UNIVERSIDADE DE LISBOA

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Roadmap for sustainable forest supply chains – A life cycle assessment approach

ANDREIA MARIA RODRIGUES DOS SANTOS

Supervisor: Doctor Ana Isabel Cerqueira de Sousa Gouveia Carvalho

Co-Supervisor: Doctor Ana Paula Ferreira Dias Barbosa Póvoa

Thesis approved in public session to obtain the PhD Degree in

Engineering and Management

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Roadmap for sustainable forest supply chains – A life cycle assessment approach

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Abstract

Sustainable supply chain management (SSCM) has gained increasing attention from both practitioners and scholars as today a company's image is not only related to the environmental and social impacts of its operations, but also to the environmental and social impacts of the entire supply chain. Life cycle assessment (LCA) is one of the most used tools to support the quantitative assessment of sustainability in SSCM. LCA results are therefore of extreme importance and the robustness of these results is critical for decision-makers. The forest sector is essential in Portugal. This importance is reflected by the fact that the Portuguese forest sector business volume contributes 5.53% to the national gross domestic product and around 2.57% of the personnel employed in Portugal are employed by the companies that make up this sector, so attaining sustainable supply chains in this sector is a vital for Portugal. Under this premise, the main goal of this doctoral thesis is to present a roadmap based on the LCA approach to guide robust sustainable forest supply chains management. This roadmap includes: i) a proposal on how the environmental and social aspects of forest supply chains should be analyzed using the LCA approach to support SSCM; ii) a detailed environmental and social LCA of specific forest supply chains; iii) a methodology able to integrate parameter uncertainty into the environmental and social LCA of supply chains; and iv) a provision of recommendations for forest products' manufactures and other supply chain partners to assist them in improving the environmental and social performance of their activities and, consequently, improve the environmental and social performance of their supply chain. The roadmap presented in this doctoral thesis will contribute to sustainable forest supply chains management and, hence, to the reduction of the potential environmental and social impacts associated with these supply chains. It is important to mention that the steps taken to develop this roadmap can be applied to supply chains in any sector in any region, thus contributing to the sustainable management of supply chains in general.

Keywords: Sustainable supply chain management, Forest supply chains, Life cycle assessment, Sustainability, Uncertainty

Resumo

A gestão de cadeias de abastecimento sustentáveis tem vindo a ganhar cada vez mais atenção de profissionais e académicos, pois atualmente a imagem de uma empresa não está apenas relacionada aos impactos ambientais e sociais das suas operações, mas também aos impactos ambientais e sociais de toda a cadeia de abastecimento. A análise do ciclo de vida (ACV) é uma das ferramentas mais utilizadas para apoiar a avaliação quantitativa da sustentabilidade na gestão de cadeias de abastecimento sustentáveis. Os resultados da ACV são portanto extremamente importantes e a robustez destes resultados é crítica para os decisores. O setor florestal é essencial em Portugal. Esta importância traduz-se no facto de o volume de negócios do setor florestal português contribuir em 5,53% para o produto interno bruto nacional e cerca de 2,57% das pessoas empregadas em Portugal estarem ao serviço das empresas que constituem este setor, por isso alcançar cadeias de abastecimento sustentáveis neste setor é vital para Portugal. Sob esta premissa, o objetivo principal desta tese de doutoramento é apresentar contribuições baseadas na abordagem ACV para orientar a gestão robusta de cadeias de abastecimento florestais sustentáveis. Estas contribuições incluem: i) uma proposta sobre como os aspetos ambientais e sociais das cadeias de abastecimento florestais devem ser analisados usando a abordagem ACV para apoiar a gestão de cadeias de abastecimento sustentáveis; ii) uma ACV ambiental e social detalhada de cadeias de abastecimento florestais específicas; iii) uma metodologia capaz de integrar a incerteza dos parâmetros em ACV ambiental e social das cadeias de abastecimento; e iv) fornecimento de recomendações para fabricantes de produtos florestais e outros parceiros da cadeia de abastecimento para auxiliá-los na melhoria do desempenho ambiental e social das suas atividades e, consequentemente, melhorar o desempenho ambiental e social de sua cadeia de abastecimento. O trabalho apresentado nesta tese de doutoramento contribuirá para a gestão sustentável das cadeias de abastecimento florestais e, por isso, para a redução dos potenciais impactos ambientais e sociais associados a estas cadeias de abastecimento. É importante mencionar que os passos seguidos para desenvolver estas contribuições podem ser aplicados a cadeias de abastecimento de qualquer setor em qualquer região, contribuindo assim para a gestão sustentável das cadeias de abastecimento no geral.

Palavras-chave: Gestão de cadeias de abastecimento sustentáveis, Cadeias de abastecimento florestais, Análise do ciclo de vida, Sustentabilidade, Incerteza

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Acronyms

Aci – Acidification

AF&PA – American Forest & Paper Association

AHP – Analytic Hierarchy Process

ALO – Agricultural Land Occupation

ANP – Analytic Network Process

AP – Acidification Potential

CC – Climate Change

CED – Cumulative Energy Demand (CED)

CEEP – Critical Excess Electricity Production

CEPI – Confederation of European Paper Industries

CF – Characterization Factor

CHN – China

CHP – Combined Heat and Power

CO2-Equiv. – Carbon Dioxide Equivalent

CR – Corporate Responsibility

EBITDA – Earnings Before Interests, Tax, Depreciation and Amortization

ECEC – Ecological Cumulative Exergy Consumption

ECF – Elemental Chlorine Free

Eco – Ecotoxicity, Freshwater

EI – Environmental Impact

EMA – Environmental Management Accounting

EP – Eutrophication Potential

EPD – Environmental Product Declaration

Eut_Fre – Eutrophication, Freshwater

Eut_Mar – Eutrophication, Marine

Eut_Ter – Eutrophication, Terrestrial

EXPANSE – EXploration of PAtterns in Near-optimal energy ScEnarios

FD – Fossil Depletion

FEco – Freshwater Ecotoxicity

FEut – Freshwater Eutrophication

FSC – Forest Stewardship Council

FU – Functional Unit

FWC – Forest-Wood-Chains

GDP – Gross Domestic Product

GHG – Greenhouse Gas

GOS – Gross Operating Surplus

GTAP – Global Trade Analysis Project

GWP – Global Warming Potential

HIIK – Heidelberg Institute for International Conflict Research

HT – Human Toxicity

HT_Car – Human Toxicity, Cancer

HT_NCar – Human Toxicity, Non-cancer

ICEC – Industrial Cumulative Exergy Consumption

IHDI – Inequality-adjusted Human Development Index

ILO – International Labour Organization

IR – Ionizing Radiation

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LU – Land USe

MCDA – Multi-Criteria Decision Analysis

MD – Metal Depletion

MEco – Marine Ecotoxicity

MEut – Marine Eutrophication

MRH – Medium Risk Hours

NCS – Natural Cork Stoppers

NGO – Non-Governmental Organizations

NLT – Natural Land Transformation

NPV – Net Present Value

OD – Ozone Depletion

PEF – Product Environmental Footprint

PEFC – Programme for the Endorsement of Forest Certification

PES – Primary Energy Supply

PM – Particulate Matter

PMF – Particulate Matter Formation

POF – Photochemical Oxidant Formation

PRT – Portugal

PSM – Problem Structuring Approach

PWR – Present Worth Ratio

RD – Relative Deviation

RHI – Relative Hazard Index

RU_F – Resource Use, Fossils

RU_M – Resource Use, Minerals and Metals

RQ – Research Question

SAF – Social Asset Factor

SDG – Sustainable Development Goal

SHDB – Social Hotspots Database

SHI – Social Hotspots Index

SRC – Short-Rotation Coppice

SS – Single Score

SSCM – Sustainable Supply Chain Management

STFs – Slips, Trips, and Falls

TA – Terrestrial Acidification

TBL – Triple Bottom Line

TCF – Total Chlorine Free

TEco – Terrestrial Ecotoxicity

ToSIA – Tool for Sustainability Impact Assessment

TZA – Tanzania

UFR – Urea-Formaldehyde Resin

UGA – Uganda

UKR – Ukraine

ULO – Urban Land Occupation

UN – United Nations

UWF – Uncoated Woodfree

WD – Water Depletion

WU – Water Use

XAC – South Central Africa

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1. Introduction

Growing stakeholders' pressure, such as stricter government regulations and increasing consumer awareness about environmental and social issues, has led companies to focus not only on maximizing profit but also on reducing the negative impacts of their activities on the planet and society (Sadjady Naeeni & Sabbaghi, 2022). In their quest for sustainability, companies should not only focus on lessen the negative environmental and social impacts of their operations but also on improving the environmental and social performance of their supply chain since a company's image is not only related to its own operations (Barbosa-Póvoa, et al., 2018). Even if an environmental or social issue, such as child labor, occurs outside the company's direct sphere of influence, it can damage its image and therefore its brands' value. For example, some of the world's largest tech companies, such as Apple and Google, have been accused of using minerals in their products mined by Congolese children working in dangerous conditions (Wakefield, 2016). This practice led to a lawsuit launched against these companies by the children's families (Kelly, 2019). Accusations of child labor or other issues may lead to customers boycotting companies (i.e. not buying their products) or it may lead to companies having to pay compensation to those affected. By considering the potential environmental and social impacts that occur along the entire supply chain, the organization can participate and correct issues that occur beyond its direct sphere of influence and thus avoid criticism that would deteriorate its image. Another reason for companies to look beyond their own operations is the fact that, in some cases, the greatest opportunities to reduce the overall impacts of a product may not be related to the company's operations but to other processes that occur along the supply chain (Zgavc, 2022). In these cases, the company might not have direct control or influence over these processes. However, it can positively influence the activities connected to other actors in the supply chain (e.g. suppliers, service providers, or customers). For example, in the last decade Adidas Brazil has been running a shoe-recycling initiative called "Sustainable Footprint" to prevent shoes from going into landfills. Customers can bring any brand of shoes into an Adidas store which are then shredded and turned into alternative fuels and raw materials. The brand provides a discount each time a customer brings in an old pair of shoes to encourage people to bring in additional old shoes and advertises the initiative in stores by displaying videos to educate customers (Esposito, et al., 2016). A further motive for companies to look beyond their own operations is the fact that sharing information with customers (using an environmental product declaration, for example) is a possibility for a company to promote its products since its environmental and social attributes play an essential role in consumers' purchasing decisions (Deloitte, 2021). Some of these attributes can only be identified by considering a supply chain perspective. For example, when promoting recycled paper, companies can advertise that this product's manufacturing involves less energy and water consumption when compared with virgin paper. However, other benefits can be communicated by looking at the whole supply chain. Upstream of the manufacturing process, paper produced using recycled fiber saves an average of 17 trees. In contrast, downstream of the manufacturing process, by using waste paper to produce new paper three cubic yards of landfill space and 95% of air pollution from incineration are reduced (Bajpai, 2014). Due to these reasons, managing supply chains while taking into account not only economic aspects but also environmental and social aspects (i.e., taking into account the three dimensions of sustainable development), has been receiving increasing attention from both practitioners and scholars in recent years (Su, et al., 2021). However, the complexity of global supply chains means that companies that begin their journey toward sustainability need quantitative tools to support sustainable supply chain management (SSCM) (Barbosa-Póvoa, et al., 2018). Life cycle assessment (LCA) is one of the techniques that can be used to support the sustainable supply chains' complex decision process. LCA forms the backbone of the environmental discussion in sustainable supply chain management (Seuring, 2013) (Barbosa-Póvoa, et al., 2018) and social LCA is one of the most used approaches to evaluate the social performance of supply chains (Basta, et al., 2018) (D'Eusanio, et al., 2019). Uncertainty, including parameter uncertainty, should be taken into consideration when using LCA as a quantitative decision support tool to provide decision-makers more confidence in the results of the life cycle assessment and the recommendations that were produced based on these results.

In line with the previous statement regarding the field of SSCM, sustainable forest supply chains are also emerging as a research topic (Santos, et al., 2019a). Forests occupy almost a third (i.e., 31%) of the earth's land surface and are a very important ecosystem globally (FAO, 2022). From an environmental point of view, forests provide habitat to several terrestrial species of animals and plants, mitigate climate change by absorbing harmful greenhouse gases (GHG), protect watersheds that supply the majority of freshwater worldwide, and serve as a buffer in natural disasters such as floods (FAO, 2022). Moreover, from a socioeconomic point of view, forests are home to 750 million people (including 60 million indigenous people) (WWF, 2020a), serve as the setting in which certain leisure and recreational activities (e.g., hiking) take place, and are the basis of the forest sector which contributes more than USD 1.52 trillion to the world's gross domestic product (GDP) and is responsible for about 1% of global employment by employing 33 million people (FAO, 2022). As in other countries in the world, forests represent the dominant land use in Portugal, occupying 36.2% (3224.2 thousand hectares) of the country's mainland (ICNF, 2015). Similarly to what was previously mentioned, the importance of forests in Portugal is reflected in environmental terms (e.g., forest land absorbs around 15% of total GHG emissions in Portugal (Eurostat, 2018)), but also in socioeconomic terms (e.g., the forest sector is responsible for generating a business volume that corresponds to 5.53% of the Portuguese GDP and for employing 2.57% of the personnel employed in Portugal (DGAE, 2020a)). Some of the most sold products in the Portuguese forest sector are particle boards which contribute 47.4% to the total quantity of wood panels sold, natural cork stoppers which contribute 63.9% to the total quantity of cork stoppers sold, and uncoated woodfree (UWF) paper that contribute 40.4% to the total quantity of paper and carboard sold, respectively (INE, 2021).

Due to the increasing attention that the fields of sustainable supply chain management and sustainable forest supply chains have been receiving, the main goal of this doctoral thesis is to present a roadmap based on the life cycle assessment approach to guide robust sustainable forest supply chains management. This roadmap includes:

- A proposal on how the environmental and social aspects of forest supply chains should be analyzed using the LCA approach to support sustainable forest supply chains management;
- A detailed analysis of the environmental and social aspects associated with specific forest supply chains using the LCA approach to demonstrate how this analysis should be conducted to support sustainable forest supply chain management. Three Portuguese forest supply chains are utilized as illustrative case studies in this doctoral thesis due to the importance of the forest sector in Portugal;
- A methodology able to integrate parameter uncertainty into the environmental and social LCA of supply chains. The determination of the environmental and social aspects associated with supply chains through the LCA approach is done using several parameters. Many of these parameters have associated uncertainty, which causes uncertainty in the outcomes of the environmental and social analysis of supply chains. To increase the confidence of the decision-makers in the results of supply chains' analysis and on the sustainable supply chain strategy developed based on these results, parameter uncertainty should be taken into account. Even though the developed methodology can be applied to both environmental and social analysis of supply chains, its applicability was demonstrated using case studies focused on the environmental analysis of supply chains, since this analysis is at a much higher level of operationalization than the social analysis of supply chains;
- A provision of recommendations for forest products' manufactures and other supply chain partners based on the analysis mentioned in the second point to demonstrated how environmental and social aspects can be considered in sustainable forest supply chains management. The purpose of these managerial insights is to assist forest products' manufactures and other supply chain partners in improving the environmental and social performance of their activities and, consequently, improve the environmental and social performance of their supply chain.

1.1 Research Scope

The main concepts explored in this doctoral thesis are presented in this section. Furthermore, a summary of relevant literature is also presented to assist in identifying research gaps.

1.1.1. Life Cycle Assessment

A life cycle assessment is comprised of four main steps (ISO, 2006). In the first step, *Goal and Scope Definition*, the goal of the assessment, the functional unit, and the boundaries of the system under analysis are established. The system refers to the object under study, which can be a product, a service, among others, but in the case of SSCM is the supply chain under analysis (EC-JRC-IES, 2010). The second step, *Inventory Analysis,* involves the quantification of the elementary flows in (e.g., resources taken from nature) and out (e.g., emissions into air, water, soil) of the system. In the third step, *Impact Assessment*, the inventory previously collected is converted into potential environmental impacts using characterization factors. These impacts can be added together to determine the overall environmental impact of the system under study after being normalized and weighted using normalization and weighting factors, respectively. The fourth and last step, *Interpretation*, involves examining and interpreting the results of the LCA. In the case of sustainable supply chain management, this last step consists of identifying the most relevant environmental impacts associated with the supply chain under analysis and the supply chain processes that most contribute to these relevant impacts. The identification of the most relevant supply chain processes is key to develop an effective strategy for enhancing the overall environmental performance of the supply chain.

LCA is also the most used methodology to analyze the environmental aspects associated with forest supply chains (Santos, et al., 2019a). Some of the literature considering the application of the LCA methodology to forest supply chains includes the environmental analysis of i) wood products' supply chains, such as a Brazilian office cabinet supply chain (Medeiros, et al., 2017) and a Malaysian particle boards supply chain (Azman, et al., 2021); ii) cork products' supply chains, such as the Catalonian natural cork stoppers supply chain (Rives, et al., 2011) and a Portuguese cork floating floor supply chain (Demertzi, et al., 2015); and iii) paper products' supply chains, such as the Portuguese printing and writing paper supply chain (Dias, et al., 2007) and a Finish paper supply chain (Corcelli, et al., 2018).

Most studies considering the application of the LCA methodology to forest supply chains focus only on part of the life cycle of forest products (generally from the raw materials' extraction to the manufacture of these products), leaving life cycle stages out of the analysis (such as the end-of-life stage). Most of these studies also do not utilize the impact assessment method recommended by the European Commission (i.e., Product Environmental Footprint) and do not consider uncertainty. Moreover, there is no comparison in the literature of the potential environmental impacts of different forest supply chains. These research gaps mean that, to date, it has not been possible to identify with robustness which environmental aspects are a priority to include in sustainable forest supply chain management.

1.1.2. Social Life Cycle Assessment

The same four steps that comprise a traditional LCA are also conducted in a social LCA since both approaches are based on the ISO 14040 standard (UNEP, 2020). The first step, *Goal and Scope Definition*, is identical in an environmental and social LCA. On the other hand, the main objective of the next step, *Inventory Analysis*, is different in an environmental and social LCA. While in a traditional LCA, the purpose of the second step is to collect a list of elementary flows (e.g., kilograms of carbon dioxide emitted), in a social LCA, the purpose of this step is to collect a list of social flows (e.g., number of worker hours in bad working conditions). The third step, *Impact Assessment*, is also identical in an environmental and social LCA with the main difference being that in a social LCA, potential social impacts are determined instead of potential environmental impacts. Consequential, in a social LCA conducted to support SSCM, the last step (i.e., *Interpretation*) involves identifying the most relevant potential social impacts associated with the supply chain under analysis and the supply chain processes that most contribute to these relevant impacts.

The social LCA methodology has been identified as a promising approach to analyze the social aspects associated with forest supply chains (Santos, et al., 2019a). The literature considering social life cycle assessments of forest supply chains boils down to the social analysis of wood products' supply chains, such as the Finnish wood product supply chain (Mattila, et al., 2018), different Malaysian hybrid timber structures supply chain (Balasbaneh, et al., 2018), and flooring supply chain (Balasbaneh, et al., 2021). To date, no study has been published on the application of this methodology to the supply chain of cork and paper products.

According to the literature summarized above, very few studies have applied the social LCA methodology to forest supply chains. This research gap means that, to date, it has not been possible to identify which social aspects are a priority to include in sustainable forest supply chain management.

1.1.3. Uncertainty in Life Cycle Assessment

The large amount of uncertainty characteristic of LCA studies reduces confidence in LCA results (Bamber, et al., 2020). There are three types of uncertainty in an LCA: parameter uncertainty; model uncertainty; and uncertainty due to choices (Huijbregts, 1998a). When it comes to parameter uncertainty, a substantial amount of data is required to ascertain the elementary input and output flows in the *Inventory Analysis* step and the various factors used in the *Impact Assessment* step (e.g., characterization factors). The uncertainty surrounding this data leads to uncertainty in the LCA parameters (i.e., the inventory, characterization, normalization, and weighting factors) and, as a result, leads to uncertainty in the end results of an LCA (Huijbregts, 1998a). Model uncertainty is related to the fact that some aspects cannot be modelled within the present LCA structure. For instance, spatial and temporal characteristics are lost by the aggregation of emissions in the *Inventory Analysis* step (Huijbregts, 1998a). Lastly, with regard to uncertainty due to choices (i.e., scenario uncertainty), the choices made when performing a life cycle assessment lead to uncertainty because different choices may generate different LCA outcomes (Huijbregts, 1998a). For example, a choice that leads to uncertainty in the *Impact Assessment*, a choice that leads to uncertainty is the choice of characterization method to quantify the characterized result of each impact category, for example (Huijbregts, 1998a).

Different structural developments related with uncertainty in LCAs were identified as being necessary several years ago by Huijbregts (1998a). One of these developments, which as still not been fully addressed, is the operationalization of parameter uncertainty. This operationalization is very relevant since, among other reasons, when utilizing LCA as a quantitative decision support tool to assist SSCM or other decision-making processes, parameter uncertainty should be taken into consideration to provide decision-makers more confidence in the outcomes of the life cycle assessment and the recommendations that were developed based on this assessment. The most common stochastic modeling approach used in LCA is Monte Carlo simulation (Igos, et al., 2019), which has long been recognized as a promising method for integrating parameter uncertainty in life cycle assessments (Huijbregts, 1998a). Uncertain parameters in a Monte Carlo simulation are assign probability distributions (e.g., normal and uniform). The output values of the simulation model are calculated by combining these parameters with some other (fixed) parameters. The uncertain parameters are sampled randomly from the probability distributions, and the output values calculated using that sample are recorded. This sampling is done multiple times, each time generating a distinct set of random values, which results in different output values. An iteration refers to the process of generating a new set of random values. As opposed to simply yielding a single estimate of results, Monte Carlo simulation generates results with a wide range of potential outcomes expressed through probability distributions, reflecting the combined parameter uncertainties (Palisade Corporation, 2016).

According to a recent literature assessment, less than 20% of the LCA studies published since 2014 include any kind of uncertainty analysis (Bamber, et al., 2020). Furthermore, it does not seem that the number of LCA studies that include uncertainty analysis is growing over time. Some of the literature that considers the uncertainty present in life cycle assessment includes the description and application of a new methodology that, among other aspects, uses Monte Carlo simulation to quantify the uncertainty related to inventory data and the characterization factors of ten impact categories (Huijbregts, et al., 2003); the analysis of the uncertainty associated with the data required to compute the characterization factors of chemicals for freshwater ecotoxicity by attributing different probability distributions to these data and conducting a Monte Carlo simulation (van Zelm & Huijbregts, 2013); the proposal of a step-wise methodology to assist decision-makers to, among others, handle the characterization factors uncertainty by applying the Monte Carlo technique (Gargalo, et al., 2016); and more recently the introduction of a method which uses the logarithmic mean Divisia index decomposition method combined with Monte Carlo simulation to quantify the contributions of underlying variables in LCA, such as characterization factors, to overall variability in the result, such as characterized results (Qin & Suh, 2021).

Even though, as discussed above, some LCA studies have included the uncertainty related to the inventory data or the characterization factors, most of these studies focus only on one parameter type (i.e., inventory data or characterization factors), few impact categories, or do not present an easily reproducible methodology of integrating this uncertainty in an LCA. Consequently, a comprehensive multi-level methodology for the operationalization of parameter uncertainty that can be easily reproduced by any LCA practitioner is still missing from the literature.

1.2 Research Questions and Conceptual Framework

Three research questions (RQ) need to be answered to accomplish the previously defined main goal of this doctoral thesis:

- **RQ1:** How to incorporate environmental aspects into forest supply chains management?
- **RQ2:** How to incorporate social aspects into forest supply chains management?
- **RQ3:** How to consider parameter uncertainty in sustainability assessment of supply chains?

To begin answering RQ1 and RQ2, a systematic literature review (Figure 1.1) was conducted to comprehend how the sustainability of different forest supply chains has been assessed in different studies. Through this understanding, it is possible to identify common practices but also gaps in the current sustainability assessment of forest supply chains and thus propose how the environmental and social aspects of these supply chains should be assessed (Objective 1). According to the results of the systematic literature review, the most used methodology to analyze the environmental aspects associated with forest supply chains is the life cycle assessment methodology (Santos, et al., 2019a). Moreover, the results of this literature review also show that the social LCA methodology is a promising approach to analyze the social aspects associated with forest supply chains (Santos, et al., 2019a). Consequently, life cycle assessment is the methodology proposed to incorporate environmental and social aspects into forest supply chains management. To indicate how this incorporation should be done and thus finish answering RQ1 and RQ2, an environmental and social life cycle assessment of three Portuguese forest supply chains (for a reason previously explained) were performed (Figure 1.1). Based on this detailed analysis of the environmental and social aspects associated with specific forest supply chains (Objective 2), a set of industry-specific recommendations for different forest supply chain partners is provided to assist them in improving their environmental and social performance and, consequently, the environmental and social performance of their supply chains (Objective 4). The results of this environmental and social analysis can be used by companies from the forest sector to benchmark the environmental and social performance of their supply chain. Moreover, these results are a valuable source of management information for the decision-makers, at both company and national levels, who aim to improve the environmental and social performance of forest supply chains.

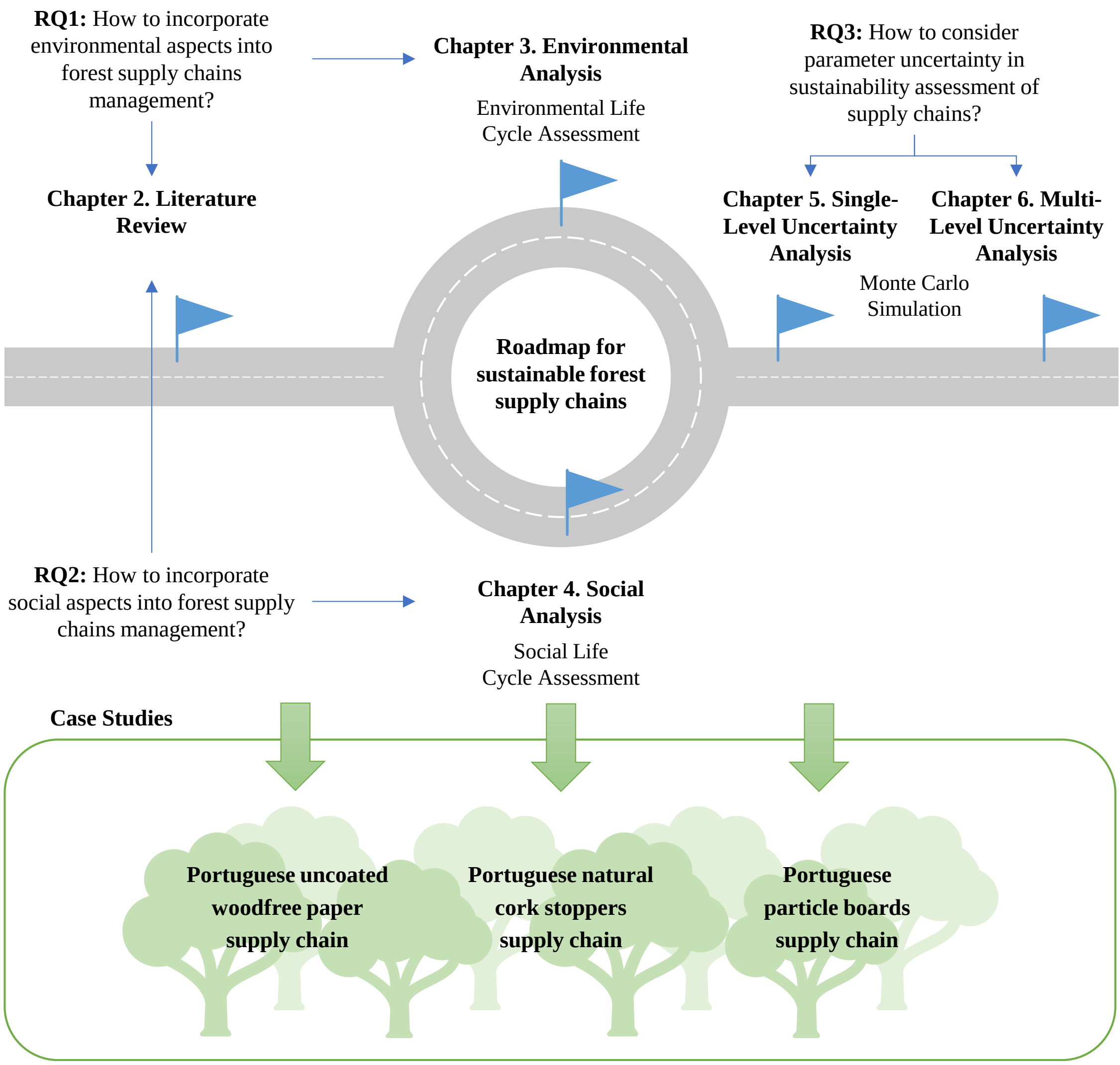

Figure 1.1 – Conceptual framework.

As a first approach to answering RQ3, a new single-level methodology for analyzing the uncertainty related to the characterization factors utilized in life cycle assessments was developed (Figure 1.1). This methodology involves conducting a traditional deterministic LCA that does not consider uncertainty, a stochastic LCA which considers the uncertainty associated with the characterization factors used in the *Impact Assessment* step through Monte Carlo simulation, and a comparison of both analyses. The proposed single-level methodology was applied to a case study where life cycle assessment is used for micro-level decision support to demonstrate how this methodology can be used in a decision-making process. Based on this first approach, a more comprehensive approach was then developed. Thus, the final approach to answering RQ3 consists in a multi-level methodology for integrating parameter uncertainty in an LCA

(Figure 1.1). In addition to considering the uncertainty related to the characterization factors, the multi-level methodology also considers the uncertainty associated with other LCA parameters, such as the inventory collected in the *Inventory Analysis* step and the normalization and weighting factors used in the *Impact Assessment* step of an LCA. The proposed multi-level methodology was applied to a case study where life cycle assessment is used in the environmental assessment of a supply chain to illustrate its applicability. Besides being used to integrate uncertainty into the environmental and social analysis of supply chains to support the development of a robust SSCM strategy (Objective 3), the proposed multi-level methodology can also be used in different LCA applications, such as the comparison of specific goods or services, which makes it valuable to both decision-makers and policy makers.

1.3 Thesis Outline and Outputs

The research work conducted to answer the three research questions identified in the Section 1.2 and accomplish the main goal of this doctoral thesis is presented over seven chapters. This research work gave rise to several scientific outputs developed by the candidate under the supervision of Doctor Ana Carvalho and Doctor Ana Barbosa-Póvoa. Table 1.1 presents the seven chapters that compose this thesis as well as the corresponding scientific outputs.

In the first chapter, Introduction, the main goal of this doctoral thesis is defined, together with the key concepts explored and the main research questions to be answered by this thesis. Furthermore, the thesis outline and outputs (i.e., research publications and conference presentations) are also described in Chapter 1.

The second chapter, Literature Review (Figure 1.1), presents the systematic literature review conducted on how the sustainability of different forest supply chains has been assessed in different studies. The published research paper "*Assessment and optimization of sustainable forest wood supply chains – A systematic literature review*" (Santos, et al., 2019a) constitutes Chapter 2. The results of this review were presented in two national conferences and one international conference (Table 1.1).

In the third chapter, Environmental Analysis (Figure 1.1), the life cycle assessment of three Portuguese forest supply chains is presented. The published research paper "*An economic and environmental comparison between forest wood products e Uncoated woodfree paper, natural cork stoppers and particle boards*" (Santos, et al., 2021) constitutes Chapter 3. The results of this environmental analysis were presented at three international conferences and included in one book chapter (Santos, et al., 2018) and conference proceedings (Santos, et al., 2016) (Table 1.1).

The fourth chapter, Social Analysis (Figure 1.1), presents the social life cycle assessment of the three aforementioned supply chains. The research paper "*A social life cycle assessment framework to analyze the social performance of supply chains*" (Santos, et al., 2023a) submitted for publication constitutes Chapter

4. The results of this social analysis were presented at four international conferences and included in two book chapters (Santos, et al., 2020a) (Santos, et al., 2022a) and one conference proceedings (Santos, et al., 2020b) (Table 1.1).

In the fifth chapter, Single-Level Uncertainty Analysis (Figure 1.1), a new methodology for analyzing the uncertainty related to the characterization factors utilized in life cycle assessments is presented. The published research paper "*A methodology for integrating the characterization factors uncertainty into life cycle assessments*" (Santos, et al., 2022b) constitutes Chapter 5. The results of this single-level uncertainty analysis were presented at one national conference and three international conferences and included in one book chapters (Santos, et al., 2019b) and one conference proceedings (Santos, et al., 2019c) (Table 1.1).

The sixth chapter, Multi-Level Uncertainty Analysis (Figure 1.1), presents a multi-level methodology for integrating parameter uncertainty in an LCA. This methodology was developed based on the single-level methodology presented in Chapter 5. The research paper "*How to turn green supply chain management more robust? A multi-level uncertainty methodology*" (Santos, et al., 2023b) submitted for publication constitutes Chapter 6. The results of this multi-level uncertainty analysis were presented at one national conference and will be presented at different international conferences in the future (Table 1.1).

In the last chapter, Conclusions and Future Research, the main conclusions of this doctoral dissertation are presented, and possible streams for future research are highlighted.

Table 1.1 – Thesis outline and achieved outputs.

Chapter	Title	Scientific Outputs	Role of the Candidate
1	Introduction	-	-
2	Literature review	**Research papers:** 1. Santos, A., Carvalho, A., Barbosa-Póvoa, A., Marques, A., & Amorim, P. (2019). Assessment and optimization of sustainable forest wood supply chains – A systematic literature review. *Forest Policy and Economics*, 105, 112-135. doi:10.1016/j.forpol.2019.05.026 **Presentations:** 2. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2017). Assessing Sustainability in Forest-based Supply Chains: A systematic review. 4ª Conferência Anual da redeAGRO. Lisbon, Portugal. 3. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2017). OR methods applied to forest-based supply chains considering economic, environmental and social perspectives – A systematic review. XVIII Congress of the Portuguese Association of Operational Research, Valença, Portugal. 4. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2017). Characterization and Analysis of the Sustainability in the Paper Supply Chain. 6th International Congress on Sustainability Science & Engineering (ICOSSE), Barcelona, Spain.	**Research papers:** 1. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Presentations:** 2. – 4. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation); Presentation

Chapter	Title	Scientific Outputs	Role of the Candidate
3	Environmental Analysis	**Research papers:** 5. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2021). An economic and environmental comparison between forest wood products – Uncoated woodfree paper, natural cork stoppers and particle boards. *Journal of Cleaner Production*, 296, 126-469. doi:10.1016/j.jclepro.2021.126469 **Book chapters:** 6. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2018). Life cycle assessment of pulp and paper production – A Portuguese case study. *30th European Symposium on Computer Aided Process Engineering*, 809-814. doi:10.1016/B978-0-444-64235-6.50142-X **Conference proceedings:** 7. Santos, A., Carvalho, A., Pinto-Varela, T., & Barbosa-Póvoa, A. (2016). Environmental impacts' comparison in design and planning of supply chain. *Proceedings of the 6th [avniR] Conference*, Lille, France. **Presentations:** 8. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2021). Supporting a sustainable management of wood products through an environmental and economic assessment. *8th EurOMA Sustainable Operations and Supply Chain Forum*, La Rochelle, France. **Posters:** 9. Santos, A., Carvalho, A., Pinto-Varela, T., & Barbosa-Póvoa, A. (2016). Comparative Performance of LCIA Methods: The Supply Chain Network Design and Planning. *6th [avniR] Conference*, Lille, France. 10. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2018). Life cycle assessment of pulp and paper production – A Portuguese case study. *28th European Symposium on Computer Aided Process Engineering*, Graz, Austria.	**Research papers and Book chapters:** 5. – 6. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Conference proceedings:** 7. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Software (implementation of the supporting code); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Presentations and Posters:** 8. – 9. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation/poster); Presentation 10. Conceptualization (ideas and formulation of overarching research goals and aims); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the poster)

Chapter	Title	Scientific Outputs	Role of the Candidate
4	Social Analysis	**Research papers:** 11. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2023). A social life cycle assessment framework to analyze the social performance of supply chains. *International Journal of Operations & Production Management* (submitted) **Book chapters:** 12. Santos, A., Norris, C., Barbosa-Póvoa, A., & Carvalho, A. (2020). Social life cycle assessment of pulp and paper production – A Portuguese case study. *30th European Symposium on Computer Aided Process Engineering*, 15-20. doi:10.1016/B978-0-12-823377-1.50144-0 13. Santos, A., Veloso, M., Carvalho, A., & Barbosa-Póvoa, A. (2022). A methodology based on social life cycle assessment for social hotspots identification. *32nd European Symposium on Computer Aided Process Engineering*, 1651-1656. doi:10.1016/B978-0-323-95879-0.50276-9 **Conference proceedings:** 14. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2019). Assessment of social sustainability hotspots in the pulp and paper supply chain. *Proceedings of the 7th Sustainable Operations and Supply Chains Forum*, Nottingham, UK. **Presentations:** 15. Santos, A., Norris, C., Carvalho, A., & Barbosa-Póvoa, A. (2020). Assessment of social sustainability hotspots in the pulp and paper supply chain. *7th EurOMA Sustainable Operations and Supply Chains Forum*, Nottingham, England. 16. Santos, A., Norris, C., Barbosa-Póvoa, A., & Carvalho, A. (2020). Social life cycle assessment of pulp and paper production – A Portuguese case study. *30th European Symposium on Computer Aided Chemical Engineering*, Milano, Italy. 17. Santos, A., Veloso, M., Carvalho, A., & Barbosa-Póvoa, A. (2022). A methodology based on social life cycle assessment for social hotspots identification. *32nd European Symposium on Computer Aided Process Engineering*, Toulouse, France. 18. Santos, A., Veloso, M., Carvalho, A., & Barbosa-Póvoa, A. (2022). Recommendations for mitigating the most relevant social issues associated with the Portuguese forest sector. *8th International Conference of S-LCA*, Aachen, Germany.	**Research papers, Book chapters, and Conference proceedings:** 11. – 14. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the framework); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Presentations and Posters:** 15. – 16. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the framework); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation); Presentation. 17. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the framework); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation). 18. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the framework); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation); Presentation.

Chapter	Title	Scientific Outputs	Role of the Candidate
5	Single-Level Uncertainty Analysis	**Research papers:** 19. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2022). A methodology for integrating the characterization factors uncertainty into life cycle assessments. *Sustainable Production and Consumption*, 33, 1018-1030. doi: 10.1016/j.spc.2022.08.018 **Book chapters:** 20. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2019). A stochastic environmental model to deal with uncertainty in life cycle impact assessment. *29th European Symposium on Computer Aided Process Engineering*, 1543-1548. doi: 10.1016/B978-0-12-818634-3.50258-7 **Conference proceedings:** 21. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2019). Environmental decision-making considering uncertainty - A pulp production process case-study. *Proceedings of the 6th Sustainable Operations and Supply Chains Forum*, Gothenburg, Sweden. **Presentations:** 22. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2018). Uncertainty Analysis in Environmental Life Cycle Assessment - A Case Study Comparing Two Pulp Bleaching Options. *XIX Congress of the Portuguese Association of Operational Research*, Aveiro, Portugal. 23. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2019). Environmental decision-making considering uncertainty - A pulp production process case-study. *6th EurOMA Sustainable Operations and Supply Chains Forum*, Gothenburg, Sweden. 24. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2019). A stochastic environmental model to deal with uncertainty in life cycle impact assessment. *29th European Symposium on Computer Aided Chemical Engineering*, Eindhoven, The Netherlands. **Posters:** 25. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2019). Decision-making considering environmental impacts – A comparison between two pulp bleaching processes. *9th Life Cycle Management Conference*, Poznan, Poland.	**Research papers, Book chapters, and Conference proceedings:** 19. – 21. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Presentations and Posters:** 22. – 23. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation); Presentation. 24. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the presentation). 25. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the poster); Presentation.

Chapter	Title	Scientific Outputs	Role of the Candidate
6	Multi-Level Uncertainty Analysis	**Research papers:** 26. Santos, A., Carvalho, A., & Barbosa-Póvoa, A. (2023). How to turn green supply chain management more robust? A multi-level uncertainty methodology. *Omega* (submitted) **Posters:** 27. Santos, A., Barbosa-Póvoa, A., & Carvalho, A. (2021). A simulation-based methodology for uncertainty analysis in life cycle assessment. *XXI Congress of the Portuguese Association of Operational Research*, Figueira da Foz, Portugal.	**Research papers:** 26. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Visualization (creation of visual support for the data collected and the results obtained); Writing (preparation of the published work). **Presentations and Posters:** 27. Conceptualization (ideas and formulation of overarching research goals and aims); Methodology (Development of the methodology); Investigation (data collection); Software (implementation of the data collected into the supporting software); Formal analysis (application of formal techniques to analyze and synthesize results); Writing (preparation of the abstract); Visualization (preparation of the poster); Presentation.
7	Conclusions and Future Research	-	-

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2. Literature Review

2.1 Introduction

The concept of sustainability was first introduced in the forestry sector at the beginning of the 18th century by Hans Carl von Carlowitz in his *Sylvicultura oeconomica*, when wood was a scarce resource, with the aim of improving the conservation and cultivation of forests (von Carlowitz, 1713). Since that time, the sustainability concept has evolved and in 1992 the United Nations Conference on Environment and Development held in Rio de Janeiro has identified the economic, environmental and social areas as equally important pillars of sustainable development (the Triple Bottom Line, TBL) (Sustainable Development Commission, 2011). Furthermore, the increasing awareness of the public regarding sustainability issues has obliged decision makers to consider not only the economic aspects but also the impact on the environment and society of their decisions. But these are complex decisions and for this reason, decision makers could use quantitative techniques, such as mathematical programming, to help them in the decision-making process (Cambero & Sowlati, 2014). The main goal of this chapter is to understand how these quantitative techniques have been applied in the forestry sector. This sector is responsible for the commercialization of wood forest products and non-wood forest products. The difference between these two groups lies in the fact that wood forest products are produced using the timber of the trees (e.g. paper and furniture) while non-wood forest products are not (e.g. game animals and mushrooms) (Ministry of Forests and Range , 2008). This chapter will focus on wood forest products since these are consider the primary forest products (FAO, 2014), considering the whole forest wood supply chain. A supply chain is a system of organizations linked together to deliver a product or service from supplier to customer (Vitasek, 2013). Specifically, the forest wood supply chain is responsible for the wood fiber transformation into finished products such as paper, lumber, furniture, and energy in all its forms (heat, electricity, and fuels). The most used quantitative technique to support supply chain decision-making considering the three sustainability dimensions is mathematical programming also known as optimization (Barbosa-Póvoa, et al., 2018). However, other techniques exist that help decision makers assess the potential economic performance and environmental and social impacts of their decisions such as multi-criteria decision analysis (MCDA) and life cycle assessment (LCA). The main goal of this work mentioned previously can then be translated into two main research questions:

RQ1. – What are the main characteristics of the assessment studies applied to forest wood supply chains?

RQ2. – What are the main characteristics of the optimization studies applied to forest wood supply chains?

Other literature reviews have been published that partially answer the aforementioned research questions. A summary of each one of these review papers is provided in Table 2.1. Each study was classified according to the scope, number of papers, period and type of studies reviewed, and the main characteristics considered.

Table 2.1 – Comparison between the present systematic literature review and the other reviews identified.

Reference	Scope	Reviewed Period	Number of Papers	Type of Study	Characteristics
(Iakovou, et al., 2010)	Biomass products	-	-	Optimization	Model characteristics & Decision levels
(An, et al., 2011a)	Biomass & Fossil products	1962 to 2010	30	Optimization	Model characteristics & Decision levels
(Sharma, et al., 2013)	Biomass products	1997 to 2011	32	Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
(Cambero & Sowlati, 2014)	Biomass products	-	89	Assessment & Optimization	Sustainability dimensions, Model characteristics & Decision levels
(Meyer, et al., 2014)	Biomass products	1997 to 2012	71	Assessment & Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
(Wolfsmayr & Rauch, 2014)	Biomass products	1989 to 2011	-	Assessment & Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
(Ghaderi, et al., 2016)	Biomass products	1997 to 2016	146	Assessment & Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
(Ba, et al., 2016)	Biomass products	2010 to 2014	124	Assessment & Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
(Jaehn, 2016)	-	-	-	Assessment & Optimization	Sustainability dimensions, Model characteristics & Decision levels
(Mirkouei, et al., 2017a)	Biomass products	2000 to mid-2015	394	Assessment & Optimization	Sustainability dimensions
(Mardani, et al., 2017)	Biomass & Fossil products	1995 to 2015	196	Assessment	Sustainability dimensions & Stakeholders involvement
(De Luca, et al., 2017)	-	2007 to 2016	32	Assessment	Sustainability dimensions & Stakeholders involvement
(Marttunen, et al., 2017)	-	2000 to 2015	68	Assessment	Stakeholders involvement
(Pérez, et al., 2017)	Biomass products	2006 to 2015	72	Optimization	Sustainability dimensions, Model characteristics, Decision levels & Uncertainty
Present review	Wood forest products	1995 to 2017	188	Assessment & Optimization	Sustainability dimensions, Stakeholders Involvement, Model characteristics, Decision levels & Uncertainty

Looking at Table 2.1 it can be concluded that most literature reviews (64%) focus on reviewing assessment and optimization studies applied exclusively to the biomass supply chain responsible for the production of biomass products such as bioenergy (heat, electricity, and fuels) and bioproducts (e.g. chemicals). Biomass refers to any organic material derived from biological organisms that has stored sunlight in the form of chemical energy (Munuswamy, et al., 2011). There are several types of biomass but the most abundant type is lignocellulosic biomass (Lin & Huber, 2009) including agricultural residue, urban woody waste, and forest biomass (Sharma, et al., 2013). From the literature reviews included in Table 2.1 that focus on reviewing studies applied to the biomass supply chain, only three focus exclusively on the forest biomass supply chain (Cambero & Sowlati, 2014) (Wolfsmayr & Rauch, 2014) (Mirkouei, et al., 2017a). The works published by An et al. (2011) and Mardani et al. (2017) reviewed optimization studies (An, et al., 2011a) and assessment studies using multi-criteria decision analysis (Mardani, et al., 2017) applied to the biomass and the fossil supply chain responsible for the production of fossil products such as petroleum-based fuel. The three remaining literature reviews presented in Table 2.1 have a much broader scope and consider more than two different fields of application. The review developed by Jaehn (2016) analyzes the use of quantitative methods such as multi-criteria decision analysis and optimization focusing on the interactions between economic, environmental and social aspects (Jaehn, 2016). De Luca et al. (2017) highlighted how life cycle approaches have been combined with MCDA and/or participatory methods in assessment studies considering agricultural and forest products, among others (De Luca, et al., 2017). Lastly, Marttunen et al. (2017) carried out an extensive literature search covering eight problem structuring approaches (PSMs), including Stakeholders Analysis, and seven MCDA methods, including Analytic Hierarchy Process, to explore how PSMs and MCDA methods are combined and what are the associated benefits and challenges (Marttunen, et al., 2017).

The present work stands out as it considers both assessment and optimization studies applied to forest wood supply chains. Most of the reviews presented in Table 2.1 only considered either assessment or optimization studies applied to biomass supply chains. Furthermore, it considers issues that have been little studied in the published literature reviews such as stakeholders' involvement in the assessment process and the inclusion of uncertainty in the optimization models, aspects that play a relevant role when designing, planning and operating forest wood supply chains (see Table 2.1).

The remaining of this chapter is organized into five sections. Section 2.2 describes the research methodology followed in the present work. Section 2.3 presents the results and findings of this paper as well as a descriptive analysis of the literature reviewed. Section 2.4 provides a critical analysis of the results and outlines some suggestions for future research. Finally, Section 2.5 presents the main conclusions providing a summary of the review.

2.2 Research methodology

In this work a systematic literature review is developed. According to Fink (Fink, 2005), a thorough stand-alone literature review must systematically follow an explicit methodology which will allow others who follow the methodology to achieve the same results. The methodology applied in this work consists of four sequential steps: questions formulation, locating studies, selection and evaluation, and finally analysis and synthesis (Denyer & Tranfield, 2009), that are explored in detail as follows:

2.2.1 Questions Formulation

The focus of a literature review is established after formulating the questions that the review proposes to answer. The two research questions identified in the Introduction of this chapter can be further detailed into the following questions:

Q1) How have the different sustainability dimensions been included in the assessment of forest wood supply chains?

In this literature review, assessment refers to the use of different methodologies (e.g. MCDA or LCA) to evaluate the outputs of different projects or compare the performance of different alternatives in terms of its economic feasibility and environmental and social impacts. The assessment studies considered in this work are those where these assessment methodologies were applied to support decision-making in different echelons of the forest wood supply chain.

