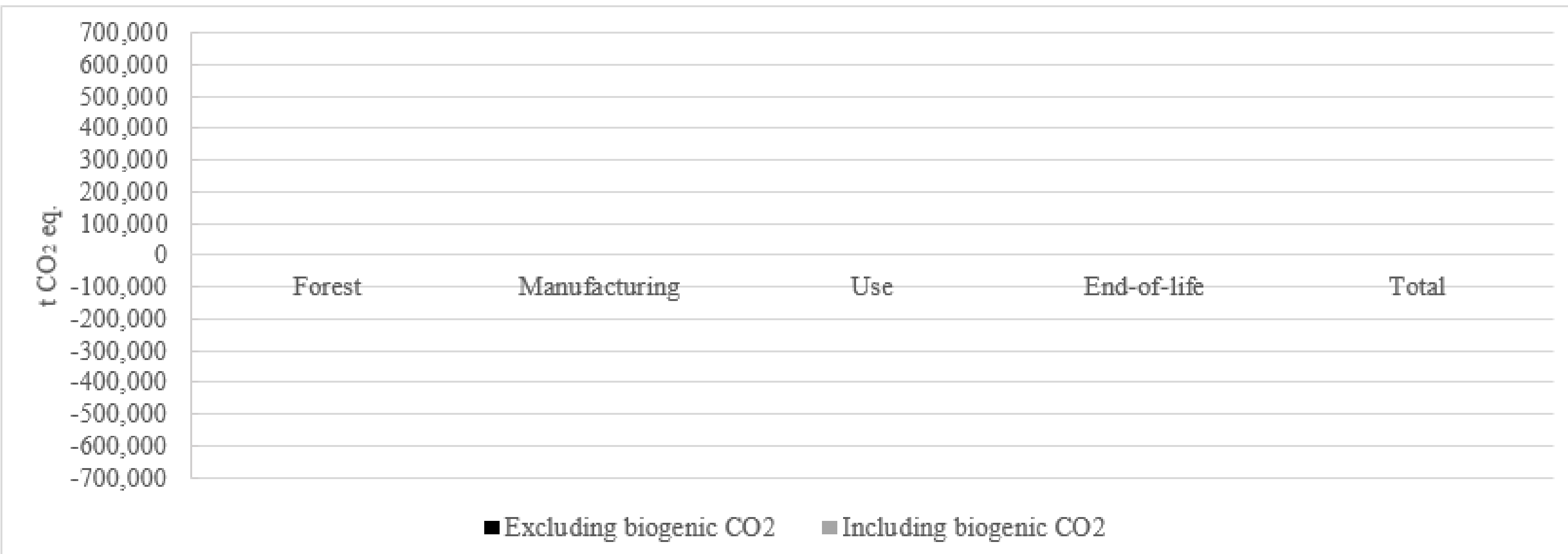
Stage	Quantity			Unit
	From processes	From transport	Total	
Cork oak forest	0	0	0	t CO_2 eq.
Granulation industry	0	0	0	t CO_2 eq.
Granulated white cork	0	0	0	t CO_2 eq.
Agglomeration industry (white cork)	0	0	0	t CO_2 eq.
Construction materials	0	0	0	t CO_2 eq.
To the user	0	0	0	t CO_2 eq.
From the granulation industry	0	0	0	t CO_2 eq.
From the agglomeration industry	0	0	0	t CO_2 eq.
End-of-life (white cork)	0	0	0	t CO_2 eq.
Incineration (impact)	0	0	0	t CO_2 eq.
Incineration (avoided burdens)	0	0	0	t CO_2 eq.
Incineration (total)	0	0	0	t CO_2 eq.
Landfilling	0	0	0	t CO_2 eq.
Total carbon footprint	0	0	0	t CO_2 eq.