Q2) Have stakeholders been involved in the assessment process?

A stakeholder is any individual or group who can affect or be affected by the achievements of an organization such as customers, employees, government, and non-governmental organizations (Freeman & Reed, 1983). Because the whole forest wood supply chain is considered in this study, several organizations are taken into account and consequently, some assessment studies include broader stakeholders (e.g. experts from academia) while other assessment studies include more specific stakeholders (e.g. managers and staff of a specific company). The stakeholders' involvement in the assessment process ranges from mere communication to up close interaction in all steps of this process including data collection, model building, criteria selection/weighting, and scenario/options description/ranking (Sala, et al., 2015).

Q3) How have the different sustainability dimensions been explored when applying optimization models to forest wood supply chains?

The optimization studies considered in this work are those where mathematical models were developed to support decision-making in different echelons of the forest wood supply chain. From these studies, the ones that consider more than one sustainability dimension include not only multi-objective optimization where several sustainability criteria are simultaneously optimized, but also optimization of a compromise sustainability criterion (e.g. cost minimization including greenhouse gas emissions costs), optimization of several sustainability criteria separately (multiple single-objective optimizations compared among them), and single-objective optimization where one sustainability dimension is included in the objective function and another sustainability dimension is included as a constraints or auxiliary calculation. In the case of multi-objective optimization where several criteria are simultaneously optimized, the ε-constraint method is typically applied but other methods, such as the weighted goal programming technique, can also be used for generation of several Pareto optimal solutions (non-dominated solutions) (Zore, et al., 2017). Decision makers will decide the solution to be selected based on the compromise he/she wishes to make (Boukherroub, et al., 2013). The use of a compromise criterion could significantly reduce the time needed to solve the optimization problem and should be used in the case of models with many variables and constraints where obtaining several points on Pareto curves could be very time consuming (Zore, et al., 2017).

Q4) What decisions levels (strategic, tactical or operational) have been addressed in the optimization of sustainable forest wood supply chains?

Strategic decisions are long-term decisions (e.g. capacity and location of conversion and intermediate storage facilities, feedstock types and production technology selection) which involve important financial investments. Tactical decisions are medium-term decisions related to production and inventory planning (e.g. how much and when to produce), and fleet and logistics management (e.g. shipment size and material flows). Finally, operational decisions are short-term decisions such as the determination of detailed vehicle routes or the daily timing of harvesting operations. The distinction between these last two types of decisions can be difficult. If the start times of tasks and/or their precise order must be specified, the decision pertains to the operational level (Ba, et al., 2016).

Q5) Do optimization models applied to forest wood supply chains considered uncertainty? If so, how?

In this study, the mathematical models considering only known and fixed parameters in their objective function and/or constraints are classified as deterministic and those that consider uncertain and random parameters are classified according to the approach used as stochastic, robust or fuzzy. In stochastic programming, the non-deterministic parameters follow a known distribution while in robust optimization these parameters are known within some bounds. For this reason, the stochastic programming is a good choice to deal with optimization problems when the distribution of uncertainty can be obtained from historical data as it often leads to a more detailed and quantitative representation of different options. Unlike stochastic programming, robust optimization models, in most cases, do not significantly increase the complexity of the problem. Fuzzy programming can provide a good alternative by using fuzzy logic to represent the truth of the uncertainty values. In this approach, the choice of parameter values is often quite subjective and depends on the user’s preference. On the other hand, the computational burden is significantly reduced and is suitable for the uncertainty that lacks information (e.g. the conversion rate and capital cost of a new technology) (Tong, et al., 2014a).

Q6) In which regions and industries of the forest sector have case studies been explored?

As mentioned in the previous section, the focus of this chapter is the forest wood supply chain responsible for the production of wood forest products. For this reason, five different industries were considered, each focusing on a specific group of wood forest products – the forestry industry focus on the establishment, growth, health, and quality of forests; the paper industry responsible for the production of different products such as newspapers, tissues, cigarette paper and coffee filters; the wood products industry responsible for the production lumber and panels to produce furniture and other engineered wood products (e.g., flooring or roofing systems); the bioenergy industry responsible for the production of heat, electricity and fuels; and the bioproducts industry, where the production of chemicals and other materials is included.

The answer to these six questions is provided in Section 2.3.

2.2.2 Locating Studies

ScienceDirect was the electronic database used and a structure keyword search was conducted to locate all relevant literature (academic papers). The research keywords were defined by combining Boolean logic operators with parenthesis: forest AND "supply chain“ AND optimization AND sustainability. Assessment was not used as a keyword because it is a word with a lot of synonyms (e.g. evaluation) and so its use could exclude from the review relevant papers. The search string first appeared in 1995 and so it was decided to analyze a period from 1995 to 2017 to guarantee a wide range of results. The last search was conducted in November 2018. Hundreds of results (959 papers) were obtained in this preliminary search of the database.

2.2.3 Selection and Evaluation

To assess the relevance of each study two major selection criteria were used:

- Only research papers written in English and published in peer-reviewed journals were included in this review;
- Papers that do not address the assessment or optimization of forest wood supply chains were excluded from the review which includes papers that focus on non-wood forest products.

Based on the first and second criteria, 319 and 452 papers were excluded, respectively. The final 188 selected papers were analyzed and synthesized.

2.2.4 Analysis and Synthesis

This step includes the analysis of every study included in the review. This analysis is related with the review questions established in step 2.1 and includes, but it is not limited to, the sustainability dimensions considered in each paper and whether the study addresses assessment or optimization of forest wood supply chains. As a result of this analysis, a full tabulation of all the included studies is displayed and by cross-tabulating the studies, key issues can be identified and cognizance that is not obvious from reading the individual studies is developed. The results of this step are presented in the next section of this paper.

2.3 Results

This section presents the main results and findings of this literature review. It starts with a descriptive analysis of the reviewed papers followed by a more detailed analysis of each assessment and optimization study considered.

The 188 studies analyzed in this chapter were published in 42 different journals. Most of these studies (139 papers) were published in 10 journals as can be seen in Figure 2.1, with the top three journals being *Journal of Cleaner Production*, *Applied Energy*, and *Biomass and Bioenergy*. These 10 journals account for 73.9% of the total reviewed publications and can be roughly allocated to the fields of energy (bioenergy), cleaner production, sustainability and operational research.

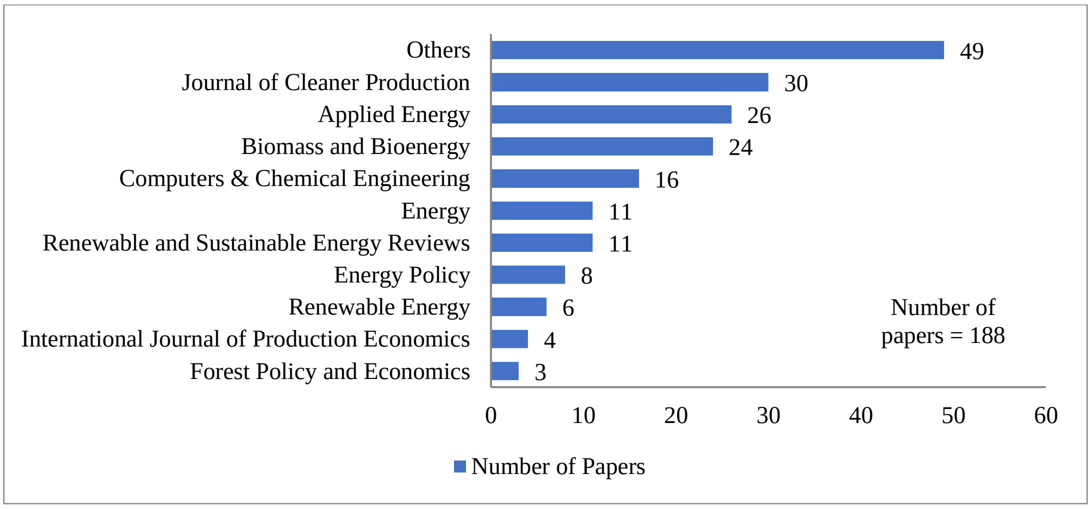

Figure 2.1 – Number of studies reviewed per journal.

By analyzing Figure 2.1 it can be concluded that the remaining 49 studies analyzed in this work were published in other journals.

The reviewed studies can be classified as being assessment or optimization studies applied to forest wood supply chains. Figure 2.2 presents the assessment and optimization studies reviewed distributed according to the year of publication.

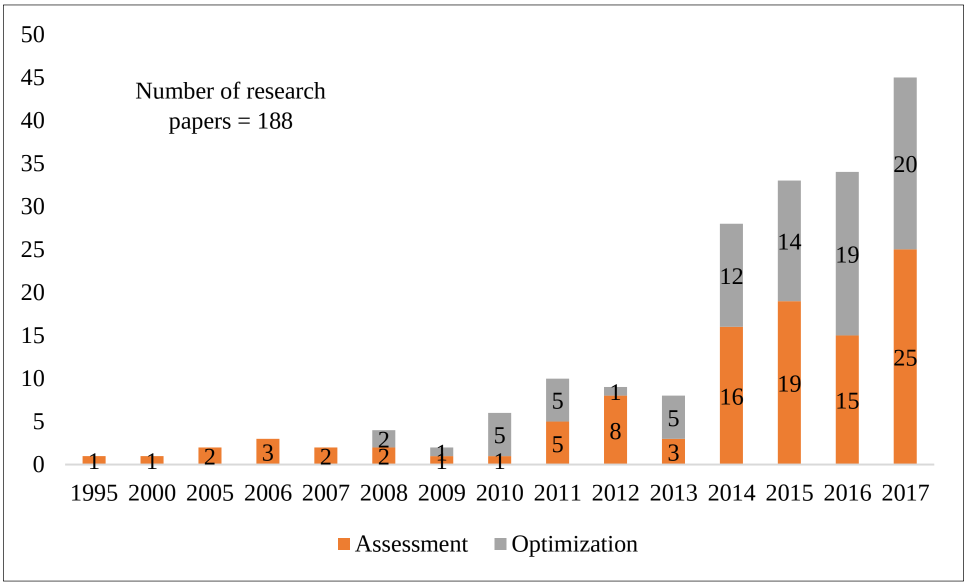

Figure 2.2 – Studies reviewed distributed according to the research methodology and year of publication.

By analyzing Figure 2.2 it can be concluded that the overall topic of assessment and optimization of forest wood supply chains arises in the mid-1990s, starting to quickly increase around 2014. The last four years considered in this review (2014 to 2017) account for 140 (74.5%) papers out of the 188 papers reviewed indicating a growing interest in the topic. Furthermore, it can be concluded by looking at Figure 2.2 that from the papers analyzed, 104 are assessment studies and 84 are optimization studies.

2.3.1 Assessment studies

From the 104 papers reviewed that address the assessment of forest wood supply chains, 53 papers focus only on one sustainability dimension (Subsection 2.3.1.1), 33 papers focus on two sustainability dimensions (Subsection 2.3.1.2), and 18 papers focus on all three (i.e. economic, environmental and social) sustainability dimensions (Subsection 2.3.1.3). The distribution of assessment studies according to the sustainability dimensions addressed is presented in Figure 2.3.

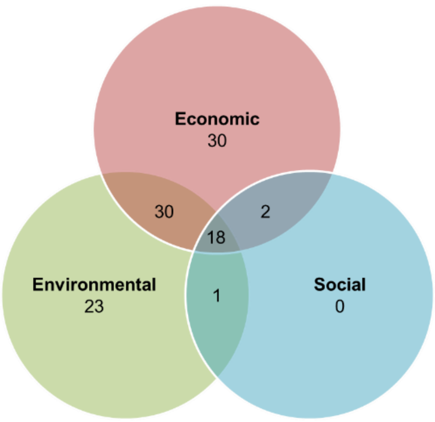

Figure 2.3 – Distribution of assessment studies according to the sustainability dimensions addressed.

At the end of this subsection, the answers to Question 1, Questions 2, and part of Questions 6 formulated in the previous section will be provided.

2.3.1.1 One Sustainability Dimension

From the 53 assessment studies that consider indicators regarding a single sustainability dimension, 30 papers focus on the economic feasibility and 23 papers focus on the environmental impact assessment of forest wood supply chains (see Figure 2.3).

Economic assessment studies are used to determine whether a project or action is desirable from a financial point of view and technically feasible, providing decision makers with a baseline for comparing between different alternatives of proposed undertakings. Table 2.2 presents a synthesis of the studies considering technical and economic assessment of forest wood supply chains.

From the analysis of Table 2.2, it can be concluded that the most common economic metrics used were overall costs, net present value (NPV), raw materials availability and energy potential.

Several assessment studies consider costs as the only economic metric. Mitchell (1995) and Wit et al. (2013) assessed the production costs of growing short rotation forestry in several countries. The study by Wit et al. (2013) also presents options for improvements in cultivation and cost reductions, which were partially obtained from expert interviews. The additional expenses caused when land availability for bioenergy production is restricted were estimated by McDowall et al. (2012). In this last study, the constraint on land availability was addressed using interviews with 12 expert stakeholders from government, academia, industry, and civil society groups. The transportation expenses of carrying wood chips from forests to energy plants were analyzed utilizing geographical resource mapping and cost distance analysis in the study developed by Möller and Nielsen (2007). Nerini et al. (2015) investigated the costs of achieving distinct levels of energy access and compared different electrification and cooking options in rural areas. Finally, the Material Flow Cost Accounting and Design of Experiments concepts were applied to a wood products manufacturer to minimize waste and reduce materials consumption by Chompu-inwau et al. (2015).

Table 2.2 – Economic assessment studies of forest wood supply chains.

Metrics	Case Study – Industry	Case Study – Region	Stakeholders Involvement	Reference
Costs	Bioenergy	Austria, Canada, Denmark, Finland, Netherlands, Sweden, UK & USA	No	(Mitchell, 1995)
		Brazil, Italy & Sweden	Yes	(Wit, et al., 2013)
		UK	Yes	(McDowall, et al., 2012)
		Denmark	No	(Möller & Nielsen, 2007)
		East Timor	No	(Nerini, et al., 2015)
	Wood Products	Thailand	No	(Chompu-inwai, et al., 2015)
Costs NPV	Bioenergy	12 developing countries	Yes	(van Eijck, et al., 2014)
NPV	Bioenergy	Belgium	No	(Kuppens, et al., 2015)
NPV Energy efficiency	Bioenergy	Sweden	No	(Joelsson, et al., 2015)
NPV Imports Exports Government consumption Private consumption Investment Gross domestic product	Forestry, Paper & Wood Products	Brazil	No	(Banerjee, et al., 2016)
Costs Raw materials availability	Bioenergy	Canada	No	(Yemshanov, et al., 2014)
		USA	No	(Martinkus, et al., 2017a)
Costs Raw materials availability Land area	Bioenergy	Italy	No	(Giglio, et al., 2017)
Raw materials availability	Bioenergy	Italy	No	(Zambelli, et al., 2012) (Sabatti, et al., 2014)
		USA	No	(Merry, et al., 2017) (Bandaru, et al., 2017)
Raw materials availability Prices	Bioenergy, Paper & Wood Products	Austria	No	(Schwarzbauer, et al., 2015)
Raw materials availability Land area Land rent	Bioenergy	Germany	Yes	(Hauk, et al., 2014)
Raw materials availability Land area Energy potential	Bioenergy	USA	No	(Saha & Eckelman, 2015)
Raw materials availability Energy potential	Bioenergy & Bioproducts	Bangladesh	No	(Hossen, et al., 2017)
Energy potential	Bioenergy	Italy	No	(Emer, et al., 2011)
		Colombia	No	(Gonzalez-Salazar, et al., 2014a)
		Switzerland	No	(Trutnevyte, 2013)
		Austria	No	(Haberl & Geissler, 2000)
Payback period	Bioenergy	Slovenia	No	(Kostevšek, et al., 2015)
Mass Index	Bioenergy	Colombia	No	(Moncada, et al., 2016)
Farmgate prices Grower payments	Bioenergy	USA	No	(Langholtz, et al., 2012)
Land area	Forestry	Taiwan	Yes	(Hsueh, 2015)
Agroclimatological aptitude	Wood Products	Brazil	No	(Santos, et al., 2017)

Another frequently used economic metric was NPV. The net present value is calculated by converting into their present values the future incoming (revenues) and outgoing (costs) cash flows generated by an investment. Then, the converted values are added which results in an overall neutral, negative, or positive result (van Eijck, et al., 2014). The NPV and total production cost for first and second-generation biofuels considering different feedstock types sourced from 12 developing countries were calculated in the assessment study by van Eijck et al. (2014). The calculations were based on specific country data partially collected through expert knowledge and checked by country partners. The NPV was also used as the only metric in the assessment of the economic feasibility of fast pyrolysis for the valorization of short rotation coppice (Kuppens, et al., 2015). A combination of NPV with energy efficiency (Joelsson, et al., 2015) and several macroeconomic indicators (Banerjee, et al., 2016) was used to evaluate the technical and economic performance of various biorefinery plant designs and the impact of an investment to promote agroforestry, forest plantations, and development natural forests, respectively.

Several studies also consider the raw materials availability and energy potential. The first metric considers the calculation of the physical amounts available of each raw material and is usually expressed in units of mass or volume. Yemshanov et al. (2014) estimated the costs and potential physical amounts of post-harvest forest residue biomass supply in Canada while Martinkus et al. (2017) used two methodologies, a past-predictive and a future-predictive, to estimate the volume and cost of delivered forest residues to a biorefinery in the United States of America. Giglio et al. (2017) carried out a thermoeconomic analysis of a hybrid direct steam generation-biomass power plant equipped with a thermal energy storage system considering the exergoeconomic cost of different streams, the area occupied by the plant and biomass availability. Forest biomass availability was estimated in different parts of Italy by Zambelli et al. (2012) and Sabatti et al. (2014), and in different parts of the United States of America by Merry et al. (2017) and Bandaru et al. (2017). These estimations can be used to identify possible locations for biorefinery plants and to propose new forest management strategies. Schwarzbauer et al. (2015) have assessed with a System-Dynamics simulation model the possible outcomes of a wood raw material scarcity on prices and raw materials availability in the Austrian forest-based sector. A comparison between sites used for short-rotation coppice (SRC) cultivation with the ones used for other crops in terms of arable land, land rents and raw material availability was conducted by Hauk et al. (2014). Information for this comparison was gathered through a standardized questionnaire mailed to SRC farmers. Energy potential can be simply explained as the amount of energy contained in biomass (Gonzalez-Salazar, et al., 2014a). There are several types of energy potentials including theoretical (theoretically extractable amount of energy); technical (amount of energy that can be extracted by a technically feasible energy conversion system), exploitable (the part of the technical potential that meets the social, legislative and environmental constraints) and economic (the exploitable potential part that is cost-effective in the whole energy mix) potential (Trutnevyte, 2013). The theoretical potential (Saha & Eckelman, 2015; Hossen, et al., 2017), together with raw material (Saha & Eckelman, 2015; Hossen, et al., 2017) and land area (Saha &

Eckelman, 2015) availability, of bioenergy crop production in potential urban marginal lands and unconventional biomass resources is explored in the assessment studies presented by Saha and Eckelma (2015) and Hossen et al. (2017); the technical potential of woody biomass is addressed in the paper by Emer et al. (2011); while both types of energy potential are included in the estimations presented by Gonzalez-Salazar et al. (2014) considering biomass uncertainty at a country level. The EXPANSE (EXploration of PAtterns in Near-optimal energy ScEnarios) methodology for assessing the exploitable and economic potential of several renewable energy sources is presented in the study developed by Trutnevyte (2013) while the net energy potential of the aboveground biomass in Austria was calculated by Haberl and Geissler (2000).

Other economic metrics used in the assessment studies reviewed include the payback period calculation of a combined heat and power plant using wood biomass (Kostevšek, et al., 2015); the use of a new concept called mass index that considers the efficiency of the conversion of biomass into final products of a biorefinery system (Moncada, et al., 2016); the evaluation of projected farmgate prices and grower payments through a price-run simulation model (Langholtz, et al., 2012); the assessment of land area of afforestation, by conducting interviews and surveys, in order to evaluate the effectiveness of community-promoted policies (Hsueh, 2015); and finally the analysis of suitable areas for the installation of wood panel industries considering different criteria such as the agroclimatological aptitude of different species and eucalyptus hybrids (Santos, et al., 2017).

Environmental assessment studies are used to identify and evaluate possible environmental effects of the proposed actions and projects, allowing decision makers to prevent or mitigate the adverse environmental impacts. Table 2.3 presents a summary of the papers reviewed that report environmental assessment studies of forest wood supply chains.

Life Cycle Assessment (LCA) was the most used methodology to estimate environmental impacts, as can be seen in Table 2.3. This methodology consists of four steps including Goal and Scope Definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and Interpretation (ISO, 2006). There are several methods to conduct a LCIA (e.g. Eco-indicator 99 and ReCiPe 2008), each considering different impact category indicators at the midpoint (e.g. acidification potential) or endpoint levels (e.g. damage to ecosystem quality) (Eskandarpour, et al., 2015). Most of the papers presented in Table 2.3 that used the LCA methodology focus on the bioenergy industry but have different purposes. A group of LCA studies compared the environmental impacts of different biomass-based supply chain configuration alternatives, including different biomass feedstock and/or other energy sources for heat generation (Pucker, et al., 2012; Bartolozzi, et al., 2017), power generation (Volkart, et al., 2013; Nian, 2016), combined heat and power generation (Pehnt, 2006), and different biofuels production (El-Houjeiri & Field, 2012; Bengtsson, et al., 2012; McNamee, et al., 2016). Bartolozzi et al. (2017) used interviews to collect data from experts in the LCI step. In other cases, LCA was used to compare distinct scenarios as is the case of the work presented by Black et al. (2011) which considers four different fertilizer scenarios for grown willow in a lignocellulosic ethanol production system, and Menten et al. (2015) where the decision to produce synthetic diesel from biomass under uncertainty regarding the political context is assessed considering two different energy policy scenarios. Handler et al. (2014) consider both the bioenergy and bioproducts industry in an assessment study with the goal of determining fossil energy demand and GHG (greenhouse gas) emissions associated with the forest-based biomass harvesting and transportation. A variety of sources to collect the data and assumptions for this study where used including a comprehensive survey sent to loggers.

Table 2.3 – Environmental assessment studies of forest wood supply chains.

Metrics	Case Study		Stakeholders Involvement	Reference
	Industry	Region		
LCA	Bioenergy	-	No	(Pucker, et al., 2012)
		Italy	Yes	(Bartolozzi, et al., 2017)
		Europe	No	(Volkart, et al., 2013)
		Singapore	No	(Nian, 2016)
		Germany	No	(Pehnt, 2006)
		-	No	(El-Houjeiri & Field, 2012)
		Sweden	No	(Bengtsson, et al., 2012)
		North America	No	(McNamee, et al., 2016)
		UK	No	(Black, et al., 2011)
		France	No	(Menten, et al., 2015)
	Bioenergy & Bioproducts	USA	Yes	(Handler, et al., 2014)
	Wood Products	Spain	Yes	(González-García, et al., 2011)
		Peru	Yes	(Avadí, et al., 2014)
		France	No	(Pommier, et al., 2016)
	Paper	Europe, Finland & Switzerland	No	(Husgafvel, et al., 2016)
LCA Material Flow Accounting Energy use Emergy	Bioenergy	Italy	No	(Nikodinoska, et al., 2017)
CO_2 emissions	Forestry	China	Yes	(Ge, et al., 2017)
Global Warming Potential	Forestry, Paper & Wood Products	New Zealand	No	(Andrew & Forgie, 2008)
GHG emissions Solid waste	Paper & Wood Products	Canada	No	(Côté, et al., 2008)
30 indicators	Bioenergy, Paper & Wood Products	USA, South Africa, Finland, Japan, China, Brazil & Canada	No	(Lähtinen, et al., 2016)
Environmental emission	Paper	Finland	Yes	(Palander, 2017)
	Wood Products	Saudi Arabia	No	(Marzouk, et al., 2017)
Environmental Footprint Resource Footprints	Bioenergy, Paper & Wood Products	EU-27 countries & China	No	(Tian, et al., 2017)

Three papers applied LCA methodology to the wood products industry, namely to determine the global warming potential (GWP) of different wood based products from the furniture sector (González-García, et al., 2011), to identify the differences in eco-efficiency between different fleet segments including wooden fleets segments (Avadí, et al., 2014), and to validate the use of the vacuum process with green veneers (Pommier, et al., 2016). Two of these studies considered stakeholders' involvement in the assessment process by conducting interviews and company meetings (González-García, et al., 2011) and using surveys and interviews with scientists and experts (Avadí, et al., 2014) to collect inventory data. The only study that considered the paper industry was developed by Husgafvel et al. (2016) and compares the GWP of eight microcrystalline cellulose manufacturing systems. Nikodinoska et al. (2017) developed and applied a multi-criteria environmental accounting framework to assess the environmental performance of a forest bioenergy value chain located in Sarentino Valley (North Italy). This assessment framework encompasses material, energy, and emergy (energy used to maintain a service or make a product) accounting as well as main emissions generated at each step of the chain assessed through the ReCiPe 2008 method.

From the environmental assessment studies reviewed that used the LCA methodology, only a few presents an exhaustive LCIA approach, with the majority choosing a small subset of impact categories and indicators. The LCIA methods and impact category indicators used in each LCA study reviewed are presented in Table 2.4.

Table 2.4 – LCA studies of forest wood supply chains.

LCIA methods, impact categories and indicators	References
ReCiPe 2008	(Volkart, et al., 2013) (Avadí, et al., 2014) (Pommier, et al., 2016) (Nikodinoska, et al., 2017)
ILCD 2011	(Bartolozzi, et al., 2017)
IPCC 2007	(Volkart, et al., 2013)
Cumulated energy demand	(Pehnt, 2006)
Global warming potential	(Pehnt, 2006) (Bengtsson, et al., 2012) (Menten, et al., 2015) (González-García, et al., 2011) (Husgafvel, et al., 2016)
Acidification potential	(Pehnt, 2006) (Bengtsson, et al., 2012)
Eutrophication potential	(Pehnt, 2006) (Bengtsson, et al., 2012)
GHG emissions	(Pucker, et al., 2012) (Nian, 2016) (El-Houjeiri & Field, 2012) (McNamee, et al., 2016) (Black, et al., 2011) (Handler, et al., 2014)
Primary energy use	(Pucker, et al., 2012) (Bengtsson, et al., 2012) (Black, et al., 2011) (Handler, et al., 2014)
Land use efficiency	(El-Houjeiri & Field, 2012)
Energy consumption	(El-Houjeiri & Field, 2012)
Particle emissions (PM10)	(Bengtsson, et al., 2012)
Agricultural land use	(Bengtsson, et al., 2012)

Three different LCIA methods were identified in the reviewed studies that used the LCA methodology. Bartolozzi et al. (2017) selected the ILCD 2011 method in their study while Volkart et al. (2013) chose the IPCC 2007 method to calculate life cycle GHG emissions and seven midpoint indicators of the ReCiPe 2008 method. The works by Avadí et al. (2014), Pommier et al. (2016), and Nikodinoska et al. (2017) also consider the ReCiPe 2008 method to calculate an endpoint single score indicator (i.e. aggregated weighted score), eight midpoint indicators, and five midpoint indicators, respectively.

Only seven of the papers reviewed that report environmental assessment studies do not use LCA. Ge et al. (2017) selected for evaluation of carbon emissions four types of landforms (mountains, hills, plains and islands) and eight villages with different industry types in the Yangtze River Delta region (China). Industry experts were interviewed and families in the eight villages were surveyed to collect data for the analysis. Andrew and Forgie (2008) used input–output analysis to assess the appropriation of GWP by eight industries considering three different responsibility perspectives related to the GHG emissions, those of consumer, producer, and shared responsibility. The opportunities to improve environmental performance by reducing GHG emissions and solid waste of small and medium enterprises linked in supply chains were explored by Côté et al. (2008). An investigation on how global forest industry companies address ecosystem services and biodiversity in supply chain management through corporate responsibility (CR) was conducted by Lähtinen et al. (2016). In this paper, CR reports of thirteen large forest industry companies in the Dow Jones Sustainability Index are analyzed and the indicators used compared to 30 environmental performance indicators of the Global Reporting Initiative guidelines. Palander (2017) assessed the environmental emission associated with transport of pulpwood within a wood procurement region of StoraEnso, an important pulp producer in the global forest industry, using the synchronized calculation method. In this study, stakeholders' involvement in the assessment process occurred in the data collection phase where a survey of StoraEnso was used. Marzouk et al. (2017) developed a model that enables the estimation of six types of emissions such as greenhouse gases and sulfur dioxide and applied it to the construction industry. Lastly, a multi-regional input-output model was employed by Tian et al. (2017) to account for the environmental and resources (i.e. energy, land, material, and water) footprints caused by the trade between China and the EU-27 countries in the year 2008.

2.3.1.2 Two Sustainability Dimensions

As mention in the beginning of Subsection 2.3.1, 33 assessment studies consider indicators regarding two sustainability dimensions. From these, 30 papers focus on the economic and environmental assessment, 2 papers focus on the economic and social assessment, and only one paper focusses on the environmental and social assessment of forest wood supply chains (see Figure 2.3). Table 2.5 presents a summary of the assessment studies applied to forest wood supply chains that address two sustainability dimensions.

Several of these studies consider costs as the only economic assessment indicator. In the works of Hamelinck et al. (2005) and Batidzirai et al. (2006), the echelons of different supply chains were analyzed and compared considering costs, energy use and CO2 emissions. In the first study, stakeholders were involved in the data collection phase through interviews. Cost and CO2 emissions calculations are also used to evaluate the logistics of supplying forest biomass to a potential power plant (Mobini, et al., 2011) and different Bio-CCS technologies such as lignocellulosic ethanol production and biomass-based combined heat and power (CHP) production (Arasto, et al., 2014). Shifting from CO2 emissions to a broader focus on GHG emissions, production costs, avoided emissions and GHG abatement costs of different biomass value chains were appraised by Gerssen-Gondelach et al. (2014) and the replacement by sustainably managed forest of timber from deforestation was evaluated using costs and GHG emissions calculations by Morello (2015). The LCA methodology was also used in conjunction with cost calculation in order to compare pellet production from firewood productions and sawmill residues (Moretti, et al., 2014), electricity and heat generation through four combustion and gasification technologies (Cambero, et al., 2015), and torrefied biomass and traditional solid biofuels (e.g. white pellets) (Thrän, et al., 2016). In the first study, the impact assessment focused on four indicators: ecosystem quality, human health, cumulative energy demand (CED), and GWP (Moretti, et al., 2014), while in the other two studies the focus was only on life cycle GHG emissions (Cambero, et al., 2015; Thrän, et al., 2016). Also, in the study by Moretti et al. (2014), a local survey was used to collect economic data. Kiss et al. (2016) developed a model to simulate and compare three different scenarios for the electricity system of Hungary considering operations, maintenance, and capital costs; energy security; and GWP calculations.

Table 2.5 – Assessment studies of forest wood supply chains that address two sustainability dimensions.

Metrics			**Case Study**		**Stakeholders Involvement**	**Reference**
Economic	**Environmental**	**Social**	**Industry**	**Region**		
Costs	Energy use CO_2 emissions	-	Bioenergy	Europe & Latin America	Yes	(Hamelinck, et al., 2005)
				Mozambique	No	(Batidzirai, et al., 2006)
	CO_2 emissions	-	Bioenergy	Canada	No	(Mobini, et al., 2011)
			Bioenergy & Paper	Finland	No	(Arasto, et al., 2014)
	GHG emissions	-	Bioenergy & Bioproducts	-	No	(Gerssen-Gondelach, et al., 2014)
			Bioenergy	Brazil	No	(Morello, 2015)
	LCA	-	Bioenergy	Italy	Yes	(Moretti, et al., 2014)
				Canada	No	(Cambero, et al., 2015)
				Spain, USA, Tanzania & Canada	No	(Thrän, et al., 2016)
	Energy sources GWP	-	Bioenergy	Hungary	No	(Kiss, et al., 2016)
Carbon avoidance cost		-	Bioenergy	Italy	No	(Nastasi, et al., 2015)
Costs PES CEEP	Energy sources CO_2 emissions	-	Bioenergy	South East Europe	No	(Dominković, et al., 2016)
				Norway	No	(Hagos, et al., 2015)
Costs Economic agent surpluses Prices Quantities	Material Flow Analysis	-	Bioenergy, Paper & Wood Products	France	No	(Lenglet, et al., 2017)
Costs	LCA		Bioenergy	Spain	No	(Sánchez-García, et al., 2017)

Metrics			Case Study		Stakeholders Involvement	Reference
Economic	**Environmental**	**Social**	**Industry**	**Region**		
Raw materials availability						
Costs Energy potential	GHG emissions	-	Bioenergy	European Union	No	(Hoefnagels, et al., 2014)
Energy potential Prices	CO_2 emission	-	Bioenergy	EU-27 countries	No	(Bertrand, et al., 2014)
Energy potential	GHG emissions	-	Bioenergy	-	No	(Koornneef, et al., 2012)
	GHG emissions Land use	-	Bioenergy	Colombia	Yes	(Gonzalez-Salazar, et al., 2017)
	LCA	-	Bioenergy & Paper	Canada	No	(Levasseur, et al., 2017)
Raw materials availability	LCA	-	Bioenergy	Japan	No	(Kanematsu, et al., 2017)
Profit	CO_2 price	-	Bioenergy	Finland	No	(Tsupari, et al., 2017)
	LCA	-	Bioenergy	Japan	Yes	(Kishita, et al., 2017)
Environmental Management Accounting		-	Paper	Canada	Yes	(Gale, 2006)
			Forestry	Greece	Yes	(Papaspyropoulos, et al., 2012)
Wood stock	CO2 stock	-	Forestry	Brazil	No	(Machado, et al., 2015)
Resource efficiency	Resource consumption	-	Bioenergy & Wood Products	Germany	No	(Risse, et al., 2017)
Several indicators	CO2 emissions	-	Paper	Austria	Yes	(Posch, et al., 2015)
Several factors		-	Bioenergy	Finland	Yes	(Proskurina, et al., 2017)
Several sub-criteria		-	Paper	Iran	Yes	(Akhundzadeh & Shirazi, 2017)
Infrastructure Transport distance Raw materials availability	-	SAF Population size	Bioenergy	USA	No	(Martinkus, et al., 2014)
Profit	-	Income	Forestry	Ethiopia	Yes	(Baumgartner, et al., 2015)
-	GHG emissions Mean species abundance Air pollutants emissions Nitrogen surplus	Calorie consumption Energy access People in water stressed areas Child deaths	-	Global	No	(van Vuuren, et al., 2015)

Nastasi et al. (2015) used carbon avoidance cost to compare two Hydro-methane production solutions. Two studies used EnergyPLAN as a modeling tool to compare different parameters of energy systems in the year 2012 and 2050 (including primary energy supply, PES, and the critical excess electricity production, CEEP) (Dominković, et al., 2016) and two different systems for the heating and transport sectors with the reference system (Hagos, et al., 2015). Lenglet et al. (2017) evaluated the potential consequences of various scenarios of raw wood exports reduction policies on both economic outcomes (e.g. variations in prices) for the different actors and material flows. The viability and optimal location of a new hypothetical wood-fired power plant was analyzed by Sánchez-García et al. (2017) by calculating the costs and GHG emissions of the supply chain.

Energy potential was one of the economic criteria used to evaluate the role of international biomass trade considering the renewable energy deployment scenarios for the EU-27 countries (Hoefnagels, et al., 2014); and to appraise the potential biomass demand from the existing power plants in Europe (Bertrand, et al., 2014). As a stand-alone economic criterion, energy potential was used to show the global potential of combining biomass with carbon capture and storage technologies (Koornneef, et al., 2012); to investigate the impacts that an accelerated deployment of bioenergy could have in Colombia until 2030 (Gonzalez-Salazar, et al., 2017); and to offer an assessment under different energy and climate policy scenarios of emerging energy pathways (Levasseur, et al., 2017). Stakeholders were involved in one of these three studies by Gonzalez-Salazar et al. (2017) where expert judgment was used to identify the alternative future scenarios investigated.

Kanematsu et al. (2017) tackled the scale design for a CHP system using woody biomass for district heating and cooling considering the temporal profile of the availability of local biomass. Feasible scale ranges were found by comparing LCA results regarding GHG emissions. The profitability of different options regarding a multifuel CHP plant planned for Helsinki considering different prices of biomass and CO2 emission allowances (Tsupari, et al., 2017); and of an energy business with a 10 MW woody biomass power generation plant considering CO2 emissions calculation (Kishita, et al., 2017) were assessed by Tsupari et al. (2017) and Kishita et al. (2017), respectively. In this last study, data was collected by means of interviews with local stakeholders, interviews with experts in the field of woody biomass and energy sciences, and literature reviews. An Environmental Management Accounting (EMA) framework was used to assess the environmental costs of a Canadian paper mill (Gale, 2006) and a Greek nonprofit forestry organization (Papaspyropoulos, et al., 2012). Data necessary for the assessment was obtained through an environmental cost survey and consultation with managers and staff of the paper mill (Gale, 2006) and short interviews with the nonprofit organization personnel (Papaspyropoulos, et al., 2012). Machado et al. (2015) developed a model for monitoring and evaluating forest growth and quantifying wood stocks and sequestered carbon. The resource consumption and resource efficiency of wood cascading compared to the use of primary wood was determined by Risse et al. (2017). A hybrid method combining a SWOT analysis with an analytic hierarchy process was used by Posch et al. (2015) to identify the most important factors that determine the strategic energy management options in the Austrian paper industry. Experts from three leading companies were involved in the identification and weighting of the factors using semi-structured interviews and surveys. The results show that cost-related factors predominate, and little attention is paid to environmental issues by experts. An overview of the current status of the Finnish wood pellet business was presented by Proskurina et al. (2017). Data regarding different factors that stimulate and inhibit development of the Finnish wood pellet industry was collected through a survey of nearly 60 experts. Akhundzadeh and Shirazi (2017) used a 2-filterd fuzzy decision-making method to assess technological alternatives in the pulp section according to the selected criteria. In this study, industry experts where asked to evaluate alternatives according to model's criteria and to determine the relative importance of each criterion.

The impacts of a project or action on society are finally introduced in the assessment studies by Martinkus et al. (2014), Baumgartner et al. (2015), and van Vuuren et al. (2015). The first study provides a framework for biorefinery siting based on biogeophysical assets (i.e. feedstock, distance from petroleum refineries, infrastructure requirements, and population concentration) and on the social assets of communities supporting these facilities. The social assets were evaluated using a Social Asset Factor (SAF) score that considers three elements - public health status, creative leadership, and social capital (Martinkus, et al., 2014). Baumgartner et al. (2015) developed a model to simulate and assess, through socio-economic indicators, the impacts of the emerging large-scale land acquisitions on the economic status of local populations. The use of focus group discussions, expert interviews, and village-level surveys allow the stakeholders to be involved in the model building. Lastly, a model-based scenario approach used to analyze what is needed, in terms of changes in technology development, lifestyle, and policies to achieve a set of 2050 sustainability objectives (e.g. eradicate hunger and conserve biodiversity) was used in the study conducted by van Vuuren et al. (2015).

2.3.1.3 Three Sustainability Dimensions

A complete sustainability assessment should include not only financial metrics but also measures of a project’s impacts on the environment and society. From the assessment studies reviewed, 18 address the three sustainability dimensions (see Figure 2.3). A summary of these studies is presented in Table 2.6.

The first study by Ooba et al. (2015) assessed four forest management scenarios in Japan, from plantation stage to wood chip production, by simulating the material cycles, estimating the economic cost of each production stage, and using an occupancy rate time index that measures the occupation time for labor, pollution, land use, and material by a human activity. A model for investigating the impacts of various energy technologies was developed by MacCarty and Bryden (2016). The outcomes of the model are the operating costs; energy consumption and global warming impact considered through life cycle analysis; and health impacts assessed using the Relative Hazard Index (RHI) that calculates the quantity of air needed to dilute the pollutants to safe levels. Shmelev and van den Bergh (2016) analyzed arrangements of renewable energy technologies using multi-criteria analysis through investment and electricity costs, water and land use, CO2 emissions, and employment.

Table 2.6 – Assessment studies of forest wood supply chains that address three sustainability dimensions.

Metrics			Case Study		Stakeholders Involvement	Reference
Economic	**Environmental**	**Social**	**Industry**	**Region**		
Costs	Occupancy Rate Time index		Bioenergy	Japan	No	(Ooba, et al., 2015)
	LCA	RHI	Bioenergy	Mali	No	(MacCarty & Bryden, 2016)
	CO_2 emissions Water use Land use	Employment	Bioenergy	UK	No	(Shmelev & van den Bergh, 2016)
Costs Local commerce Supply security	Competition for fertile land Pollution	Planning and monitoring needs Diversity and certainty in ownership and business schemes Training needs Employment rate	Bioenergy	Uganda	Yes	(Buchholz, et al., 2009)
Several indicators			Forestry	Austria	Yes	(Wolfslehner, et al., 2005)
Costs Infrastructure	Weather & Climate Water protection Nature protection	Noise emissions Phytosanitary risks Land use category	Bioenergy	Austria	Yes	(Kühmaier, et al., 2014)
Costs Infrastructure Supply security Energy content Fuel smuggling	CO_2 emissions	Safety Social acceptance Social welfare	Bioenergy	Iran	Yes	(Sehatpour, et al., 2017)
Costs Capacity Factor	GHG emissions Air pollution Land use Water use	Fatalities Jobs	Bioenergy	USA	No	(Klein & Whalley, 2015)
Costs Resource use	GHG emissions Energy use	Employment Occupational safety and health	Wood Products	Germany	No	(Lindner, et al., 2010)
Costs Raw materials availability Energy potential	CO_2 emissions Nature protection	Recreational use	Forestry	Austria	No	(Kraxner, et al., 2016)
Energy potential	Carbon storage Habitat services	Food production Aesthetic values	Bioenergy	Italy	No	(Gissi, et al., 2016)
Industrial and Ecological Cumulative Exergy			Wood Products	USA	No	(Ukidwe & Bakshi, 2007)
Extended Exergy			Bioenergy	China	No	(Chen, et al., 2014)
Total Cumulative Exergy Loss			Bioenergy	Netherlands	No	(Stougie & van der Kooi, 2016)
PWR	LCA	IHDI				
Food self-sufficiency Fuel self-sufficiency Access to clean water	Forests Flood frequency Soil quality index	Health security Livelihood security Cultural dependence	Forestry	Indonesia, China & Japan	Yes	(Suneetha, et al., 2011)

Metrics			Case Study		Stakeholders	Reference
Economic	**Environmental**	**Social**	**Industry**	**Region**	**Involvement**	
GOS GDP Imports	Ecological footprint Water withdrawal GHG emissions Energy consumption	Tax Income Injuries	Forestry	USA	No	(Kucukvar, et al., 2014)
	Several sub-criteria		Paper & Wood Products	-	Yes	(Parkouhi & Ghadikolaei, 2017)
	Community capitals		Bioenergy	USA	No	(Martinkus, et al., 2017b)

With a focus also on multi-criteria analysis (MCA) is the studies by Buchholz et al. (2009), Wolfslehner and Vacik (2005), Kühmaier et al. (2014), Sehatpour et al. (2017) and Klein and Whalley (2015). The goal of the study by Buchholz et al. (2009) was to compare four MCA tools (NAIADE, Decision Lab, DecideIT, and Super Decisions), by applying them to a case study, in terms of their suitability to assess bioenergy systems' sustainability with a special focus on multi-stakeholder inclusion in selection and weighting of criteria and description and ranking of scenarios. Also a comparative study is the work developed by Wolfslehner and Vacik (2005) where two different MCA approaches, the analytic hierarchy process (AHP) and the analytic network process (ANP), were used to compare four silvicultural strategies with a set of six criteria and 43 indicators. Stakeholders were involved in selecting and ranking the criteria according to their relevance and practicality through a national Delphi survey and by European experts, respectively. In the work carried out by Kühmaier et al. (2014), a spatial multi-criteria decision model was built to determine the most appropriate areas for storing biomass considering several criteria. Weights were assigned to each criterion by a group of experts (i.e. operational managers and researchers) using an AHP method. Sehatpour et al. (2017) evaluated eight different alternative fuels with both fossil and renewable bases using several metrics. Experts' judgment was used to score each alternative against each criterion in six alternative scenarios, including one base scenario and five scenarios with different weight settings of criteria. Lastly, MCA with quantitative input values (maximum, nominal, and minimum) for several sustainability criteria and decision-maker preference scenarios were used by Klein and Whalley (2015) to compare a variety of non-renewable and renewable options. In this research the different weight values attributed to each sustainability criterion in each scenario were not assigned by decision makers but by the authors of the article. The objective of the paper written by Lindner et al. (2010) was to present a software called Tool for Sustainability Impact Assessment (ToSIA) of Forest-Wood-Chains (FWCs). Two FWCs that produce timber and only differ in the management alternatives of Norway spruce were compared using six sustainability indicators (costs, resource use, GHG emissions, energy use, employment, and occupational safety and health) provided by the tool. The study by Kraxner et al. (2016) conducts a geospatial analysis of urban forests in order to assess its potential of increasing feedstock for bioenergy generation by calculating the physical amounts of biomass available and respective energy potential in the urban forests area excluding major areas used for either nature protection or recreation. Furthermore, the supply chain costs and the CO2 emissions were roughly calculated. Gissi et al. (2016) aims to evaluate suitable areas for biomass production considering interactions and trade-offs between biomass-based energy sources and other ecosystem services such as aesthetic values, habitat services carbon storage, and food production. The exergy concept was used in the studies by Ukidwe and Bakshi (2007), Chen et al. (2014), and Stougie and van der Kooi (2016). The first study calculated the industrial cumulative exergy consumption (ICEC) and the ecological cumulative exergy consumption (ECEC) of 488 industry sectors (e.g. sawmills sector and venner and plywood manufacturing sector) in the United States of America. While ICEC considers the exergy of all natural resources used directly and indirectly by each sector, the ECEC also accounts for the exergy used for generating each natural resource (Ukidwe & Bakshi, 2007). The paper by Chen et al. (2014) used the extended exergy to analyze the changes of the natural resources input into China for 8 years. This metric emphasizes the primary production factors such as capital, labor, and environmental remediation. At last, Stougie and van der Kooi (2016) compared the Total Cumulative Exergy Loss method to the Present Worth Ratio (PWR), ReCiPe endpoint single score indicator, and the Inequality-adjusted Human Development Index (IHDI). This method considers all exergy losses caused by a technological system during its life cycle. Suneetha et al. (2011) developed an indicator-based assessment framework that integrates data from biophysical parameters related to changes of flood frequency, soil quality, and forest area; and socioeconomic parameters related to populations basic needs (e.g. food self-sufficiency and health security), livelihoods and their spiritual requirements. This framework can be used to detect alterations to productive resources of ecosystems and trace the dependence of local populations' well-being on those ecosystems. In this study data was partially collected through surveys in multi-stakeholder forums. A comprehensive TBL sustainability assessment framework to analyze the impacts of the USA final demand categories (e.g. household consumption) was proposed by Kucukvar et al. (2014). Several macro-level indicators were included in the framework such as the Gross Operating Surplus (GOS), the Gross Domestic Product (GDP), the Ecological Footprint, and the Income of employees. Parkouhi and Ghadikolaei (2017) proposed a model comprising qualitative and quantitative sub-criteria (e.g. freight cost) to measure supplier resiliency. This model was applied to a large industrial unit in the Wood and Paper Industry allowing the identification of the most resilient suppliers. Experts of the Wood and Paper Industry who are also the decision makers in the supplier selection were asked to determine the degree of relevance of each sub-criterion, to identify sub-criteria that were not given in the model but were important, and to rank the suppliers regarding each sub-criterion used. The last assessment study reviewed to consider all three sustainability dimensions was the one carried out by Martinkus et al. (2017) where the potential of pulp mills to be repurposed as biorefineries was assessed considering community capitals such as natural capital measured as the total delivered feedstock cost.

After the detailed analysis above provided of the assessment studies regarding forest wood supply chains, Questions 1, Questions 2 and part of Questions 6 can be answered.

Q1) How have the different sustainability dimensions been included in the assessment of forest wood supply chains?

Figure 2.4 to Figure 2.6 summarize how the economic, environmental and social sustainability dimensions have been considered.

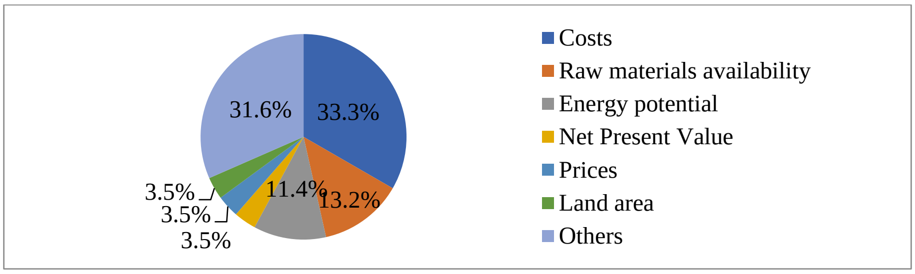

Figure 2.4 – Metrics used in the economic assessment of forest wood supply chains.

On the economic dimension, cost assessment is the most used metric to determine the economic feasibility of forest wood supply chains, followed by raw materials availability and energy potential estimations. Other metrics used include the impact on the GDP, payback period assessment and profit estimations.

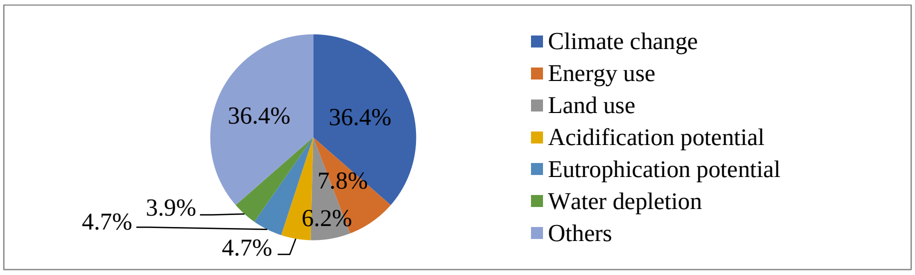

Figure 2.5 – Metrics used in the environmental assessment of forest wood supply chains.

On the environmental impacts, the most used metrics are related to climate change. These include the GWP, CO2 and GHG emissions calculations. While some assessment studies focus only on CO2 emissions, other have a broader scope and consider more greenhouse gases such as methane (CH4). These last studies convert the GHG emissions into a common unit, i.e. carbon dioxide equivalent (CO2-Equiv.), to compare the impact that different greenhouse gases have on climate change (Husgafvel, et al., 2016).

Energy, land, and water use and together with acidification and eutrophication potential were also considerably utilized. Other metrics used include ozone depletion, toxicity, and particle emissions.

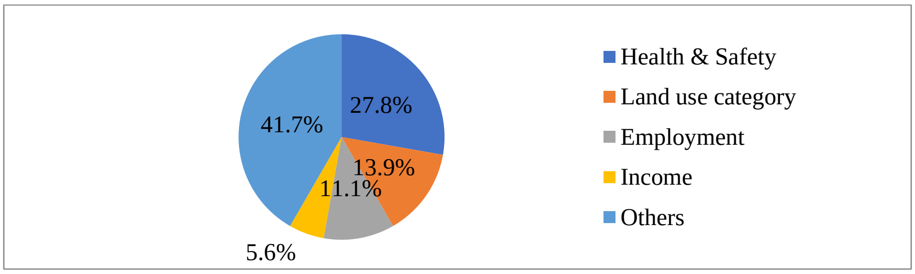

Figure 2.6 – Metrics used in the social assessment of forest wood supply chains.

On the social dimension, the most used metrics are related to the populations' health (e.g. calorie consumption and child deaths) and employee's safety (e.g. injuries). Land use category (e.g. recreational use and food production lands), employment and income are the following most used type of indicators. Other metrics include energy access and training needs.

Q2) Have stakeholders been involved in the assessment process?

Stakeholders were involved in 26 % of the assessment studies reviewed. The steps of the assessment process in which they were involved are presented in Table 2.7.

Table 2.7 – Stakeholders involvement in the assessment process of forest wood supply chains.

Steps	References
Data collection	(Wit, et al., 2013) (van Eijck, et al., 2014) (Hauk, et al., 2014) (Hsueh, 2015) (Bartolozzi, et al., 2017) (Handler, et al., 2014) (González-García, et al., 2011) (Avadí, et al., 2014) (Ge, et al., 2017) (Palander, 2017) (Hamelinck, et al., 2005) (Moretti, et al., 2014) (Kishita, et al., 2017) (Gale, 2006) (Papaspyropoulos, et al., 2012) (Suneetha, et al., 2011)
Model building	(Baumgartner, et al., 2015)
Criteria selection	(Posch, et al., 2015) (Akhundzadeh & Shirazi, 2017) (Buchholz, et al., 2009) (Wolfslehner, et al., 2005) (Parkouhi & Ghadikolaei, 2017)
Criteria weighting	(Posch, et al., 2015) (Akhundzadeh & Shirazi, 2017) (Buchholz, et al., 2009) (Wolfslehner, et al., 2005) (Kühmaier, et al., 2014) (Sehatpour, et al., 2017) (Parkouhi & Ghadikolaei, 2017)
Options/Scenario description	(Wit, et al., 2013) (McDowall, et al., 2012) (Gonzalez-Salazar, et al., 2017) (Buchholz, et al., 2009)
Options/Scenario ranking	(Proskurina, et al., 2017) (Akhundzadeh & Shirazi, 2017) (Buchholz, et al., 2009) (Sehatpour, et al., 2017) (Parkouhi & Ghadikolaei, 2017)

Q6) In which regions and industries of the forest sector have case studies been explored?

Figure 2.7 depicts the regions and industries used as case studies. It is important to mention that in the case of the European region some studies focus on the whole region while others focus on a specific European country. For this reason, the country-specific studies appear separate in Figure 2.7. For example, five studies consider a French case study while seven case studies used the entire European region as a case study (see Figure 2.7).

Case studies related to the bioenergy industry are the most frequently used, followed by the paper, wood products and forestry industries. The least considered industry is the bioproducts industry. Europe was by far the most studied region (72 papers) but several assessment papers have also started to consider case studies in developing countries such as Ethiopia, Malaysia and Uganda.

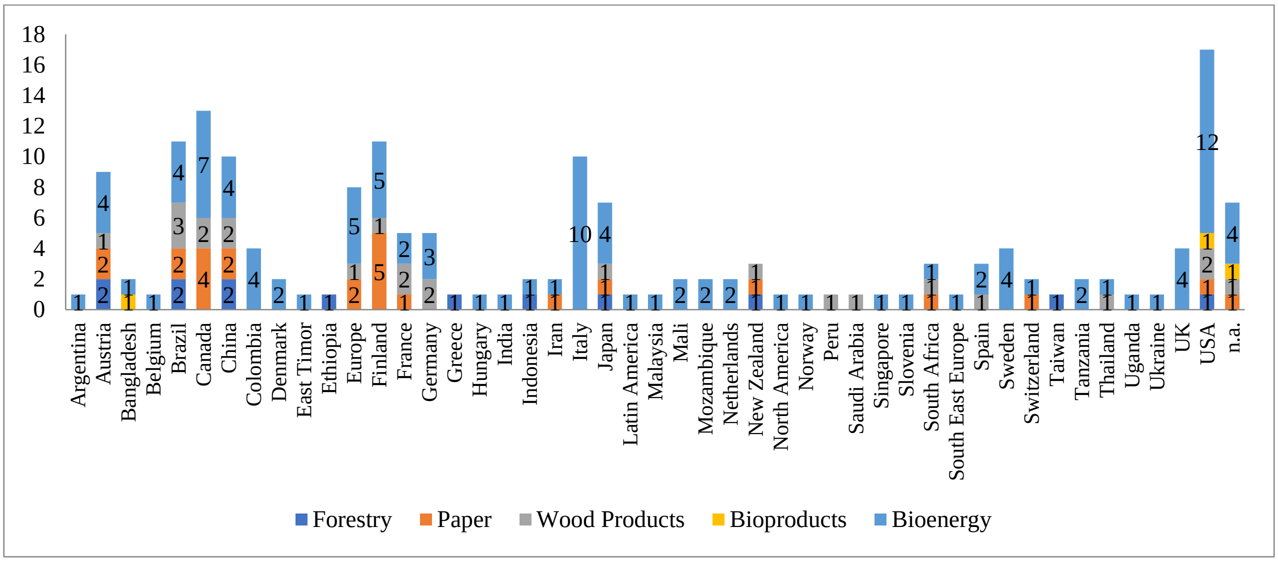

Figure 2.7 – Regions and industries used as case studies in the assessment of forest wood supply chains.

Assessment studies are utilized to evaluate and compare forest wood supply chains from an economic, environmental and/or social perspective, but they cannot be used to determine optimal solutions on those supply chains. For this purpose, the use of mathematical programming is required.

2.3.2 Optimization studies

From the 84 papers reviewed that address optimization of forest wood supply chains, 33 studies focus only on one sustainability dimension (Subsection 2.3.2.1), 43 papers focus on the economic and environmental sustainability dimensions (Subsection 2.3.2.2), and only 8 studies focus on all three sustainability dimensions (Subsection 2.3.2.3). The distribution of optimization studies according to the sustainability dimensions explored is presented in Figure 2.8.

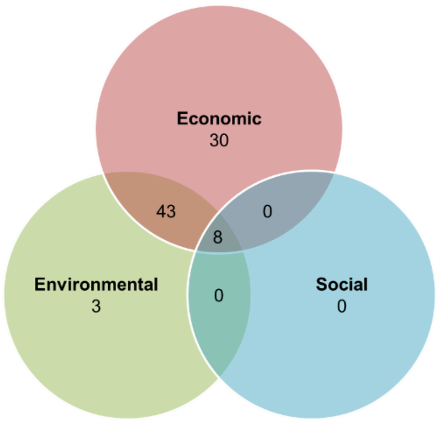

Figure 2.8 – Distribution of optimization studies regarding forest wood supply chains according to the sustainability dimensions explored.

At the end of this subsection, the answers to Questions 3, Questions 4, Questions 5 and part of Questions 6 formulated in Section 2.2 will be provided.

2.3.2.1 One Sustainability Dimension

From the 33 optimization studies that present a single-objective optimization model based on the optimization a single criterion of sustainability, 30 papers focus on the economic optimization and 3 papers focus on environmental optimization of forest wood supply chains (see Figure 2.8). A summary of the single-objective optimization models reviewed in this work is presented in Table 2.8.

Looking at Table 2.8 it is possible to conclude that many economic optimization models regarding forest wood supply chains address strategic, strategic and tactical, or tactical decisions while maximizing profit or minimizing the total supply chain cost. Other single-objective economic optimization studies regarding forest wood supply chains consider the maximization of net present value (Machani, et al., 2015), harvest volume (Galatsidas, et al., 2013) (Gautam, et al., 2015) and satisfied demand (Santibañez-Aguilar, et al., 2015); and the minimization of raw materials' waste (Oliveira, et al., 2016). The studies by Galatsidas et al. (2013) and Oliveira et al. (2016) focus on strategic decision levels. In the first case, two linear programming models are developed for the production and harvesting scheduling optimization of fuelwood produced from even-aged (coppice) Oak forests (Galatsidas, et al., 2013) while Oliveira et al. (2016) developed an information system that optimizes the use of raw materials, addressing the materials procurement and the use of these materials in the production environment. With a focus on both strategic and tactical decision are the works of Gautam et al. (2015) where decision regarding cut blocks allocation for each year, silvicultural treatment prescribed to each cut block, and monthly harvesting schedules to meet the prevailing demand are considered, and Santibañez-Aguilar et al. (2015) who developed a model capable of selecting the plants and technologies, final products and raw materials in order to maximize the satisfied product demand while also assessing the gross profit. The objective function used by Machani et al. (2015) was net present value maximization in their scenario-based modeling approach. This approach was used to help a pulp and paper company in identifying the most robust strategic options considering different scenarios.

Table 2.8 – Optimization studies of forest wood supply chains that address one sustainability dimension.

Model	Decision Levels	Objective Function	Case Study: Industry	Case Study: Region	Reference
Linear Deterministic	Strategic	Costs	Bioenergy	USA	(Huang, et al., 2010)
				Portugal	(Paulo, et al., 2015)
				Sweden	(de Jong, et al., 2017)
		Profit	Bioenergy	USA	(Parker, et al., 2010)
				Colombia	(Gonzalez-Salazar, et al., 2014b)
		Harvest volume	Bioenergy	Greece	(Galatsidas, et al., 2013)
		Waste of raw materials	Wood Products	Europe	(Oliveira, et al., 2016)
		Carbon Footprint	Wood Products	USA	(Carrano, et al., 2015)
		GWP	Bioenergy	Ireland	(Murphy, et al., 2016)
		GWP Fossil energy consumption	Bioenergy	Denmark	(Tonini, et al., 2017)
	Strategic & Tactical	Costs	Bioenergy	Austria	(Heckl, et al., 2015)
				South Korea	(Lee, et al., 2017)
			Bioenergy & Bioproducts	South Korea	(Kim & Kim, 2016)
			Bioproducts	South Korea	(Woo, et al., 2016)
		Profit	Bioenergy	USA	(Kim, et al., 2010)
					(An, et al., 2011b)
		Harvest volume	Forestry	Canada	(Gautam, et al., 2015)
	Tactical	Costs	Forestry	Sweden	(Whitman, et al., 2017)
			Bioenergy	USA	(Stasko, et al., 2011)
				Australia	(Ghaffariyan, et al., 2013)
				South Korea	(Seulki & Kim, 2017)
		Profit	Bioenergy	Canada	(Boukherroub, et al., 2017)
			Bioproducts	-	(Mansoornejad, et al., 2013)
Linear Stochastic	Strategic	Costs	Bioenergy	Bhutan	(Feuerbacher, et al., 2016)
				-	(Zamar, et al., 2015)
				-	(Zamar, et al., 2017)
	Strategic & Tactical	Profit	Bioenergy	USA	(Kim, et al., 2011)
		Costs	Bioenergy	USA	(Poudel, et al., 2016)
Linear Stochastic/Robust	Strategic & Tactical	Profit	Bioenergy	USA	(Azadeh, et al., 2014)
Linear Robust	Strategic	Net Present Value	Paper	Canada	(Machani, et al., 2015)
	Strategic & Tactical	Costs	Bioenergy	USA	(Tong, et al., 2014a)
Linear Fuzzy	Strategic & Tactical	Costs	Bioenergy	USA	(Tong, et al., 2014b)
Non-linear Deterministic	Strategic & Tactical	Satisfied demand	Bioenergy	Mexico	(Santibañez-Aguilar, et al., 2015)

Only 3 single-objective optimization models focus on an environmental objective function and they consider strategic decisions. Carrano et al. (2015) developed an optimization model to investigate the effects of different pallet management strategies in the carbon footprint considering different scenarios. This metric is expressed in the same unit as GWP and GHG emission (i.e. CO2-Equiv.). Murphy et al. (2016) determine, for the year 2020, the optimal amount of different biomass types that supplies each CHP and power plants while minimizing the global warning potential. Other environmental impacts were considered through an LCA including the cumulative energy demand (CED), the eutrophication potential (EP), and the acidification potential (AP). Finally, Tonini et al. (2017) identified the identified the optimal uses of Denmark biomass resources considering global warming contribution and fossil energy resource consumption minimization.

Most of these optimization models were applied to the bioenergy industry, the bioproducts industry (Woo, et al., 2016) (Mansoornejad, et al., 2013) or both (Kim & Kim, 2016). Other works were applied to the wood products industry (Oliveira, et al., 2016) (Carrano, et al., 2015), the paper industry (Machani, et al., 2015), and two studies do not mention a specific industry being more focused on silvicultural treatments that deal with the growth, health, and quality of forests (Gautam, et al., 2015) and the transportation of forest commodity (Whitman, et al., 2017). Most of the single-objective optimization studies regarding forest wood supply chains consider linear models with only one study considering nonlinearity (Santibañez-Aguilar, et al., 2015). Most of these optimization studies are deterministic and non-deterministic parameters were included through stochastic programming using scenario analysis, stochastic and robust programming (Azadeh, et al., 2014), robust optimization (Machani, et al., 2015) (Tong, et al., 2014a) and fuzzy programming (Tong, et al., 2014b). No uncertainty was considered in studies dealing only with tactical decisions and on the three environmental optimization studies.

2.3.2.2 Two Sustainability Dimension

Most optimization studies that consider two sustainability dimensions integrate economic and environmental criteria as part of the objective function(s). These studies include multi-objective optimization studies, compromise criterion optimization studies, and studies where multiple single-objective optimizations are performed. A summary of these studies is presented in Table 2.9.

From these three different approaches to incorporate economic and environmental sustainability dimensions in the optimization of forest wood supply chains, the most used approach was the optimization of economic and environmental objective functions simultaneously using multi-objective optimization. Cost minimization was the most used economic objective function simultaneously optimized with GHG emissions (Guo, et al., 2016) (Gao & You, 2017) (Balaman, 2016) and global warming potential (Arora, et al., 2017) minimization, ecological footprint (amount of land needed to support the resource consumption and rectify the corresponding wastes of a given population) and emergy minimization (Vance, et al., 2015), GHG emissions and use of non-renewable energy sources minimization and use of renewable energy sources maximization (Kostevšek, et al., 2016), and environmental index minimization (Neto, et al., 2008). These multi-objective optimizations were used to address strategic (Guo, et al., 2016) (Vance, et al., 2015) (Kostevšek, et al., 2016) (Arora, et al., 2017), strategic and tactical (Gao & You, 2017) (Balaman, 2016), and tactical (Neto, et al., 2008) decisions of bioenergy, bioproducts (Arora, et al., 2017), and paper (Neto, et al., 2008) supply chains. Profit and NPV maximization were simultaneously optimized with GHG emissions (Zhang, et al., 2014) (Hombach & Walther, 2015) and Eco-indicator 99 (Pinto-Varela, et al., 2011) (Santibañez-Aguilar, et al., 2016) minimization to determine strategic (Zhang, et al., 2014) (Hombach & Walther, 2015), and strategic and tactical (Pinto-Varela, et al., 2011) (Santibañez-Aguilar, et al., 2016) decisions in bioenergy (Hombach & Walther, 2015) (Santibañez-Aguilar, et al., 2016), bioproducts (Zhang, et al., 2014), and paper (Pinto-Varela, et al., 2011) supply chains.

Table 2.9 – Optimization studies of forest wood supply chains that address two sustainability dimensions as objective functions.

Integration Sustainability Dimensions	Model	Decision Levels	Objective Functions	Case Study: Industry	Case Study: Region	Reference
Multi-objective	Linear Deterministic	Strategic	Costs GHG emissions	Bioenergy	UK	(Guo, et al., 2016)
			Costs Ecological footprint & Emergy	Bioenergy	-	(Vance, et al., 2015)
			Costs GHG emissions & Energy sources	Bioenergy	Slovenia	(Kostevšek, et al., 2016)
			Costs GWP	Bioproducts	Australia, Brazil & India	(Arora, et al., 2017)
			Profit GHG emissions	Bioproducts	USA	(Zhang, et al., 2014)
			Net Present Value GHG emissions	Bioenergy	German	(Hombach & Walther, 2015)
		Strategic & Tactical	Profit Eco-indicator 99	Paper	Portugal	(Pinto-Varela, et al., 2011)
		Tactical	Costs Environment index	Paper	Europe	(Neto, et al., 2008)
	Linear Stochastic	Strategic & Tactical	Profit Eco-indicator 99	Bioenergy	Mexico	(Santibañez-Aguilar, et al., 2016)
			Costs GHG emissions	Bioenergy	USA	(Gao & You, 2017)
	Linear Fuzzy	Strategic & Tactical	Costs GHG emissions	Bioenergy	Turkey	(Balaman, 2016)
Compromise criterion	Linear Deterministic	Strategic	Costs GHG emissions	Bioenergy	USA	(Zhang, et al., 2016)

Integration Sustainability Dimensions	Model	Decision Levels	Objective Functions	Case Study Industry	Case Study Region	Reference
			Costs CO2 emissions	Bioenergy	Alpine Region	(Mesfun, et al., 2017)
		Strategic & Tactical	Costs GHG emissions & Energy use	Bioenergy	USA	(Zhang, et al., 2017)
	Linear Stochastic	Strategic	Costs CO2 emissions	Bioenergy	Austria	(Schmidt, et al., 2010)
		Strategic & Tactical	Costs CO2 emissions	Bioenergy & Paper	USA	(Quddus, et al., 2017)
			Profit GHG emissions	Bioenergy	USA	(Osmani & Zhang, 2014)
Multiple single objective	Linear Deterministic	Strategic	Costs Carbon Footprint	Bioenergy	Europe	(Lam, et al., 2010)
			Net Present Value GHG emissions & Energy Balance	Bioenergy	Italy	(Fiorese, et al., 2013)
			Net Present Value & Energy production Climate regulation & Air quality regulation	Bioenergy	USA	(Hanes, et al., 2017)
		Strategic & Tactical	Profit & Costs GHG emissions	Bioenergy	UK	(Samsatli, et al., 2015)
			Profit CO2 sequestration	Bioenergy, Paper & Wood Products	Canada	(Bouchard, et al., 2017)

The other two approaches to incorporate economic and environmental sustainability dimensions in the optimization of forest wood supply chains are the use of compromise criterion optimization and multiple single-objective optimizations. Cost minimization (Zhang, et al., 2016) (Mesfun, et al., 2017) (Zhang, et al., 2017) (Schmidt, et al., 2010) (Quddus, et al., 2017) and profit maximization (Osmani & Zhang, 2014) were used to determine strategic (Zhang, et al., 2016) (Mesfun, et al., 2017) (Schmidt, et al., 2010), and strategic and tactical (Zhang, et al., 2017) (Quddus, et al., 2017) (Osmani & Zhang, 2014) decisions of bioenergy and paper supply chains. In these studies, GHG emissions (Zhang, et al., 2016) (Zhang, et al., 2017) (Osmani & Zhang, 2014), CO2 emissions (Mesfun, et al., 2017) (Schmidt, et al., 2010) (Quddus, et al., 2017), and energy used (Zhang, et al., 2017) were monetized through carbon credits and directly incorporated into the objective functions. Lam et al. (2010) considered the separated minimization of cost and carbon footprint; Fiorese et al. (2013) used the maximization of three objective functions separately: net energy balance, net CO2eq emissions avoided, and net present value of investment; and Hanes et al. (2017) considered NPV, energy production, net climate regulation supply and net air quality regulation supply maximization to determine strategic level decisions. Addressing both strategic and tactical decisions are the work by Samsatli et al. (2015) and Bouchard et al.

(2017) where profit (Samsatli, et al., 2015) (Bouchard, et al., 2017) and CO2 sequestration (Bouchard, et al., 2017) maximization along with costs and GHG emissions (Samsatli, et al., 2015) minimization, were used separately as objective functions. These studies were applied mostly to the bioenergy industry but also to the paper and wood products industries (Bouchard, et al., 2017).

Other studies have integrated the economic and environmental sustainability dimensions in the optimization of forest wood supply chains by considering economic objective functions and including the environmental dimension as constraints or as auxiliary calculations. A summary of these studies is presented in Table 2.10.

The strategic level of decision making has been the most addressed in the single-objective optimization studies where the environmental sustainability dimension was integrated as a constraint. Liu et al. (2014)(2016) developed an optimization model in order to determine the quantity of biomass procured from each location considering overall costs minimization where the GHG emissions were included in the objective function as tax or incentives imposed on emissions and in a constraint so as to ensure that the emissions will not exceed a defined limit. Frombo et al. (2009) developed an Environmental Decision Support System for the optimal utilization of agro-forest biomass and wood residues considering profit maximization and a constraint restricting its collection to prevent species extinction. A mixed integer programming model for the optimal design of second-generation biofuel supply chains considering net present value maximization was studied by Hombach et al. (2016). One of the model's constraints ensures that the total amount of GHG emissions from the produced second-generation biofuel and the used first-generation biofuel does not exceed the maximum amount allowed. Bettinger and Boston (2008) considered as an objective function the minimization of the deviations between target harvest volume and scheduled harvest volume subject to several constraints related to habitat levels, harvest age, green-up period, and adjacency of clearcuts. The economic and ecological impacts of different business policies were evaluated by Rijal and Lussier (2017) by developing six business models in a linear programming framework. These models were also simulated using a hard constraint to preserve at least 20% of old-growth forest area. Mansuy et al. (2015) developed a model to optimized the amount of harvesting residues and biomass used to supply pellet plants considering the maximization of biomass satisfied demand. An ecological constraint was applied in order to exclude the biomass procurement that presents more than 75% risk of provoking damage to the ecosystem. Finally, Najmi et al. (2016) addressed a model that optimizes, based on profit maximization, the quantity of final products, feedstocks, crude oil, and design of an advanced hydrocarbon biofuel supply chain integrated with existing petroleum refineries. GHG emissions' cost is considered in the objective function and an emission cap is considered as a constraint.

Table 2.10 – Optimization studies of forest wood supply chains that address two sustainability dimensions as objective functions and constraints or auxiliary calculations.

Model	Decision Levels	Sustainability Dimensions		Case Study		Reference
		Objective Function	**Constraint/Calculation**	**Industry**	**Region**	
Linear Deterministic	Strategic	Costs GHG emissions	GHG emissions	Bioenergy	USA	(Liu, et al., 2014) (Liu, et al., 2016)
		Profit	Species extinction	Bioenergy	Italy	(Frombo, et al., 2009)
		Net Present Value	GHG emissions	Bioenergy	Germany	(Hombach, et al., 2016)
		Harvest volume	Habitat levels Harvest age Green-up period Adjacency of clearcuts	Wood Products	USA	(Bettinger & Boston, 2008)
		Net Present Value & Harvest volume	Proportion of area occupied by old-growth stands	Wood Products	Canada	(Rijal & Lussier, 2017)
		Satisfied demand	Risk of damage	Bioenergy	Canada	(Mansuy, et al., 2015)
		Costs	CO2 emissions	Bioenergy	South Korea	(Kraxner, et al., 2014)
					Finland	(Zakeri, et al., 2015)
			GHG emissions	Bioenergy	Brazil	(Jonker, et al., 2016)
				Bioproducts	USA	(Mirkouei, et al., 2016)
		Profit	GWP Water consumption Fossil energy usage	Bioenergy	USA	(Liu, et al., 2017)
	Strategic & Tactical	Profit	GHG emissions	Bioenergy	-	(Čuček, et al., 2014)
		Costs	GHG emissions	Bioenergy	USA	(Elia, et al., 2011)
		Net Present Value	CO2 emissions	Bioenergy & Bioproducts	Spain	(Lainez-Aguirre, et al., 2017)
	Tactical	Costs CO2 emissions	CO2 emissions	Bioenergy	USA	(Palak, et al., 2014)
Linear Stochastic	Strategic & Tactical	Costs	CO2 emissions	Bioenergy	Canada	(Parkinson & Djilali, 2015)
		Costs CO2 emissions	CO2 emissions	Bioenergy	USA	(Marufuzzaman, et al., 2014)
	Tactical	Costs	GWP	Bioenergy	Pacific Northwest	(Mirkouei, et al., 2017b)
Non-linear Deterministic	Strategic	Profit GHG emissions	GHG emissions	Bioenergy	Iran	(Najmi, et al., 2016)
		Costs	CO2 emissions	Bioenergy	USA	(Sanchez & Callaway, 2016)

A combination of strategic and tactical decisions was also studied. Cost minimization was the objective function considered to study the United States energy supply chain network subject to an environmental constraint that imposes a GHG emission target level for each natural gas to liquids plant (Elia, et al., 2011), and in the case of electricity generation planning in British Columbia, Canada considering constraints related to CO2 emissions (Parkinson & Djilali, 2015). Lainez-Aguirre et al. (2017) constructed a model to establish the optimal carbon capture and utilization supply chain configuration under a CO2 emissions abatement condition and using the NPV maximization as an objective function. A two-stage stochastic programming model considering technology development and feedstock uncertainties was discussed by Marufuzzaman et al. (2014) in order to determine the design and management decisions of a biodiesel supply chain. Four extensions of the model formulation were developed to capture the impact that different carbon regulatory policies (e.g. carbon tax and carbon cap) have on these decisions. The same four extensions were proposed by Palak et al. (2014) to capture the impact of such policies on tactical decisions (e.g. supplier and transportation mode selection).

As previously mention, the environmental sustainability dimension has also been integrated as an auxiliary calculation in economic optimization models [192-197, 203, 205]. Cost minimization was the most utilized economic objective function and CO2 (Kraxner, et al., 2014) (Zakeri, et al., 2015) (Sanchez & Callaway, 2016), GHG emissions (Jonker, et al., 2016) (Mirkouei, et al., 2016), and global warming potential (Mirkouei, et al., 2017b) were used to calculate the environmental impacts of strategic and tactical (Mirkouei, et al., 2017b) decisions in bioenergy and bioproducts (Mirkouei, et al., 2016) supply chains. Profit maximization was used to define strategic (Liu, et al., 2017) (Čuček, et al., 2014) and tactical (Čuček, et al., 2014) decisions of a bioenergy supply chain while calculating GWP, water consumption and fossil energy usage (Liu, et al., 2017), and GHG emissions (Čuček, et al., 2014).

Two optimization studies regarding forest wood supply chains that consider the economic and environmental sustainability dimensions include nonlinearities (Najmi, et al., 2016) (Sanchez & Callaway, 2016) while the majority does not. Most models do not consider parameters' uncertainty and the ones that do use stochastic and fuzzy programming.

2.3.2.3 Three Sustainability Dimension

From the optimization studies reviewed, 8 address the three sustainability dimensions (see Figure 2.8). A summary of these studies is presented in Table 2.11.

Optimization of forest wood supply chains considering the three dimensions of sustainability first appeared in 2012 when Herran and Nakata (2012) introduced a strategic optimization model for designing decentralized energy systems using biomass for rural electrification in developing countries. The goal was to minimize total net costs and assess the mitigation of CO2 emissions and the changes in the net local income (the difference between the income resulting from selling local biomass and the electricity bills paid). The model presented by Cambero and Sowlati (2016) addresses the strategic design of a forest-based biorefinery supply chain considering net present value, GHG emission saving potential and social benefit maximization. This social criterion bases the impacts of new jobs on their type and location. Strategic and tactical decisions were considered in the problem formulation developed by Santibañez-Aguilar et al. (2014) with the goal of determining the optimal configuration of a distributed biorefining supply chain and the associated planning decisions that simultaneously maximize profit and number of jobs generated and minimizes the Eco-indicator99. Both models developed by Cambero and Sowlati (2016) and Santibañez-Aguilar et al. (2014) were solved using the ε-constraint method. Miret et al. (2016) suggested a model to optimize a biomass supply chain's network design, facilities locations, storage level and logistics management decisions considering total annual costs and ecocosts minimization and job creation maximization. Ecocosts are calculated by allocating a cost penalization to the use of an alternative that would be less environmentally friendly. A new compromise criterion termed "sustainability profit" composed of economic, environmental and social indicators for multi-criteria evaluation of sustainable systems was developed by Zore et al. (2017). All these indicators are expressed in monetary terms, which allows for the different criteria to be merged, and a multi-objective optimization problem can be reduced to a single-objective one. Since people are used to thinking in monetary terms, the solution obtained is intuitive and all elements of sustainability can be directly compared. The new concept for measuring sustainability is based on microeconomic (company's viewpoint) and on wider macroeconomic perspectives (combined government's and company's viewpoint) and is illustrated using three examples of supply networks including a large-scale biorefinery supply network.

Table 2.11 – Optimization studies of forest wood supply chains that address three sustainability dimensions.

Model	Decision Levels	Sustainability Dimensions		Case Study		Reference
		Objective Function	Calculation	Industry	Region	
Linear Deterministic	Strategic	Costs	CO_2 emissions Income	Bioenergy	Colombia	(Herran & Nakata, 2012)
		Net Present Value GHG emissions Social benefit	-	Bioenergy	Canada	(Cambero & Sowlati, 2016)
	Strategic & Tactical	Profit Eco-indicator 99 Job creation	-	Bioenergy	Mexico	(Santibañez-Aguilar, et al., 2014)
		Costs EcoCosts Job creation	-	Bioenergy	France	(Miret, et al., 2016)
		Profit Eco-profit Social profit	-	Bioenergy	-	(Zore, et al., 2017)
	Tactical	Costs GHG emissions Job creation	-	Wood Products	Canada	(Boukherroub, et al., 2013)
		Costs GHG emissions Job creation & Employment stability	-	Wood Products	Canada	(Boukherroub, et al., 2015)
Linear Stochastic	Strategic	Profit GHG emissions Job creation	-	Bioenergy	USA	(Osmani & Zhang, 2017)

The only optimization studies to focus on the tactical level were developed by Boukherroub et al. (2013)(2015) and are also the only ones that do not consider a bioenergy supply chain but instead a wood products supply chain (i.e. the Canadian lumber supply chain) in their case studies. The weighted goal programming technique was used and three sustainability objectives were selected: cost and GHG emission reduction, and local job creation (Boukherroub, et al., 2013; Boukherroub, et al., 2015) and employment stability which considers the total number of hires and layoffs (Boukherroub, et al., 2015) maximization. The majority of the optimization studies reviewed that address the three sustainability dimensions are based on linear and deterministic models with the exception of the study developed by Osmani and Zhang (2017) where a multi-objective optimization model to design a sustainable multi-period second generation biomass-to-bioethanol supply chain under multiple uncertainties was proposed. This study considered strategic and tactical decisions in the problem formulation with the goal of simultaneously maximize profit and number of jobs generated and minimizes GHG emissions. The ε–constraint method was used, and the three uncertain parameters were considered lignocellulosic-biomass supply, bioethanol demand and selling price.

After the detailed analysis of the optimization studies regarding forest wood supply chains, Questions 3, Questions 4, Question 5, and part of Questions 6 can be answered.

Q3) How have the different sustainability dimensions been explored when applying optimization models to forest wood supply chains?

The different sustainability dimensions can be included in the optimization models as objective function(s) or as constraints and calculations. For this reason, the answer to Question 6 is provided in Figure 2.9 to Figure 2.11 regarding the use of the economic, environmental and social sustainability dimensions as objective function(s), respectively, and Figure 2.12 regarding the inclusion of the different sustainability dimensions as constraints or calculations.

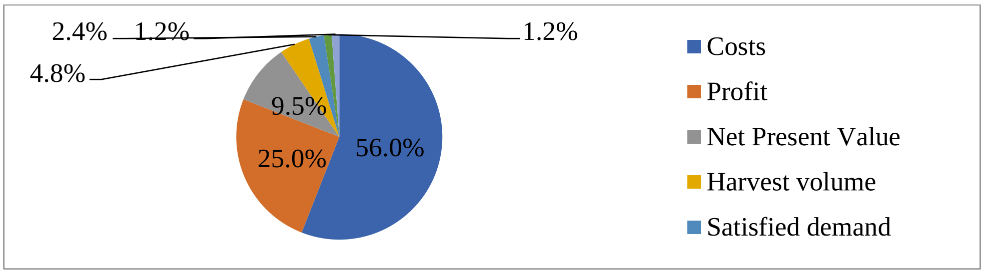

Figure 2.9 – Objective functions used in the economic optimization of forest wood supply chains.

The most used economic objective function is cost minimization, followed by profit, NPV, harvest volume, and satisfied demand maximization. The least used economic objective functions are waste of raw material minimization and energy production maximization.

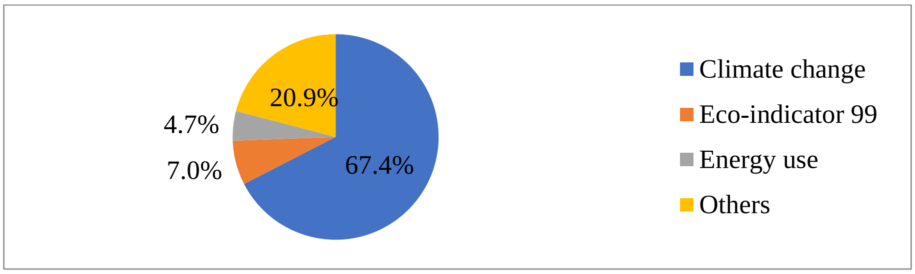

Figure 2.10 – Objective functions used in the environmental optimization of forest wood supply chains.

The environmental dimension is the one that presents a more varied range of objective functions, with a total of 12 different objective functions used. Most of these objective functions, such as the minimization of GHG emission, CO2 emissions, carbon footprint, and GWP, are all related to the supply chain impacts of climate change. Eco-indicator 99 minimization was also used as an environmental objective function although more recent LCIA methodologies are available. Other environmental objective functions used include ecological footprint minimization and eco-profit maximization.

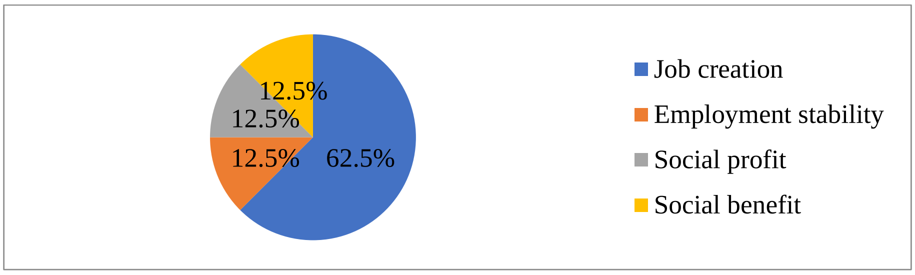

Figure 2.11 – Objective functions used in the social optimization of forest wood supply chains.

Only 7 optimization studies considered the social sustainability dimension as an objective function with 4 studies considering job creation maximization while social profit, social benefit, and employment stability together with job creation maximization were only considered in one study each.

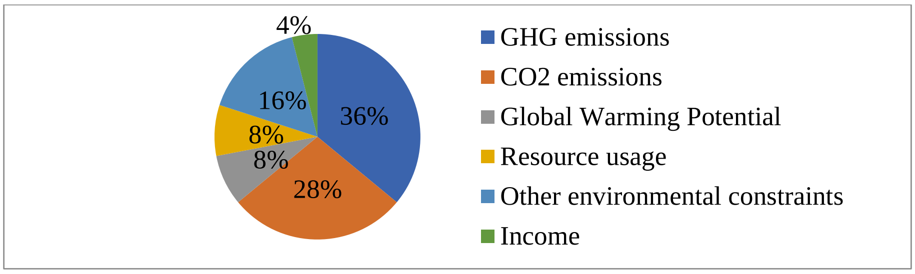

Figure 2.12 – Constraints and calculations considered in the optimization of forest wood supply chains.

Greenhouse gas and CO2 emissions, species extinction, habitat levels, harvest age, green-up period, adjacency of clearcuts, risk of damage, and proportion of area occupied by old-growth stands were included in some optimization studies reviewed as environmental constraints (Figure 2.12). Furthermore, some economic optimization studies also calculate the environmental (i.e. GHG and CO2 emissions, GWP and resource usage) and social (i.e. income) impacts of the solutions.

Q4) What decisions levels (strategic, tactical or operational) have been addressed in the optimization of sustainable forest wood supply chains?

The answer to this question is provided in Figure 2.13.

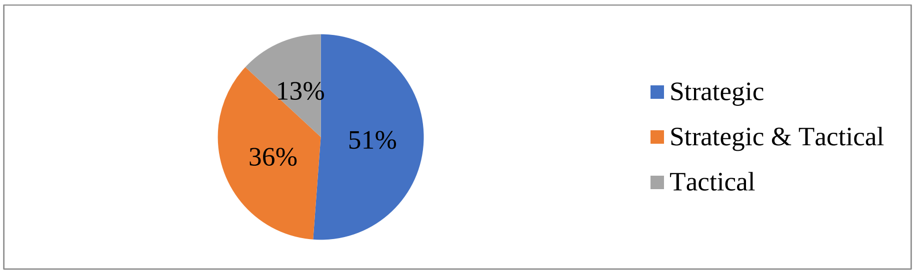

Figure 2.13 – Decision levels addressed in the optimization of sustainable forest wood supply chains.

More than half of the studies focus only on the strategic level, with 36% focusing on both strategic and tactical level and only 13% focusing on exclusively tactical decisions. No operational decisions have been treated, and thus as lack of these studies exist.

Q5) Do optimization models applied to forest wood supply chains considered uncertainty? If so, how?

Figure 2.14 provides the answer to this question. Most optimization studies reviewed consider deterministic parameters, but the integration of uncertainty is also present in a considerable amount of studies (22%) using stochastic programming, robust optimization or fuzzy programming.

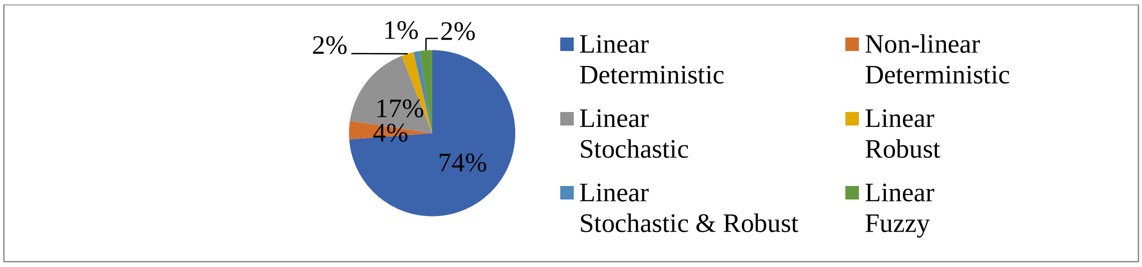

Figure 2.14 – Main characteristics of the optimization models applied to forest wood supply chains.

The most studied uncertainties are supply, demand, supply chain costs, raw materials' and end products' prices. Other non-deterministic parameters considered include technology development, conversion efficiency, environmental performance and yield of intermediate and final products. This information is summarized in Figure 2.15.

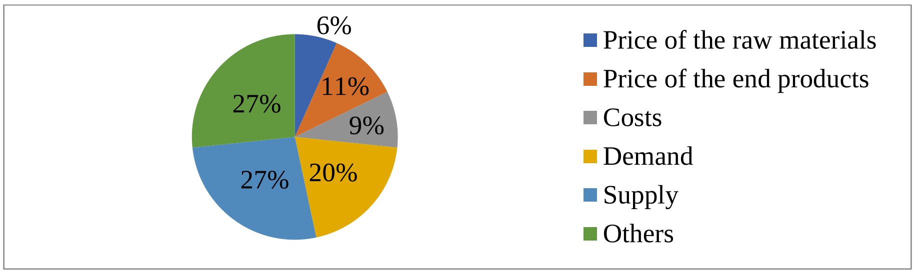

Figure 2.15 – Non-deterministic parameters used in the optimization of forest wood supply chains.

Q10) In which regions and industries of the forest sector have case studies been explored?

The answer to this question is provided in Figure 2.16.

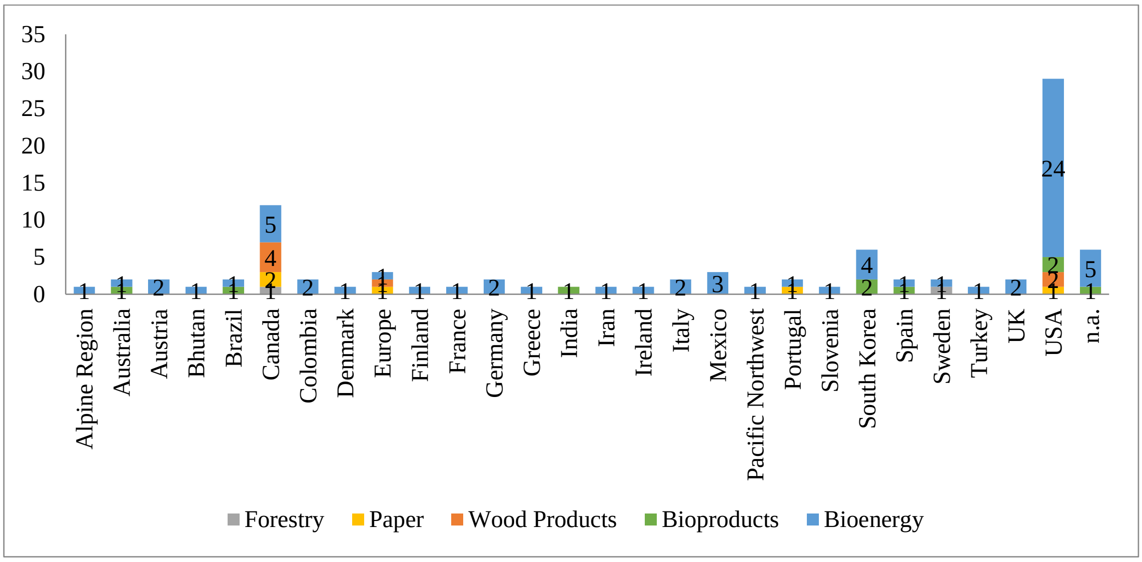

Figure 2.16 – Regions and industries used as case studies in the optimization of forest wood supply chains.

Case studies related to the bioenergy industry are the most frequently used, followed by the bioproducts, wood products and paper industries. The least considered industry is the forestry industry. North America was by far the most studied region.

2.4 Main Results and Research Gaps

The assessment and optimization of forest wood supply chains have received increasing attention from companies and research groups in recent years. Assessment studies are required to evaluate not only the economic feasibility but also the environmental and social impacts of supply chains.

Major conclusions can be drawn from the work conducted in Subsection 2.3.1 regarding the assessment of forest wood supply chains:

- Most assessment studies applied to forest wood supply chains reviewed in this work focus on economic and/or environmental assessment;
- Most of the economic assessment studies account for overall costs of forest wood supply chains;
- LCA was the most used methodology to assess the environmental impacts of forest wood supply chains, in particular, the impact on climate change through GHG emissions and GWP calculations;
- The social pillar of sustainability is the most overlooked in the assessments of forest wood supply chains and was only included as part of studies considering other sustainability dimensions. The social indicators most used are related to the populations' health and employees' safety;
- There is a lot of variability and lack of standardization in terms of the metrics used;

- Most assessment studies reviewed do not consider stakeholders' involvement in the assessment process probably due to the need for timely decisions;
- When stakeholders' involvement was considered, it was mostly used in the data collection step. The involvement was done mostly by conducting interviews and surveys and the stakeholders involved include experts or professionals from government departments, academia, and the industry.

Assessment studies are very useful in the decision-making process, but they cannot determine optimal decisions when multiple alternatives exist. For this task, optimization studies are required. The main conclusions drawn from the work conducted in Subsection 2.3.2 regarding the optimization of forest wood supply chains are:

- Most optimization studies reviewed focus on the economic and/or environmental optimization of forest wood supply chains while the social aspects are the most overlooked and have only been optimized alongside economic and environmental aspects;
- The most used objective functions per sustainability pillar so far are the minimization of costs (economic), minimization of greenhouse gas emissions (environmental), and maximization of job creation (social);
- Although more recent LCIA methodologies are available, such as ReCiPe, the one used as an environmental objective function in three optimization studies was the Eco-indicator 99;
- Several works included the environmental sustainability dimension as a constraint or complementary calculation instead of objective function. In these cases, the most used criterion was the GHG emissions;
- The inclusion of the social sustainability dimension as a constraint was not found in the studies reviewed;
- Deterministic optimization models were the most used, but the inclusion of uncertainty as non-deterministic parameters has started to appear;
- Supply, demand, supply chain costs, the price of raw material and end products are the most used non-deterministic parameters. Few studies have considered the uncertainty related to environmental parameters while none has considered social parameters as non-deterministic;
- Most optimization studies were mainly focused on strategic decisions but there is an increasingly recent trend to include tactical decisions related to material flows and inventory management.

The assessment and optimization studies reviewed were mostly focused on bioenergy supply chains, particularly in Europe and North America. This can be explained by the increasing attractiveness of using biomass to substitute fossil fuels in many applications, including the production of bioenergy in the form of heat, electricity, transportation fuels (Demirbas, et al., 2009). This attractiveness comes from the fact that using biomass in substitution of fossil fuels will help countries enhance their energy security by diversifying their energy sources (Quispe, et al., 2017) and could lead to GHG emissions reduction since fossil CO2 released from energy production and combustion is responsible for the majority of greenhouse gas emissions (Herzog, 2009). From all biomass types, forest biomass is the most commonly used (Hossen, et al., 2017) and so the growing research efforts from the academic community regarding forest biomass-to-bioenergy supply chains is justifiable. Future biomass-to-bioenergy supply chains should draw upon existing research towards the development of sustainable forest biomass supply chain networks. Considering the regions which have been the focus of the reviewed papers, it can be concluded that the application of assessment and optimizations studies to international forest wood supply chains is lacking in the literature as most studies consider only one region. This is justified because, despite the rapid expansion in the international trade of forest products, most forest-based production is destined for consumption in the domestic markets of the producing countries (Mersmann, 2018). However, this rapid expansion in the international trade has created more pressure on governments and private sector to address the impact of this trade on sustainable forest management due to the increasing concern that international trade will lead to forest degradation and loss of forest cover (Rytkönen, 2003). Although most of the international trade in forest products takes place between developed countries and rapidly emerging markets (e.g. China), forest production for international markets is limited to a relatively small number of developing countries which have received little attention in the literature. This can be explained since, according to the Food and Agriculture Organization of the United Nations, apart from Europe and North America (the most studied regions), other markets tend to show little concern for the environmental and social impacts of forest operations.