SYSTEM 3
REPRODUCTION CORK

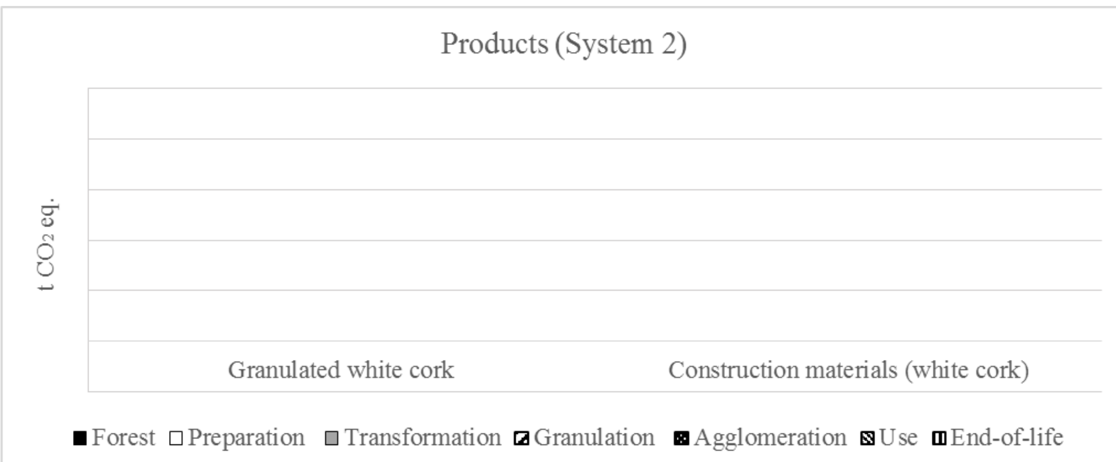
Stage	Quantity			Unit
	From processes	From transport	Total	
Cork oak forest	0	0	0	t CO_2 eq.
Preparation industry	0	0	0	t CO_2 eq.
Transformation industry (natural cork stoppers)	0	0	0	t CO_2 eq.
Natural cork stoppers	0	0	0	t CO_2 eq.
Transformation industry (natural cork discs)	0	0	0	t CO_2 eq.
Natural cork discs	0	0	0	t CO_2 eq.
Granulation industry	0	0	0	t CO_2 eq.
Granulated white cork	0	0	0	t CO_2 eq.
Agglomeration industry	0	0	0	t CO_2 eq.
Champagne cork stoppers	0	0	0	t CO_2 eq.
Technical cork stoppers	0	0	0	t CO_2 eq.
Agglomerated cork stoppers	0	0	0	t CO_2 eq.
Construction materials	0	0	0	t CO_2 eq.
To the user	0	0	0	t CO_2 eq.
From the transformation industry	0	0	0	t CO_2 eq.
From the granulation industry	0	0	0	t CO_2 eq.
From the agglomeration industry	0	0	0	t CO_2 eq.
End-of-life (agglomerated products)	0	0	0	t CO_2 eq.
Incineration (impact)	0	0	0	t CO_2 eq.
Incineration (avoided burdens)	0	0	0	t CO_2 eq.
Incineration (total)	0	0	0	t CO_2 eq.
Landfilling	0	0	0	t CO_2 eq.
End-of-life (natural cork stoppers)	0	0	0	t CO_2 eq.
Incineration (impact)	0	0	0	t CO_2 eq.
Incineration (avoided burdens)	0	0	0	t CO_2 eq.
Incineration (total)	0	0	0	t CO_2 eq.
Landfilling	0	0	0	t CO_2 eq.
Recycling	0	0	0	t CO_2 eq.
Total carbon footprint	0	0	0	t CO_2 eq.

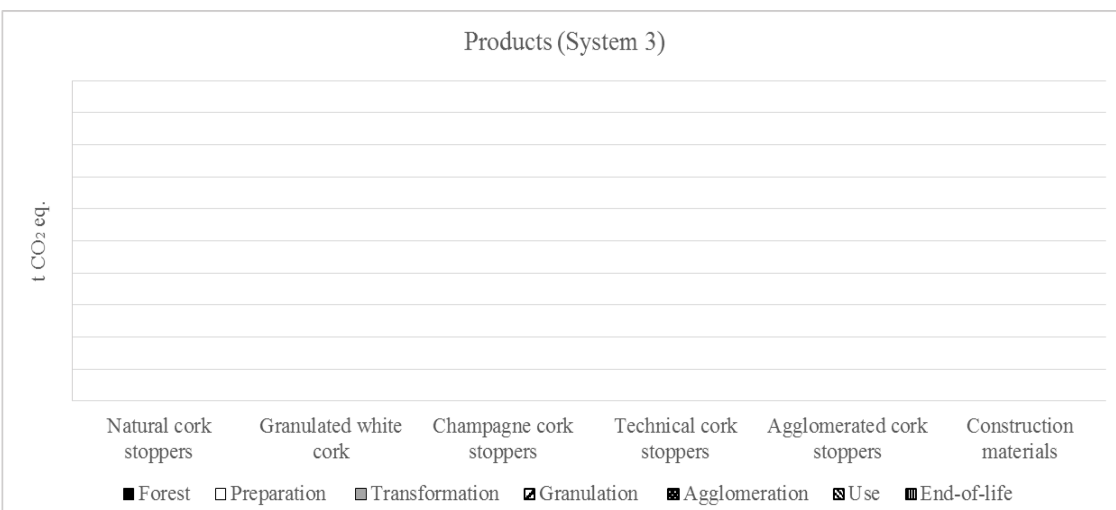
Comparison of the results when accounting for the biogenic carbon emissions

Stages	Excluding biogenic CO_2	Including biogenic CO_2	Units
Forest	0	0	t CO_2 eq.
Manufacturing	0	0	t CO_2 eq.
Use	0	0	t CO_2 eq.
End-of-life	0	0	t CO_2 eq.
Total	**0**	**0**	t CO_2 eq.



Carbon footprint of the most representative products of the cork sector and the influence of the various cork industries





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