The above main results are summarized in Figure 2.17. These results allow the identification of research gaps and consequently major lines of possible research in the assessment and optimization of forest wood supply chains:

- An effort must be made to ensure consistency between the sustainability criteria used in the assessment and optimization studies;
- Considering the economic sustainability dimension, the use of net present value or other similar methods (e.g. internal rate of return) should be explored because they consider not only a project's cash outflows, which has been the main economic criterion used, but also cash inflows;
- In terms of the environmental sustainability dimension, an effort should be made to include other criteria besides impacts related with climate change, which has been the main environmental criterion used. Conducting complete LCAs considering specific

LCIA methods such as the ReCiPe 2008 is a good alternative because this LCIA method considers several impacts (e.g. terrestrial acidification);

- The social sustainability dimension should be the focus of the academia now as it is the least explored of the three dimensions. The Social LCA framework presents a promising approach and considers several impact categories which haven't been used in the literature such as cultural heritage and human rights.
- Stakeholders input should be obtained not only on the data collection step as it has been done but in all phases of the assessment process to guarantee that the most adequate criteria are selected, and their relative importance is considered;
- The inclusion of the operational level of decision making in future optimization studies should also be explored;
- There is also a need to study the uncertainty associated with environmental and social parameters (e.g. forest disturbances by wildfire or insect diseases) since non-deterministic economic parameters are by far the most frequently studied;
- Although the current focus of the academia on biomass-to-bioenergy supply chains is justifiable (as mentioned previously), efforts should be made to consider the three sustainability dimensions in the assessment and optimization studies applied to more traditional supply chains such as the paper supply chain because they are still responsible for most forest wood consumption (FAO, 2009).
- Furthermore, the impact of international trade of forest products should be investigated in the literature. Sustainability assessment studies applied to developing countries should be the focus of future research as these are very important in the international markets of forest products.

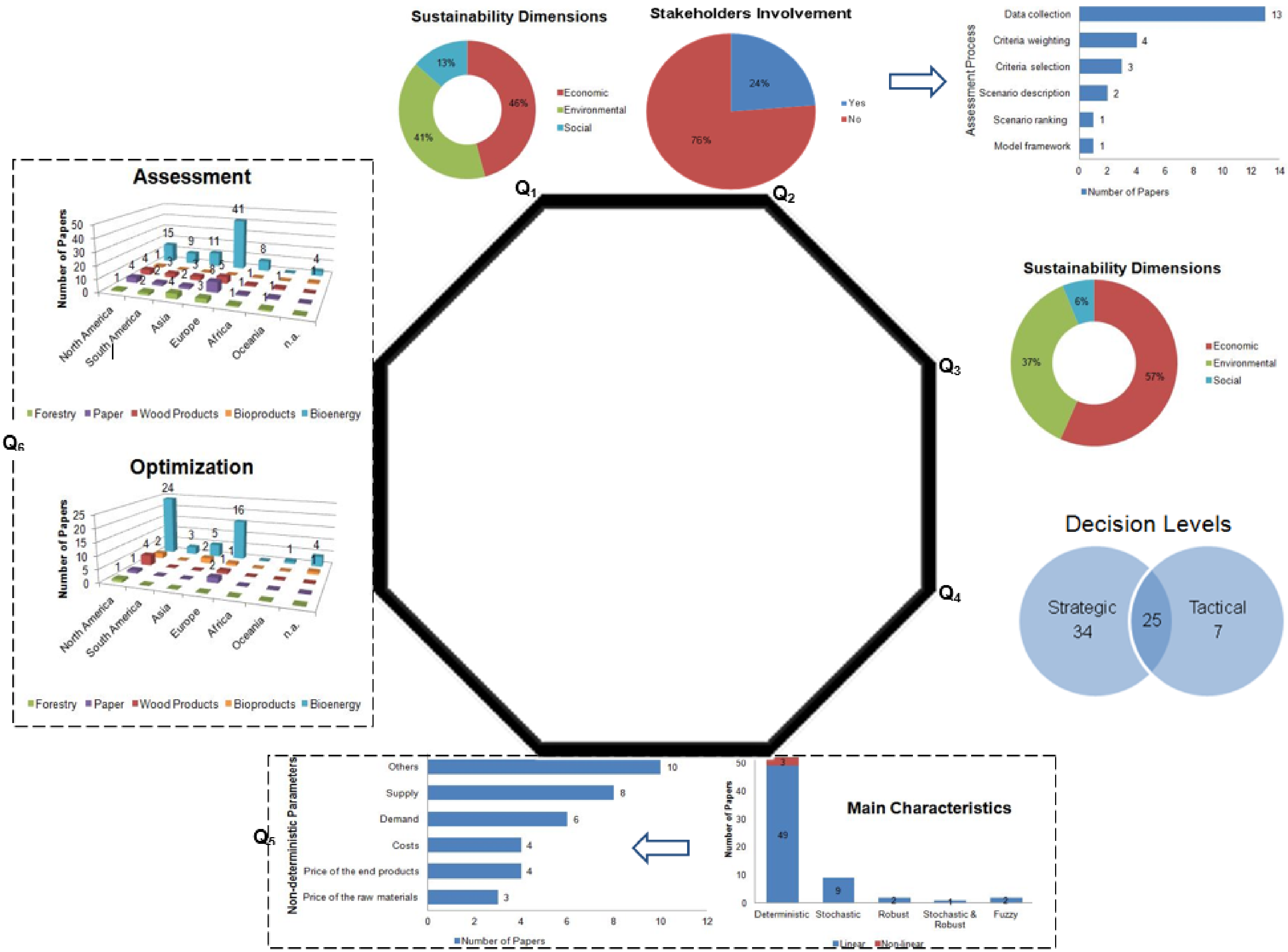

Figure 2.17 – Main results of this literature review.

2.5 Conclusion

This chapter provides a systematic literature review on the assessment and optimization of forest wood supply chains considering economic, environmental and social criteria. This review is significantly different from other reviews in the field as it considers both assessment and optimization studies of forest wood supply chains and classifies these studies according to several criteria rarely considered such as stakeholders' involvement in the assessment process and the inclusion of uncertainties in the optimization models.

From the results obtained it can be concluded that, so far, most assessment and optimization studies focus only on one or two sustainability dimensions, with the social dimension being the least analyzed. The most used metrics for each sustainability dimension are overall costs (economic), greenhouse gas emissions (environmental) human health and job creation (social). Stakeholders' were involved in a quarter of the assessment studies. Most optimization studies reviewed focus on strategic decisions, considers linear models and deterministic parameters. In some optimization studies, these parameters were considered uncertain, mostly raw materials' supply, products' demand, supply chain costs, the price of raw materials' and products' price. Bioenergy supply chains, particularly in the United States of America, are the most investigated with 12 assessment studies and 24 optimization studies choosing this region and supply chain as a case study.

The main findings of this review were used to outline a future research agenda useful for both practitioners in companies and academics as they identify the main characteristics of forest wood supply chain that should be considered when addressing sustainability goals.

Although a sound review was provided through this work some limitations always exist. The main limitation of this review is a consequence of the systematic methodology followed and relates to the fact that not all assessment and optimization studies regarding forest wood supply chains were considered due to the keywords and database selected. However, it is the authors believe that the results obtained in this review can be extrapolated because they are in agreement with previous reviews in the area namely the one conducted by Cambero and Sowlati (2014). Another limitation concerns the fact that some results are dependent on the concepts' definitions used (e.g. the classification of the optimization studies regarding the decision levels addressed). Other definitions could lead to other results but once again the results of this review are in agreement with those obtained by other researchers such as Ba et al. (2016) and Cambero and Sowlati (2014).

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3. Environmental Analysis

3.1 Introduction

About 182 million hectares (42%) of the total land area in the European Union is covered by forests and wooded land (Eurostat, 2018). The European forest sector comprises different forest-based industries, including the wood industry, the cork industry, and the pulp, paper, and cardboard industry (DGAE, 2020b). These industries have evident importance for the European continent, which is reflected in economic terms (contribution to the creation of value and the Gross Domestic Product of several European countries) and social terms (through job creation). As in Europe, forests represent the dominant land use, occupying 36.2% (3224.2 thousand hectares) of mainland Portugal (ICNF, 2015). The most common forest species in this country are Eucalyptus (26.2%), followed by *Quercus suber* (22.3%) and *Pinus pinaster* (22.1%) (ICNF, 2015). Eucalyptus (specifically *Eucalyptus globulus*) is a tree species native to south-eastern Australia, mainly cultivated in the Iberian Peninsula to be used in the pulp, paper, and cardboard industry (Cerasoli, et al., 2016). *Quercus suber*, commonly known as cork oak, is a tree species native to the Mediterranean region and most noted for its thick bark (cork) used in the cork industry (Houston Durrant, et al., 2016). *Pinus pinaster*, commonly known as maritime pine, is a tree species native to the western Mediterranean basin mostly used in the wood industry (Abad Viñas, et al., 2016). In terms of economic benefits, the Portuguese forest-based industries' business volume, approximately 10 billion euros, corresponds to 4.93% of the national Gross Domestic Product and the exports of goods from these industries, approximately 5.9 billion euros, represents 9.97% of total Portuguese exports of goods. In terms of social benefits, about 75 324 people are employed by the companies that make up the Portuguese forest-based industries, which corresponds to 1.86% of the personnel employed in Portugal (DGAE, 2020b). The most manufactured products by these industries are uncoated woodfree (UWF) paper contributing 61.4% to the total quantity of paper and carboard manufactured by the Portuguese pulp, paper and cardboard industry; natural cork stoppers contributing 81.7% to the total quantity of cork stoppers manufactured by the Portuguese cork industry, and particle boards contributing 58.7% to the total quantity of wood panels manufactured by the Portuguese wood industry (ICNF, 2018).

Despite its economic and social benefits, forest-based industries are also responsible for some environmental benefits but also some environmental impacts such as the destruction of forest cover, the emission to air of toxic and non-toxic particulates, the discharge of many pollutants in surrounding water bodies, and the disposal of solid waste (Fuwape, 2003). Therefore, it is necessary to assess the environmental impact of these industries' activities to ensure that it does not outweigh the economic and social benefits described. Different environmental accounting methods have been developed in the last four decades to quantify the effects of human activity on the environment. From these methods, life cycle assessment (LCA) has the most systematic and widely accepted methodology (Patterson, et al., 2017). This methodology was also considered by the European Commission has the best framework for assessing the potential environmental impacts of products (European Commission, 2003). LCA is a four-step methodological tool used to quantify the environmental impacts associated with the life cycle of a system (i.e., the specific object under analysis) (Goedkoop, et al., 2009). In many cases, the system refers to a product, but it may also be a service, a process, a country, or other (EC-JRC-IES, 2010). This methodology has been applied to different forest products to measure the environmental impact of their life cycles. However, most of the LCA studies found in the literature focus on the use of forest biomass to produce bioenergy. In contrast, other more traditional forest products, such as writing paper or furniture, have not received equal attention (Santos, et al., 2019a).

Some of the recent literature, which considers the application of the LCA methodology to more traditional forest products, specifically wood products, includes the work conducted by Murphy et al. (2015), where the energy requirements and GHG emissions associated with the production of several timber products, including sawn wood, are analyzed; the work conducted by Ferro et al. (2018), where the environmental impacts associated to the Brazilian oriented strand boards' production are assessed; and the work conducted by Dias et al. (2020), where 23 environmental product declarations of solid wood and glued laminated timber structural elements are reviewed. Regarding cork products, some of the recent literature considering the application of the LCA methodology includes the work conducted by Demertzi et al., where the environmental performance of cork floating floor (Demertzi, et al., 2015) and natural cork stoppers (Demertzi, et al., 2016) are evaluated; and the work conducted by Sierra-Pérez et al. (2016) and Bottino-Leone et al. (2019), where the environmental implications of using cork as a natural-based insulation material are assessed. In terms of the application of the LCA methodology to paper products, recent literature includes the work conducted by Silva et al. (2015), where a cradle-to-gate life cycle assessment of offset paper production in Brazil is performed; the work conducted by Corcelli et al. (2018), where a life cycle assessment of papermaking from the chemical pulp in Finland is done; and the work conducted by Santos et al. (2018), where the environmental impacts of producing chemical pulp, printing and writing paper, and tissue paper in a Portuguese company are assessed.

The LCA methodology has also been applied to compare wood with alternative materials (e.g., comparison between a multi-storey building with a wooden frame and a similar one with a concrete frame (Börjesson & Gustavsson, 2000)), as highlighted in the review conducted by Petersen and Solberg (2005). However, there is no comparison in the literature of different forest wood products. Thus, in this study, the environmental impacts associated with the life cycles of three forest products manufactured in Portugal are compared. The products selected were uncoated woodfree (UWF) paper, natural cork stoppers (NCS), and particle boards since these are the most manufactured forest products in Portugal in each of the three primary forest-based industries (ICNF, 2018). It was assumed that these products are manufactured from the three most common forest species in Portugal - *Eucalyptus globulus*, *Quercus suber*, and *Pinus pinaster*, respectively. The three life cycles were modeled using the SimaPro software, and the environmental impacts were determined using the LCA methodology. Although the primary focus of this study will be on the environmental impact of the three identified products' life cycles, the economic benefit will also be considered by taking into account the net present value (NPV) of the cash flows generated by the sales of each forest wood product. NPV is one of the most commonly used economic metrics in assessment studies of forest wood supply chains (Santos, et al., 2019a) and is also commonly used in Life Cycle Cost Analysis studies (Li, et al., 2019).

The main goal of this study is to conduct an environmental and economic assessment of three systems and compare the results of this assessment to determine the best use, from an environmental and economic perspectives, that can be given to land between the plantation of *Eucalyptus globulus* to produce uncoated woodfree paper, the plantation of *Quercus suber* to produce natural cork stoppers, and the plantation of *Pinus pinaster* to produce particle boards. The innovative component of this study lies on the fact that, according the authors best knowledge, no study has been done where different forest products have been compared (as mentioned above). Such comparison can be used by governments to support territory management policies. In summary, the main contributions of this study are as follow:

- The development of a model describing the forest sector in the Portuguese context;
- The comparison of three different forest wood products based on their life cycle assessment results and the present value of their cash flows;
- The identification of the most critical environmental impacts in the three systems to determine whether there is commonality between the critical environmental issues;
- The identification of the life cycle stage that most contribute to the overall environmental impact of the three systems to provide informed suggestions that can help companies reduce the environmental impacts associated with the life cycles of these three forest wood products;
- Proposal of a set of recommendations for different stakeholders in the forest sector including companies, business associations, and academics.

The remainder of this chapter is organized into five sections. Section 3.2 and 3.3 describe how the environmental and economic assessment of the three life cycles is performed by presenting the life cycle assessment methodology and the net present value technique, respectively, as well as its application to the case study. Section 3.4 presents the analysis of the environmental and economic results. In Section 3.5, recommendations for forest sector stakeholders (including companies, business associations, and academics) are given based on the results analyzed in the previous section. Lastly, Section 3.6 presents the conclusions of this work, including highlights and limitations of the current study, and suggestions for future work.

3.2 Environmental Assessment

The environmental impacts associated with the three life cycles considered are assessed using the life cycle assessment methodology which consists of four steps documented in the ISO 14040-series (ISO, 2006). These steps are:

- Step 1 – Goal and Scope Definition;
- Step 2 – Life Cycle Inventory (LCI);
- Step 3 – Life Cycle Impact Assessment (LCIA);
- Step 4 – Interpretation.

This section is organized according to these four steps and includes an explanation of each of these steps and how they were applied to the case study under analysis.

3.2.1 Goal and Scope Definition

The first step of an LCA study, Goal and Scope Definition, consists of establishing the LCA goal and characterizing the system(s) under analysis through the definition of the functional unit and system boundary (EC-JRC-IES, 2010). In this study, a comparative LCA is conducted where the life cycle of three forest products are analyzed and compared. These three systems are described as:

- System 1 – Uncoated woodfree paper manufacture from *Eucalyptus globulus*;
- System 2 – Natural cork stoppers manufacture from *Quercus suber*;
- System 3 – Particle boards manufacture from *Pinus pinaster*.

3.2.1.1 Functional Unit

The functional unit (FU) is a measure of the function(s) provided by the analyzed system(s), and it serves as a reference to which all other inputs and outputs flow identified in the LCI step quantitatively relate. The functional unit names and quantifies the qualitative and quantitative aspects of the function(s) along with several questions such as "what", "where", and "for how long" (EC-JRC-IES, 2010).

In a comparative LCA, which is the case of this study, the functional unit selected must allow valid comparisons. Since the three products under study have different functions, identifying a functional unit that allows for valid comparisons becomes a difficult task. Even though the three products under study have different functions, they are all forest wood products, which means they have the same primary raw material – wood. Moreover, one of the main purposes of this study is to determine the best use, from an environmental and economic point of view, that can be given to land if the goal is to produce forest wood products. For these reasons, the functional unit selected is the utilization of one hectare of forest land in Portugal for 100 years. Figure 3.1 presents a representation of the functional unit for each of the three systems, including the quantities of forest wood products considered, to assist in visualizing the choice of functional unit made.

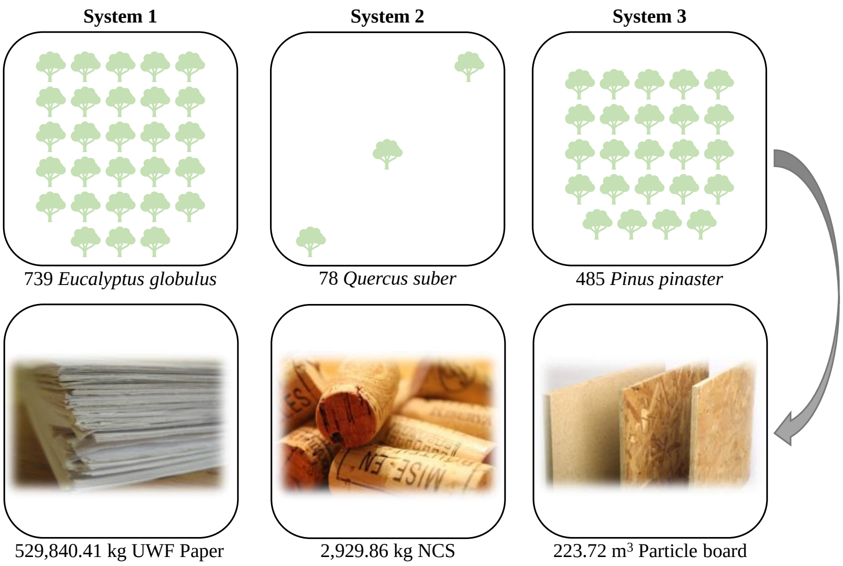


Figure 3.1 – Representation of the functional unit for each of the three systems.

Notice that the utilization of one hectare of forest land in Portugal for 100 years will result in different quantities of forest wood products since the number of trees that can be planted per hectare is different for each of the three forest species considered and each tree species has a different recommended rotation period (i.e., the time between each harvest) and is capable of generating different amounts of wood per harvest. The quantities presented in Figure 3.1 will be explained in Subsections 3.2.2.1 and 3.2.2.2.

3.2.1.2 System Boundaries

The system boundary determines which parts of the system(s) life cycle will be considered in the LCA study (EC-JRC-IES, 2010). Different system boundaries can be assumed, including cradle-to-grave which considers the entire life cycle from raw materials' extraction to product disposal; cradle-to-gate which considers all steps from raw materials' extraction to another step in the life cycle; and gate-to-gate which only considers a single step in the life cycle (Eskandarpour, et al., 2015). In a comparative LCA, the same system boundary must be considered for each of the systems under study.

Since the three products under analysis in this study are very different in each life cycle stage, a cradle-to-grave boundary was selected. This boundary includes four main life cycle stages, (1) Raw materials' extraction; (2) Products' manufacture; (3) Products' distribution; and (4) Products' end-of-life.

3.2.2 Life Cycle Inventory

The second step of an LCA study, Life Cycle Inventory, involves quantifying flows in (e.g. raw materials) and out (e.g. emissions) of the system. All these flows must quantitatively relate to the functional unit established in the previous step. To determine the flows, the system(s) under analysis must be modeled, which requires the collection of foreground and background data. The first type of data includes specific data required to model the system(s) under analysis. In contrast, the second type of data includes generic data that is not specific to the system(s) under analysis, such as information for energy, transport, and waste management. This last type of data can be found in literature and databases (EC-JRC-IES, 2010). It is the modeling of the system(s) and the required data collection that makes the LCI the most time-consuming step of an LCA and the step that requires the highest efforts.

In this study, the three systems were modeled in SimaPro, and the foreground data was collected considering the four life cycle stages identified in the previous step. A representation of the three life cycles modeled in this study is presented in Figure 3.2.

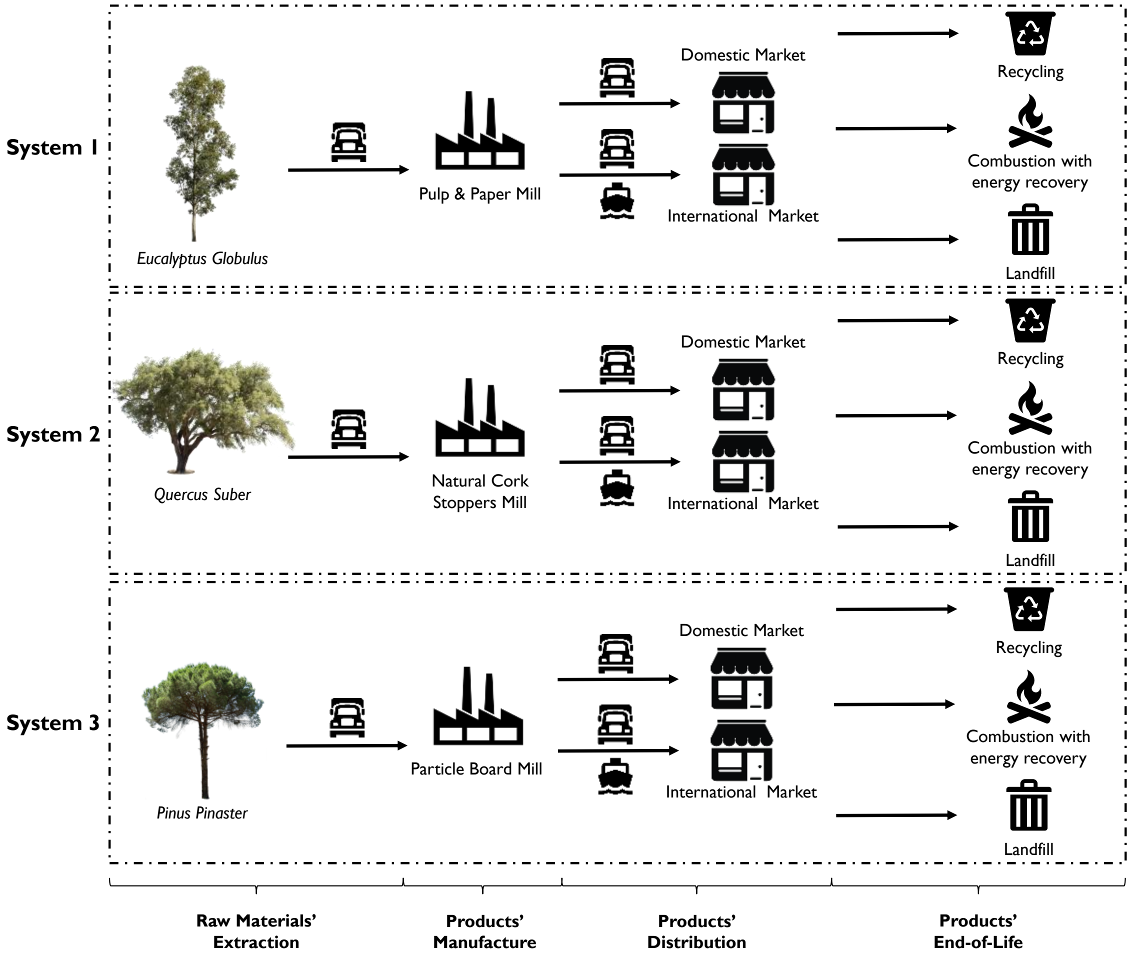


Figure 3.2 – Representation of the three life cycles modeled and analyzed.

As shown in Figure 3.2, the companies in the forest sector (i.e., products' manufacturers) are only one of the links in the wood supply chain. Since the environmental impact assessment in this study follows a life cycle perspective, other links in the supply chain are considered, such as raw materials' providers and distributors. Thus, the environmental impacts calculated are distributed across the entire supply chain.

The modeling of the three life cycles and the foreground data used are explained in more detail below. Background data concerning other substances that are part of the three products' life cycles, such as electricity, chemicals, and fuels, were taken from the Ecoinvent database (Wernet, et al., 2016).

3.2.2.1 Raw Materials' Extraction

The first life cycle stage consists of extracting the primary raw material used in the three systems – wood (Systems 1 and 3) and cork (System 2).

System 1 – Uncoated woodfree paper manufacture from *Eucalyptus globulus*

To model the first stage of System's 1 life cycle, it was necessary to determine the amount of pulpwood that could be harvest from one hectare of forest land in Portugal planted with *Eucalyptus globulus* given a time horizon of 100 years.

This volume (cubic meters) of pulpwood is calculated through Equation 3.1.

$$Pulpwood\ (m^3) = T \times \left[\beta_0 \left(\frac{d}{100}\right)^{\beta_1} h^{\beta_2}\right] \times R \qquad (3.1)$$

where β_0, β_1, and β_2 are dimensionless constants, *d* denotes the tree diameter (centimeters) at 1.30 meters height, *h* denotes the total tree height (meters), *T* denotes the number of *Eucalyptus globulus* trees per hectare, and *R* denotes the number of harvests possible in the 100 years' time horizon defined. This equation was adapted from the study by Tomé et al. (2007a), where the volume (cubic meters) of pulpwood that can be harvest from a *Eucalyptus globulus* tree was defined. The values of the parameters considered in this study are presented in Table 3.1. The constants values (β_0, β_1, and β_2) were taken from the study by Tomé et al. (2007a). The average tree density in a stand of *Eucalyptus globulus* in Portugal is 739 trees per hectare (ICNF, 2015). According to information collected from the Portuguese paper industry association (CELPA, 2020), most *Eucalyptus globulus* stands in Portugal are harvest every 12 years. At this age, these trees will have, on average, 20 centimeters in diameter and 25 meters in height. Given a rotation period of 12 years, eight harvests are possible in the 100 years' time horizon defined in the functional unit. Taking into account the parameters identified in Table 3.1 and by applying Equation 3.1, it can be concluded that one hectare of forest land in Portugal planted with *Eucalyptus globulus* will generate 1,721.43 cubic meters of pulpwood given a time horizon of 100 years.

Eucalyptus globulus trees exist in different subregions of mainland Portugal being more common in the *Região de Coimbra* subregion. Table A.1 in Appendix A presents the quantity and share of *Eucalyptus globulus* trees that exist in the 23 different subregions of mainland Portugal (ICNF, 2015). These shares were used together with the volume of pulpwood previously calculated (1,721.43 cubic meters) to determine the volume of pulpwood provided by each of the 23 subregions (see Table A.2 in Appendix A). For example, from the 845.01 thousand hectares of *Eucalyptus globulus* in mainland Portugal, 25.45 (3.01%) thousand hectares are located in the *Alto Minho* subregion (see Table A.1 in Appendix A). Consequently, it was considered that 51.85 cubic meters of pulpwood (see Table A.2 in Appendix A) were sourced from this subregion which corresponds to 3.01% of the total pulpwood volume (1,721.43 cubic meters).

The inventory data for the life cycle stage Raw Materials' Extraction considered in System 1 are given in Appendix A (see Table A.3). This data was adapted from Werner (2010) taking into account the tree density and time horizon considered.

System 2 – Natural cork stoppers manufacture from *Quercus suber*

To model the first stage of System's 2 life cycle, it was necessary to determine the amount of cork that could be harvest from one hectare of forest land in Portugal planted with *Quercus suber* given a time horizon of 100 years.

This amount (kilograms) of cork is calculated through Equation 3.2.

$$Cork\ (kg) = T \times \left[\beta_0 du^{\beta_1} hdv^{[\beta_2 + \beta_3 \ln(npd)]}\right] \times R \qquad (3.2)$$

where β_0, β_1, β_2, and β_3 are dimensionless constants, *du* denotes the tree diameter (centimeters) under bark at breast height (1.30 meters), *hdv* denotes the tree vertical debarked height (meters), *npd* denotes the tree number of debarked branches, *T* denotes the number of *Quercus suber* trees per hectare, and *R* denotes the number of stripping (i.e., removal of cork) possible in the 100 years' time horizon defined. This equation was adapted from the study by Paulo and Tomé (2010), where the amount (kilograms) of cork that can be harvest from a *Quercus suber* tree was defined. The values of the parameters considered in this study are presented in Table 3.1. The constants values (β_0, β_1, β_2, and β_3) were taken from the study by Paulo and Tomé (2010). The average tree density in a stand of *Quercus suber* in Portugal is 78 trees per hectare (ICNF, 2015). The national and regional legislation protects the *Quercus suber* stands and imposes hefty fines for the trees' damage or improper management. These rules state that a young tree can only be stripped for the first time when it reaches at least 25 years of age, and it is at least 70 cm in diameter and 130 cm in height. Furthermore, it is forbidden to harvest the cork at intervals of less than nine years (even if an individual tree is ready to be harvested before this period) (APCOR , 2020a). The first two harvests produce virgin and secondary cork, respectively, which do not have the high standard of quality required for producing cork stoppers. Only after the third stripping (at 43 years of age) does the cork, known as reproduction cork, reaches the quality necessary (Corticeira Amorim , 2020a). Consequently, seven harvests of reproduction cork are possible in the 100 years' time horizon defined in the functional unit. After nine years, a *Quercus suber* tree will have, on average, 36.3 centimeters in diameter under bark at breast height (1.30 meters), 2.4 meters in vertical debarked height, and three debarked branches (Paulo & Tomé, 2010). Taking into account the parameters identified in Table 3.1 and by applying Equation 3.2, it can be concluded that one hectare of forest land in Portugal planted with *Quercus suber* will generate 14,649.29 kilograms of cork given a time horizon of 100 years.

Quercus suber trees exist in different subregions of mainland Portugal being more common in the *Alentejo Central* subregion. Table A.1 in Appendix A presents the quantity and share of *Quercus suber* trees that exist in the 23 different subregions of mainland Portugal (ICNF, 2015). These shares were used together with the amount of cork previously calculated (14,649.29 kilograms) to determine the amount of cork provided by each of the 23 subregions (see Table A.2 in Appendix A) as explained for System 1.

The inventory data for the life cycle stage Raw Materials' Extraction considered in System 2 are given in Appendix A (see Table A.4). This data was adapted from Werner (2012) taking into account the tree density and time horizon considered. Please notice that, contrary to pulpwood, no diesel, lubricating oil, or power sawing is considered as an input. This is because the stripping of cork is done manually (contrary to pulpwood, which is usually harvested using chainsaws).

System 3 – Particle boards manufacture from *Pinus pinaster*

To model the first stage of System's 3 life cycle, it was necessary to determine the amount of roundwood that could be harvest from one hectare of forest land in Portugal planted with *Pinus pinaster* given a time horizon of 100 years.

This volume (cubic meters) of roundwood is calculated through Equation 3.3.

$$Roundwood\ (m^3) = T \times \left[\beta_0 d^{\beta_1} h^{\beta_2}\right] \times R \qquad (3.3)$$

where β_0, β_1, and β_2 are dimensionless constants, d denotes the tree diameter (centimeters) at 1.30 meters height, h denotes the total tree height (meters), T denotes the number of *Pinus pinaster* trees per hectare, and R denotes the number of harvests possible in the 100 years' time horizon defined. This equation was adapted from the study by Falcão (1994), where the volume (cubic meters) of roundwood that can be harvest from a *Pinus pinaster* tree was defined. The values of the parameters considered in this study are presented in Table 3.1. The constants values (β_0, β_1, and β_2) were taken from the study by Tomé et al. (2007b). The average tree density in a stand of *Pinus pinaster* in Portugal is 485 trees per hectare (ICNF, 2015). According to information collected from Centro Pinus (Centro Pinus, 2020), most *Pinus pinaster* stands in Portugal are cut after 40 years. At this age, these trees will have, on average, 26.9 centimeters in diameter and 19 meters in height (Oliveira, 1985). Given a rotation period of 40 years, two harvests are possible in the 100 years' time horizon defined in the functional unit. Taking into account the parameters identified in Table 3.1 and by applying Equation 3.3, it can be concluded that one hectare of forest land in Portugal planted with *Pinus pinaster* will generate 382.01 cubic meters of roundwood given a time horizon of 100 years.

Pinus pinaster trees exist in different subregions of mainland Portugal being more common in the *Região de Coimbra* subregion. Table A.1 in Appendix A presents the quantity and share of *Pinus pinaster* trees that exist in the 23 different subregions of mainland Portugal (ICNF, 2015). These shares were used together with the volume of roundwood previously calculated (382.01 cubic meters) to determine the volume of roundwood provided by each of the 23 subregions (see Table A.2 in Appendix A) as explained for System 1.

As for the other two systems, the inventory data for the life cycle stage Raw Materials' Extraction considered in System 3 are also given in Appendix A (see Table A.5). This data was adapted from Werner (2014) taking into account the tree density and time horizon considered.

3.2.2.2 Products' Manufacture

The second life cycle stage consists of the production of the three products considered – uncoated woodfree paper (System 1), natural cork stoppers (System 2), and particle board (System 3). To model this stage of each system under study, it was necessary to determine the quantity of each product that can be manufacture using the raw materials (wood and cork) harvest from one hectare of forest land in Portugal given a time horizon of 100 years.

System 1 – Uncoated woodfree paper manufacture from *Eucalyptus globulus*

The production of uncoated woodfree paper starts with growing and harvesting the trees. Then, each tree's trunk is bucked into logs, which are delivered to mills where they are debarked (bark contains few cellulose fibers) and chipped. The next stage is pulp production (i.e., pulping) using mechanical, semi-mechanical, or chemical methods. The purpose of this stage is to separate the cellulose fibers from the other wood components such as lignin (the "glue" that cements the fibers together), extractives (e.g., fats, waxes, and alcohols), minerals and other inorganics. Chemical methods are the most effective in this separation, which means that the pulp obtained using these methods is not considered wood since most of the other wood components are removed. This is why uncoated woodfree paper (System 1), manufactured using chemical pulp, is known as woodfree. The most common chemical method is the Kraft (sulfate) method. In this method, the wood chips are pressure-cooked with water and chemicals, sodium hydroxide (NaOH) and sodium sulfide (Na2S), in a digester. The resulting pulp is screened to remove uncooked wood and washed to remove the spent cooking mixture. Depending on the final product, the pulp can be bleached (using chlorine dioxide, oxygen, or hydrogen peroxide) after being produced due to the brown coloration of the raw pulp caused by the presence of lignin that was not removed during cooking. The next stage consists of transforming the wood pulp into a continuous sheet by pumping the pulp onto a slightly vibrating rolling wire screen mat to allow water to drain out and help the fibers interlock into sheets. The newly created web undergoes compression between a long series of rollers that press out more water, followed by steam-heated dryers where most of the remaining moisture is removed. Finally, large sheets of dry paper are wound onto rolls that can be cut to produce a variety of paper products (Bajpai, 2012).

The quantity (kilograms) of UWF paper that can be manufactured from the amount of pulpwood that could be harvest from one hectare of forest land in Portugal planted with *Eucalyptus globulus* given a time horizon of 100 years is calculated through Equation 3.4.

$$UWF\ Paper\ (kg) = \frac{T \times \left[\beta_0 \left(\frac{d}{100}\right)^{\beta_1} h^{\beta_2}\right] \times\ R}{N} \tag{3.4}$$

where *N* denotes the quantity of pulpwood required to produce one kilogram of UWF paper. The value of this parameter considered in this study is presented in Table 3.1. According to Hischier (2010), the production of one kilogram of UWF paper requires 3.25E-03 cubic meters of pulpwood. The parameters in the numerator of Equation 3.4 were previously presented in Subsection 3.2.2.1 (see System 1), and their value is also shown in Table 3.1. Taking into account the parameters identified in this table and by applying Equation 3.4, it can be concluded that a total of 529,840.41 kilograms of UWF paper (see Figure 3.1) can be produced with the volume of pulpwood (1,721.43 cubic meters) that is generated by one hectare of forest land in Portugal planted with *Eucalyptus globulus* given a time horizon of 100.

Since most companies that manufacture UWF paper in Portugal are located in the *Região de Coimbra* subregion (INE, 2018a), it was assumed in this study that this was where the UWF paper is manufactured (see Figure 3.3). The distance from the 23 subregions where the pulpwood was sourced and the *Região de Coimbra* subregion (see Table A.2 in Appendix A) was considered to calculate the transportation input included in Table A.3 (see Appendix A).

The inventory data for the life cycle stage Product's Manufacture considered in System 1 are given in Appendix A (see Table A.6). This data was adapted from Hischier (2010).

System 2 – Natural cork stoppers manufacture from *Quercus suber*

The production of natural cork stoppers starts with stripping the cork from the *Quercus suber* trees. The cork planks are cooked in clean, boiling water to clean the cork and extract water-soluble substances. After boiling, a period of stabilization occurs, which serves to flatten the planks and enables cork to reach the moisture content (around 14%) necessary for processing. The planks are then separated into quality categories and cut into strips that are perforated with a drill. As a result of this drilling process called punching, a cylindrical stopper is obtained and then rectified to regularize the stopper's surface and reach the specified dimensions. The next operation is the selection where finished stoppers are separated into different grades, and defective stoppers are eliminated. Usually, using hydrogen peroxide or peracetic acid, the stoppers are washed in order to be disinfected. The final stage is marking the natural cork stoppers according to customers' specifications and treating the surface with paraffin or silicon to make the stopper easier to insert and extract from the bottle (APCOR , 2020b).

The quantity (kilograms) of natural cork stoppers that can be manufactured from the amount of cork that could be harvest from one hectare of forest land in Portugal planted with *Quercus suber* given a time horizon of 100 years is calculated through Equation 3.5.

$$Natural\ Cork\ Stoppers\ (kg) = \frac{T \times \left[\beta_0 du^{\beta_1} hdv^{[\beta_2+\beta_3 \ln(npd)]}\right] \times R}{N} \quad (3.5)$$

where *N* denotes the quantity of cork required to produce one kilogram of natural cork stoppers. The value of this parameter considered in this study is presented in Table 3.1. According to Demertzi et al. (2016), the production of one kilogram of natural cork stoppers requires five kilograms of cork. The parameters in the numerator of Equation 3.5 were previously presented in Subsection 3.2.2.1 (see System 2), and their value is also shown in Table 3.1. Taking into account the parameters identified in this table and by applying Equation 3.5, it can be concluded that a total of 2,929.86 kilograms of natural cork stoppers (see Figure 3.1) can be produced with the amount of cork (14,649.29 kilograms) that is generated by one hectare of forest land in Portugal planted with *Quercus suber* given a time horizon of 100 years.

It was assumed in this study that the natural cork stoppers are manufactured in the *Área Metropolitana do Porto* subregion since this is where most companies that manufacture this product in Portugal are located (INE, 2018a) (see Figure 3.3). The distance from the 23 subregions where the cork was sourced and the *Área Metropolitana do Porto* subregion (see Table A.2 in Appendix A) was considered to calculate the transportation input included in Table A.4 (see Appendix A).

The inventory data for the life cycle stage Product's Manufacture considered in System 2 are given in Appendix A (see Table A.7). This data was adapted from Demertzi et al. (2016).

System 3 – Particle boards manufacture from *Pinus pinaster*

The manufacturing of particle board starts with the growing and harvesting of the trees. The trunk of each tree is then bucked into logs, debarked, and cut into small chips. These chips are further reduced in size, which can be accomplished using several different ways, such as using a hammer mill. The next stage consists in reducing the moisture content of the wood particles using a dryer. Once the wood particles have been dried, they are sprayed with adhesive resin (usually urea formaldehyde, melamine formaldehyde, or phenol-formaldehyde) and a particle mattress consisting of the face and core layers is formed. Usually, the core of the board consists of large particles and the face layers consist of finer particles, allowing improved surface finish. The particle mattress is then pressed at high temperatures using either a continuous or batch process. The last stage consists of sanding, adding any coating or lacquers, and cutting to size the boards (Irle & Barbu, 2010) (Jones & Brischke, 2017).

The quantity (cubic meters) of particle boards that can be manufactured from the amount of roundwood that could be harvest from one hectare of forest land in Portugal planted with *Pinus pinaster* given a time horizon of 100 years is calculated through Equation 3.6.

$$Particle\ Board\ (m^3) = \frac{T \times \left[\beta_0 d^{\beta_1} h^{\beta_2}\right] \times R}{N} \tag{3.6}$$

where *N* denotes the quantity of roundwood required to produce one cubic meter of particle boards. The value of this parameter considered in this study is presented in Table 3.1. According to Werner (2013), the production of one cubic meter of particle boards requires 1.71 cubic meters of roundwood. The parameters in the numerator of Equation 3.6 were previously presented in Subsection 3.2.2.1 (see System 3), and their value is also shown in Table 3.1. Taking into account the parameters identified in this table and by applying Equation 3.6, it can be concluded that a total of 223.72 cubic meters of particle boards (see Figure 3.1) can be produced with the volume of roundwood (382.01 cubic meters) that is generated by one hectare of forest land in Portugal planted with *Pinus pinaster* given a time horizon of 100 years.

Since most companies that manufacture particle boards in Portugal are located in the *Viseu Dão Lafões* subregion (INE, 2018a), it was assumed in this study that this is where this product is manufactured (see Figure 3.3). The distance from the 23 subregions where the roundwood was sourced and the *Viseu Dão Lafões* subregion (see Table A.2 in Appendix A) was considered to calculate the transportation input included in Table A.5 (see Appendix A).

The inventory data for the life cycle stage Product's Manufacture considered in System 3 are given in Appendix A (see Table A.8). This data was adapted from Werner (2013).

Table 3.1 – Parameters used to calculate the quantity of wood/cork and final products consider in each system.

Parameters	System 1	System 2	System 3
β_0	1.24E-01	1.04E-01	2.47E-05
β_1	1.78E+00	1.34E+00	2.11E+00
β_2	1.16E+00	6.71E-01	9.26E-01
β_3	-	1.47E-01	-
d (cm)	20 (12 years)	-	26.9 (40 years)
h (m)	25 (12 years)	-	19 (40 years)
du (cm)	-	36.3 (9 years)	-
hdv (m)	-	2.4 (9 years)	-
npd	-	3.0	-
T	739	78	485
R	8 (12 years)	7 (9 years)	2 (40 years)
N	3.25E-03	5	1.71

The location of the manufacturing sites considered in each of the three systems studied are represented in Figure 3.3.

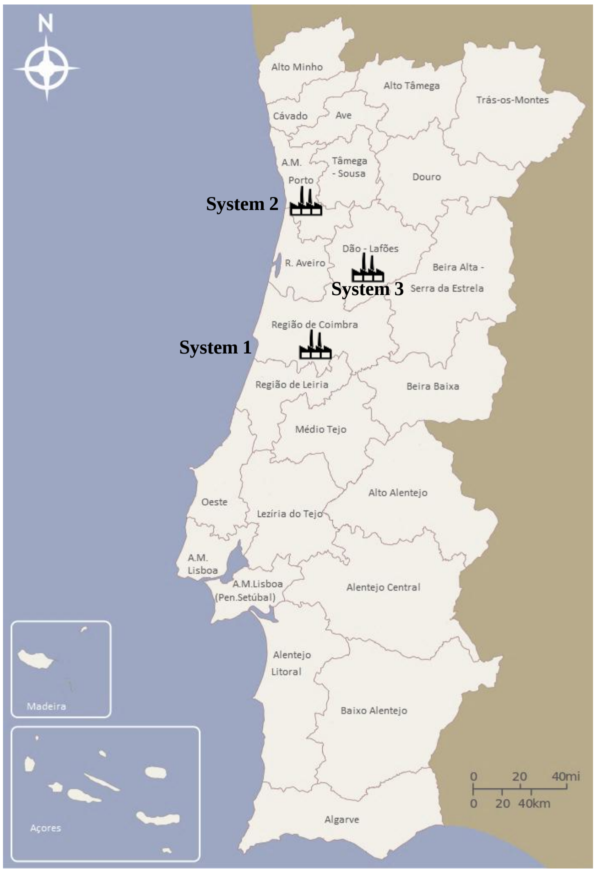


Figure 3.3 – Location of the manufacturing facilities for the three forest products considered.

3.2.2.3 Products' Distribution

The third life cycle stage consists of distributing the three products considered. To model this stage, it was necessary to determine the quantity of each product distributed to the domestic and international markets. This information was collected from the Portuguese National Statistical Institute (INE, 2018b) (INE, 2018c) and the Food and Agriculture Organization of the United Nations (FAO, 2017):

- System 1 – 92% of the UWF paper produced in Portugal and imported to this country is exported to the international market while the remaining 8% stays in Portugal. From the 529,840.41 kilograms of UWF paper that can be produced from the pulpwood generated by one hectare of forest land in Portugal planted with *Eucalyptus globulus* given a time horizon of 100 years, 41,886.77 kilograms are distributed in the domestic market while 487,953.64 kilograms are distributed in the international market;
- System 2 – 8% of the natural cork stoppers manufactured in Portugal and imported to this country are exported to the international market while the remaining 92% stay in Portugal. From the 2,929.86 kilograms of natural cork stoppers that can be produced from the cork generated by one hectare of forest land in Portugal planted with *Quercus suber* given a time horizon of 100 years, 2,685.80 kilograms are distributed in the domestic market while 244.06 kilograms are distributed in the international market;
- System 3 – 42% of the particle boards produced in Portugal and imported to this country is exported to the international market while the remaining 58% stay in Portugal. From the 223.72 cubic meters of particle boards that can be produced from the roundwood generated by one hectare of forest land in Portugal planted with *Pinus pinaster* given a time horizon of 100 years, 129.92 cubic meters are distributed in the domestic market while 93.80 cubic meters are distributed in the international market.

To determine the quantities of each product that distributed to each market and the distances traveled to guarantee this distribution, some assumptions had to be made:

- For the domestic market, 23 points of demand were considered which correspond to the 23 subregions previously identified (see Figure 3.3). Each product's demand was considered to be proportional to the population of each subregion (INE, 2011). These subregions and their relative contribution for the domestic market are presented in Table 3.2. Road transportation was considered for the domestic market distribution;
- For the international market, it was necessary to determine the countries to which the three forest wood products are exported. The most recent statistical data (Growth Lab, 2017) was used, and only countries that contributed more than 1% to the total exports of each product were considered. These countries and their relative contribution are presented in Table 3.2. Both road and maritime transportation were considered for the distribution in the international market.

Table 3.2 – Demand points considered for the domestic and international markets and their relative contribution.

Domestic Market		International Market					
		UWF Paper		Natural Cork Stoppers		Particle Boards	
Subregions	**Share**	**Country**	**Share**	**Country**	**Share**	**Country**	**Share**
Alto Minho	2.44%	France	12.74%	United States of America	25.91%	Spain	55.88%
Alto Tâmega	0.94%	Germany	10.93%	France	25.38%	United Kingdom	20.65%
A.M. Porto	17.56%	United States of America	10.07%	Spain	10.38%	Morocco	8.52%
Ave	4.25%	Turkey	9.56%	Italy	8.44%	Ireland	2.27%
Cávado	4.09%	Spain	8.67%	Mexico	4.29%	France	2.22%
Douro	2.05%	Italy	7.77%	United Kingdom	3.83%	Israel	1.62%
Tâmega e Sousa	4.32%	United Kingdom	4.92%	Chile	3.76%	Italy	1.51%
Terras de Trás-os-Montes	1.17%	Egypt	4.41%	Germany	3.03%	Germany	1.03%
Beira Baixa	0.89%	Algeria	3.88%	Australia	2.95%		
Beiras e Serra da Estrela	2.36%	Netherlands	2.83%	Argentina	2.42%		
Médio Tejo	2.20%	Belgium	1.82%	South Africa	1.57%		
Oeste	3.62%	Morocco	1.72%	Switzerland	1.51%		
Região de Aveiro	3.70%	Switzerland	1.45%				
Região de Coimbra	4.59%	Saudi Arabia	1.24%				
Região de Leiria	2.94%	Greece	1.07%				
Viseu Dão Lafões	2.67%						
A.M. Lisboa	28.16%						
Alentejo Central	1.66%						
Alentejo Litoral	0.98%						
Alto Alentejo	1.18%						
Baixo Alentejo	1.26%						
Lezíria do Tejo	2.47%						
Algarve	4.50%						

Based on the demand points identified and their relative contribution presented in Table 3.2, the quantities of each product that are distributed to each market and the distances traveled to guarantee their distribution were determined and can be consulted in Tables A.9 to A.12 available in Appendix A. For example, as previously mentioned in the beginning of this subsection, 41,886.77 kilograms of UWF paper are distributed to the domestic market. From these, 1,023.39 kilograms (2.44%) are distributed to the *Alto Minho* subregion (see Table 3.2) using road transportation. The distance by truck (195.99 km) presented in Table A.9 (see Appendix A) corresponds to the distance from the manufacturing location (*Região de Coimbra* subregion) considered in System 1 (see Figure 3.3) and the *Alto Minho* subregion. Please notice that the total quantity presented in Table A.9 for System 1 is 41,886.77 kilograms which corresponds to the quantity of UWF paper distributed to the domestic market. In terms of the international market, as previously mentioned in the beginning of this subsection, 487,953.64 kilograms of UWF paper are distributed to this market. From these, 62,165.29 kilograms (12.74%) are distributed to France (see Table 3.2) using road transportation. The distance by truck (1,586.00 km) presented in Table A.10 (see Appendix A) corresponds to the distance from the manufacturing location (*Região de Coimbra* subregion) considered in System 1 (see Figure 3.3) and the French capital (Paris). Please notice that the total quantity presented in Table A.10 for System 1 is 405,391.88 kilograms which does not corresponds to the total quantity of UWF paper distributed to the international market. This is due to the fact that only countries that contributed more than 1% to the total exports of each product were considered when modeling this phase of the life cycle.

3.2.2.4 Products' End-of-Life

The final life cycle stage consists in the end-of-life phase of the three products considered. To model this stage, it was necessary to determine each product's amount that goes to each end-of-life destination. Different end-of-life destinations were considered in this study, including recycling, combustion with energy recovery, and landfill. The three products analyzed in this study are different at this stage of the life cycle. Despite sharing the same end-of-life destinations, the percentage of product that goes to each of these destinations is different (EPA, 2017):

- System 1 – In terms of UWF paper, it is considered that 65.9% is recycled, 6.7% is combusted with energy recovery, and 27.4% is landfilled;
- System 2 – There is no information available regarding the end-of-life destination of natural cork stoppers. When analyzing the environmental impacts of cork products, other studies have assumed that the end-of-life destination of these products is the same as the end-of-life destination of wood products. Therefore, in this study, the end-of-life stage of natural cork stoppers is similar to the end-of-life stage of particle boards;
- System 3 – Regarding particle boards, it is considered that 16.7% is recycled, 15.8% is combusted with energy recovery, and 67.5% is landfilled.

Based on the percentages presented, the quantity of each product that goes to each end-of-life destination was determined and can be consulted in Tables A.13 to A.15 available in Appendix A. For example, from the 529,840.41 kilograms of UWF paper manufactured, 349,247.14 kilograms (65.9%) will be recycled.

The main data determined to model the three systems under study is summarized in Table 3.3.

Table 3.3 – Main foreground data determined to model the three systems under study.

	System 1	System 2	System 3
Raw materials' extraction	1,721.43 cubic meters	14,649.29 kilograms	382.01 cubic meters
Products' manufacture	529,840.41 kilograms	2,929.86 kilograms	223.72 cubic meters
Products' distribution			
Domestic market	41,886.77 kilograms	2,685.80 kilograms	129.92 cubic meters
International market	487,953.64 kilograms	244.06 kilograms	93.80 cubic meters
Products' end-of-life			
Recycling	65.9%	16.7%	16.7%
Combustion with energy recovery	6.7%	15.8%	15.8%
Landfill	27.4%	67.5%	67.5%

3.2.3 Life Cycle Impact Assessment

In the third step of an LCA study, Life Cycle Impact Assessment, the inventory collected in the previous step is converted into environmental impacts using LCIA methods. These methods can be divided into two types - the problem-oriented methods, which only consider impact categories at the midpoint level (e.g., CML 2001), and damage-oriented methods, which consider impact categories at the midpoint level but further aggregate these into fewer impact categories at the endpoint level (e.g., ReCiPe 2008). The results of the impact categories at the midpoint level are calculated by multiplying the substances collected in the second step of an LCA (i.e., LCI step) with the characterization factors that are specific to each substance and category. Then, if the LCIA method selected is damage-oriented, the midpoint impact categories are aggregated into endpoint impact categories using mid-to-end factors. The endpoint categories can then be normalized using normalization factors and multiplied by the corresponding weight. The normalized and weighted results can be added to determine the single score (SS) representing the overall environmental impact of the system(s) under analysis. Equation 3.7 shows how the SS is calculated.

$$SS\ (Pt) = \sum_{s,m,e} \frac{(Inv_s \times CF_{s,m} \times MEF_{s,m,e}) \times W_e}{NF_e} \qquad (3.7)$$

where *s* denotes the substance, *m* denotes the midpoint impact category, *e* denotes the endpoint impact category, *Inv* denotes the inventory, *CF* denotes the characterization factor, *MEF* denotes the mid-to-end factor, *NF* denotes the normalization factor, and *W* denotes the weight.

The work developed by the European Commission et al. (2011) with recommendations on models and parameters that should be used for impact assessment can be consulted to help decide which LCIA method to use.

The LCIA method selected in this study is ReCiPe 2008 (Goedkoop, et al., 2009) because it is, according to the European Commission, the most recommended as a default method (Carvalho, et al., 2014). ReCiPe 2008 is a combination of two other LCIA methods, Eco-indicator 99 and CML 2002, and considers 18 midpoint categories including – Climate Change (CC), Ozone Depletion (OD), Human Toxicity (HT), Photochemical Oxidant Formation (POF), Particulate Matter Formation (PMF), Ionizing Radiation (IR), Terrestrial Acidification (TA), Freshwater Eutrophication (FEut), Marine Eutrophication (MEut), Terrestrial Ecotoxicity (TEco), Freshwater Ecotoxicity (FEco), Marine Ecotoxicity (MEco), Agricultural Land Occupation (ALO), Urban Land Occupation (ULO), Natural Land Transformation (NLT), Metal Depletion (MD), Fossil Depletion (FD), and Water Depletion (WD).

For any of these results, the higher the value, the worst it is the environmental impact.

3.2.4 Interpretation

The fourth and last step of an LCA study, Interpretation, consists of examining and interpreting the study results. Depending on the goal of the LCA defined in the first step, this interpretation may include the recognition of the most critical environmental impacts, the determination of priority areas (i.e., hotspots), where changes must be made to reduce the environmental impacts, and the suggestion of potential alterations to accomplish this reduction.

In this study, different results are analyzed, including:

- Overall environmental impact – Comparison of the overall environmental impact (i.e., single score) of the three life cycles analyzed in terms of absolute value but also considering the overall environmental impact per euro of net present value generated;
- Critical environmental impacts – Identification of the midpoint impact categories responsible for most of the overall environmental impact. The use of a Pareto analysis can be used as an approach for this identification (Carvalho, et al., 2014). Generally speaking, the purpose of this analysis is to determine if a minority of independent variables is responsible for the majority of the effects with the "80/20" rule being the most consider (i.e., in the case of an LCA, if 80% of the environmental impact is caused by 20% of the midpoint categories) (Vitasek, 2006). Because these impact categories have different units of measurement, the Pareto analysis can only be applied after they are normalized or weighted;
- Hotspots – Identification of the life cycle stage responsible for the majority of the overall environmental impact. This identification will allow to give more informed recommendations for the companies in the forest sector.

Due to the uncertainty associated with some of the foreground data used to model the three systems, a sensitivity analysis was conducted. This analysis aims to measure how the impact of uncertainties of different input variables (i.e., parameters) can lead to uncertainties on the output variables (i.e., results). Thus, it is usually applied considering the uncertain parameters that most contribute to the results under study. Using such an analysis helps determine the reliability of these results and identify the parameters' values beyond which the results change significantly (Absollhi, 2014). The results of the sensitivity analysis are also presented in Section 3.4.

3.3 Economic Assessment

The economic assessment is performed using the net present value (NPV) technique which involves estimating the present value of future net cash flows (i.e., the difference between the cash inflows and outflows) over a period of time. The notion of present value is related with the fact that the same amount of money earned in the future won't be worth as much as the same amount earned in the present. To calculate the present value of future net cash flows, a discount rate is used to account for this decrease in the value of money. The NPV can be calculated using Equation 3.8 (Li, et al., 2019).

$$NPV\ (€) = \sum_{a=1}^{n} \frac{B_a - C_a}{(1+i)^a} \tag{3.8}$$

where B_a denotes the benefits (cash inflows) gained during a single period a, C_a denotes the costs (cash outflows) incurred during a single period a, i denotes the discount rate or return that could be earned in alternative investments, a denotes the time period, and n denotes the number of time periods (Li, et al., 2019).

EBITDA (Earnings Before Interests, Tax, Depreciation and Amortization) can be used as a proxy for net cash flows (Poort & Kerste, 2014). This accounting measure is calculated by subtracting the cost of goods sold and all expenses except for interest, amortization, depreciation and taxes from the sales revenue. The use of EBITDA as a proxy for net cash flows is not uncommon since it allows for a simpler, less assumption-based analysis based on available data on EBITDA. However, there is one instance where EBITDA is not a good proxy for net cash flows. This is the case in companies with high depreciation values which often lead to high investment needs. This investment will impact net cash flows, but it will not impact EBITDA since this accounting measure thus not include depreciation. Hence, except for capital intensive industries such as Oil and Gas, EBITDA can be used as a proxy for net cash flows (Poort & Kerste, 2014). This is the case of the forest industries. The EBITDA margin is calculated by dividing the EBITDA by total revenue (Pradhan, et al., 2019). The application of these concepts to each of the three systems under study is explained below.

System 1 – Uncoated woodfree paper manufacture from *Eucalyptus globulus*

According to information provided in Subsection 3.2.2.1, the rotation period considered in System 1 is 12 years. Hence, the first harvest of *Eucalyptus globulus* occurs at the end of the 12^{th} year. It was assumed that the volume of pulpwood generated by this first harvest is used to manufacture UWF paper that will be sold at the same rate between the 13th year and the 24th year when the next harvest occurs. Given the rotation period of 12 years, seven more harvests are possible in the 100 years' time horizon defined in the functional unit which means that the final harvest will occur at the end of the 96th year. For this reason, and given that an equal annual demand was considered, the volume of pulpwood generated by this last harvest is used to manufacture UWF paper that will be sold at the same rate between the 97th year and the 108th year. Consequently, the 529,840.41 kilograms of UWF paper manufactured with the volume of pulpwood generated by one hectare of forest land in Portugal planted with *Eucalyptus globulus* given a time horizon of 100 will be sold between the 13th year and the 108th year which corresponds to a total of 5,519.17 kilograms of UWF paper sold per year. According to the Portuguese national statistical institute (INE, 2017), each kilogram of UWF paper sold generates 0.65 euros in revenue. Thus, the 5,519.17 kilograms of UWF paper sold per year generate a revenue of 3,604.70 euros. The average EBITDA margin for Portuguese companies in the pulp, paper and cardboard industry is 21.1% (APCOR, 2019). Consequently, to an annual revenue of 3,604.70 euros corresponds an EBITDA of 760.59 euros. This value will be used as a proxy for the annual net cash flows considered in System 1 (see Table A.16 in Appendix A).

System 2 – Natural cork stoppers manufacture from *Quercus suber*

The first stripping of cork from *Quercus suber* can only be done after 25 years (see Subsection 3.2.2.1). After this, subsequent stripping will occur every 9 years (i.e., the rotation period considered in System 2). However, only after the third stripping (at 43 years of age) does the cork reaches the quality necessary to be used in the manufacturing of natural cork stoppers. It was assumed that the amount of cork generated by this stripping is used to manufacture natural cork stoppers that will be sold at the same rate between the 44th year and the 52th year when the next stripping occurs. Given the rotation period of 9 years, six more harvests are possible in the 100 years' time horizon defined in the functional unit which means that the final stripping will occur at the end of the 97th year. For this reason, and given that an equal annual demand was considered, the amount of cork generated by this last harvest is used to manufacture natural cork stoppers that will be sold at the same rate between the 98th year and the 106th year. Consequently, the 2,929.86 kilograms of natural cork stoppers manufactured with the amount of cork generated by one hectare of forest land in Portugal planted with *Quercus suber* given a time horizon of 100 will be sold between the 44th year and the 106th year which corresponds to a total of 46.51 kilograms of natural cork stoppers sold per year. Each kilogram of natural cork stoppers sold generates 3.67 euros in revenue (INE, 2017). Thus, the 46.51 kilograms of natural cork stoppers sold per year generate a revenue of 170.69 euros. According to the Portuguese Cork Association, the average EBITDA margin for Portuguese companies in the cork industry is 8.9% (APCOR, 2019). Hence, to an annual revenue of 170.69 euros corresponds an EBITDA of 15.19 euros. This value will be used as a proxy for the annual net cash flows considered in System 2 (see Table A.17 in Appendix A).

System 3 – Particle boards manufacture from *Pinus pinaster*

The rotation period considered in System 3 is 40 years (see Subsection 3.2.2.1). Consequently, the first harvest of *Pinus pinaster* occurs at the end of the 40th year. It was assumed that the volume of roundwood generated by this first harvest is used to manufacture particle boards that will be sold at the same rate between the 41th year and the 80th year when the next harvest occurs. Given the rotation period of 40 years, one more harvests is possible in the 100 years' time horizon defined in the functional unit which means that the final harvest will occur at the end of the 80th year. For this reason, and given that an equal annual demand was considered, the volume of roundwood generated by this last harvest is used to manufacture particle boards that will be sold at the same rate between the 81th year and the 120th year. Thus, the 223.72 cubic meters of particle boards manufactured with the volume of roundwood generated by one hectare of forest land in Portugal planted with *Pinus pinaster* given a time horizon of 100 will be sold between the 41th year and the 120th year which corresponds to a total of 2.80 cubic meters of particle boards sold per year. Each cubic meter of particle boards sold generates 222.24 euros in revenue (INE, 2017). Hence, the 2.80 cubic meters of particle boards sold per year generate a revenue of 621.49 euros. The average EBITDA margin for Portuguese companies in the wood industry is 12.8% (APCOR, 2019) which means that to an annual revenue of 621.49 euros corresponds an EBITDA of 79.55 euros. This value will be used as a proxy for the annual net cash flows considered in System 3 (see Table A.18 in Appendix A).

To calculate the NPV using Equation 3.8 it is also required to define the discount rate or return that could be earned in alternative investments. The discount rate should reflect the risk level of the project under analysis. The alternative investment considered was the investment in Portuguese treasure certificates. The average interest rate in this type of investment is 1.38% (CTT, 2020) and this was the discount rate chosen for this study. Since the three forest products under analysis are all from the forest sector, it was assumed the same level of risk for the three different systems.

Using the annual net cash flows calculated previously for each system and the discount rate chosen, the NPV of each system can be determined (see Table A.16 to A.18 in Appendix A). Table 3.4 presents the main data considered for the economic assessment of the three systems under study.

Table 3.4 – Main data considered for the economic assessment of the three systems under study.

	System 1	System 2	System 3
Quantity	529,840.41 kg	2929.86 kg	223.72 m^3
Revenue	0.65 €/kg	3.67 €/kg	222.24 €/m^3
EBITDA Margin	21.1%	8.9%	12.8%
Net Present Value (euros)	34,213.09	353.13	6,093.68

3.4 Results Analysis and Discussion

The results of the environmental and economic assessment of the three systems considering all previously identified information are presented in this section. These results will be used in Section 3.5 to provide informed suggestions to forest companies.

3.4.1 Environmental and Economic Assessment

The single score of the three systems analyzed is presented in Table 3.5. From the analysis of this table, it is possible to conclude that System 1 presents the highest SS, while System 2 presents the lowest SS. It is essential to mention that this comparison is based on the functional unit previously defined. As seen in Figure 3.1, this functional unit is translated into different quantities of forest wood products. This figure shows that this quantity in System 1 (529,849.41 kilograms of UWF paper) is higher than this quantity in System 2 (2,929.86 kilograms of natural cork stoppers). This difference might be why System 1 presents the highest and System 2 presents the lowest single score.

Table 3.5 – Main results of applying the LCA methodology to the three systems.

	System 1	System 2	System 3
Quantity Sold	529,840.41 kg	2,929.86 kg	223.72m^3
Net Present Value (euros)	34,213.09	353.13	6,093.68
Single Score (Pt)	99,172.41	21,403.70	31,602.83
Environmental Impact (Pt/euro)	2.90	60.61	5.19

The net present value calculated for each system in Section 3.3 is also presented in Table 3.5. It is possible to conclude that the system with the highest single score is also the system with the highest net present value (System 1). At the same time, the system with the lowest single score is also the system with the lowest net present value (System 2). This represents a trade-off – the worst system from an environmental perspective is simultaneous the best system from an economic perspective and vice versa. Hence, the ratio between the single score and the net present value was calculated for each system under study. These ratios are presented in Table 3.5 and based on these results it is possible to conclude that System 1 generates the lowest amount of single score per euro of NPV (2.90 Pt/euro), while System 2 generates the highest amount of single score per euro of NPV (60.61 Pt/euro). Thus, the plantation of *Eucalyptus globulus* to produce uncoated woodfree paper in Portugal is the best course of action from an environmental and economic perspective.

These results are surprising since paper production has been known for its environmental impacts (WWF, 2020b), including large consumption of resources and the use of hazardous chemicals (Sahay, 2004), and yet it is System 1 that has the lowest SS per euro of NPV. Natural cork stoppers are, as the name indicates, a natural product manufactured using low amounts of chemicals (see Subsection 3.2.2.2). Also, natural cork stoppers require a manual extraction of the raw material (contrary to pulpwood, which is harvest using chainsaws). For these reasons, it is surprising that System 2 has the highest SS per euro of revenue.

The next subsections are dedicated to understanding the reason behind these results.

3.4.2 Critical environmental impacts

A Pareto analysis was conducted to determine the impact categories that contribute the most to each system's single score. The result of this analysis is presented in Figure 3.4.

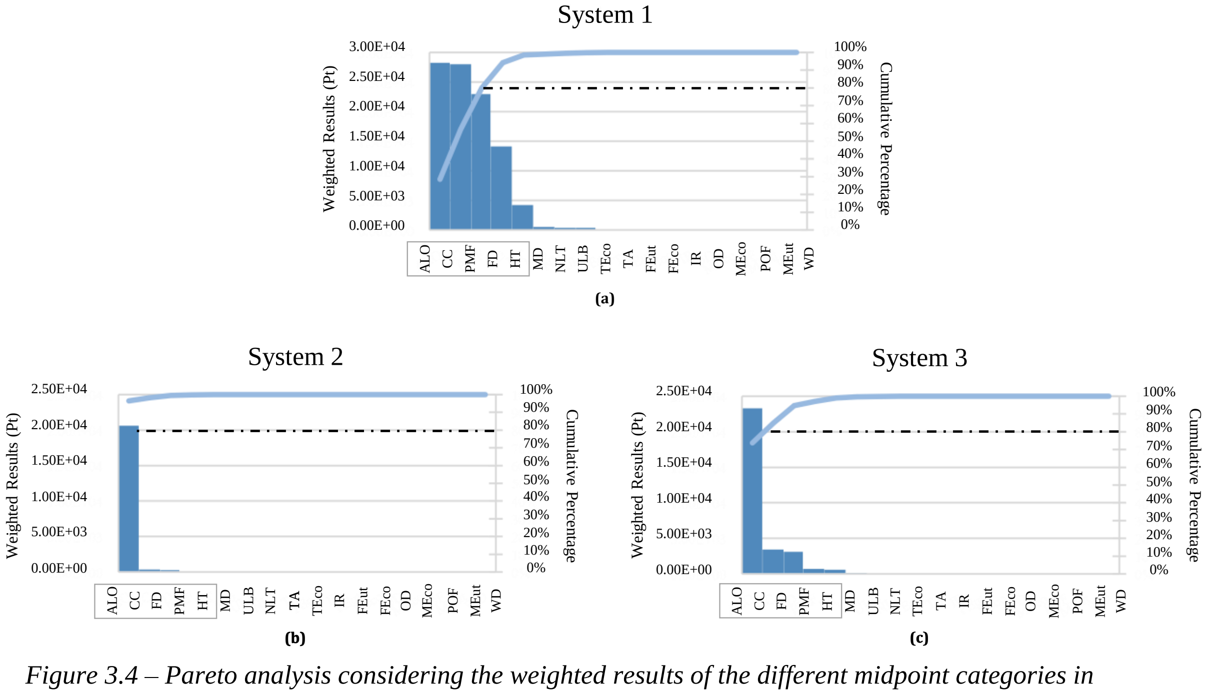
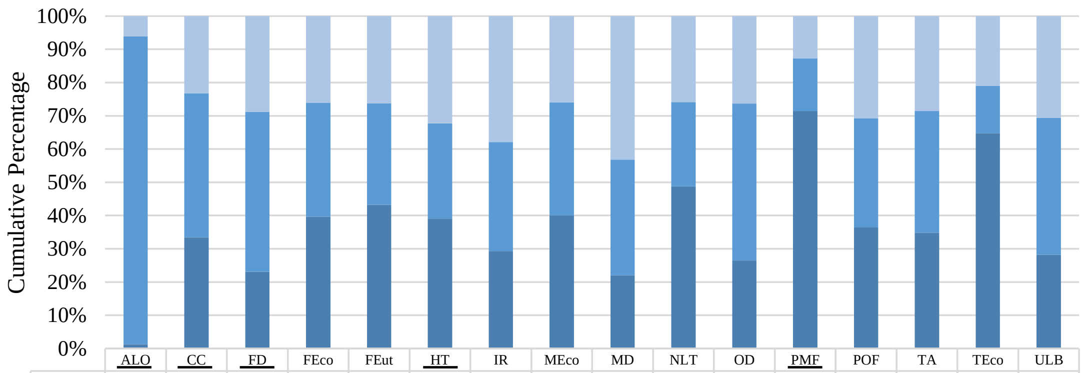


Figure 3.4 – Pareto analysis considering the weighted results of the different midpoint categories in System 1 (a), System 2 (b), and System 3 (c).

From the analysis of Figure 3.4, it is possible to conclude that the most critical environmental impacts in the three systems are: i) agricultural land occupation, ii) climate change, iii) fossil depletion, iv) particulate matter formation, and v) human toxicity.

The weighted results per euro of NPV of each midpoint category are presented in Figure 3.5 for the three systems. In this figure, the worst result per category is underlined with the worst result in the five most critical impact categories underlined in a darker color.



	ALO	CC	FD	FEco	FEut	HT	IR	MEco	MD	NLT	OD	PMF	POF	TA	TEco	ULB
System 3	3.83E+00	5.70E-01	5.16E-01	2.91E-04	3.93E-04	1.02E-01	5.30E-04	5.86E-05	3.02E-02	6.27E-03	9.13E-05	1.20E-01	5.05E-05	7.99E-04	1.09E-03	1.26E-02
System 2	5.84E+01	1.06E+00	8.60E-01	3.84E-04	4.57E-04	9.09E-02	4.59E-04	7.64E-05	2.43E-02	6.13E-03	1.64E-04	1.49E-01	5.41E-05	1.03E-03	7.44E-04	1.70E-02
System 1	8.26E-01	8.19E-01	4.14E-01	4.43E-04	6.48E-04	1.24E-01	4.10E-04	9.01E-05	1.54E-02	1.18E-02	9.19E-05	6.71E-01	6.00E-05	9.74E-04	3.37E-03	1.16E-02

Figure 3.5 – Weighted results of the three systems analyzed considering the different midpoint categories.

From the analysis of Figure 3.5, it is possible to conclude that:

- System 1 presents worse weighted results per euro in half of the impact categories (see underlined results from Figure 3.5);
- System 2 presents worse weighted results per euro in less impact categories than System 1 (see underlined results from Figure 3.5);
- System 2 presents the worst result per euro in the three most critical impact categories (ALO, CC, and FD) (see underlined results from Figure 3.5);
- The combination of the previous points explain why System 2 has the worst overall impact per euro of NPV (see Table 3.5) – Even though it is not the system with the worst result in most impact categories, it has the worst result in the most critical impact categories (i.e., the categories that impact the most the single score).

These results reinforce the importance of a complete study of an LCA since it is the only way to identify the real impact and the most relevant aspects that should be considered when trying to reduce the environmental impacts.

3.4.3 Hotspots

Finding the life cycle stage(s) that contribute the most to the single score (i.e., hotspots) allows to identify where improvements could be made so that environmental impacts can be reduced. Figure 3.6 presents the contribution of each life cycle stage to the single score of the three systems.

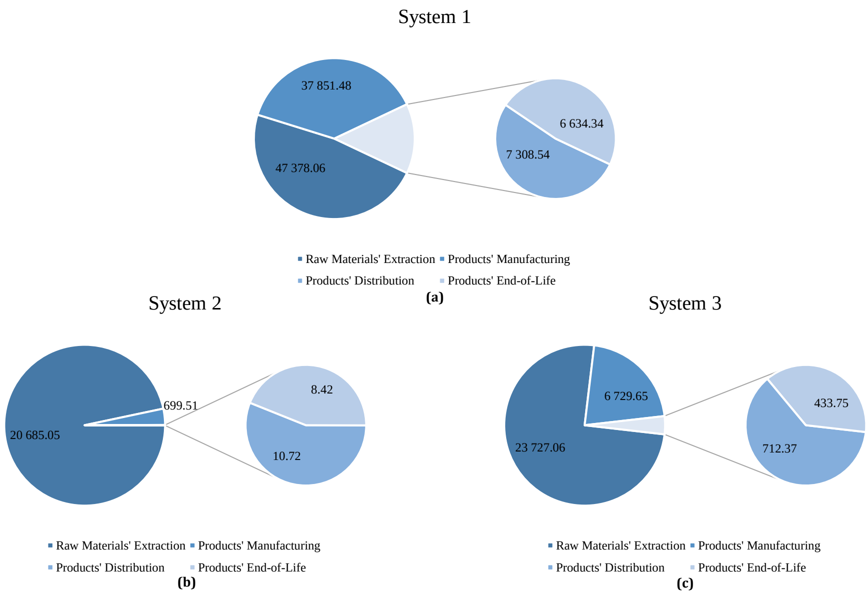


Figure 3.6 – Contribution of each life cycle stage to the single score of System 1 (a), System 2 (b), and System 3 (c).

Figure 3.6 shows that Raw Materials' Extraction is the most critical life cycle stage in terms of environmental impact (highest percentage), followed by Products' Manufacture (second highest percentage), for the three systems. These are the two life cycle stages where changes could make a more significant improvement in the environmental impact reduction (the same conclusion to the three systems). The material and energy flows that most contribute to these two life cycle stages are analyzed below to provide more accurate recommendations. Recommendations are provided in Section 3.5.

System 1 - Uncoated woodfree paper manufacture from *Eucalyptus globulus*

From Figure 3.6a, it was possible to verify that the environmental impact of System 1 is equitably distributed across the four life cycle stages. The Raw Materials' Extraction of System 1 contributes 47.77% to the single score of this system, while Products' Manufacture contributes 38.17% (see Figure 3.6a). This system is where the Products' Manufacture stage contributes almost as much as the Raw Materials' Extraction to the single score. Figure 3.7 presents the inputs and outputs flows obtained in the LCI step that contributes the most to the single score of these life cycle stage.

From the analysis of Figure 3.7, it is possible to conclude that the occupation and transformation of land by the *Eucalyptus globulus* trees is the most critical flow in the Raw Materials' Extraction stage, contributing 91.1%, followed by the transportation of the pulpwood to the *Região de Coimbra* subregion, where the manufacture of UWF paper was assumed to be (see Figure 3.3). It is also possible to conclude that the emissions to air and water resulting from the manufacture of UWF paper and electricity consumption are the most critical flows in the Products' Manufacture stage, contributing 50.5% for the environmental impact of this stage.

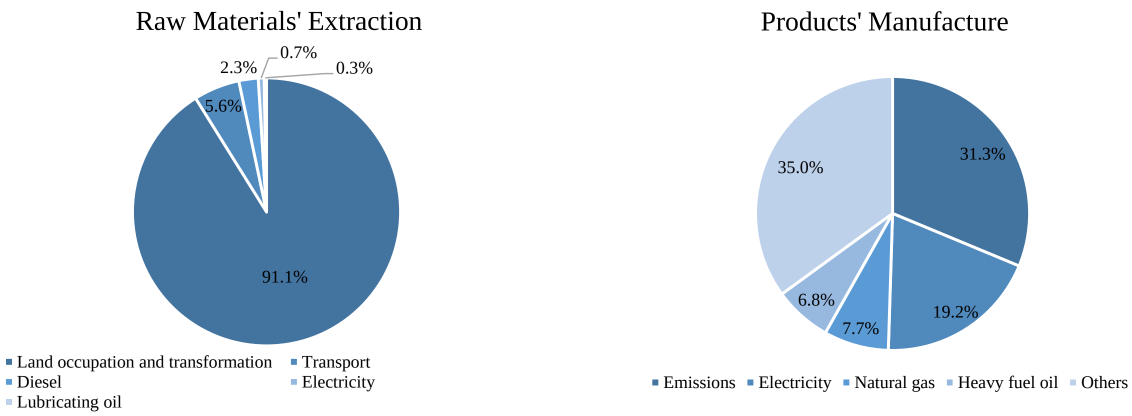


Figure 3.7 – Inputs and outputs that most contribute to the single score of the Raw Materials' Extraction (left side) and Products' Manufacture (right side) life cycle stages in the case of System 1.

System 2 - Natural cork stoppers manufacture from *Quercus suber*

In System 2, the Raw Materials' Extraction contributes 96.64% to the single score, while Products' Manufacture only contributes 3.27% (see Figure 3.6b). This system is where the Raw Materials' Extraction stage contributes the most to the single score. Figure 3.8 presents the inputs and outputs obtained in the LCI step that most contribute to the environmental impact of the two most critical life cycle stages.

From Figure 3.8, it is possible to conclude that the occupation and transformation of land by the *Quercus suber* trees is the most critical flow in the Raw Materials' Extraction stage, contributing 99.7% for the environmental impact of this stage. In comparison, the transportation of the cork to the *Área Metropolitana do Porto* subregion where the manufacture of natural cork stoppers was assumed to be (see Figure 3.3) only contribute 0.3%. Please notice that, contrary to System 1 (see Figure 3.7), no diesel, lubricating oil, or electricity appears in the results of the Raw Materials' Extraction stage for System 2 (see Figure 3.8). This is because the stripping of cork is done manually (contrary to pulpwood, which is usually harvested using chainsaws), as previously explained in Subsection 3.2.2.1.

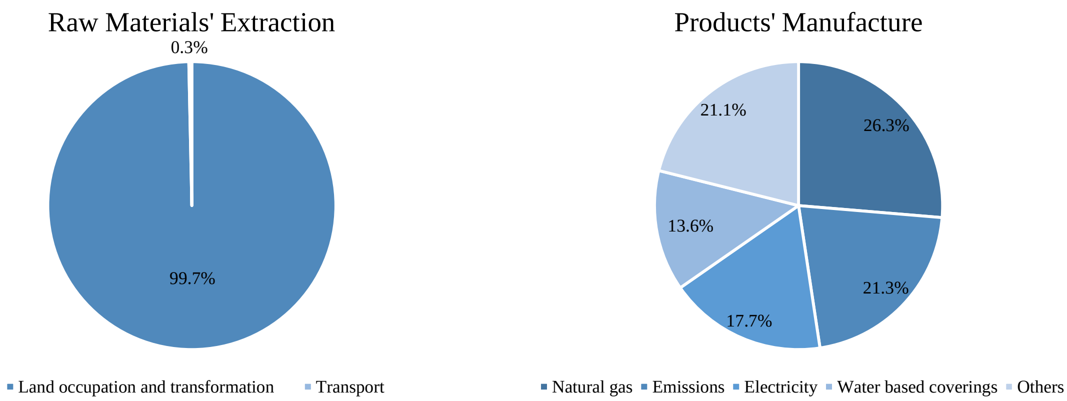


Figure 3.8 – Inputs and outputs that most contribute to the single score of the Raw Materials' Extraction (left side) and Products' Manufacture (right side) life cycle stages in the case of System 2.

In the Products' Manufacture stage, the most critical flows are natural gas consumption and the emissions to air caused by natural gas combustion (39.0% of the environmental impact).

System 3 – Particle boards manufacture from *Pinus pinaster*

In System 3, Raw Materials' Extraction contributes 75.08% to the single score, while Products' Manufacture contributes 21.29% (see Figure 3.6c). Figure 3.9 presents the inputs and outputs obtained in the LCI step that most contribute to the environmental impact of these life cycle stages.

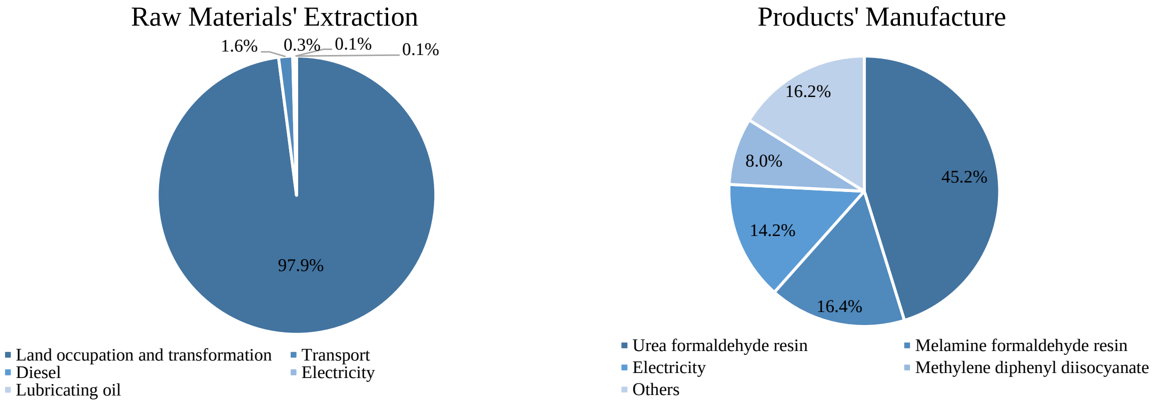


Figure 3.9 – Inputs and outputs that most contribute to the single score of the Raw Materials' Extraction (left side) and Products' Manufacture (right side) life cycle stages in the case of System 3.

From the analysis of Figure 3.9, it is possible to conclude that the occupation and transformation of land by the *Pinus pinaster* trees is the most critical flow in the Raw Materials' Extraction stage, contributing 97.9% for the environmental impact of this stage. In comparison, the transportation of the roundwood to the *Viseu Dão Lafões* subregion, where the manufacture of particle boards was assumed to be (see Figure 3.3) only contribute 1.6%. It is also possible to conclude that the adhesive resin (urea formaldehyde and melamine formaldehyde) used in the manufacture of particle boards are the most critical flows in the Products' Manufacture stage contributing 61.6% for the environmental impact of this stage.

3.4.4 Sensitivity Analysis

The data used to model the three systems has uncertainty associated and, for this reason, a sensitivity analysis was conducted. This type of analysis allows to understand how the results of this study are affected by the uncertainty of the input data used. The main result used to compare the three systems was the environmental impact per euro of NPV. This indicator was calculated based on the results of the environmental and economic assessments. These assessments were conducted using uncertain parameters, and for this reason, this sensitivity analysis focus on understanding the influence of these parameters on the conclusions.

3.4.4.1 Environmental Assessment

From the previous analysis, it was concluded that Raw Materials' Extraction is the life cycle stage that most contribute to the environmental impact of the three systems (see Figure 3.6). The parameters used to model this stage were (Subsection 3.2.2.1):

- Tree dimensions – The value of this parameter for each system was taken from scientific studies (System 2 and 3), where the measurement of real trees was considered or was provided by forest associations (System 1) with extensive knowledge on the subject. For this reason, the values of these parameters presented in Table 3.1 are considered reliable;
- Rotation period – The value of this parameter for each system was provided by forest associations based on the rotation periods usually considered by Portuguese forest owners. For this reason, the values of these parameters presented in Table 3.1 are considered reliable;
- Forest density – The value of this parameter for each system was taken from the National Forest Inventory (ICNF, 2015). An average number of 739 *Eucalyptus globulus* trees, 78 *Quercus suber* trees, and 485 *Pinus pinaster* trees per hectare were considered (see Table 3.1 parameter *T*). However, from the 6th National Forest Inventory (ICNF, 2015), it is possible to conclude that the number of *Eucalyptus globulus* and *Pinus pinaster* trees per hectare could vary from less than 300 to more than 1500, and the number of *Quercus suber* trees per hectare could vary from less than 40 to more than 200. For this reason, this parameter has uncertainty associated.

To determine the impact of varying the forest density considered in the three systems, the number of trees per hectare was changed, and the single score obtained for each of these variations was registered. The results of this analysis are presented in Figure 3.10 using solid lines (see left side of Figure 3.10). The single score per euro of NPV previously determined (see Table 3.5) are also represented in Figure 3.10 using dashed lines. To facilitate the analysis of this figure, the shaded area was magnified (see right side of Figure 3.10). Please notice that for System 2 a maximum density of 300 *Quercus suber* per hectare was considered while for Systems 1 and 3 a maximum density of 1500 *Eucalyptus globulus* and *Pinus pinaster* per hectare were considered, respectively (see left side of Figure 3.10). This is because in Portugal the number of *Quercus suber* trees per hectare vary from less than 40 to more than 200 while the number of *Eucalyptus globulus* and *Pinus pinaster* trees per hectare vary from less than 300 to more than 1500. From the analysis of Figure 3.10, it is possible to conclude that a higher number of trees per hectare (x-axis) would generate a lower single score per euro of NPV (y-axis). This happens because more wood/cork can be generated from the occupation of the same area (one hectare) during the same amount of time (100 years).

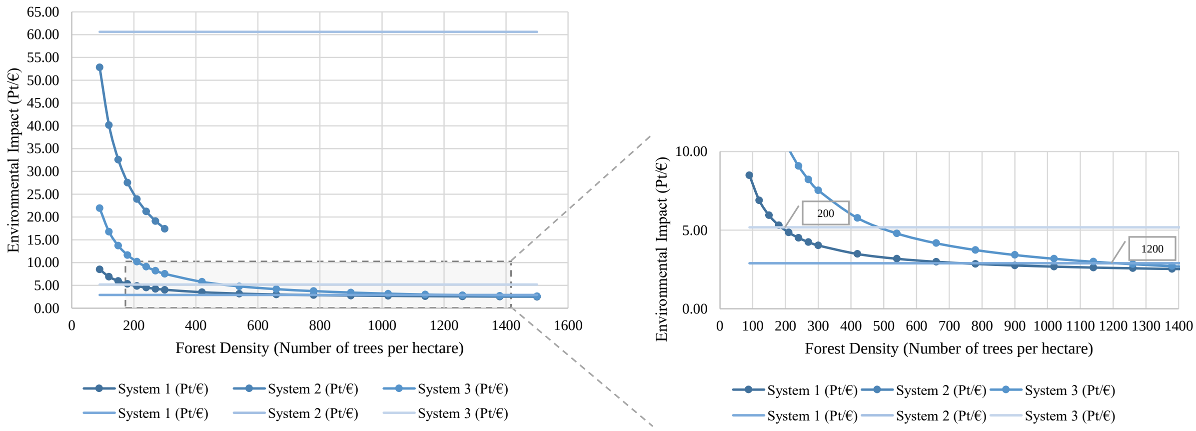


Figure 3.10 – Sensitivity analysis considering the variation of the number of trees per hectare for the three systems.

From the analysis of Figure 3.10, it is possible to conclude that:

- The single score per euro of System 1 reaches 5.19 Pt per euro (System 3) when a forest density of 200 *Eucalyptus globulus* trees per hectare is considered (see callout data on the right side of Figure 3.10);
- Only with a forest density equal to 27% (200 *Eucalyptus globulus* trees per hectare) or less of what was originally considered (739 *Eucalyptus globulus* trees per hectare), would System 3 be considered better, from an economic and environmental perspective (lower SS per euro), than System 1;
- Since a large reduction (73%) in the number of *Eucalyptus globulus* trees per hectare considered is necessary for the results to change, the conclusion that System 1 is the best system, from an economic and environmental perspective, is consider reliable;
- Regardless of the forest density considered, the single score per euro of System 2 would never reach the single score per euro of System 3 (5.19 Pt per euro);
- Since no number of *Quercus suber* trees per hectare is enough for the results to change, the conclusion that System 2 is the worst system, from an economic and environmental perspective, is consider reliable;
- The single score per euro of System 3 reaches 2.90 Pt per euro (System 1) when a forest density of 1200 *Pinus pinaster* trees per hectare is considered (see callout data on the right side of Figure 3.10);
- Only with a forest density equal to 244% (185 *Pinus pinaster* trees per hectare) or more of what was originally considered (485 *Pinus pinaster* trees per hectare), would System 3 be considered better, from an economic and environmental perspective (lower SS per euro), than System 1;

- Since a large increase (144%) in the number of *Pinus pinaster* trees per hectare is necessary for the results to change, the conclusion that System 3 is a worst system than System 1, from an economic and environmental perspective, is consider reliable.

The sensitivity analysis allows to conclude that if different forest densities had been considered, the results achieved in terms of SS per euro of NPV might not have been the same. However, only large reductions or increases in the number of trees per hectare considered would lead to a change in the conclusions. For this reason, these are considered reliable.

This sensitivity analysis considers variations in the forest density of one system while the forest densities of the other two systems remain constant (see Figure 3.10). An analysis was conducted where the forest densities of two systems varied, and the respective single scores per euro were calculated to determine which system is better from an economic and environmental perspective (lower SS per euro). Figure 3.11 presents a summary of this analysis, including which system is better from an economic and environmental perspective for each pair of forest densities. It also includes the forest densities considered in this study (see squares in Figure 3.11). This figure allows to conclude how different forest density values would affect the results obtained and the conclusion drawn. In Portugal, the number of *Eucalyptus globulus* and *Pinus pinaster* trees per hectare vary from less than 300 to more than 1500, and the number of *Quercus suber* trees per hectare vary from less than 40 to more than 200 (ICNF, 2015). For this reason, a maximum forest density of 1590 *Eucalyptus globulus* and *Pinus pinaster* trees per hectare (System 1 and 3, respectively), and 300 *Quercus suber* trees per hectare were considered.

From the analysis of Figure 3.11:

- For any number of *Eucalyptus globulus* trees per hectare and any forest density smaller than 210 *Quercus suber* trees per hectare, System 1 is better than System 2 from an economic and environmental perspective. On the other hand, for any number between 240 and 300 *Quercus suber* trees per hectare and a forest density of 30 *Eucalyptus globulus* trees per hectare, System 2 is better than System 1 from an economic and environmental perspective (see Figure 3.11a);
- For any number higher than 90 *Quercus suber* trees per hectare and a forest density of 30 *Pinus pinaster* trees per hectare, System 2 is better than System 3 from an economic and environmental perspective. On the other hand, for any number of *Pinus pinaster* trees per hectare and any forest density smaller than 60 *Quercus suber* trees per hectare, System 3 is better than System 2 from an economic and environmental perspective (see Figure 3.11b);
- For any number of *Eucalyptus globulus* trees per hectare and any forest density smaller than 120 *Pinus pinaster* trees per hectare, System 1 is better than System 3 from an economic and environmental perspective. On the other hand, for any number higher than 180 *Pinus pinaster* trees per hectare and a forest density of 60 *Eucalyptus globulus*

trees per hectare, System 3 is better than System 1 from an economic and environmental perspective (see Figure 3.11c);

- For the same forest density (e.g., a forest density of 600 *Eucalyptus globulus* and *Pinus pinaster* trees per hectare), System 1 is better than System 3 from an economic and environmental perspective (see Figure 3.11c);
- For the forest densities considered in this study (see Table 3.1 parameter *T*) of 739 *Eucalyptus globulus*, 78 *Quercus suber*, and 485 *Pinus pinaster* trees per hectare (see squares in Figure 3.11), System 1 is the best, from an economic and environmental perspective, followed by System 3 and System 2. This conclusion took based on Figure 3.11 matches the one presented in Subsection 3.4.1.

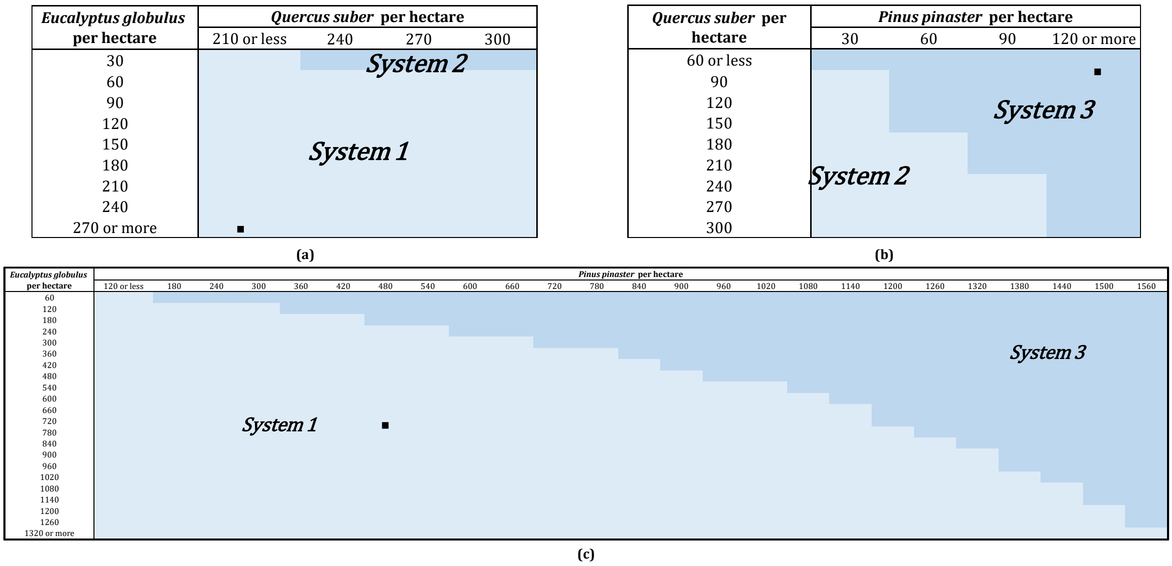


Figure 3.11 – Sensitivity analysis considering the variation of the number of trees per hectare and identification of which system is better from an economic and environmental perspective.

3.4.4.2 Economic Assessment

The average EBITDA margin for Portuguese companies in the pulp, paper and cardboard industry is 21.1% (see Section 3.3). However, the median value of the EBITDA margin for a Portuguese company in the pulp, paper and cardboard industry is 7.5% (APCOR, 2019). The same median value is true for Portuguese companies in the cork industry and wood industry. Furthermore, even though the average EBITDA margin for Portuguese companies in the cork industry is 8.9%, the average EBITDA margin for Portuguese companies in the cork industry that manufacture cork stoppers is 9.5% (APCOR, 2019). Thus, the EBITDA margin considered depends on whether absolute or median values are being taken into account and also if the whole industry or just specific segments are being considered. For these reasons, this parameter has uncertainty associated.

To determine the impact of varying this parameter, a variation of the EBITDA margin considered in the three systems was performed, and the single score obtained for each of these variations was registered. The results of this analysis are presented in Figure 3.12 using solid lines (see left side of Figure 3.12). The single score per euro of NPV previously determined (see Table 3.5) are also represented in Figure 3.12 using dashed lines. To facilitate the analysis of this figure, the shaded area was magnified (see right side of Figure 3.12). From the analysis of Figure 3.12, it is possible to conclude that a higher EBITDA margin (x-axis) would generate a lower single score per euro of NPV (y-axis). This happens because the higher the EBITDA margin is, the lower are a company´s operating expenses in relation to its total revenue (i.e., the higher the net cash flows are) and, consequently, the higher the NPV is. Since the single score per euro is calculated by dividing the single score by the NPV generated, the higher the denominator (i.e., NPV), the lower the SS per euro.

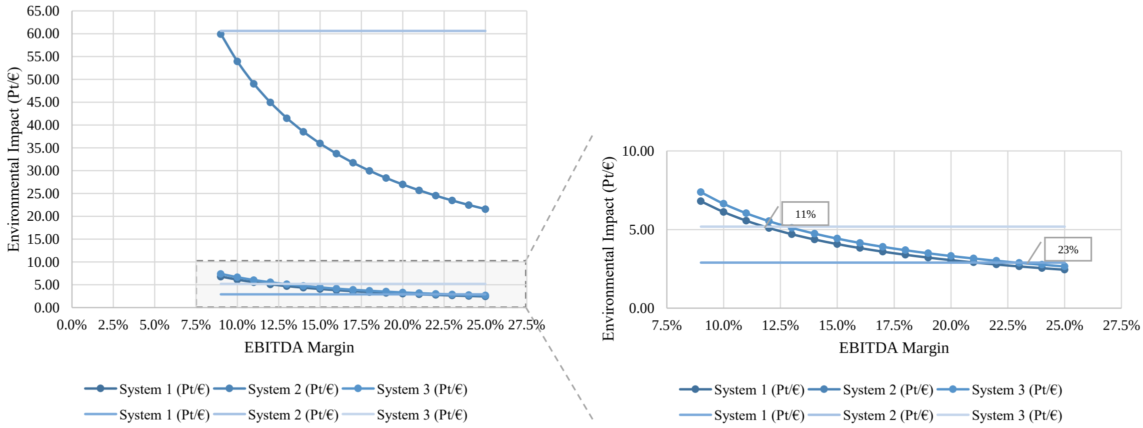


Figure 3.12 – Sensitivity analysis considering the variation of the EBITDA margin assumed in the three systems.

From the analysis of Figure 3.12, it is possible to conclude that:

- The single score per euro of System 1 reaches 5.19 Pt per euro (System 3) when an EBITDA margin of 11% is considered (see callout data on the right side of Figure 3.12);
- Only with an EBITDA margin equal to 52% (11%) or less of what was originally considered (21.1%), would System 3 be considered better, from an economic and environmental perspective (lower SS per euro), than System 1;
- Since a large reduction (48%) in the EBITDA margin considered in System 1 is necessary for the results to change, the conclusion that System 1 is the best system, from an economic and environmental perspective, is consider reliable;
- Regardless of the EBITDA margin considered, the single score per euro of System 2 would never reach the single score per euro of System 3 (5.19 Pt per euro);
- Since no EBITDA margin is enough for the results to change, the conclusion that System 2 is the worst system, from an economic and environmental perspective, is consider reliable;
- The single score per euro of System 3 reaches 2.90 Pt per euro (System 1) when an EBITDA margin of 23% is considered (see callout data on the right side of Figure 3.12);

- Only with an EBITDA margin equal to 180% (23%) or more of what was originally considered (12.8%), would System 3 be considered better, from an economic and environmental perspective (lower SS per euro), than System 1;
- Since a large increase (80%) in the EBITDA margin considered in System 3 is necessary for the results to change, the conclusion that System 3 is a worst system than System 1, from an economic and environmental perspective, is consider reliable.

The sensitivity analysis allows to conclude that if different EBITDA margins had been considered, the results achieved in terms of SS per euro of NPV might not have been the same. However, only large reductions or increases in the EBITDA margins considered would lead to a change in the conclusions. For this reason, these are considered reliable.

This sensitivity analysis considers variations in the EBITDA margin of one system while the other two systems' EBITDA margins remain constant (see Figure 3.12). An analysis was conducted where the EBITDA margins of two systems were varied together, considering a minimum margin of 5% and a maximum margin of 25%, and the respective single scores per euro were calculated to determine which system is better from an economic and environmental perspective (lower SS per euro). From this analysis it was concluded that Systems 1 and 3 are better than System 2, from an economic and environmental perspective, for any EBITDA margin between 5% and 25%. The comparison between Systems 1 and 3 is not so straightforward and therefore Figure 3.13 presents a summary of this comparison, including which system is better from an economic and environmental perspective for each pair of EBITDA margins considered. It also includes the EBITDA margins considered in this study for these two systems (see square in Figure 3.13).

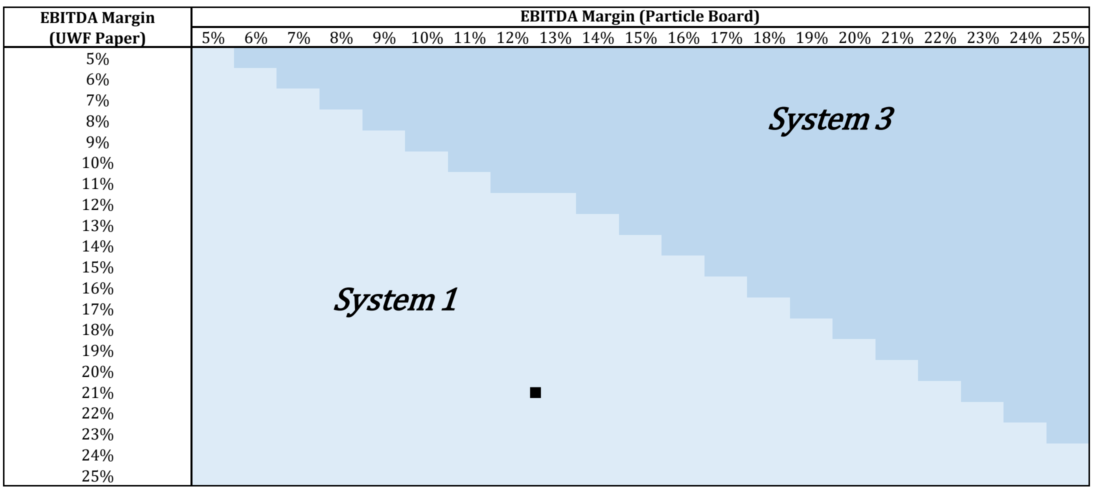


Figure 3.13 – Sensitivity analysis considering the variation of the EBITDA margin and the identification of which system is better from an economic and environmental perspective.

From the analysis of Figure 3.13:

- For any EBITDA margin considered in System 1 and an EBITDA margin of 5% considered in System 3, System 1 is better than System 3 from an economic and environmental perspective;
- On the other hand, for any EBITDA margin considered in System 3 higher than 6% and an EBITDA margin of 5% considered in System 1, System 3 is better than System 1 from an economic and environmental perspective;
- For the same EBITDA margin (e.g., an EBITDA margin of 15%), System 1 is better than System 3 from an economic and environmental perspective;
- For the EBITDA margins considered in this study (see Table 3.4) of 21.1% in System 1 and 12.8% in System 3 (see square in Figure 3.13), System 1 is better, from an economic and environmental perspective, than System 3. This conclusion took based on Figure 3.13 matches the one presented in Subsection 3.4.1.

3.5 Recommendations for Stakeholders in the Forest Sector

The results presented in the previous section allow us to define recommendations for different stakeholders in the forest sector including companies, business associations, and academics. For companies, a set of generic and industry-specific recommendations are provided. These recommendations demonstrate how life cycle assessment can be used to support environmental management, and aim to help companies to reduce the environmental impacts of their products. Additionally, as an economic assessment was also performed, recommendations also aim to support companies to increase their net cash flows.

3.5.1 Generic recommendations:

- The same five midpoint impact categories (ALO, CC, PMF, FD, and HT) are the most critical in the three systems analyzed (see Subsection 3.4.2). This similarity means that regardless of the forest industry considered, the most critical environmental impacts remain, leading to a common concern across the forest sector. Hence, when assessing and reporting the environmental impacts of this sector, governmental organizations should consider these impact categories. Moreover, if a company in this sector reports an environmental product declaration (for example), ALO, CC, PMF, FD, and HT are the categories to report;
- The Raw Materials' Extraction stage was found to be the life cycle stage responsible for most of the environmental impact in the three systems. Furthermore, the occupation of land by the different forest species was the major contributor to this result (see Subsection 3.4.3). Hence, the environmental impacts of the analyzed forest wood products' life cycle could be considerably reduced if land occupation is better managed.

This improved management can be accomplished by increasing the number of trees per hectare (see Subsection 3.4.4) or reducing the rotation period. These changes would result in more wood/cork generated from the occupation of the same area (one hectare) during the same amount of time (100 years). However, these changes should take into account the limitations of each forest species. For example, fewer than nine years of rotation are forbidden by the national and regional legislation for the stripping of cork from the *Quercus suber* tree. This indicates that research and development should be concentrated in this field. Also, funding agencies should consider these results as well as governments should also reassess legislation so that impacts can be reduced. For example, even though rotation periods shorter than nine years are not allowed for the stripping of cork from the *Quercus suber* tree, research has shown that it is possible to reduce the first cycle of cork extraction from 25 years to 8 years by implementing improved irrigation systems (Corticeira Amorim, 2020b). In this case, nine harvests of reproduction cork are possible in the 100 years' time horizon defined in the functional unit, instead of the seven harvests considered (see Table 3.1 System 2 parameter *R*). According to the results presented in Table 3.5, the environmental impact per kilogram of natural cork stoppers is 7.31 Pt/kg. This change of reducing the first cycle of cork extraction from 25 years to 8 years would result in an environmental impact per kilogram of natural cork stoppers of 5.74 Pt/kg which represents a 21.4% reduction in the environmental impact;

- To increase their net cash flows, companies can increase their revenue (e.g. by increasing the sales of existing products to existing customers or sell existing products to new customers) or reduce their costs (e.g. by increasing manufacturing efficiencies or eliminate known redundant expenses). Often, proposals made to reduce environmental impacts can also have positive consequences for economic performance. For example, a company that wants to go green (i.e., reduce its environmental impacts) by switching from a non-renewable to a renewable energy source may opt to install solar panels. The energy generated by the solar panels can cover most or even all of a company's energy needs and, ergo, help to reduce its electricity bill (i.e., costs). If the energy generated by the solar panels is higher than the energy consumed, the company can sell the surplus energy back to the grid. In addition to helping the company reduce its costs, the switch from a non-renewable to a renewable energy source can also help increase its revenues. In this sense, the improvement in the land occupation management suggested in the previous point to reduce the environmental impacts of forest wood products' life cycles would result in a more efficient occupation of the land and, consequently, a reduction in the operating expenses per unit sold. For instance, reducing the first cycle of cork extraction from 25 years to 8 years would result in an NPV per kilogram of natural cork stoppers of 0.137 €/kg, which represents a 13.8% increase in the net present value (initial value 0.121 €/kg, see Table 3.5). This improvement in the economic performance coupled with the 21.4% reduction in the environmental impact mentioned in the previous point would result in a reduction in the environmental impact per euro of 31.0% (from 60.61 Pt/€ to 41.85 Pt/€).

3.5.2 Specific recommendations:

After the Raw Materials' Extraction stage, the Products' Manufacture stage was found to be the life cycle stage responsible for most of the overall environmental impact for the three systems. The industry-specific recommendations that follow focus on the reduction of the environmental impact of this stage. These include:

- The emissions to air and water resulting from the manufacturing process and the electricity consumption are the most critical issues in the Products' Manufacture stage of the UWF paper life cycle (see Subsection 3.4.3). As a result, companies from the paper industry producing this product might consider the establishment of systems to monitor and control emissions, install chemical recovery systems to capture chemicals in exhaust gases or reduce the use of bleaching chemicals (U.K. Government, 2020). These alterations will help reduce the emissions to air and water resulting from the manufacturing process. The use of renewable sources of energy might also be considered as a way of reducing the environmental impacts of electricity consumption;
- Natural gas consumption and the emissions caused by natural gas combustion are the most critical issues in the Products' Manufacture stage of the natural cork stoppers life cycle (see Subsection 3.4.3). As a result, companies from the cork industry producing this product might consider substituting natural gas for a source of energy that has a lower environmental impact. Since natural gas is considered the cleanest fossil fuel (EIA, 2020), renewable energy sources must be explored;
- The adhesive resin (urea formaldehyde and melamine formaldehyde) used in the manufacturing process are the most critical issues in the Products' Manufacture stage of the particle board life cycle (see Subsection 3.4.3). As a result, companies from the wood industry producing this product might consider using other non-formaldehyde-based resins. Besides its environmental impacts, these types of resins release formaldehyde. Since regulations are limiting the maximum concentration of formaldehyde in the air, this can restrict the number of particle boards bonded with these resins used indoors (Irle & Barbu, 2010). This further reinforces the importance of the ongoing research that exists considering the utilization of non-formaldehyde-based resins (Jones & Brischke, 2017).

Companies that manufacture and sell forest wood products can also use the results obtained in this study to benchmark their economic performance and the environmental impacts associated with their products' life cycle. For example, a company that manufactures and sells uncoated woodfree paper can use 2.90 Pt per euro of NPV (see Table 3.5) as a reference value for the benchmark. To benchmark their economic performance and the environmental impacts of their products' life cycle, companies that manufacture and sell forest wood products need to apply the assessment presented in this study to their products' specific context. When applying the environmental assessment to other forest wood products or regions, the model shown in Section 3.2 needs to be adapted. The following points give insights into what needs to be adjusted:

- Raw materials' extraction – Equations 3.1 to 3.3 can be used in other contexts as long as the tree species under assessment are *Eucalyptus globulus*, *Quercus suber*, and *Pinus pinaster*, respectively. In this case, parameters β_0 to β_3 can remain unchanged while the remaining parameters shown in Table 3.1 need to be adapted. For example, parameter *T* (forest density) should reflect the average forest density considered in tree plantations from where wood is sourced. If other tree species are used, Equations 3.1 to 3.3 should be substituted by other equations that correctly translate the volume of wood generated by the tree plantations. The inventory data presented in Appendix A (see Tables A.3 to A.5) can also remain unchanged. However, companies should update this inventory data whenever specific data is available, making it more reliable for their context. For example, the distance between tree plantations and the factories should be updated, since these locations will vary depending on the supply chain;
- Products' manufacture – Equations 3.4 to 3.6 can be used in other contexts as long as the tree species used to manufacture the products under assessment are *Eucalyptus globulus*, *Quercus suber*, and *Pinus pinaster*, respectively. If other tree species are used, the numerator of these equations should be substituted by other equations found in the literature. The denominator of these equations (parameter *N*, see Table 3.1) should be adapted to reflect the quantity of wood required to produce one kilogram of the product(s) under assessment. The inventory data presented in Appendix A (see Tables A.6 to A.8) can remain unchanged as long as the product(s) under assessment are uncoated woodfree paper, natural cork stoppers, and particle boards, respectively. However, companies should update this inventory data whenever specific data is available, making it more reliable for their context. For example, the manufacturing process's electricity should be adjusted, since it depends on the process itself. If other products are considered, the inventory data should be modified to reflect the corresponding manufacturing process;
- Products' distribution – When modeling this life cycle stage given a different system, all parameters should be adapted including the quantity of each product that is

distributed to the domestic and international markets, the distances between the factories and these markets, and modes of transportation used to ensure this distribution, because these depend on the supply chain;

- Products' end-of-life – In many regions, the end-of-life destinations proposed in this stage are the most common. For this reason, these could remain unchanged. However, whenever specific data is available, the different ends-of-life for each product under study should be adjusted. The quantity of each product that goes to each end-of-life should also be adapted.

When applying the economic assessment, companies that manufacture and sell forest wood products should use their cash inflows and outflows to determine the net cash flows. If this information is not available, the EBITDA margin could be used similar to what was done in this study. In this case, the average EBITDA margin for companies in the region and industry under study should be used. Moreover, the latter should be applied for benchmarking purposes since this was the approach followed in this study.

For business associations, such as the Confederation of European Paper Industries (CEPI) and the American Forest & Paper Association (AF&PA), the results presented in the previous section may support such associations to reduce the environmental impact associated with forest wood products. One way these forest sector associations may explore to promote this environmental impacts' reduction is by providing a sector-specific environmental impact assessment tool. Such tool should undoubtedly assess the impacts considering the five critical impact categories (ALO, CC, PMF, FD, and HT) and identify the hotspots (i.e., priority areas) where changes must be made to reduce the environmental impacts. Business associations should also provide best practice guidelines. Being the Raw Materials' Extraction stage criticality highlighted in the previous section, these guidelines should include sustainable forest management principles. Another way that business associations could explore to help reduce the environmental impact associated with forest wood products is by promoting collaboration between its members and other stakeholders to foment solutions that will advance the sector's sustainability and, consequently, its competitiveness. This collaboration should be both vertical (i.e., between companies in different stages of the supply chain such as a supplier and a manufacturer) and horizontal (i.e., between companies of the same sector and in the same stage of the supply chain such as different suppliers).

Besides recommendations for companies and business associations operating in the forest sector, the analysis conducted in this study also allow to make recommendations for academics considering to conduct research related with the environmental impacts of forest wood products. Future research should include the five midpoint impact categories (ALO, CC, PMF, FD, and HT) identified as the most critical in this study. This recommendation is important since most LCA studies that focus on forest wood products do not give proper attention to these critical environmental impacts. A literature review conducted by Mäkelä (2017) has shown that the most commonly analyzed categories in these LCA studies are climate change, photochemical oxidant formation, acidification and eutrophication. Only one of these categories, climate change, was found to be critical in this study. Furthermore, the most critical category, agricultural land occupation, is one of the least analyzed categories in LCA studies that focus on forest wood products (Mäkelä, 2017). This mismatch between the critical environmental impacts and the ones that are actually analyzed in the literature must be corrected.

3.6 Conclusions

This study proposes an environmental and economic assessment of three forest wood products – uncoated woodfree paper, natural cork stoppers, and particle boards produced from *Eucalyptus globulus*, *Quercus suber*, and *Pinus pinaster* trees, respectively. The life cycle of these three products were modelled using foreground data of the Portuguese forest sector and the environmental impacts of these life cycles were assessed and compared using the life cycle assessment methodology. This methodology has been used to assess the environmental impacts of different forest wood products and to compare wood with alternative materials. However, to the authors best knowledge, this is the first work where a comparison of different forest wood products was conducted, which reinforces its innovative component. This study allows the support of companies operating in the forest sector and it can also be used to support territory management policies on the usage of land considering economic and environmental goals. The economic assessment was conducted using the net present value method.

From the results, it is possible to conclude that the production of uncoated woodfree paper from *Eucalyptus globulus* (System 1) generates the least environmental impact per euro of NPV. On the other hand, the production of natural cork stoppers from *Quercus suber* (System 2) generates the highest environmental impact per euro of NPV. Comparing the results of these two systems from an economic perspective, it is possible to conclude that the production and sale of uncoated woodfree paper generates a lower net present value (0.06 €/kg) than the production and sale of natural cork stoppers (0.12 €/kg). Thus, for the same quantity of product manufactured and sold, natural cork stoppers are a better choice from an economic perspective. This conclusion is a little surprising since the average EBITDA margin for Portuguese companies in the pulp, paper and cardboard industry (21.1%) is higher than the average EBITDA margin for Portuguese companies in the cork industry (8.9%). However, the revenue generated per kilogram of UWF paper sold (0.65 €/kg) is lower than the revenue generated per kilogram of NCS sold (3.67 €/kg), and the difference in operating profitability (EBITDA margin) of both industries is not enough to compensate the difference in revenue. Hence, the production of natural cork stoppers is a better choice from an economic perspective. Looking into the environmental assessment, it is possible to conclude that the life cycle of UWF paper generates a lower environmental impact (0.19 Pt/kg) than the life cycle of natural cork stoppers (7.31 Pt/kg). Thus, for the same quantity of product, UWF paper is a better choice from an environmental perspective. Once more, this conclusion is surprising since paper production has been known for its environmental impacts. From the analysis conducted in this study, it was determined that the Raw Materials' Extraction stage is responsible for most of the environmental impact of each life cycle studied mainly due to the occupation of land by the different forest species. *Eucalyptus globulus*' plantation presents a more efficient land occupation than *Quercus suber*' plantation due to a higher forest density for the same area and a higher number of harvests in the same period. Since System 1 is better in the most critical life cycle stage, UWF paper is a better choice from an environmental perspective. It is essential to notice that the economically better system (System 2) is different from the environmentally better system (System 1). However, System 1 (production of UWF paper from *Eucalyptus globulus*) is the better choice considering both an economic and environmental perspective (lower environmental impact per euro). This is because the difference between these systems' environmental performance (where System 1 is better than System 2) is enough to compensate the difference between these systems' economic performance (where System 2 is better than System 1).

The same five impact categories were found to be the most critical in the three analyzed life cycles. These categories are agricultural land occupation, fossil depletion, climate change, particulate matter formation, and human toxicity. This commonality indicates the relevance of including the results of these five impact categories in future LCA studies considering forest products. Furthermore, the life cycle stage that most contribute to each life cycle's environmental impact is the Raw Materials' Extraction stage, mainly due to land occupation by the different forest species. Hence, if a company operating in the forest sector wishes to reduce its products' life cycle's environmental impact, it should improve the land occupation. This can be achieved by increasing the number of trees per hectare or reducing the rotation period. However, these changes should respect the current legislation on the management of each forest species. In addition to reducing the environmental impacts of its products' life cycle, companies operating in the forest sector may also wish to increase their net cash flows by reducing their costs or increasing their revenue. Frequently, changes made to reduce environmental impacts can also positively affect the economic performance of a business. The improvement in the land occupation suggested to reduce the environmental impacts of forest wood products' life cycles would result in a more efficient occupation of the land and, consequently, reduce the operating expenses per unit sold.

The uncertainty associated with the data considered when modeling the three systems was taken into account using sensitivity analysis. The forest density and EBITDA margin were the parameters varied in this analysis. It was concluded that the main results obtained in this study are reliable.

The limitations of this study are mostly related to some of the assumptions made in the LCI step. The amount of wood and cork that could be harvested from one hectare of land in Portugal, considering a time horizon of 100 years, is associated with uncertainty. The impact of this assumption was taken into account in the sensitivity analysis. In the products' distribution stage, only countries that contribute more than 1% to the exports of each of the forest products analyzed were taken into account. Furthermore, in the end-of-life stage, it was assumed that the end-of-life destinations of natural cork stoppers are similar to the end-of-life destinations of particle boards. Wood and cork have different components and, consequently, some of the emissions that depend on the composition of the waste are different. Since the results showed that these two life cycle stages (products' distribution and end-of-life) do not contribute much to the overall environmental impact of the analyzed life cycles, these limitations did not significantly affect the results obtained. Another limitation is related with the economic assessment. The consideration of a 100-year time horizon can make the determination of future cash flows unreliable. However, this time horizon was necessary to reflect the different rotation periods considered for each of the systems under study.

Although the uncertainty associated with some of the data used in this study was taken into account using a sensitivity analysis, a more complete uncertainty analysis should be conducted to assess the results' robustness using a stochastic modelling technique such as Monte Carlo simulation. The environmental and economic assessment conducted in this study should be complemented by using the social life cycle assessment methodology to consider the social impacts associated with the life cycles of the three analyzed systems. Future research should extend the analysis conducted in this chapter to include more forest wood products and other countries. This will allow determining whether the conclusions hold for other products or regions. For this extension of the analysis, some of the parameters used in this study would have to be adapted while others could remain the same as previously mentioned in Section 3.5.

4. Social Analysis

4.1 Introduction

The growing pressures from various stakeholders, especially customers, government regulators, and non-governmental organizations (NGOs) is driving companies to adopt a certain level of commitment to sustainability practices (Hassini, et al., 2012). In their quest for sustainability, companies should not only focus on the environmental and social impacts of their operations but also on the performance of their supply chain (Barbosa-Póvoa, et al., 2018). For this reason, managing supply chains considering the three dimensions of sustainable development (i.e., economic, environmental, and social) has become an increasing concern for companies (Seuring, 2013). However, in the field of sustainable supply chain management (SSCM), these three dimensions are not on the same level of development. While the economic and environmental dimensions have been thoroughly addressed in the SSCM field (Seuring, 2013), the social dimension has not yet been adequately addressed, even though studies on social sustainability have increased in recent years (D'Eusanio, et al., 2019). In fact, the topic of social impacts and issues was found to be one of the least well represented sustainability topics in supply chain management (Quarshie, et al., 2016) which is worrying since companies are facing more and more pressure to integrate measures with a positive contribution to society into their supply chain management strategies (Mani, et al., 2018).

In line with the previous statement regarding the social dimension of sustainability in the field of SSCM, a recent review found that most assessment studies applied to forest supply chains focus on economic and environmental aspects, while the social dimension of sustainability is the most overlooked (Santos, et al., 2019a). The forest sector is comprised by three primary forest-based industries – the wood industry, the cork industry, and the pulp, paper, and cardboard industry (DGAE, 2020b). These industries are a major player in the economies of different countries, such as Portugal, due to their contribution to the Gross Domestic Product (GDP), exports, and employment. The forest sector contributes 4.93% to the Portuguese GDP, 9.97% to the exports of goods, and 1.86% to the number of existing jobs (DGAE, 2020b). In Portugal, the most manufactured products in the forest sector are particleboards in the wood industry, natural cork stoppers (NCSs) in the cork industry, and uncoated woodfree (UWF) paper in the pulp, paper, and cardboard industry (ICNF, 2018).

Social life cycle assessment (LCA) is one of the most used approaches to evaluate the social performance of supply chains (Basta, et al., 2018) (D'Eusanio, et al., 2019). This approach is used to examine the potential positive and negative social impacts of a system's (i.e., the specific object under analysis) life cycle. The same four steps that comprise an environmental LCA are also conducted in a social LCA since both approaches are based on the ISO 14040 standard (UNEP, 2020). In the first step, Goal and Scope Definition, the reasons for carrying out the study are described and the main details of the study are defined. The next step, Life Cycle Inventory (LCI), consists in modeling the system under study to collect social flows (i.e., inventory). In the third step, Life Cycle Impact Assessment (LCIA), the inventory collected in Step 2 is converted into potential social impacts using characterization factors. After normalizing and weighting these characterized social impacts using normalization and weighting factors, the total potential social impact (i.e., single score) of the system under consideration can also be calculated in the third step. To achieve the objective set forth in the first step, the fourth and final step, Interpretation, entails reviewing and analyzing the findings of the LCA study.

The primary goal of this study is to advance the field of SSCM by proposing a social LCA framework for analyzing the social performance of supply chains. This analysis is critical for the development of informed recommendations to mitigate the most relevant potential social impacts associated with supply chains. By providing a framework with clear guidelines for practitioners and researchers on how to apply social LCA to assess social aspects in supply chains, this work contributes to a clear understanding on how this methodology can be applied as a decision support tool in sustainable supply chain management. To demonstrate the structure and applicability of the proposed framework, the supply chains of the most manufactured Portuguese wood products, namely the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains, are used as an illustrative case study. By choosing these supply chains as case study, this work extends the existing economic and environmental assessments of the aforementioned supply chains, such as the one conducted by Santos et al. (2021), by adding a social perspective, being this aspect the second contribution of this chapter. Furthermore, recommendations are provided based on the results obtained from applying the proposed social LCA framework to the three different supply chains. These recommendations will support different forest supply chain partners strengthen their own social performance and subsequently improve their supply chains' social performance. The Sustainable Development Goals (SDGs) impacted by these are also identified.

The remainder of this chapter is organized into four sections. Section 4.2 presents the proposed social LCA framework. The following section presents an application of this framework to the three supply chains selected as an illustrative case study. Section 4.4 provides industry-specific recommendations for different supply chain partners wishing to mitigate their contribution to the relevant social issues identified, together with the identification of the SDGs to which these recommendations contribute. Lastly, the conclusions of this work are presented in Section 4.5, along with the current study's limitations and recommendations for further research.

4.2 Social LCA framework

The proposed social LCA framework for analyzing the supply chains' social performance consist of eight mains steps identified in Figure 4.1: Define the goal and scope (S1), Model the supply chain (S2), Collect social indicators (S3), Conduct the social impact assessment (S4), Identify the most relevant social issues (S5), Determine the social hotspots (S6), Identify the most relevant sectors/regions (S7), and Determine the key stakeholders (S8). Since the proposed framework is based on the social LCA approach, each of the eight steps that comprise this framework is related to one of the four steps that comprise a social LCA (UNEP, 2020). This relation is also represented in Figure 4.1.

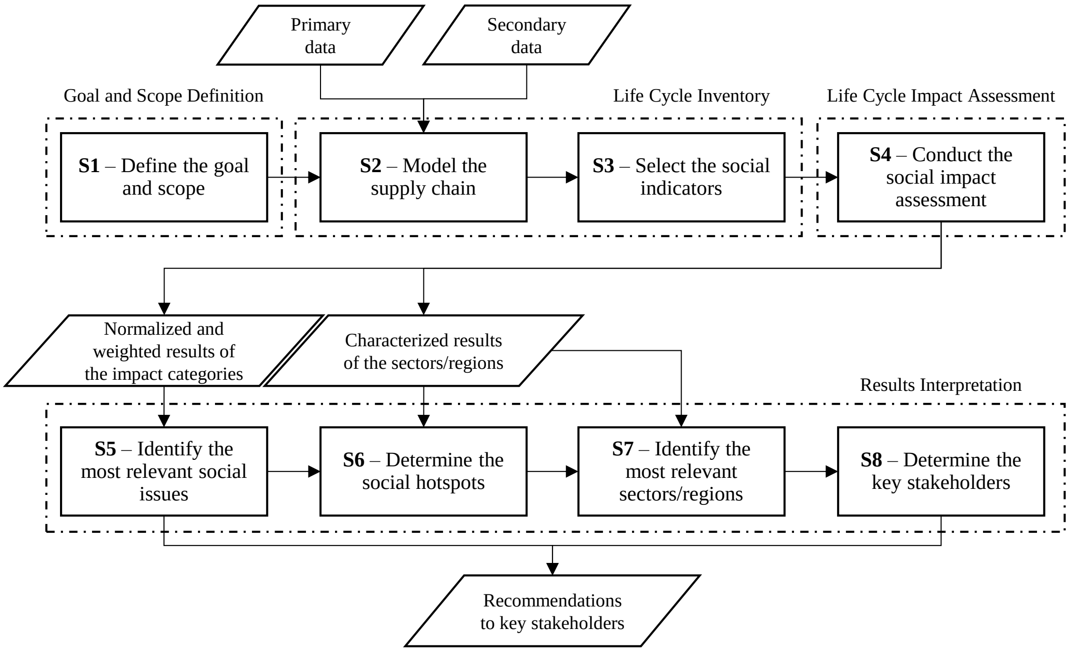


Figure 4.1 – Social LCA framework to analyze the social performance of supply chains.

The following subsections provide a detailed description of the eight steps presented in Figure 4.1.

4.2.1 Step 1 – Define the goal and scope

The first step of a social LCA is to establish the goal and scope of the study. Different goals can be defined for supply chain social assessment, including comparing the social impacts of different products sharing the same logistics channels, informing about governmental policy and programs for SCM collaboration, and analyzing the supply chain social performance to identify effective actions to mitigate the most relevant potential social impacts (Norris, et al., 2019).

Establishing the functional unit and the system boundary are part of the scope definition. The functional unit (i.e., a representative component of the system under assessment) provides a reference for collecting the inventory and, consequently, estimating the respective potential social impacts (EC-JRC-IES, 2010). The system boundary determines which supply chain stages and corresponding processes will be taken into account (EC-JRC-IES, 2010). There are different types of system boundaries, including cradle-to-grave, which considers the entire supply chain from raw materials extraction to product disposal, and gate-to-gate, which considers a single supply chain stage (e.g., products' manufacturing) (Eskandarpour, et al., 2015). For a complete analysis of the supply chain, a broader boundary (e.g., cradle-to-grave) must be selected.

4.2.2 Step 2 – Model the supply chain

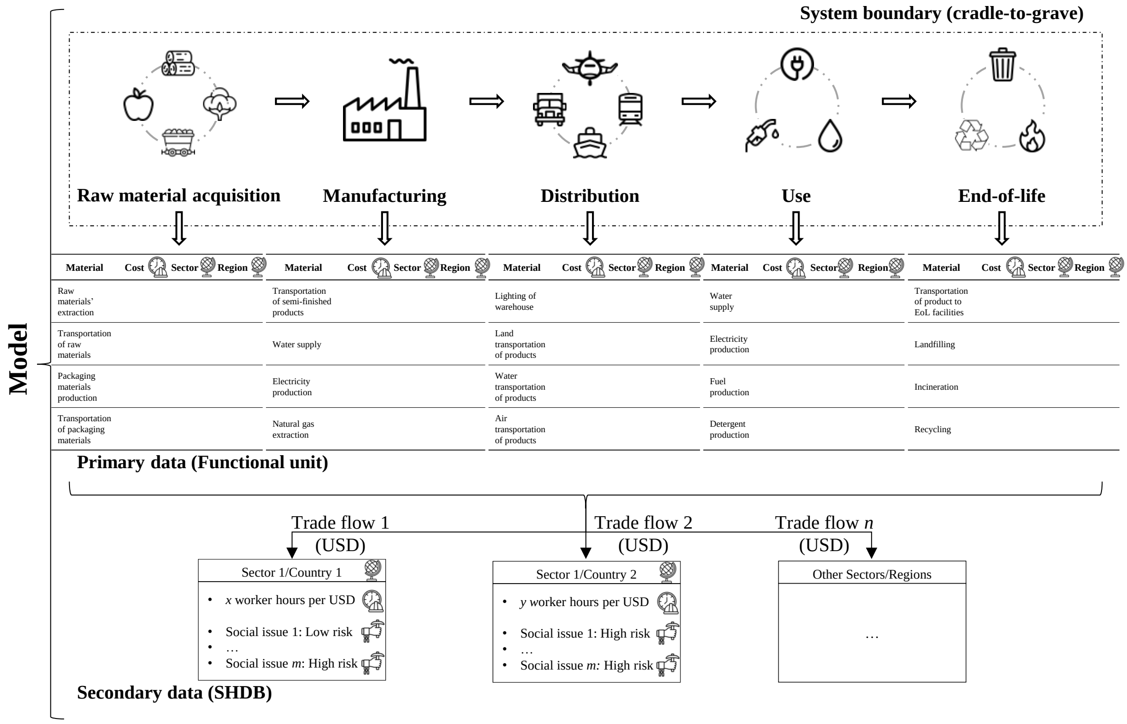
This step's purpose is to compile a list of social flows (e.g., worker hours in poor working conditions). To estimate these social flows, the supply chain under assessment must be modeled using information gathered for the various unit processes contained within the system boundary specified in Step 1 (UNEP, 2020). A unit process (e.g., raw materials' extraction, transportation, recycling) is the smallest element for which information is collected when performing a life cycle assessment (ISO, 2006). The information collected for the different unit processes can be classified as primary or secondary data. Primary data refers to information directly collected by the LCA practitioner. This type of data can be collected through different means including direct contact with the organizations involved in the supply chain under analysis or auditing the purchase records and utility bills of these organizations (UNEP, 2020). Secondary data refers to information initially collected and manipulated by another person/institution other than the LCA practitioner or collected for another purpose than the one being currently considered. This type of data can be collected through different means including literature reviews, web searches, or existing social LCA databases (UNEP, 2020) such as the Social Hotspots Database (SHDB) (New Earth B, 2022). Figure 4.2 presents the primary and secondary data usually required to model a supply chain in a social LCA considering a non-exhaustive list of unit processes (e.g., Recycling) included in five default life cycle stages (e.g., End-of-Life) (Zampori & Pant, 2019). This data includes information concerning (Norris, et al., 2019):

- Supply chain composition – Knowing where (geographically) the different unit processes occur is critical in social assessments due to the influence of political, societal, and cultural differences between regions on the potential social impacts. For each unit process included within the system boundary, primary data related to supply chain composition includes the region (e.g., country) where the unit process occurs and the economic sector to which this process belongs to (Figure 4.2). Secondary data related to supply chain composition includes all economic sectors and regions involved with the sector/region defined for each unit process (Figure 4.2). For instance, the SHDB includes secondary data on supply chain composition based on trade information provided by the Global Trade Analysis Project (GTAP') global economic equilibrium model version 9. For the reference year 2011, this version of the GTAP model includes information on the commercial transactions (in US dollars) between 57 economic sectors from 140 regions (GTAP, 2019);
- Labor intensity – Data regarding labor intensity (i.e., worker hours) is relevant because it represents evidence of the intensity of work required by each unit process included

within the system boundary. For each unit process included within the system boundary, primary data related to labor intensity includes the cost associated with the output of that process (Figure 4.2). Secondary data related to labor intensity includes the worker hours involved in each unit process (Figure 4.2). The SHDB, for instance, contains information on the number of worker hours per US dollar of output for each of the 57 economic sectors in each of the 140 regions stated above in 2011.

4.2.3 Step 3 – Select the social indicators

Social indicators can be qualitative, semi-quantitative, or quantitative and provide the most direct evidence about the condition of specific social aspects (UNEP, 2020). Several social indicators have been proposed by many sources, with *The Methodological Sheets for Subcategories in S-LCA* (UNEP, 2013) providing a comprehensive overview of such indicators. Similarly to the data used in Step 2 to model the supply chain, data regarding these indicators can also be classified as primary or secondary data. Primary data can be collected in different ways including by conducting interviews and surveys with stakeholders from the entities involved in the supply chain under analysis, while secondary data can be obtained through many sources, including scientific and grey literature and social LCA databases (UNEP, 2020). These databases are a good source of social indicators (UNEP, 2020). For example, the Social Hotspots Database has information on the social risks associated with 244 regions and 57 sectors (Figure 4.2) based on more than 160 social impact indicators gathered from various sources such as national statistics, academic papers, reports from non-governmental organizations, and intergovernmental databases (e.g., the International Labor Organization database).



Social risks	Supply chain composition & Labor intensity			Social flows (worker hours)
	Sector 1/Country 1	Sector 1/Country 2	Other Sectors/Regions	
Social issue 1: Low risk	*x* worker hours per USD × Trade flow 1 (USD) = Worker hours	-	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with low risk in Social issue 1
Social issue 1: Medium risk	-	-	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with medium risk in Social issue 1
Social issue 1: High risk	-	*y* worker hours per USD × Trade flow 2 (USD) = Worker hours	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with high risk in Social issue 1
Social issue 1:Very high risk	-	-	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with very high risk in Social issue 1
…	…	…	…	…
Social issue *m*: High risk	*x* worker hours per USD × Trade flow 1 (USD) = Worker hours	*y* worker hours per USD × Trade flow 2 (USD) = Worker hours	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with high risk in Social issue *m*
Social issue *m*:Very high risk	-	-	Worker hours per USD × Trade flow *n* (USD) = Worker hours	Number of worker hours with very high risk in Social issue *m*

Legend:

Information on supply chain composition — Information on labor intensity — Information on social risks

Figure 4.2 – Primary and secondary data usually collected when conducting a social LCA.

Based on the economic sector, location, and cost of each unit process collected as primary data and using the information on the commercial exchanges between sectors/regions collected as secondary data in Step 2, it is possible to determine the trade flows between each unit process and different sectors/regions. The sum of the trade flows between each unit process and different sectors/regions allows the calculation of all trade flows involved with the supply chain under analysis (Figure 4.2). By combining these trade flows with the worker hours involved per US dollar of output collected as secondary data in Step 2 and the social indicators selected in Step 3, it is possible to quantify the social flows associated with the supply chain under analysis (Figure 4.2) and, consequently, achieve the purpose of the LCI.

4.2.4 Step 4 – Conduct the social impact assessment

The next step consists of converting the inventory collected in the previous step into potential social impacts. A potential social impact is understood as the likely social impact resulting from the activities/behaviors of organizations involved in a supply chain. From the two main impact assessment approaches (Reference Scale Approach and Impact Pathway Approach) that can be used when conducting a social LCA, the Reference Scale Approach is the most utilized (UNEP, 2020).

The reference scale approach evaluates an organization's social performance using reference scales that typically include 1 to 5 levels (i.e., performance reference points). As a result, each social indicator gathered in Step 3 needs to have an associated reference scale with clearly defined levels (UNEP, 2020). The Social Hotspots Index (SHI) included in the SHDB is one of the Type I impact assessment methods currently operational. This method considers 25 impact subcategories further aggregated into five impact categories (Norris, et al., 2019) presented in Table 4.1. The 160 social impact indicators referred in the previous subsection are used to evaluate these impact subcategories. While some subcategories are evaluated using several indicators, other are evaluated using just one indicator. Each indicator has a four-level reference scale with clearly defined risk thresholds (very high, high, medium, and low) (Norris, et al., 2019). Table 4.2 presents the reference scale utilized in the SHI method.

Table 4.1 – Social Hotspots Index categories and subcategories.

Impact Categories	Impact Subcategories
Labor Rights and Decent Work	Forced Labor; Excessive Working Time; Poverty; Freedom of Association; Wage Assessment; Migrant Labor; Unemployment; Child Labor; Labor Laws; Discrimination; and Social Benefits
Health and Safety	Injuries and Fatalities; and Occupational Toxics and Hazards
Human rights	Indigenous Rights; Communicable Diseases; Non-Communicable Diseases; Gender Equity; and High Conflict Zones
Governance	Legal System; and Corruption
Community	Access to Hospital Beds; Access to Drinking Water; Children Out of School; Access to Sanitation; and Smallholder vs. Commercial Farms

Each risk level considered by the SHDB has a corresponding characterization factor (Table 4.2), representing the relative likelihood of an unfavorable circumstance (Norris, et al., 2019).

Table 4.2 – Reference scale utilized in the Social Hotspots Index method.

Scale level	Characterization factors
Very high risk	10
High risk	5
Medium risk	1
Low risk	0.1

Equation 4.1 can be used to calculate the potential social impacts in medium risk hours equivalent (MRH eq.) by combining the characterization factors presented in Table 4.2 with the social flows determined in the LCI step.

$$Characterized\ Result_c = \sum_r (Inv_{c,r} \times CF_r) \tag{4.1}$$

where $c = 1, \ldots, C$ denotes the impact subcategory, $r = 1, \ldots, R$ denotes the risk level, *Inv* is the inventory (i.e., social flow), and *CF* is the characterization factor. In Figure 4.2, the characterized result of each social issue is obtained by multiply the number of worker hours with low risk by 0.1, the number of worker hours with medium risk by 1, the number of worker hours with high risk by 5, the number of worker hours with very high risk by 10, and adding these four results together.

The characterized results of each impact subcategory can be normalized using the normalization factors provided by the SHI method. After being normalized, the results of each impact subcategory can be weighted by multiplying the normalized result by the respective weight. The SHI method considers equal weighting, where all impact subcategories are assumed to have equal weight (weight equals one). The sum of the weighted results of all impact subcategories is equal to the single score representing the total potential social impact of the supply chain under assessment.

4.2.5 Step 5 – Identify the most relevant social issues

The first step in Interpretation when analyzing the social performance of a supply chain is to determine the most relevant social issues because these are the social issues that most affect the social performance of a supply chain. In traditional life cycle assessment studies, the "80/20" rule, also known as the Pareto Principle, has been used to identify the most relevant environmental issues. According to this principle, 20% of all causes (i.e., impact categories) account for 80% of outcomes (i.e., overall environmental effect) (Vitasek, 2006). The social impact categories must be sorted in order of decreasing normalized and weighted results and the top 20% must be chosen to determine the most relevant social issues.

4.2.6 Step 6 – Determine the social hotspots

The next step in Interpretation is to identify the social hotspots. A social hotspot is a process in a region (such as chemical production in Portugal) where a relevant potential social impacts is expected to occur (UNEP, 2020) (Garrido, 2017). These are the processes that need to be altered or replaced to lessen the most significant potential social impacts related to a supply chain and, as a result, enhance its social performance. The social hotspot is identified for each relevant impact category established in Step 5 by ranking the processes and regions in decreasing order of characterized results and choosing the top result.

4.2.7 Step 7 – Identify the most relevant sectors/regions

Determining the most relevant sectors/regions is the third step in Interpretation. It is possible to identify which economic sector and region are most likely responsible for the subpar social performance of the social hotspots determined in Step 6 based on the secondary data typically collected when performing a social LCA (Figure 4.2). This information is relevant because it allows to determine if this poor social performance is likely caused by the activities/behaviors of the organization responsible for the social hotspot or by the activities/behaviors of other organizations involved in the supply chain under analysis. For example, if chemical production in Portugal is identified as a social hotspot associated with the social issue Corruption, identifying the most relevant sector/region associated with this hotspot allows to determine if its poor social performance in the social issue Corruption is likely due to the activities/behaviors of Portuguese chemical manufactures or due to the activities/behaviors of other supply chain partners (e.g., suppliers from other regions) with whom these manufactures trade with. For each social hotspot identified in the previous step, the most relevant sector/region is determined by sorting the sectors/regions involved with this hotspot in decreasing order of characterized results and choosing the top result.

4.2.8 Step 8 – Determine the key stakeholders

The last step in Interpretation is to identify the key stakeholders. For each relevant impact category identified in Step 5, the key stakeholders are determined based on the social hotspot and most relevant sector/region identified in Step 6 and Step 7, respectively. For example, based on the example that has been used in the previous steps, the key stakeholders may only be the Portuguese chemical manufactures or it may the Portuguese chemical manufactures together with other supply chain partners.

However, due to the use of secondary data when modeling the supply chain and to quantify the social indicators (Figure 4.2), it is possible that some of the social hotspots and most relevant sectors/regions identified in Step 6 and Step 7, respectively, end up not being involved with any relevant social issue (UNEP, 2020). For this reason, the social hotspots and most relevant sectors/regions identified in these steps represent the unit processes of the supply chain where primary data to quantify the social indicators must be collected to verify the results of the social assessment. This data collection can be done in different ways including interviewing or surveying stakeholders (UNEP, 2020) (as explained in Step 3). If the results of the social assessment are verified, the stakeholders determined in this step are crucial to improve the supply chain's overall social performance. Based on the key stakeholders identified for each relevant impact category, recommendations can be provided to assist these stakeholders in strengthening their own social performance and, as a result, improving their supply chain's social performance.

4.3 Case Study

This section presents the application of the eight steps presented in Figure 4.1 to the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains to illustrate the structure and applicability of the proposed framework.

4.3.1 Step 1 – Define the goal and scope

This study's primary objective is to examine the social performance of three different supply chains, namely the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains, and use this analysis to generate well-informed recommendations on how these social performances can be improved.

One ton of forest product (i.e., uncoated woodfree paper, natural cork stoppers, and particleboards) was used as functional unit in this study. Cradle-to-grave was the system boundary selected, which encompasses all unit processes from four of the five default life cycle stages identified in Figure 4.2: Raw Material Acquisition, Manufacturing, Distribution, and End-of-Life.

4.3.2 Step 2 – Model the supply chain

As explained in Section 4.2, modelling the supply chain under analysis requires the collection of primary and secondary data for each unit process included within the system boundary defined in Step 1. This study focuses on the generic supply chain of three forest products manufactured in Portugal. For this reason, the primary data related to supply chain composition and labor intensity required to model the supply chains under assessment in this study had to be collected using secondary sources, such as scientific literature and country statistics.

Primary data collection will be explained below using the supply chain of Portuguese UWF paper as an example. The same reasoning was used to gather information about the supply chain of Portuguese natural cork stoppers and particleboards. All primary data collected for the three supply chains under analysis and the data sources used are presented in the Supplementary Material (Appendix B). The secondary data related to supply chain composition and labor intensity required to model the supply chains under analysis was collected using the Social

Hotspots Database. The collected primary data available in the Supplementary Material (Appendix B) and the background data available in the SHDB were used to model the three supply chains using the SimaPro 8.4.0 software (PRéConsultants, 2021). Figure 4.3 presents the model developed for the Portuguese UWF paper supply chain.

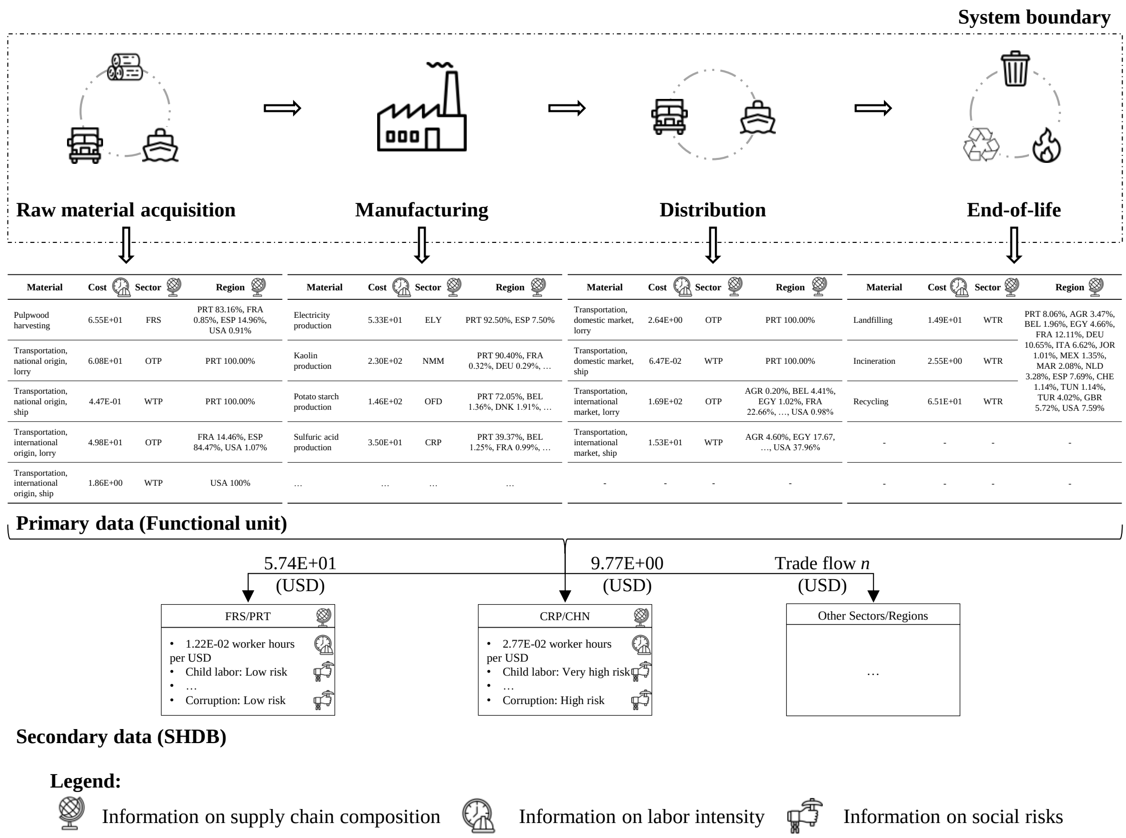


Figure 4.3 – Portuguese UWF paper supply chain model.

The other two models developed for the Portuguese natural cork stoppers and particleboards supply chains can be consulted in the Supplementary Material (Figures B.1 to B.3).

4.3.2.1 Raw Material Acquisition

According to Figure 4.2, the unit processes that should be included in this life cycle stage are, among others, "Raw material's extraction", "Transportation of raw materials", "Packaging materials production", and "Transportation of packaging materials". In this study, packaging was not considered for any of the three products under analysis due to the different possibilities available. Furthermore, to give greater emphasis to the main raw material (i.e., wood), this stage only includes the unit processes of harvesting this main raw material as well as its transportation from the areas where it is harvested to the manufacturing facilities where it is transformed into the main products. Hence, two unit processes were included in this life cycle stage, namely "Raw material's extraction" and "Transportation of raw materials". For the first process, "Raw material's extraction", the following primary data was collected (Figure 4.3):

- Cost – Around 3.25 cubic meters of pulpwood (i.e., timber harvested to manufacture pulp for paper production) are required to manufacture one ton (i.e., functional unit) of UWF paper (Hischier, 2010). Each cubic meter of pulpwood cost around 20.80 euros on average in 2020 (ICNF, 2020), which corresponds to around 20.16 US dollars in 2011 (Macrotrends, 2021) (DollarTimes, 2021). Please notice that all costs collected in this study were converted into US dollars for 2011 since the SHDB, used in this study to collect the background data, considers 2011 as a reference year (Section 4.2). Hence, 3.25 cubic meters of pulpwood were worth \$ 6.55×10^1 in 2011;
- Sector – Looking into the 57 economic sectors identified by GTAP, it can be concluded that pulpwood harvesting belongs to the "FRS – Forestry" economic sector (GTAP, 2019);
- Region – According to the Portuguese National Statistics Institute (INE, 2018b) (INE, 2018c), 83.16% of pulpwood used in Portugal is from Portugal. Using the Atlas of Economic Complexity (Growth Lab, 2018), it is possible to determine that the remaining 16.84% are mostly imported from Spain (14.96%), the United States of America (0.91%), and France (0.85%). In this study, only nations that supplied more than 1% to the total imports of each material were taken into account.

Concerning the "Transportation of raw materials" process, it was assumed that both road and maritime transportation were used to transport pulpwood from different sources to the manufacturing facility. The following primary data was collected (Figure 4.3):

- Cost – Determining the cost associated with the "Transportation of raw materials" process requires calculating transportation quantities (in kg.km) based on the amount of pulpwood sourced from each location (in kilograms) and the distance between these locations and the manufacturing facility (in kilometers). For a more detailed analysis, the share of pulpwood sourced from Portugal (i.e., 83.16%) was subdivided into 25 Portuguese subregions (Table B.6 available in the Supplementary Material). This subdivision was accomplished using the information provided by the latest National Forest Inventory (ICNF, 2015) regarding the location of the existing *Eucalyptus globulus* trees in Portugal since this tree is mainly cultivated in Europe for paper pulp production (Cerasoli, et al., 2016). The percentages presented in Table B.6 (Supplementary Material) were used to calculate the pulpwood sourced from each location in cubic meters which were later converted in kilograms considering an average dried weight of 820 kilograms per cubic meter (The Wood Database, 2021). Please notice that only 99.88% (i.e., 83.16% from Portugal and 16.72% from other countries) of the total amount of pulpwood is presented in this table because only nations that supplied more than 1% to the total imports were considered (as previously explained). Defining the location of the manufacturing facility was needed to calculate the distances (in kilometers) provided in Table B.6 (Supplementary Material). The *Região de Coimbra* subregion is where the majority of UWF paper manufacturing companies in Portugal are located (INE, 2018a). Consequently, this was the location assumed for the UWF paper manufacturing facility. Each kilogram transported per kilometer cost, in 2011, around $ 2.00E-04 using road transportation and around $ 1.28E-05 using maritime transportation (Schade, et al., 2006) (Macrotrends, 2021) (DollarTimes, 2021). This information allowed to calculate the transportation costs presented in Figure 4.3;

- Sector – Looking into the 57 economic sectors identified by GTAP, it can be concluded that road transportation belongs to the "OTP – Other transport" economic sector and maritime transportation belongs to the "WTP – Water transport" economic sector (GTAP, 2019);
- Region – The regions (i.e., Portugal, Spain, the United States of America, and France) from where pulpwood is sourced were considered. For each transportation mode (i.e., road and maritime) and origin (i.e., domestic and international), the percentages associated with each region (Figure 4.3) were determined based on the transportation quantities (in kg.km) associated with each region and the total transportation quantity.

4.3.2.2 Manufacturing

According to Figure 4.2, the unit processes that should be included in this life cycle stage are, among others, "Transportation of semi-finished products", "Water supply", "Electricity production", and "Natural gas extraction". In this study, transportation of semi-finished products was not considered for any of the three products since it was assumed that products' manufacture takes place in a single location. Thus, the unit processes included in this life cycle stage are utilities (e.g., electricity) and raw materials (e.g., potato starch) production. Figure 4.3 presents the primary data collected for the Portuguese UWF paper supply chain considering some of the unit processes included in the Manufacturing stage. Please recall that the primary data collected for all unit processes is available for consultation in the Supplementary Material (Appendix B). For these processes, the following primary data was collected (Figure 4.3):

- Cost –The study conducted by Hischier (2010) (Hischier, 2010) was used to determine the different materials and respective quantities required to manufacture one ton (i.e., functional unit) of UWF paper. To determine the cost of these materials, different suppliers were contacted to obtain the unit cost (per kilogram, for example) in euros for 2021. These unit costs were then converted into US dollars for 2011 (Macrotrends, 2021) (DollarTimes, 2021) and multiplied by the quantity of each material to determine the costs presented in Figure 4.3;

- Sector –The economic sectors were defined by looking into the 57 economic sectors identified by GTAP (GTAP, 2019). For example, electricity production belongs to the "ELY – Electricity" economic sector while sulfuric acid production belongs to the "CRP – Chemical Rubber Products" economic sector;
- Region – The Portuguese Strategy and Studies Office was the primary data source used to determine, for each material, the percentage that is sourced from Portugal and other countries. For example, according to this data source, 39.37% of chemicals used in Portugal are from Portugal, while the remaining 60.63% are imported (GEE, 2018). The Atlas of Economic Complexity (Growth Lab, 2018) was used to identify the importing countries. For example, sulfuric acid was assumed to be sourced from Portugal (39.37%) (GEE, 2018), Belgium (1.25%), France (0.99%), among others (Growth Lab, 2018). As previously explained, only nations that supplied more than 1% to the total imports of each material were taken into account.

4.3.2.3 Distribution

According to Figure 4.2, the unit processes that should be included in this life cycle stage are, among others, "Lighting of warehouse", "Land transportation of products", "Water transportation of products", and "Air transportation of products". In this study, lighting of warehouse was not considered for any of the three products under analysis due to the difficulty in estimating the costs associated with the energy input required. Consequently, this stage only includes the transportation of the final products to the different demand points considered. Road and maritime transportation were assumed to transport the final product (i.e., UWF paper) from the manufacturing facility to the different demand points considered. The following primary data was collected (Figure 4.3):

- Cost – Determining the cost associated with the "Land transportation of products" and "Water transportation of products" processes require calculating transportation quantities (in kg.km) based on the quantity of UWF paper distributed to each destination (in kilograms) and the distance between these locations and the manufacturing facility (in kilometers). The Portuguese National Statistics Institute indicates that only 8.06% of the UWF paper available in Portugal is sold on the domestic market, with the remaining 91.94% being exported to other countries (INE, 2018b) (INE, 2018c). The 25 Portuguese subregions that were previously indicated in the Raw Material Acquisition stage were taken into account as 25 demand points for the domestic market. Each subregion's demand for UWF paper was thought to be proportional to the subregion's population (INE, 2018d). For the international market, the Atlas of Economic Complexity (Growth Lab, 2018) defined the exportation countries and their respective share considering only nations that contribute more than 1% to the total exports. These countries include France (12.11%), Germany (10.65%), Morocco (2.08%), and Tunisia (1.14%), among others. The percentages presented in Table B.6 (Supplementary Material) were used to calculate the quantity of UWF paper distributed to each location (in kilograms). Please notice that only 82.53% (i.e., 8.06% to Portugal and 74.47% to other countries) of the total amount of UWF paper (one ton) is presented in this table because only nations that contributed more than 1% to the total exports were taken into account. To calculate the distances (in kilometers) provided in Table B.6 (Supplementary Material), the manufacturing facility's previously defined location (i.e., *Região de Coimbra* subregion) was used. Similar to what was previously explained in the Raw Material Acquisition stage, each kilogram transported per kilometer cost, in 2011, around $ 2.00E-04 using road transportation and $ 1.28E-05 using maritime transportation. This information allowed to calculate the transportation costs presented in Figure 4.3;

- Sector – Looking into the 57 economic sectors identified by GTAP, it can be concluded that road transportation belongs to the "OTP – Other transport" economic sector and maritime transportation belongs to the "WTP – Water transport" economic sector (GTAP, 2019);
- Region – The regions (i.e., Portugal, France, Germany, Morocco, among others) to where UWF paper is distributed to were considered. For each transportation mode (i.e., road and maritime) and market (i.e., domestic and international), the percentages associated with each region (Figure 4.3) were determined based on the transportation quantities (in kg.km) associated with each region and the total transportation quantity.

4.3.2.4 End-of-Life

According to Figure 4.2, the unit processes that should be included in this life cycle stage are, among others, "Transportation of product to end-of-life facilities", "Landfilling", "Incineration", and "Recycling". In this study, the transportation of the final products to end-of-life facilities was not considered for any of the three products under analysis since it was assumed that the distance covered in this transport would be very small when compared to the distance covered in the Distribution stage. Consequently, this stage only includes the disposal of the final products. This study took into account three distinct end-of-life options, including landfilling, incineration, and recycling. For these processes, the following primary data was collected Figure 4.3):

- Cost – According to information provided by the Environmental Protection Agency, it was assumed that 27.4% of UWF paper is landfilled (i.e., 274 kilograms), 6.7% are combusted (i.e., 67 kilograms), and 65.9% are recycled (i.e., 659 kilograms) (EPA, 2017). The cost of disposing of UWF paper was assumed to be in 2011, on average, around $ 5.44E-02 per kilogram landfilled (CEWEP, 2020), $ 3.81E-02 per kilogram combusted (APA, 2021), and $ 9.88E-02 per kilogram recycled (Eurostat, 2020). Hence, 274 kilograms of UWF paper landfilled cost $ 1.49x10^{1}, 67 kilograms of UWF paper combusted cost $ 2.55 and 659 kilograms of UWF paper recycled cost $ 6.51x10^{1};

- Sector – Looking into the 57 economic sectors identified by GTAP, it can be concluded that the three end-of-life destinations belong to the "WTR – Water" economic sector (GTAP, 2019);
- Region – UWF paper was assumed to be disposed of in the country it was sold. Hence, 8.06% of UWF paper were assumed to be disposed of in Portugal, 3.47% in Algeria, 1.96% in Belgium, and so on.

4.3.3 Step 3 – Select the social indicators

The social indicators available in the Social Hotspots Database were selected. These indicators include, among others: the unemployment percentage in each country and sector, the percentage of rural access to an improved source of drinking water in each country, fatality rate of injuries in each country and sector, and the gender inequality index of each country (Norris, et al., 2019).

4.3.4 Step 4 – Conduct the social impact assessment

The inventory gathered in Step 3 was converted into potential social impacts using the Social Hotspots Index (SHI) method. Figure 4.4, Figure 4.5, and Figure 4.6 present a summary of the key findings obtained for the Portuguese UWF paper, natural cork stopper, and particleboard supply chains, respectively. These results are discussed in detail in the next subsections.

4.3.5 Step 5 – Identify the most relevant social issues

In accordance to what was previously defined in Section 4.2, the most relevant social impacts were determined by ranking the 25 impact subcategories taken into account by the SHI method in decreasing order of normalized and weighted results, and selecting the top 20% (i.e., the five impact subcategories with the highest normalized and weighted results). The normalized and weighted results of the impact subcategories obtained for each of the three supply chains under analysis are presented in Table B.19 available in the Supplementary Material. As previously explained in Section 4.2, the sum of the weighted results in Table B.19 is the single score obtained for each supply chain. Based on the weighted results available in Table B.19, the first column of Figure 4.4 to Figure 4.6 was constructed. For the Portuguese UWF paper supply chain, for example, a single score of 4.41x10^{4} Pt was obtained. The weighted result obtained for the Injuries and Fatalities impact subcategory was 9.11x10^{3} Pt. Thus, this impact subcategory contributed 20.6% (Figure 4.4 – Column 1) to the single score obtained. The five impact subcategories with the highest weighted results identified for the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains are highlighted in the first column of Figure 4.4, Figure 4.5, and Figure 4.6, respectively.

As shown in Figure 4.4 (Column 1), the most relevant impact subcategories associated with the Portuguese UWF paper supply chain are Injuries and Fatalities, Occupational Toxics and Hazards, Corruption, Legal System, and High Conflict Zones.

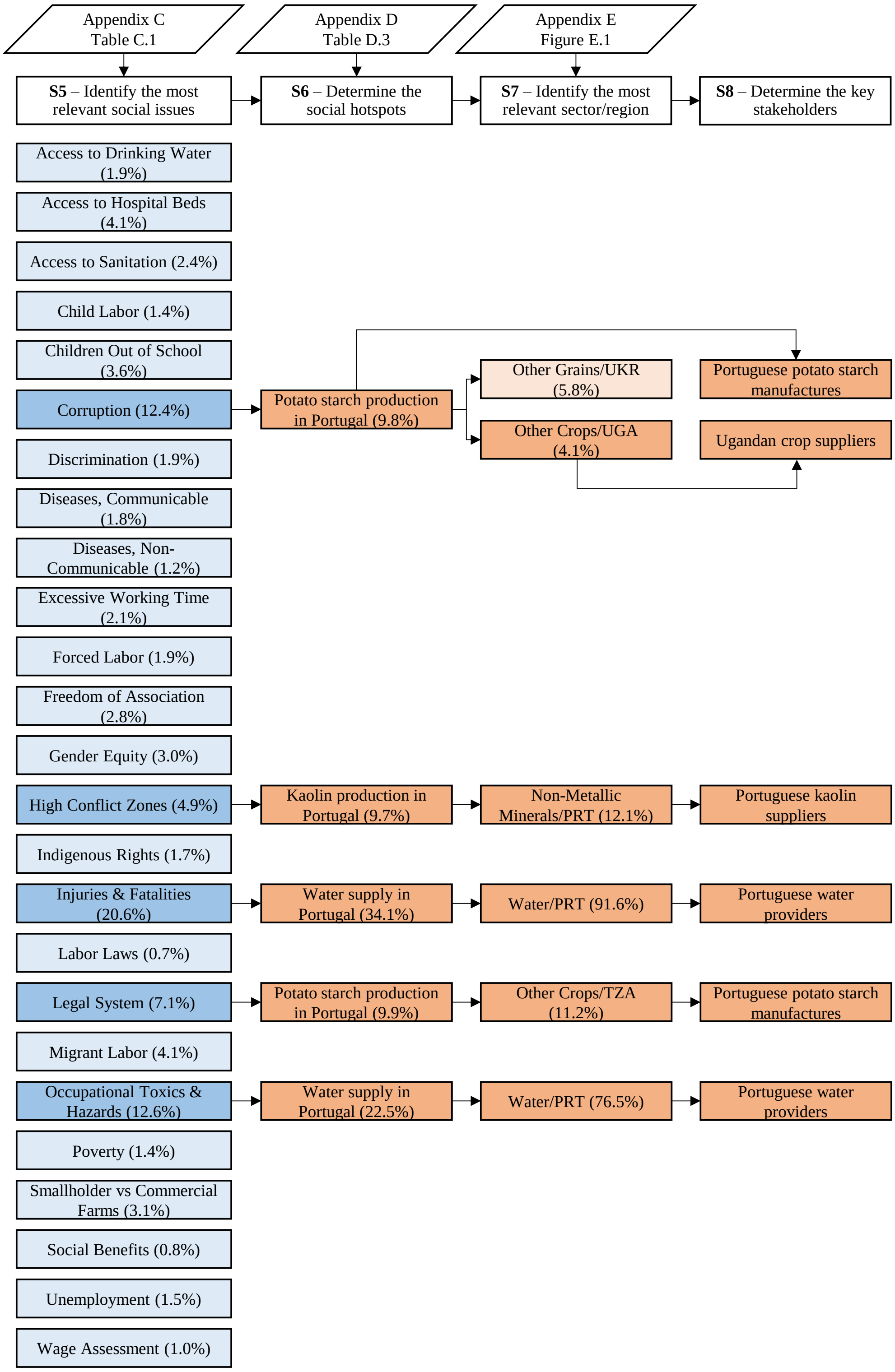


Figure 4.4 – Key findings obtained for the Portuguese UWF paper supply chain.

As shown in Figure 4.5 (Column 1), the most relevant impact subcategories associated with the Portuguese natural cork stoppers supply chain are Injuries and Fatalities, Occupational Toxics and Hazards, Corruption, Migrant Labor, and Children Out of School.

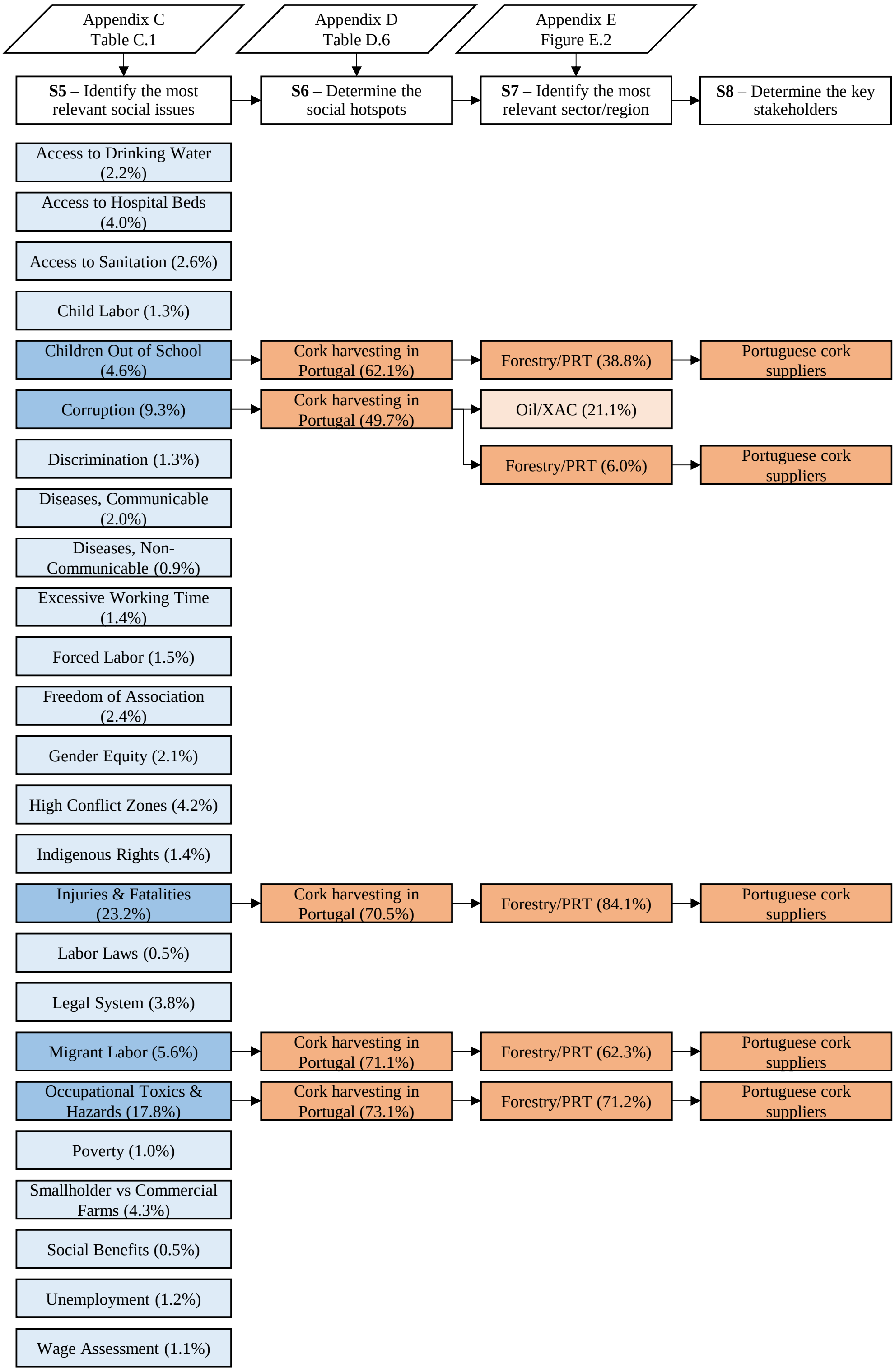


Figure 4.5 – Key findings obtained for the Portuguese natural cork stoppers supply chain.

As shown in Figure 4.6 (Column 1), the most relevant impact subcategories associated with the Portuguese UWF paper supply chain are Injuries and Fatalities, Occupational Toxics and Hazards, Corruption, Legal System, and High Conflict Zones.

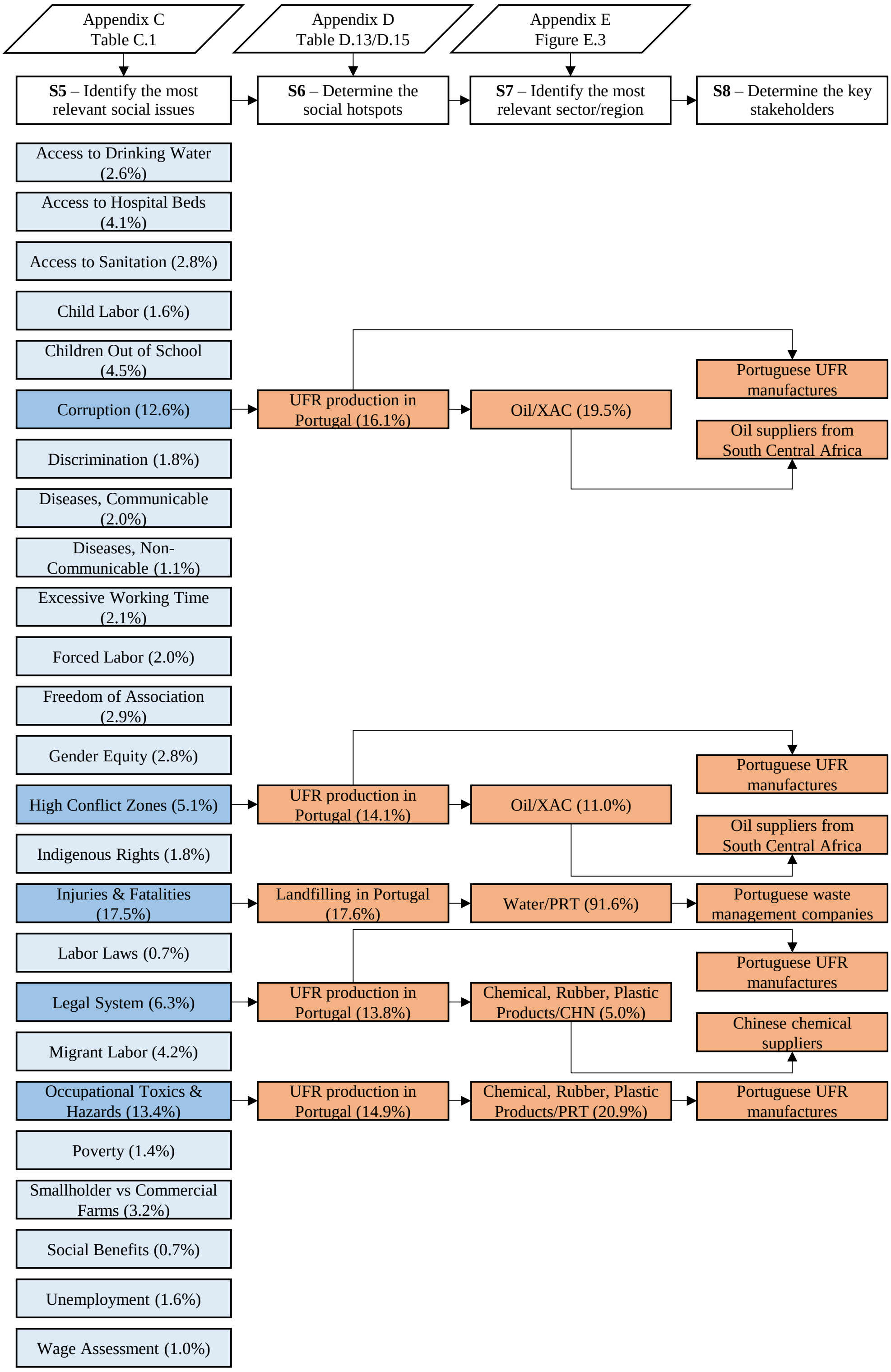


Figure 4.6 – Key findings obtained for the Portuguese particleboards supply chain.

Considering the results obtained for the three supply chains under analysis, a total of seven impact subcategories were recognized as relevant (Figure 4.4, Figure 4.5, and Figure 4.6).

4.3.6 Step 6 – Determine the social hotspots

The social hotspots were identified by ranking the processes and regions in decreasing order of characterized results and choosing the top result for each relevant impact subcategory identified in Step 5 in accordance with what was previously defined in Section 4.2. The characterized results of the different processes and regions in the relevant impacts subcategories previously identified for the three supply chains under analysis are presented in Tables B.20 to B.34 available in the Supplementary Material. Based on these characterized results, the second column of Figure 4.4 to Figure 4.6 was constructed. A characterized result of 6.05×10^2 MRH eq. in the impact subcategory Corruption was obtained for the unit process "Cork harvesting in Portugal" (Table B.25 available in the Supplementary Material), for example. Since the overall characterized result obtained in this impact subcategory for the Portuguese natural cork stoppers supply chain was 1.22×10^3 MRH eq. (Table B.19 available in the Supplementary Material), it can be concluded that the unit process "Cork harvesting in Portugal" contributed 49.7% (Figure 4.5 – Column 2) to the characterized result obtained for Corruption. The social hotspots identified for the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains are highlighted in the second column of Figure 4.4, Figure 4.5, and Figure 4.6, respectively.

The social hotspots associated with the Portuguese UWF paper supply chain are all related to the Manufacturing stage. These hotspots are "Water supply in Portugal" for the impact subcategories Injuries and Fatalities and Occupational Toxics and Hazards, "Potato starch production in Portugal" for the impact subcategories Corruption and Legal System, and "Kaolin production in Portugal" for the impact subcategory High Conflict Zones (Figure 4.4 – Column 2).

For the five relevant social issues found in the case of the Portuguese natural cork stoppers supply chain, one social hotspot connected to the stage of Raw Material Acquisition was discovered. This social hotspot is "Cork harvesting in Portugal" (Figure 4.5 – Column 2).

The two social hotspots associated with the Portuguese particleboards supply chain are related to the Manufacturing stage and the End-of-Life stage. These social hotspots are "Landfilling in Portugal" for the impact subcategory Injuries and Fatalities and "Urea-formaldehyde resin (UFR) production in Portugal" for all other four relevant social issues (Figure 4.6 – Column 2).

4.3.7 Step 7 – Identify the most relevant sectors/regions

In accordance to what was previously defined in Section 4.2, for each social hotspot identified in Step 6, the most relevant sector/region was determined by sorting the sectors/regions involved with the hotspot in decreasing order of characterized results and choosing the top result. Figures B.4 to B.6 available in the Supplementary Material present the contribution of each sector/region to the characterized result of the different hotspots identified in the previous step. Based on these contributions, the third column of Figure 4.4 to Figure 4.6 was constructed. According to Figure B.6, for example, the "Chemical, Rubber, Plastic Products/PRT" sector/region contributes 20.9%

to the characterized result of $2.86x10^1$ MRH eq. obtained for the social hotspot "Urea-formaldehyde resin (UFR) production in Portugal" in the impact subcategory Occupational Toxics and Hazards (Table B.32 available in the Supplementary Material). This corresponds to the percentage presented in Figure 4.6 (Column 3) for this sector/region in the aforementioned impact subcategory. The most relevant sectors/regions identified for the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains are highlighted in the third column of Figure 4.4, Figure 4.5, and Figure 4.6, respectively. Two specific instances are worth mentioning in this step.

The first instance relates to the Portuguese UWF paper supply chain and the most relevant sector/region identified for the social hotspot "Potato starch production in Portugal" in the impact subcategory Corruption. According to Figure 4.4 (Column 3), the sector/region most responsible for the poor social performance of "Potato starch production in Portugal" in the impact subcategory Corruption is "Other Grains/UKR". This result is surprising since grains are not involved in the production of potato starch. When gathering the primary data regarding the Portuguese UWF paper supply chain, the economic sector "Other Food" (i.e., ofd) was attributed to potato starch (Table B.3 available in the Supplementary Material) since this economic sector includes starches (GTAP, 2019). However, this sector also includes other cereal grain products (e.g., corn flakes) (GTAP, 2019) which is why it has trade flows with the economic sector "Other Grains". This provides a reason for the fact that "Other Grains/UKR" was found to be the main responsible for the poor social performance of the hotspot "Potato starch production in Portugal" (i.e., Other Food/PRT) even though grains are not involved in the production of potato starch. Consequently, to determine the most likely responsible for the poor social performance of this hotspot, the second economic sector and region that contributes to this social performance needs to be identified. This corresponds to "Other Crops/UGA" (Figure 4.4 – Column 3) which makes more sense since crops (e.g., vegetable seeds) are involved in the production of potato starch.

The second instance relates with the Portuguese NCS supply chain and the most relevant sector/region identified for the social hotspot "Cork harvesting in Portugal" in the impact subcategory Corruption. According to Figure 4.5 (Column 3), the sector/region most responsible for the poor social performance of "Cork harvesting in Portugal" in the impact subcategory Corruption is "Oil/XAC". This result is surprising since oil is not involved in cork harvesting. When gathering the primary data regarding the Portuguese NCS supply chain, the economic sector "Forestry" (i.e., frs) was attributed to cork (Table B.7 available in the Supplementary Material) since this economic sector includes forestry, logging and other related service activities (GTAP, 2019). Some forestry operations, such as logging, are sometimes performed using power saws that require liquid fuel (e.g., diesel) to operate which is why it has trade flows with the economic sector "Oil". This provides a reason for the fact that "Oil/XAC" was found to be the main responsible for the poor social performance of the hotspot "Cork harvest in Portugal" (i.e., Forestry/PRT). However, since cork harvesting is a process done manually (APCOR, 2015) and, consequently, does not require oil, the second economic sector and region most responsible for the poor social performance of this hotspot needs to be identified to determine the most likely responsible for this social performance. This corresponds to “Forestry/PRT” (Figure 4.5 – Column 3).

4.3.8 Step 8 – Determine the key stakeholders

The last step is to identify the key stakeholders based on the results of Step 6 and Step 7. In the case of the Portuguese NCS supply chain and the impact subcategory Injuries and Fatalities, for example, the social hotspot “Cork harvesting in Portugal” and the most relevant sector/region “Forestry/PRT” were identified (Figure 4.5 – Columns 2 and 3). This finding suggests that Portuguese cork suppliers’ activities/behaviors are the main responsible for the hotspot "Cork harvesting in Portugal" inadequate social performance in the relevant social issue Injuries and Fatalities. On the other hand, in the case of the Portuguese UWF paper supply chain and the impact subcategory Corruption, for example, the social hotspot “Potato starch production in Portugal” and the most relevant sector/region “Other Crops/UGA” were identified (Figure 4.4 – Columns 2 and 3). This finding suggests that it is not the Portuguese potato starch manufactures’ activities/behaviors the main responsible for the subpar social performance of the hotspot “Potato starch production in Portugal” in the relevant social issue Corruption, but the activities/behaviors of Ugandan crops suppliers with whom these manufactures trade with. The key stakeholders determined for the Portuguese UWF paper, NCS, and particleboards supply chains are highlighted in the fourth column of Figure 4.4, Figure 4.5, and Figure 4.6, respectively.

As previously explained in Section 4.2, due to the use of secondary data when modeling the supply chain and to quantify the social indicators (Figure 4.2), primary related to the social hotspots and most relevant sectors/regions identified should be collected to determine if the results of the social assessment represent real social issues. For example, according to the results previously analyzed, “Cork harvesting in Portugal” was recognized as the social hotspot for the impact subcategory Injuries and Fatalities due to the activities/behaviors of the Portuguese cork suppliers. To determine if Injuries and Fatalities is a social issue that affects these supply chain partners, site-specific data regarding Portuguese cork suppliers should be collected by conducting on-site visits or interviewing management. If the social issue is confirmed, Portuguese cork suppliers can modify their activities/behaviors to improve their social performance and, as a result, that of the Portuguese natural cork stoppers supply chain. To assist in this task, the following section provides a set of recommendations tailored to each supply chain that can be used by the different supply chain partners identified as being most likely responsible for the relevant social issues.

4.4 Recommendations

Organizations can play a critical role in helping achieve the Sustainable Development Goals if they modify their activities/behaviors to address different economic, environmental, and social issues (Rosati & Faria, 2019). The SDGs are a set of 17 goals identified and agreed upon by the United Nations (UN) in 2015 and are intended to be achieved by 2030. Each goal is composed of different targets (United Nations, 2021).

A deeper look at the seven relevant impact subcategories previously identified is provided below, including reasons why companies should care about these social issues, informed recommendations on what the key stakeholders previously identified can do to mitigate these potential social impacts, and to what Sustainable Development Goals are they contributing when implementing these recommendations.

4.4.1 Injuries and Fatalities

The International Labour Organization (ILO) defines an occupational injury as "*any personal injury, disease or death resulting from an occupational accident*". Given this definition, an occupational injury can be classified as non-fatal with lost work time or fatal where the death occurred within one year of the day of the accident (ILO, 2021a). For companies, the costs of workplace accidents can be destabilizing. These costs include direct costs (e.g., health care costs and employee compensation costs) and indirect costs (e.g., lost productivity and employee morale) (ILO, 2012). Furthermore, safe and healthy working conditions are a fundamental human right (UNEP, 2013).

As previously discussed in Section 4.3, Injuries and Fatalities is the most relevant impact subcategory in the three supply chains analyzed, namely the Portuguese UWF paper, NCS, and particleboards supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the three supply chains in this impact subcategory, Portuguese water providers (Figure 4.4), Portuguese cork suppliers (Figure 4.5), and Portuguese waste management companies (Figure 4.6), respectively, should implement prevention and safety measures to minimize occupational accidents that may result in injuries or fatalities (Table 4.3):

- Portuguese UWF paper supply chain – Slips, trips, and falls (STFs) are the most common causes of injuries among workers from the water supply industry (Bureau of Labor Statistics, 2020). Strategies to prevent injury from STFs to occur include (1) identifying trip hazards (e.g., trailing cables) and encourage good housekeeping by workers; and (2) providing workers with appropriate footwear with a sole pattern/material that helps prevent slips (ILO, 2021b);

- Portuguese NCS supply chain – Some of the most common injuries in the case of cork harvest, which is mostly done manually using an axe, are open wounds (e.g., lacerations) and falls from cork trees (EU-OSHA, 2008). To prevent open wounds, the head of the hand tool used should be fixed securely onto the handle with an effective device (e.g., bolt) and, when not in use, the head should be sheathed with an appropriate device (ILO, 1998). To prevent falls from cork trees, only experienced and fully trained persons should be employed in tree climbing operations, and these operations should not be performed when visibility is seriously impaired (e.g., heavy rain) (ILO, 1998). Personal protective equipment (PPE), such as gloves and safety helmet, should also be provided to forestry workers in case the aforementioned strategies are not effective (ILO, 1998);
- Portuguese particleboards supply chain – Similar to the water supply industry, the most common causes of injuries among landfill workers are slips, trips, and falls (Bureau of Labor Statistics, 2020). Thus, the same strategies previously provided to prevent injury from STFs (ILO, 2021b) are also suggested for Portuguese waste management companies.

By implementing these recommendations, Portuguese water providers, cork suppliers, and waste management companies can contribute to *SDG 8 – Decent Work and Economic Growth* which aims to promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. Notably, they will contribute to achieving *Target 8.8 – Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment* (United Nations, 2021).

4.4.2 Occupational Toxics and Hazards

According to ILO, an occupational disease is "*a disease contracted as a result of an exposure over a period of time to risk factors arising from work activity*" (ILO, 2021a). Examples of occupational diseases include hearing loss due to exposure to high levels of occupational noise and occupationally induced cancers due to exposure to known or probable human carcinogens (e.g., asbestos) (Norris, et al., 2019). Similarly to an occupational injury, an occupational disease may be non-fatal (e.g., hearing loss) or fatal (e.g., cancer). Most workers who die each year from poor working conditions (i.e., 2.78 million workers) die from work-related diseases (i.e., 2.4 million workers), while the remaining 380,000 workers die due to occupational injuries (ILO, 2019a) (as explained in the previous subsection). The same direct and indirect costs borne by employers for workplace accidents may occur when workers contract an occupational disease. Apart from the pain and suffering of the employees affected by a work-related disease, there is also economic repercussion, such as possible loss of income if they miss out on several days of work and poorer economic prospects (ILO, 2012).

The Occupational Toxics and Hazards subcategory is the second most relevant impact subcategory in the three supply chains analyzed, namely the Portuguese UWF paper, NCS, and particleboards supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the three supply chains in this impact subcategory, Portuguese water providers (Figure 4.4), Portuguese cork suppliers (Figure 4.5), and Portuguese UFR manufactures (Figure 4.6), respectively, should implement prevention and safety measures to minimize workers' exposure to health hazards that may cause them harm and, consequently, minimize the occurrence of work-related illnesses (Table 4.3):

- Portuguese UWF paper supply chain – The most common health hazards in water supply is overexertion in lifting or lowering (Bureau of Labor Statistics, 2020). Measures to reduce workers' exposure to this hazard include (1) adjusting the area layout to minimize the need to carry out such movements; (2) considering if the carrying distance can be minimized; and (3) assessing if the load can be broken down to smaller, lighter components (ILO, 2021b);
- Portuguese NCS supply chain – In the case of cork harvest, common occupational diseases include occupational asthma and hypersensitivity pneumonitis (i.e., suberosis) due to cork dust inhalation (Nunes, et al., 2012). A possible safety measure includes providing cork workers with respiratory protective equipment (RPE) such as filtering facepieces (ILO, 2021b);
- Portuguese particleboards supply chain – When it comes to resin manufacturing, the most common health hazards is exposure to harmful substances or environments (Bureau of Labor Statistics, 2020). Formaldehyde is a harmful substance present in the case of urea-formaldehyde resin production. Due to the high toxicity of this substance, possible safety measures include (1) ensuring an adequate supply of fresh air through natural ventilation (e.g., doors or windows) or controlled ventilation where air is supplied and/or removed by a powered fan; and (2) installing a local exhaust ventilation (LEV) which will draw fumes through a hood or booth away from the worker. If necessary, workers should also be provided with RPE (ILO, 2021b).

Similar to the previous social issue, by implementing the recommendations provided, Portuguese water providers, cork suppliers, and UFR manufactures can contribute to *Target 8.8 – Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment* defined for *SDG 8 – Decent Work and Economic Growth* previously presented (United Nations, 2021).

Table 4.3 – Recommendations for the different supply chain partners to assist them in improving their social performance.

Relevant Social Issue	**Recommendations**			**SDGs**	
	UWF paper	Natural cork stoppers	Particleboards	Goal	Target
Injuries and Fatalities	Portuguese water providers should identify trip hazards, encourage good housekeeping by workers, and provide workers with appropriate footwear with a sole pattern/material that helps prevent slips.	Portuguese cork suppliers should ensure that the head of the hand tool used is fixed securely onto the handle and only experienced and fully trained persons are employed in tree climbing operations.	Portuguese waste management companies should identify trip hazards and provide workers with appropriate footwear with a sole pattern/material that helps prevent slips.	8	8.8
Occupational Toxics and Hazards	Portuguese water providers should adjust the area layout to minimize lifting or lowering movements and to minimize the carrying distance.	Portuguese cork suppliers should ensure an adequate supply of fresh air and provide cork workers with respiratory protective equipment.	Portuguese UFR manufactures should install a local exhaust ventilation and provide workers with respiratory protective equipment.		
Migrant Labor	-	Portuguese cork suppliers should provide equality and diversity training for all workers and translate documents to ensure that migrant workers understand their legal rights and duties.	-		
Corruption	Portuguese potato starch manufactures should demand that their Ugandan crop suppliers publish financial accounts.	Portuguese cork suppliers should make sure that cork workers know how to report any suspicion of bribery or corruption.	Portuguese UFR manufactures should demand that their oil suppliers from South Central Africa publish financial accounts.	16	16.5
Legal System	Portuguese potato starch manufactures should sponsor a fund to provide access to legal resources to Tanzanian crop farmers.	-	Portuguese UFR manufactures should advocate for gender equality with its Chinese chemical suppliers.		16.3
High Conflict Zones	Portuguese kaolin suppliers should consult with local communities and implement strategic social investment.	-	Portuguese UFR manufactures should monitor how their oil suppliers from South Central Africa obtain resources.		16.1
Children Out of School	-	Portuguese cork suppliers should provide scholarships to children and create apprenticeship programs.	-	4	4.1

Legend: *CHN (China), PRT (Portugal), TZA (Tanzania), UGA (Uganda), UKR (Ukraine), XAC (South Central Africa)*

4.4.3 Corruption

Transparency International has defined corruption as "*the abuse of entrusted power for private gain*" (Transparency International, 2021). There are different types of corruption, including bribery (i.e., an offer or receipt of money or favor to or from any person to influence the judgment or conduct of a person in a position of trust (Merriam-Webster, 2022)), extortion (i.e., threats that endanger the personal integrity of the people involved as an incentive to do something dishonest or illegal (UN Global Compact, 2021)), and nepotism (i.e., the practice by an influential person of giving favors such as jobs based on kinship (Merriam-Webster, 2021)). For companies, eliminating corruption has become a priority due to the high legal and reputational risks faced if they fail to combat corruption in all its forms and the potential costs associated with these risks. Legal risks are related to the fact that most forms of corruption are illegal. A potential cost associated with this legal risk is the money spent on lawsuits and sanctions that companies may be forced to pay if they are involved in corruption activities. Reputational risks are related to losing trust among customers, employees, and investors in companies whose policies and practices have failed to meet high ethical standards. A potential cost associated with this reputational risk is the loss of revenue due to customers switching to rival products (UN Global Compact, 2021). Corruption also affects the general population because it further exacerbates inequality, weakens democracy, and hampers economic development (Transparency International, 2021) since close to $1 trillion are lost by many countries due to fraud, corruption, and shady business transactions (UN Global Compact, 2021).

Corruption is the third most relevant impact subcategory in the three supply chains analyzed, namely the Portuguese UWF paper, NCS, and particleboards supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the three supply chains in this impact subcategory, Portuguese potato starch manufactures (in partnership with their Ugandan crops suppliers) (Figure 4.4), Portuguese cork suppliers (Figure 4.5), and Portuguese UFR manufactures (in partnership with their oil suppliers from South Central Africa) (Figure 4.6), respectively, should implement measures to fight corruption (Table 4.3):

- Portuguese UWF paper supply chain – In Uganda, corruption is widespread and seen as one of the greatest obstacles to the country's economic development. The most recurrent form of corruption in the country is the payment of bribes by citizens and companies. When conducting businesses in Uganda, several documents, payments and procedures are required which encourages companies to pay bribes to public officials to speed up such processes (Martini, 2013). Portuguese potato starch manufactures should advocate for the development and implementation of an anti-corruption system with its Ugandan crop suppliers and demand that these suppliers publish financial accounts, detailing the taxes and other contributions made to each government (Transparency International, 2017);

- Portuguese NCS supply chain – Possible measures to be implemented by the Portuguese cork suppliers include making sure that cork workers know how to report any suspicion of bribery or corruption (e.g., by using the company's whistleblowing channels) and ensuring that any gift or hospitality a cork worker receives meet key criteria such as being proportionate (i.e., reasonable and not unnecessarily luxurious) and transparent (i.e., declared in the company's Gift and Hospitality Register) (Dodd, 2021);
- Portuguese particleboards supply chain – Corruption is commonplace in most countries from South Central Africa where politicians and other governmental officials accept bribes, use public funds to finance their private life, and award jobs to individuals based on familial ties (Afrikanza, 2017). In African oil-producing countries, such as Angola, oil and gas assets are controlled by state-owned companies which are responsible for awarding lucrative oilfield contracts. This encourages private companies to pay bribes to these state-owned companies and politicians in exchange for being awarded these oilfield contracts (Kelly, 2018). To help fight corruption in South Central Africa, Portuguese UFR manufactures should demand that their oil suppliers from this region publish financial accounts, including details of the fees, royalties and other payments made to governments and state oil companies (Resilience, 2004).

By implementing these recommendations, the Portuguese potato starch manufactures, cork suppliers, and UFR manufactures can contribute to *SDG 16 – Peace, Justice, and Strong Institutions*, which aims to promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels. Mainly, they will contribute to achieving *Target 16.5 – Substantially reduce corruption and bribery in all their forms*.

4.4.4 Legal System

According to the World Justice Project, an international civil society organization, the rule of law "*is a durable system of laws, institutions, norms, and community commitment*" (WJP, 2019). This organization also developed a set of four universal principles that constitute a working definition of the rule of law, including the principle of (1) accountability (all organizations and individuals are accountable under the law); (2) just law (legislation is clear, disclosed, and consistently applied); (3) open government (procedures for enacting, administering, adjudicating, and enforcing the law are accessible, fair, and efficient.); and (4) accessible and impartial justice (competent, ethical, and independent representatives who have enough resources and reflect the makeup of the communities they serve execute justice on time) (WJP, 2019). Unfortunately, for three consecutive years (i.e., 2018 to 2020), more countries declined than improved in the overall rule of law performance which is worrisome because it indicates a continuing weakening of the rule of law around the world (WJP, 2020). Conducting businesses where the rule of law performance is strong is very important for companies because without any legal means to protect their best interests, doing business would be very difficult.

Furthermore, an organization that fails to comply with a region's law is vulnerable to audits and lawsuits, which can lead to fines or, worse, having the organization dissolved entirely (Southern Cross University, 2017). Advancing the rule of law would also help solve other sustainability issues confronting international business, such as human rights or anti-bribery, since these issues are challenging to resolve where the rule of law is weak (Odgers Berndtson, 2018).

The Legal System subcategory is the fourth most relevant impact subcategory in two of the three supply chains analyzed, namely the Portuguese UWF paper supply chain and the Portuguese particleboards supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the two supply chains in this impact subcategory, Portuguese potato starch manufactures (in partnership with their Tanzanian crops suppliers) (Figure 4.4) and Portuguese UFR manufactures (in partnership with their Chinese chemicals suppliers) (Figure 4.6), respectively, should implement measures to help advance the rule of law (Table 4.3):

- Portuguese UWF paper supply chain – Around 38% of the rural population in Tanzania lives below the poverty line despite this country's comparative advantage in the production of many crops and abundance of natural resources (Arce & Caballero, 2015). The lack of financial capacity is one of the main reasons for lack of access to justice. Hence, to help advance the rule of law, Portuguese potato starch manufactures should focus on strategic social investment (UN Global Compact, 2015) by sponsoring a fund whose mission is to provide access to legal resources (e.g., lawyers) to low-income Tanzanian crop farmers;
- Portuguese particleboards supply chain – Even though China has been active in promoting gender equality and China's female labor participation rate is one of the highest in the world, since the 1990's this rate has been declining due to an overall improvement in livelihoods combined with certain difficulties women face in the workplace (e.g., harassment) (ILO, 2019b). Hence, Portuguese UFR manufactures should focus on advocacy and public policy engagement (UN Global Compact, 2015) to help advance the rule of law by advocating for gender equality with its Chinese chemical suppliers and by demanding that these suppliers have a zero-tolerance environment regarding violence and harassment in the workplace. Portuguese UFR manufactures should also sponsor a fund whose mission is to provide access to legal resources (e.g., lawyers) to low-income female workers in China.

If Portuguese potato starch and UFR manufactures implement the recommendations provided, they will contribute to *Target 16.3 – Promote the rule of law at the national and international levels and ensure equal access to justice for all* defined for *SDG 16 – Peace, Justice and Strong Institutions* previously presented (United Nations, 2021).

4.4.5 High Conflict Zones

Conflicts are defined by the Heidelberg Institute for International Conflict Research (HIIK) as "*the clashing of interests over national values of some duration and magnitude between at least two parties* *(organized groups, states, groups of states, organizations) that are determined to pursue their interests and achieve their goals"* (Heidelberg Institute for International Conflict Research (HIIK), 2005). To distinguish between different forms of conflicts, the HIIK institute developed a classification that sorts conflicts according to five different intensity levels – level 1 (latent conflict), 2 (manifest conflict), 3 (crisis), 4 (severe crisis), and 5 (war). A region where conflicts arise is called a conflict zone (Heidelberg Institute for International Conflict Research (HIIK), 2005). Companies tend to avoid conducting business in conflict zones because the risks exceed the benefits of such locations. Some of these risks include (1) limited access to infrastructures (conflicts enhance infrastructure degradation since transport links, energy, and fuel facilities are often targeted); (2) lack of a stable regulatory environment (conflicts foster a very informal way of conducting business resulting in few impediments to using price manipulation or other questionable tactics); and (3) high security and insurance costs (conducting businesses in a conflict zone poses a significant danger to both workers and assets' safety since companies become targets of a variety of threats, including kidnapping for ransom, which increases the cost of insurance and security) (Alexander, 2013). Besides the impacts on businesses, conflicts also affect the population from the conflict zones. Each year, up to 180,000 people are killed, and at least another 200,000 people die indirectly (e.g., war-related malnutrition) from armed conflicts worldwide (Muggah, 2015).

The High Conflict Zones subcategory is the fifth most relevant impact subcategory in two of the three supply chains analyzed, namely the Portuguese UWF paper supply chain and the Portuguese particleboards supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the two supply chains in this impact subcategory, Portuguese kaolin suppliers (Figure 4.4) and Portuguese UFR manufactures (in partnership with their oil suppliers from South Central Africa) (Figure 4.6), respectively, should implement measures to ensure that their operations contribute to peace-building (Table 4.3):

- Portuguese UWF paper supply chain – Kaolin mining has been the cause of conflicts between companies and residents that live near the mines in Portugal. For example, the Barqueiros mine SA (Mibal) was opened in 1965 with the purpose of exploiting the mineral deposits of kaolin. Divergences between Mibal and local residents emerged when these residents claimed that their wells had dried up and that there was a the lack of maintenance of the craters opened up by the mine. When in 1989 Mibal insisted on starting a new exploration, the population took to the streets to express their displeasure. The actions of the police forces led to the death of a twenty-year-old youth (Environmental Justice Atlas, 2018). Given the nature of these conflicts, Portuguese kaolin suppliers should focus on local stakeholder engagement (UN Global Compact, 2010) to contribute to peace-building by consulting with local communities about business decision that might affect them. These supply chain partners should also implement strategic social investment to mitigate or compensate for the impacts of their operations (UN Global Compact, 2010);

- Portuguese particleboards supply chain – A study focusing on African countries found that many specific cases suggest that oil can motivate and prolong armed conflicts. It generally does so through the funding of rebellions and the repression of peaceful protests and political opposition (Billon, 2010). Given the nature of these conflicts, Portuguese UFR manufactures should monitor how their oil suppliers from South Central Africa obtain raw materials and other resources in conflict-affected areas. By applying this suggestion, Portuguese UFR manufactures can guarantee that they are not funding armed actors who may profit from selling such raw materials and resources (UN Global Compact, 2010).

Similar to the two previous social issues, the Portuguese kaolin suppliers and UFR manufactures can contribute to *SDG 16 – Peace, Justice, and Strong Institutions* by implementing the recommendations provided. Notably, they will contribute to achieving *Target 16.1 – Significantly reduce all forms of violence and related death rates everywhere* (United Nations, 2021).

4.4.6 Migrant Labor

At the end of 1990, the *International Convention on the Protection of the Rights of All Migrant Workers and Members of Their Families* was adopted by the General Assembly of the United Nations. This convention contains the most comprehensive definition of migrant workers available. According to this definition, a migrant worker is "*a person who is to be engaged, is engaged or has been engaged in a remunerated activity in a State of which he or she is not a national"*. Excluded from this definition are students and trainees, refugees and stateless persons, employees of international organizations, Government officials, among others (United Nations, 1990). There are approximately 169 million migrant workers worldwide, which represents 4.9 percent of the global labor force (ILO, 2021c). These workers have benefited businesses in different ways. Research analyzing the impacts that migrants had on businesses found that the most significant benefits are related to (1) the skills of the migrant workers, which allows businesses to expand their workforce and select better-qualified candidates; (2) knowledge transfer from migrants to businesses which allows the upskilling of native co-workers and the expansion of the business's knowledge base; and (3) migrants' connections which supports business expansion and growth into new markets overseas and strengthens client relationships in existing markets abroad (BIS, 2015). Migrant workers also contribute to the economic development of their host country (e.g., by helping local economies respond to worker shortages) and home country (e.g., through the remittances they send home). Despite their contributions to businesses and the growth and development in their countries of destination and origin, migrant workers face several challenges such as the lack of social protection and discrimination, which may result in decreased access to employment, increased violence, exploitation, human trafficking, and poor working conditions (Norris, et al., 2019).

The Migrant Labor subcategory is the fourth most relevant impact subcategory in one of the three supply chains analyzed, namely the Portuguese NCS supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the aforementioned supply chain in this impact subcategory, Portuguese cork suppliers (Figure 4.5), should implement supportive measures for the migrant workers they employ (Table 4.3):

- Portuguese NCS supply chain – To help migrant workers integrate with native co-workers, Portuguese cork suppliers should provide equality and diversity training for all workers and have a suitable induction process that includes introducing the new workers to their team. Organizing team events involving every personnel is also a good strategy to help with integration among staff. Another possible measure is to focus on communication since many migrant workers deal with language barriers. Even if this involves translating documents, it should be ensured that migrant workers understand their legal rights and duties. Providing a flexible schedule to allow attendance at courses in the native language for speakers of other languages would assist in breaking the language barrier and, at the same time, reduce the need for translation (nibusinessinfo, 2021).

By implementing the recommendations provided, cork suppliers can contribute to achieving *Target 8.8 – Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment* defined for SDG *8 – Decent Work and Economic Growth* (United Nations, 2021).

4.4.7 Children Out of School

The right to education has been established by different UN Conventions, from the Universal Declaration of Human Rights in 1948 to the Convention on the Rights of the Child in 1989 (Norris, et al., 2019). However, about 258 million children and youth are out of school, including 59 million children of primary school age, 62 million of lower secondary school age, and 138 million of upper secondary age (UNESCO Institute of Statistics, 2018). These numbers highlight the fact that as children get older, there is an increase in the risk that they will be out of school either because they never started school or because they dropped out. As unskilled jobs become scarce, the next generation of workers will require significantly more education and advanced skills. Despite the need for a more skilled workforce, too many graduates lack basic reading, writing, and math skills. If future workers lack proper education and cannot meet high standards, businesses will have to bear the cost of retraining them. In fact, companies in America spend more than $60 billion each year on training, much of that on correcting or improving deficient skills in reading, writing, and mathematics (Corporate Voices For Working Families, 2021). For this reason, organizations should invest in education to develop a more skilled, employable, and productive population and reduce the waste of human potential, particularly of women and underprivileged groups (Sandbu, 2018). In addition to creating a better-skilled workforce, investment in education is also critical to achieving sustainable development. It is only possible to mitigate climate change, reduce inequalities, end extreme poverty, empower girls, and achieve other accomplishments if all stakeholders, including companies, commit themselves to advance the education goal (SDG Compass, 2015).

The Children Out of School subcategory is the fifth most relevant impact subcategory in one of the three supply chains analyzed, namely the Portuguese NCS supply chain. According to the key stakeholders identified, it is possible to conclude that to improve the social performance of the aforementioned supply chain in this impact subcategory, Portuguese cork suppliers (Figure 4.5), should implement measures to ensure that all children go to school and that their education is of good quality (Table 4.3):

- Portuguese NCS supply chain – Usually, the recommendations provided to address this social issue focus on mitigating the consequences of poverty since (1) poor communities may not have the infrastructures (e.g., schools and transportation) and resources (e.g., books and supplies) to support a school system; (2) low-income families may be unable to offer adequate nutrition to their children which means that students are hungry at school and are not able to concentrate and absorb information; and (3) parents living in poverty are reluctant to send their children to school and instead encourage their sons to earn a living and girls to get married early (Buitenbos, 2021). However, even though there is poverty in Portugal (i.e., where the social hotspot is located), its consequences are not as extreme as the examples provided. For this reason, the recommendations provided to Portuguese cork suppliers must be in accordance with the reality of this country. For example, these suppliers can help reduce the financial barrier to access education by providing grants and scholarships to children (SDG Compass, 2015) and create programs (e.g., apprenticeship) to teach younger generations cork harvesting, a traditional and artisanal practice very valuable in Portugal (Green Cork, 2014). Through these apprenticeship programs, cork suppliers will be contributing to the formation of skilled labor.

By implementing the recommendations provided, the Portuguese cork suppliers can contribute to *SDG 4 – Quality Education* which aims to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. Mainly, they will contribute to achieving *Target 4.1 – By 2030, ensure that all girls and boys complete free, equitable, and quality primary and secondary education, leading to relevant and effective learning outcomes* (United Nations, 2021).

4.5 Conclusions

This study proposes a social LCA framework for analyzing the social performance of supply chains and demonstrates its structure and applicability through a case study considering three different forest supply chains, namely the Portuguese UWF paper, natural cork stoppers, and particleboards supply chains. Based on the findings obtained through the application of the social LCA framework to the three forest supply chains, a set of recommendations tailored to each supply chain are offered to assist manufacturers of forest products and other supply chain participants enhance their social performance and, in turn, improve their supply chains' social performance. These recommendations contribute to

Goal 4 – Quality Education, *Goal 8 – Decent Work and Economic Growth*, and *Goal 16 – Peace, Justice, and Strong Institutions*, which are three of the 17 Sustainable Development Goals.

Future work should include the application of the proposed social LCA framework to other supply chains to further validate it. The proposed framework should also be integrated with other economic and environmental analysis of supply chains. A comprehensive analysis is critical to achieve an effective SSCM strategy. Lastly, future research should include the development of a methodology to integrate uncertainty into social LCA. Only after this integration, can the robustness of the conclusion reached in a social LCA be determined.

5. Uncertainty Analysis – Single Level

5.1 Introduction

Environmental sustainability has become an essential part of how executives manage their businesses, not only due to the increasingly demand from consumers that businesses reduce their environmental impact but also due to the fear that the increasing number of climate-related events will negatively affect their business operations (Deloitte, 2020). This paradigm shift means that companies have ceased to exist just to maximize their profit, and currently have a role to play in protecting the environment, which requires them to be aware of their products' environmental impacts. When assessing these impacts, companies should look beyond their operations and consider the different life cycle stages of their products, from raw material's extraction to product's disposal. The main reason for considering the whole product life cycle is that the significant environmental impacts of a product may be related to the extraction of the raw materials used, or to the manufacturing, transport, use and disposal of that product. Only by considering the different life cycle stages can an organization determine where the significant environmental impacts occur and potentially mitigate them (ISO, 2015).

According to the European Commission, Life cycle assessment (LCA) is the best methodological tool currently available for assessing the environmental impacts of a system's life cycle (European Commission, 2021a). The system refers to the specific object under analysis, which in many cases is a product (EC-JRC-IES, 2010). Four well-documented steps comprise an LCA study (ISO, 2006). Firstly, in the Goal and Scope Definition step, the main goal of the life cycle assessment study is defined and the system's boundary is established. The second step, Inventory Analysis, involves quantifying the inputs (e.g., raw materials) and outputs (e.g., air emissions) of all life cycle stages within the system boundary defined in the previous step. In the next step, Impact Assessment, the inventory previously collected is converted into environmental impacts using characterization factors (CFs). Lastly, in the Interpretation step, the LCA results are examined and interpreted taking into account the goal defined in the first step of the study. Life cycle assessment is utilized in diverse decision-making applications including comparing different scenarios for the treatment and utilization olive pomace (Duman, et al., 2020) and toy materials (Levesque, et al., 2022) to determine the most environmentally friendly option. These applications make the reliability of LCA results extremely important for decision-makers. This reliability is affected by the uncertainty that is always present in life cycle assessments (Björklund, 2002). To increase the confidence of the decision-makers in LCA results and, consequently, on the decisions taken under these results, a suitable uncertainty analysis should always be present when performing a life cycle assessment.

A recent literature review conducted by Bamber et al. (2020) revealed that less than 20% of the LCA studies published since 2014 include any kind of uncertainty analysis. Moreover, the rate of LCA studies which report uncertainty analysis does not appear to be increasing over time. Most LCA studies considering uncertainty focus on uncertainty at the Inventory Analysis step, neglecting the Goal and

Scope Definition and Impact Assessment steps (Piano & Benini, 2022). The need to consider uncertainty in the Impact Assessment step, particularly in the data used to compute characterization factors, was identified several years ago by Huijbregts (1998a) as a requirement to address uncertainty in an LCA study adequately. Different studies acknowledged the uncertainty associated with characterization factors. Huijbregts et al. (2003) outlined a new methodology that quantifies, among others, the uncertainty associated with characterization factors of ten impact categories by means of Monte Carlo simulation. The lognormal distribution was chosen to represent uncertainty in the characterization factors because it avoids negative values, it captures a large value range, and the uncertainty in many parameters follows a skewed distribution. Van Zelm and Huijbregts (2013) studied the uncertainty associated with the data required to compute the characterization factors of chemicals for freshwater ecotoxicity by attributing different probability distributions to these data and conducting a Monte Carlo simulation. Gargalo et al. (2016) proposed a step-wise methodology to assist decision-makers to, among others, handle the characterization factors uncertainty by applying the Monte Carlo technique. It was assumed that uncertainty in the characterization factors follows a uniform distribution and three classes of uncertainties were defined: Class 1 (i.e., 25% variation around the nominal value of each CFs), Class 2 (i.e., 50% variation around the nominal value of each CFs), and Class 3 (i.e., 75% variation around the nominal value of each CFs). More recently, Qin and Suh (2021) introduced a method which uses the logarithmic mean Divisia index decomposition method combined with Monte Carlo simulation to quantify the contributions of underlying variables in LCA, such as characterization factors, to overall variability in the result, such as characterized results. The results of applying this method to a case study showed that the inventory and characterization factors contribute 32% and 68%, respectively, to the uncertainty of the characterized result for carcinogenic human toxicity.

Even though, as discussed above, some LCA studies have included the uncertainty associated with characterization factors, most of these studies focus only on a few impact categories or do not present an easily reproducible methodology of integrating this uncertainty in an LCA. Consequently, a comprehensive methodology (i.e., covering all relevant environmental issues) for the integration of uncertainty in the characterization factors that can be easily reproduced by any LCA practitioner is still missing from the literature. To address this research gap, this study presents a methodology with clear guidelines on how to integrate in an LCA study the uncertainty related with the characterization factors of all impact categories identified in the *General Guide for Life Cycle Assessment* (EC-JRC-IES, 2010). This methodology involves conducting a traditionally deterministic LCA that does not consider uncertainty, a stochastic LCA which considers the uncertainty related with the characterization factors used in the Impact Assessment step, and a comparison of both assessments. The stochastic modeling technique applied in this study is the Monte Carlo simulation because it is the most adequate approach to integrate uncertainty in an LCA study (Thies, et al., 2019). By providing an easily reproducible systematic procedure to address the uncertainty related with the characterization factors utilized in the Impact Assessment step of an LCA, this study will contribute to an increase on the rate of LCA studies which report uncertainty analysis. To demonstrate the structure and applicability of the proposed methodology, the comparison of two pulp bleaching techniques is used as an illustrative case study. By applying the developed methodology to a case study, this study shows how it can be used as part of a decision-making process and how it can assist decision-makers by having robust LCA results and, consequently, more informed decisions.

The remainder of this chapter is organized into four sections. Section 5.2 describes the methodology developed. The next section presents an application of this methodology to a case study to illustrate how it can be applied as part of a decision-making process. Section 5.4 includes a discussion of the methodology’s highlights. Lastly, Section 5.5 presents the conclusions of this work and suggestions for future work.

5.2 Methodology

The work-flow describing the developed methodology is presented in Figure 5.1. This methodology involves ten main steps: Define the goal and scope (S1); Model the systems (S2); Select the impact assessment method (S3); Conduct a deterministic impact assessment (S4); Analyze the deterministic results (S5); Assign a probability distribution to the uncertain parameters (S6); Generate random samples of the uncertain parameters (S7); Conduct a stochastic impact assessment (S8); Analyze the stochastic results (S9); and Compare the results (S10). As previously mentioned, the stochastic modeling technique chosen in this study is Monte Carlo simulation. In this type of simulation, probability distributions (e.g., normal and uniform) are assigned to uncertain parameters. These parameters, along with certain (fixed) parameters, are combined to calculate the simulation model's output values. The uncertain parameters are sampled randomly from the probability distributions, and the output values calculated using that sample are recorded. This sampling is done several times, each time using a different set of random values, which results in different output values. Each time a different set of random values is generated is called an iteration. Instead of generating just a single estimate of results, the Monte Carlo simulation generates results with a wide range of possible outcomes represented through probability distributions, reflecting the combined parameter uncertainties (Palisade Corporation, 2016).

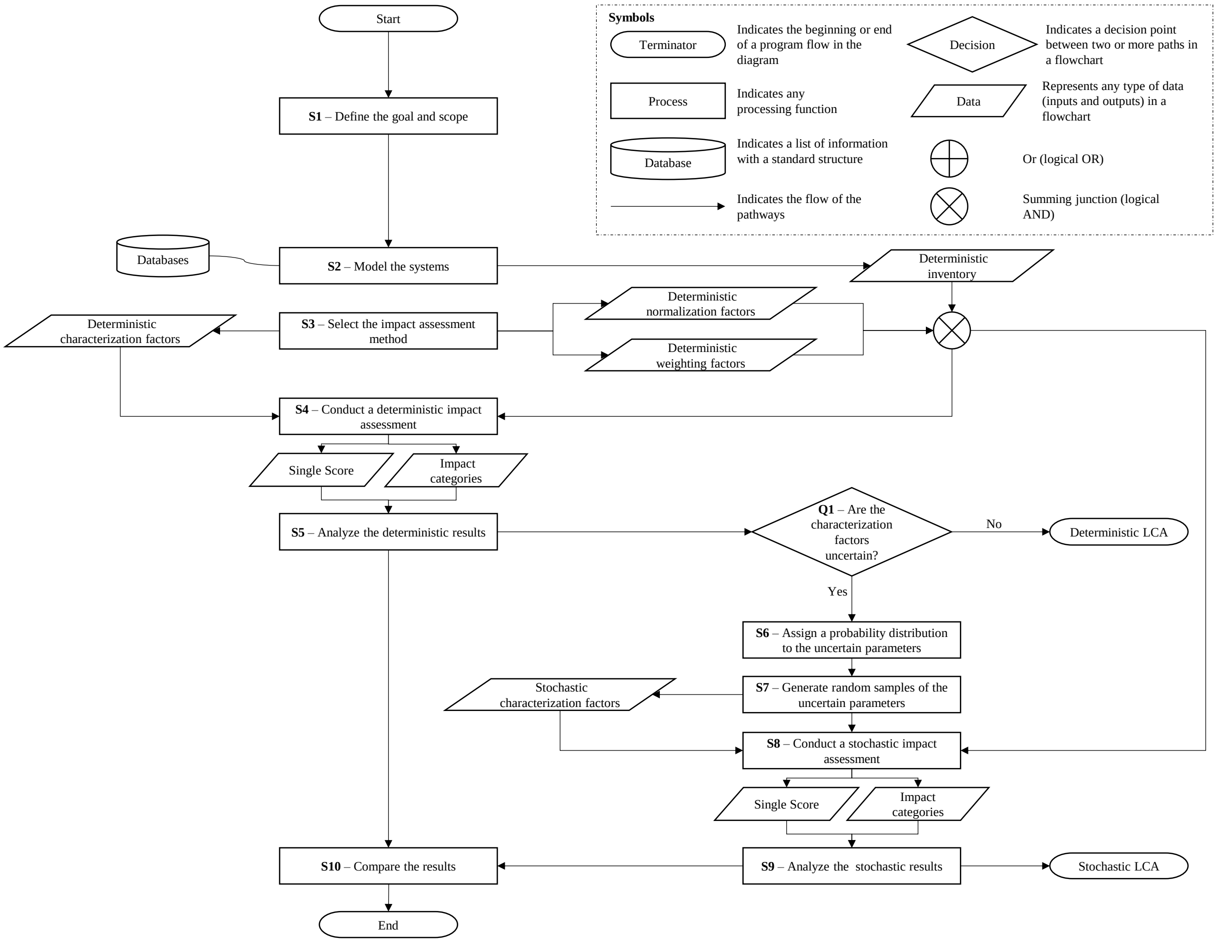


Figure 5.1 – Methodology for integrating the uncertainty in the characterization factors into life cycle assessments.

5.2.1 Step 1 – Define the goal and scope (S1)

The purpose of this step is establishing the goal of the life cycle assessment and characterizing the systems under study (i.e., scope).

In terms of goal definition, LCA can be utilized for three primary purposes (EC-JRC-IES, 2010), namely micro-level decision support, meso/macro-level decision support, and accounting. A comparative LCA where two or more systems are analyzed and compared is considered when life cycle assessment is used in micro-level or macro-level decision support. In the case of accounting, a stand-alone LCA is used, where only one system is analyzed.

Scope definition requires defining the system boundary and functional unit. The system boundary establishes which stages of the system's life cycle will be taken into account in the life cycle assessment (EC-JRC-IES, 2010). Various system boundaries exist from the most extensive (i.e., cradle-to-grave) which includes all life cycle stages from raw materials' extraction to product disposal to the most restricted (i.e., gate-to-gate) which only includes a single step in the life cycle (Eskandarpour, et al., 2015). The functional unit serves as the foundation for calculating all input and output flows in the next step. A equivalent system boundary and the same functional unit must be define for each studied system in a comparative life cycle assessment.

5.2.2 Step 2 – Model the systems (S2)

The second step consists of modeling the systems under analysis. This modeling can be accomplished using a life cycle assessment software (e.g., openLCA, SimaPro, or GaBi) and allows quantifying the elementary input and output flows of all foreground and background processes within the system boundary. Foreground processes are those which are under the control of the decision-maker for which an LCA is carried out (e.g., manufacturing process) (Frischknecht, 1998). For this reason, for these processes there is usually direct access to information (Zampori & Pant, 2019). Hence, the elementary input and output flows associated with foreground processes can be determined by recording the raw materials needed by these processes and any direct emissions to air, soil, and water (Shaked & Jolliet, 2019). On the other hand, background processes are those on which no or, at best, indirect influence may be exercised by the decision-maker for which an LCA is carried out (e.g., waste management) (Frischknecht, 1998). Thence, for these processes there is usually no direct access to information (Zampori & Pant, 2019). Consequently, to estimate the elementary input and output flows associated with background processes, LCA experts have created inventory databases, such as the ecoinvent database (Shaked & Jolliet, 2019). The output of this step is an inventory list of elementary flows and corresponding quantities (e.g., kilograms of methane emitted) that quantitatively relate to the functional unit established in Step 1 (EC-JRC-IES, 2010).

5.2.3 Step 3 – Select the impact assessment method (S3)

This step of the methodology consists of selecting the impact assessment method used to convert the inventory collected in Step 2 into environmental impacts. Different literature can be consulted to help in this decision such as the work developed by the European Union (EC-JRC-IES, 2011) with recommendations for impact assessment in the European context and by Carvalho et al. (2014) where a generic methodology was proposed that can guide any decision-maker on the selection of the most promising method to use on the environmental evaluation. The selected impact assessment method determines which characterization, normalization, and weighting factors will be used in the next step.

5.2.4 Step 4 – Conduct a deterministic impact assessment (S4)

This step consists in converting the inventory collected in Step 2 into environmental impacts using the impact assessment method selected in Step 3. Regardless of the method selected, the first task when conducting an impact assessment is to calculate the characterized results of the impact categories (e.g., terrestrial acidification) by multiplying the inventory collected in the previous step with the characterization factors of each impact category. Depending on the method selected, the next task might consists of normalizing and weighting the characterized results using normalization and weighting factors, respectively. The normalized and weighted results of the impact categories can be summed to calculate the single score (SS) that represents the overall environmental impact of the systems under analysis. This step of the methodology requires several input parameters identified in Figure 5.1. The resulting outputs are the single scores and the characterized, normalized, and weighted results of the impact categories.

5.2.5 Step 5 – Analyze the deterministic results (S5)

The next step of the methodology consists of analyzing the outputs of the previous step. For any of these results, the lower the value, the better it is from an environmental perspective.

In the case of a comparative LCA, the environmental impacts of the systems under study should be compared in terms of relative deviation (RD) using Equation 5.1 (Mimoso, et al., 2015).

$$RD = \frac{EI_{Base} - EI_{Alternative}}{EI_{Base}} \tag{5.1}$$

where *EI* denotes the environmental impact compared using this equation and can be the SS or the result of each impact category. *Base* and *Alternative* refer to the base and alternative systems being compared, respectively. The *Base* system usually represents the current version of the system while the *Alternative* system usually represents the possible future version of the system. For example, when LCA is used to support the eco-design of a product, the *Base* system represents the current version of that product and the *Alternative* system represents the sustainable version of that product designed taking into special consideration the environmental impacts. Hence, the relative deviation between the single scores of both systems will allow to determine if the eco-design was successful and the improvement of the overall environmental impact accomplished by switching from the current to the sustainable version of the product. There can be more than one alternative system under analysis in a comparative LCA, in which case several relative deviations need to be computed. The RD can be positive or negative:

- Positive RD – The environmental impact of the alternative system is smaller than the environmental impact of the base system. Thus, from an environmental perspective, the alternative system is better than the base system. Switching from the base system to the alternative system will result in an improvement (i.e., reduction) of the environmental impact equal, in percentage, to the RD;
- Negative RD – The environmental impact of the alternative system is greater than the environmental impact of the base system. Thus, from an environmental perspective, the alternative system is worse than the base system. Switching from the base system to the alternative system will result in a deterioration (i.e., increase) of the environmental impact equal, in percentage, to the RD.

When comparing the relative deviations of the different characterized results, if all the RD are positive, then it can be concluded that the alternative system is environmentally better than the base system. On the other hand, if all the RD are negative, then it can be concluded that the alternative system is environmentally worse than the base system. Suppose the RD of some characterized results is positive, and the RD of the remaining characterized results is negative. In that case, it is necessary to calculate the relative deviations of the single scores to identify which system is overall better from an environmental perspective.

In the case of a stand-alone LCA, the environmental impacts of the system under study can be used to determine if the life cycle of this system has negative or positive impacts on the environment. A positive result indicates that the system under study has a negative impact on the environment. In contrast, a negative result indicates that the system under study has a positive impact on the environment.

5.2.6 Question 1 – Are the characterization factors uncertain?

If there is no uncertainty associated with the characterization factors used in the impact assessment, then there is no need for further analysis. In this case, the life cycle assessment comes to an end. However, given the large amount of data needed to calculate the characterization factors, it is likely that these parameters are uncertain. This data is sometimes inaccurate (i.e., data obtained through imprecise measurements), unrepresentative (i.e., data is incomplete or outdated), or lacking (i.e., there is no data) (Huijbregts, 1998a) which causes the uncertainty associated with the characterization factors.

It is important to mention that even if the decision-maker determines that the characterization factors are uncertain, he/she might choose to not consider this uncertainty. In this case, the answer to Question 1 of the methodology should reflect this choice, which might be due to an assumption that the uncertainty associated with the characterization factors does not greatly impact the results obtained, a lack of knowledge on how to deal with this uncertainty, or because dealing with the uncertainty associated with the characterization factors requires an added effort that the decision-maker is not willing to make. However, it is advised that if the characterization factors are uncertain, the decision-maker takes into account this uncertainty. The next steps of the proposed methodology intends to help practitioners integrate the uncertainty in the characterization factors into life cycle assessments and interpret the results.

5.2.7 Step 6 – Assign a probability distribution to the uncertain parameters (S6)

To deal with the uncertainty related to the characterization factors used in Step 4, the Monte Carlo simulation method was chosen as the stochastic modeling technique. The first step when conducting a Monte Carlo simulation is to assign probability distributions to uncertain parameters (i.e. characterization factors). To accomplish this assignment, it is necessary to identify which characterization factors should be considered. To do so, two main approaches might be used:

- Consider the CFs of the most relevant impact categories – A Pareto analysis can be utilized to determine the most relevant impact categories (Carvalho, et al., 2014). This focused approach allows dedicating the research efforts on understanding the impact that the uncertainty of the characterization factors used to calculate the most relevant impact categories would have on the environmental impacts of the studied systems, simplifying the analysis of considering the uncertainty of all characterization factor (Gaete-Morales, et al., 2018). In this approach, probability distributions are only assigned to the relevant impact categories' characterization factors;

- Consider the CFs of all impact categories – Although the previous approach simplifies the analysis, it does not consider the uncertainty of all characterization factors not allowing to fully accomplish the goal of providing confidence in LCA results used for decision-making. This goal is better accomplished if the characterization factors of all impact categories are considered. In this approach, probability distributions are attributed to all impact categories' characterization factors.

5.2.8 Step 7 – Generate random samples of the uncertain parameters (S7)

To simulate the uncertain parameters, Monte Carlo simulation is used. During this process, the characterization factors considered uncertain will be sampled at random from the probability distributions defined in the previous step. Different sampling types can be used in a Monte Carlo simulation, including Monte Carlo sampling and Latin Hypercube sampling. The difference between the two lies in how they draw samples from a distribution. The first consists of randomly sampling the uncertain parameters, while the latter consists of more stratified sampling. With Latin Hypercube sampling (LHS), the probability distributions of uncertain parameters are divided into several non-overlapping intervals of equal probability. The random values of the uncertain parameters are selected from each interval according to the probability distribution within the interval.

The stopping criterion commonly defined when conducting a Monte Carlo simulation is the number of iterations. However, sometimes the number of iterations defined is not enough for the simulation results to converge, leading to unreliable statistics being generated and analyzed. The more iterations are run, the more stable the results are, but, at some point, additional iterations will not change the results significantly, and the simulation should stop. It is, therefore, difficult to determine the right number of iterations and a rule of thumb of 10,000 iterations is normally applied (Igos, et al., 2019). To ensure that the number of iterations performed are sufficient for the results to converge, other stopping criteria can be used, such as the convergence tolerance and confidence level. In this case, the simulation runs until the results have reached the convergence tolerance and confidence level defined (Palisade Corporation, 2016). The output of this step is the simulated characterization factors of the different impact categories.

5.2.9 Step 8 – Conduct a stochastic impact assessment (S8)

This step of the methodology is very similar to Step 4, and it consists of converting the inventory collected in Step 2 into environmental impacts. The input parameters used in this step are identified in Figure 5.1, with the characterization factors used being the ones simulated using Monte Carlo simulation. For each sample of random characterization factors generated, the impact assessment results are calculated using the same normalization and weighting factors considered in Step 4. Consequently, and contrary to Step 4, the outputs of Step 8 are not a single estimate of the single scores and the characterized, normalized, and weighted results of the impact categories but instead, a range of different values for these outputs, reflecting the combined uncertainty of the characterization factors.

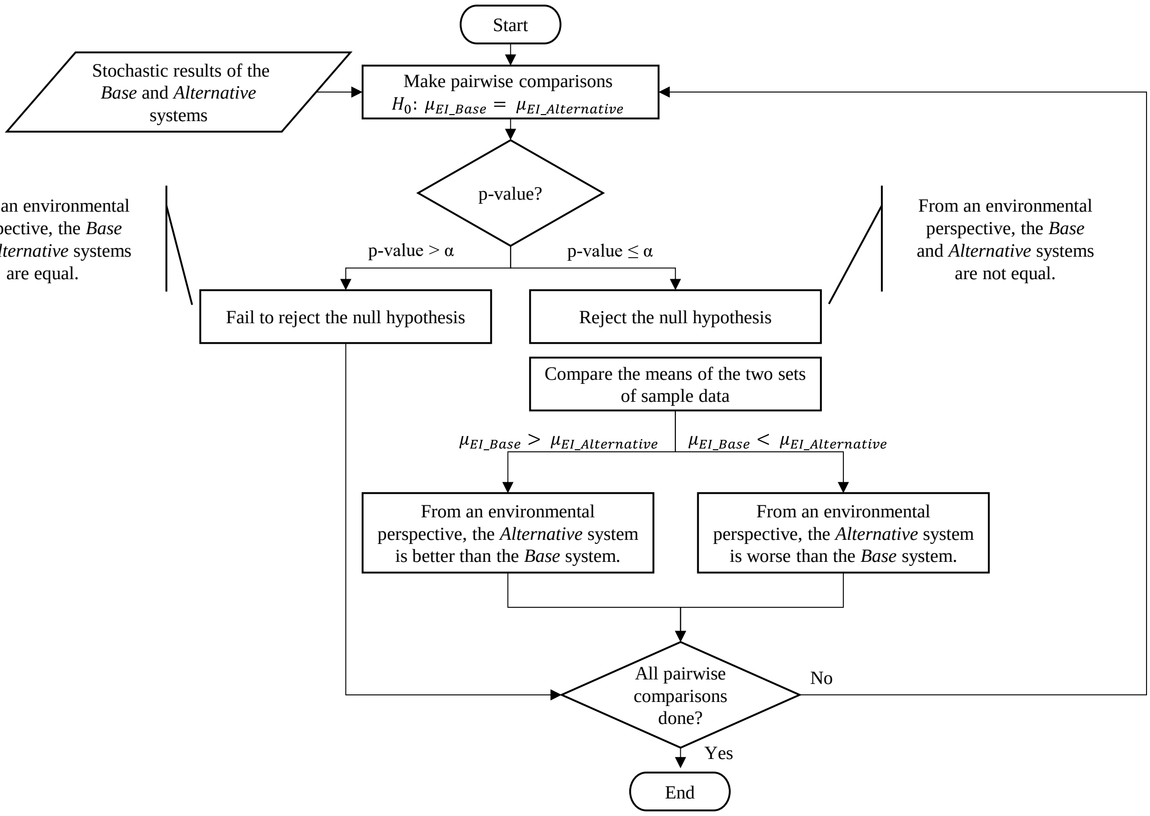
5.2.10 Step 9 – Analyze the stochastic results (S9)

The ninth step of the methodology comprises the analysis of the outputs of Step 8. Statistical hypothesis tests have been applied to analyze the results of stochastic LCAs (Lesage, et al., 2018). The purpose of a statistical hypothesis test is to determine whether a null hypothesis (H_0) should be rejected or not based on the comparison of a pre-established significance level (α) with a calculated probability value (p-value) (Graybill, et al., 1998):

- p-value ≤ α: Reject the null hypothesis of the statistical test;
- p-value > α: Fail to reject the null hypothesis of the statistical test.

The statistical hypothesis tests that can be conducted in the case of a comparative LCA are highlighted in Figure 5.2. Three assumptions must be verified to identify which statistical hypothesis test is the most appropriate (Graybill, et al., 1998):

- Independence of observations/variables: The stochastic results involved in the statistical hypothesis tests identified in Figure 5.2 are independent since the stochastic results obtained for the *Base* system are not influenced by the stochastic results obtained for the *Alternative* system;
- Normality of data: This assumption does not need to be verified in sufficiently large sets of sample data (i.e., more than 100 data points) (Lumley, et al., 2002). Hence, if the number of iterations is greater than 100, the sets of stochastic results obtained for each system under analysis can be considered sufficiently large and this assumption does not need to be verified. On the other hand, if the number of iterations is less than 100, this assumption should be verified using a statistical hypothesis test such as the Shapiro–Wilk test;
- Homogeneity of variance: The Levene's test (Lim & Loh, 1996) should be utilized to verify this assumption. Given the stochastic results involved in the statistical hypothesis tests identified in Figure 5.2, the Levene's tests should test the null hypothesis that the variances of the stochastic results of the systems under analysis are equal ($H_0\colon \sigma^2_{EI\_Base} = \sigma^2_{EI\_Alternative}$). For each Levene's test, a p-value lower or equal than the significance level indicates a statistical evidence that there is no homogeneity of variance. On the other hand, a p-value higher than the significance level indicates a statistical evidence that there is homogeneity of variance.



Note: The environmental impact (EI) compared can be the single score or the results of each impact category.

Figure 5.2 – Statistical hypothesis tests that can be conducted in the case of a comparative LCA.

According to Figure 5.2, the statistical hypothesis tests conducted in the case of a comparative LCA are used to determine if the true means of the environmental impacts obtained for the systems under analysis are equal (e.g., $H_0: \mu_{SS\_Base} = \mu_{SS\_Alternative}$). These pairwise comparisons can be tested using standard independent two samples t-tests if the three assumptions mentioned above are verified or a Welch's t-tests if the assumption of homogeneity of variances is not verified, for example.

In the case of a stand-alone LCA, statistical hypothesis tests can be used to determine if the true means of the environmental impacts obtained for the system under study are above or below zero to determine if the life cycle of this system is likely to have negative or positive impacts on the environment, respectively. Similarly to what was previously defined, three assumptions must be verified to identify which statistical hypothesis test is the most appropriate, namely the independence of observations/variables, normality of data, and the variable type (i.e., the dependent variable must be measured on a continuous or ordinal scale). One sample t-tests can be conducted in the case of a stand-alone LCA if the independence of observations/variables and normality of data are verified because the environmental impacts obtained for the systems under analysis are measured on a continuous scale.

5.2.11 Step 10 – Compare the results (S10)

Lastly, in the final step of the methodology the deterministic and stochastic results are compared.

In a comparative LCA, comparing the deterministic and stochastic results will allow determining how robust is the conclusion that the alternative system is better (or worse) than the base system from an environmental perspective. The different possibilities that can occur when comparing these results are presented in Table 5.1.

Table 5.1 – Comparison between the deterministic and stochastic results conducted in the case of a comparative LCA where EI denotes the environmental impact (i.e., single score or the result of each impact category).

Deterministic Results	**Stochastic Results**		
	High chance that the true mean of EI_Base is lower than the true mean of EI_Alternative.	*High chance that the true mean of EI_Base is equal to the true mean of EI_Alternativ.*	*High chance that the true mean of EI_Base is higher than the true mean of EI_Alternative.*
$EI\_Base < EI\_Alternative$	The deterministic result is robust	The deterministic result is not robust	The deterministic result is not robust
$EI\_Base = EI\_Alternative$	The deterministic result is not robust	The deterministic result is robust	The deterministic result is not robust
$EI\_Base > EI\_Alternative$	The conclusion result is not robust	The deterministic result is not robust	The deterministic result is robust

In the case of a stand-alone LCA, comparing the deterministic and stochastic results will allow determining how robust is the conclusion that the life cycle of the system under study has negative or positive impacts on the environment. The different possibilities that can occur when comparing these results are presented in Table 5.2.

Table 5.2 – Comparison between the deterministic and stochastic results conducted in the case of a stand-alone LCA where EI denotes the environmental impact (i.e., single score or the result of each impact category).

Deterministic Results	**Stochastic Results**		
	High chance that the true mean of EI is less than zero.	*High chance that the true mean of EI is equal to zero.*	*High chance that the true mean of EI is greater than zero.*
$EI < 0$	The deterministic result is robust	The deterministic result is not robust	The deterministic result is not robust
$EI = 0$	The deterministic result is not robust	The deterministic result is robust	The deterministic result is not robust
$EI > 0$	The conclusion result is not robust	The deterministic result is not robust	The deterministic result is robust

The next section presents an application of the methodology mentioned above to a case study.

5.3 Results

The pulp and paper industry is responsible for various devastating environmental impacts due to its intense use of resources (e.g., it consumes more than 40% of all wood traded globally) and unsustainable operations (e.g., discharging a lot of pollutants into nearby bodies of water). For this reason, it is essential for pulp and paper companies to consider the environmental impacts of their decisions and opt for more responsible forestry management strategies, cleaner manufacturing processes, and the use of more recycling content (WWF, 2019). Life cycle assessment can be utilized to assist with this task. Thus, the developed methodology has been applied to a case study in the pulp and paper industry. This application is thoroughly explained below, considering the ten steps previously defined (see Section 5.2).

5.3.1 Step 1 – Define the goal and scope (S1)

Pulp bleaching is one of the main contributors to the environmental impact generated by pulp and paper manufacturing due to the chlorinated and organic compounds and nutrients that are discharged to the wastewater (Gavrilescu, et al., 2012). The objective of the life cycle assessment presented in this chapter is to compare the environmental impacts of two pulp bleaching techniques to ascertain which one is environmentally better. The first stage of wood pulp manufacturing involves growing and harvesting trees. The next stage is to buck into logs the trunk of each tree, which are then delivered to mills. The bark is removed, and the logs are chipped. Next, the cellulose fibers (the main component of paper products) and other wood components (e.g., lignin) are separated. The Kraft (sulfate) process is the most frequently used in this stage. It consists of pressure-cooking in a digester the wood chips in an aqueous solution together with different chemicals such as sodium hydroxide (NaOH) and sodium sulfide (Na_2S). To remove uncooked wood and the spent cooking mixture, the pulp is screened and washed, respectively. This raw pulp has a brown coloration due to the residual lignin that remained after cooking, which is why, in some cases, the pulp needs to be bleached (Bajpai, 2018). The pulp manufacturing process, with all different stages previously explained, is represented in Figure 5.3.

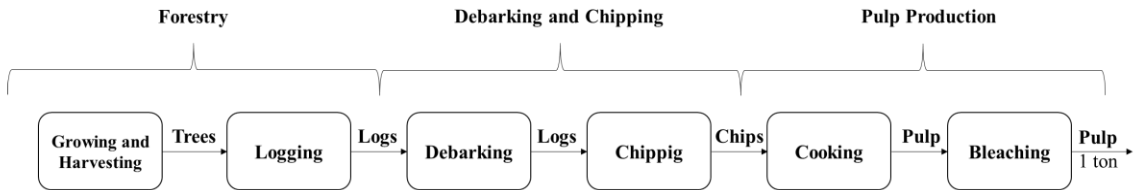


Figure 5.3 – Pulp manufacturing process, including the functional unit.

The two pulp bleaching techniques compared in this study are Elemental Chlorine Free (ECF) and Total Chlorine Free (TCF). The difference between these two techniques is the presence or absence of chlorine compounds during the bleaching stage. The bleaching technique TCF, as the name implies, does not use any chlorine compounds, while ECF does not use elemental chlorine but uses chlorine dioxide. Most companies still use ECF as a bleaching technique. The industry argues that there is no significant environmental difference between the two techniques because, even though TCF does not use any chlorine compounds, it uses ozone or higher dosages of peroxide in the bleaching process (Mondi, 2021). The two systems compared in this study can be defined as:

- ECF (Base system) – Production of 1 ton of bleached pulp in Europe using the ECF technique considering the life cycle steps from forestry to pulp production;

- TCF (Alternative system) – Production of 1 ton of bleached pulp in Europe using the TCF technique considering the life cycle steps from forestry to pulp production.

Because ECF is the most used bleaching technique by companies in the pulp and paper industry, the ECF system is considered the base system. In contrast, the TCF system is considered the alternative system in the comparative LCA conducted in this work. The purpose is to determine whether or not an environmental impact reduction could be obtained if companies switched from ECF to TCF. Thus, this LCA study's goal fits with the first of the three primary purposes identified in the previous section (i.e., micro-level decision support). Cradle-to-gate is the system boundary considered, including the life cycle stages represented in Figure 5.3, where the functional unit (i.e., 1 tonne of bleached pulp) is also represented.

5.3.2 Step 2 – Model the systems (S2)

The elementary input and output flows of the two systems analyzed was obtained from the ecoinvent v3.3 database (Wernet, et al., 2016) assessed through the SimaPro 8.4.0 software (PRéConsultants, 2021). Two SimaPro references were selected, each representing one of the systems studied:

- ECF – Sulfate pulp {RER}| production, elementary chlorine free bleached | Cut-off, U
- TCF – Sulfate pulp {RER}| production, totally chlorine free bleached | Cut-off, U

This step resulted in a list of 1376 tracked substances, and corresponding quantities for each of the systems studied.

5.3.3 Step 3 – Select the impact assessment method (S3)

The impact assessment method selected in this study is the Product Environmental Footprint (PEF) which was developed with the aim of harmonizing future life cycle assessments in Europe (European Commission, 2021b). It considers 16 impact categories (see Table 5.3).

Table 5.3 – PEF impact categories with respective characterization methods (Zampori & Pant, 2019).

Impact Category	Acronym	Unit	Characterization method	Robustness
Acidification	Aci	mol H+ eq.	Accumulated Exceedance (Seppälä, et al., 2006) (Posch, et al., 2008)	II
Climate Change	CC	kg CO_2 eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013 (IPCC, 2013))	I
Ecotoxicity, Freshwater	Eco	CTUe	USEtox model 2.1 (Fantke, et al., 2017)	III
Eutrophication, Freshwater	Eut_Fre	kg P eq.	EUTREND model (Struijs, et al., 2009) as implemented in ReCiPe	II
Eutrophication, Marine	Eut_Mar	kg N eq.	EUTREND model (Struijs, et al., 2009) as implemented in ReCiPe	II
Eutrophication, Terrestrial	Eut_Ter	mol N eq.	Accumulated Exceedance (Seppälä, et al., 2006) (Posch, et al., 2008)	II
Human Toxicity, Cancer	HT_Car	CTUh	USEtox model 2.1 (Fantke, et al., 2017)	III
Human Toxicity, Non-cancer	HT_NCar	CTUh	USEtox model 2.1 (Fantke, et al., 2017)	III
Ionizing radiation	IR	kBq U235 eq.	Human health effect model as developed by Dreicer et al. 1995 (Dreicer, et al., 1995) (Frischknecht, et al., 2000)	II
Land Use	LU	pt	Soil quality index based on LANCA (Beck, et al., 2010) (Bos, et al., 2016)	III
Ozone Depletion	OD	kg CFC-11 eq.	Steady-state ODPs as in (WMO 2014 (World Meteorological Organisation (WMO), 2014) + integrations)	I
Particulate Matter	PM	disease incidence	PM method recomended by UNEP (UNEP (United Nations Environment Programme), 2016)	I
Photochemical Ozone Formation	POF	kg NMVOC eq.	LOTOS-EUROS model (Van Zelm, et al., 2008) as implemented in ReCiPe	II
Resource Use, Fossils	RU_F	MJ	CML 2002 (Guinée, et al., 2002) and van Oers et al. 2002 (Van Oers, et al., 2002)	III
Resource Use, Minerals and Metals	RU_M	kg Sb eq.	CML 2002 (Guinée, et al., 2002) and van Oers et al. 2002 (Van Oers, et al., 2002)	III
Water Use	WU	m3 eq.	Available WAter REmaining (AWARE) as recommended by UNEP (UNEP (United Nations Environment Programme), 2016)	III

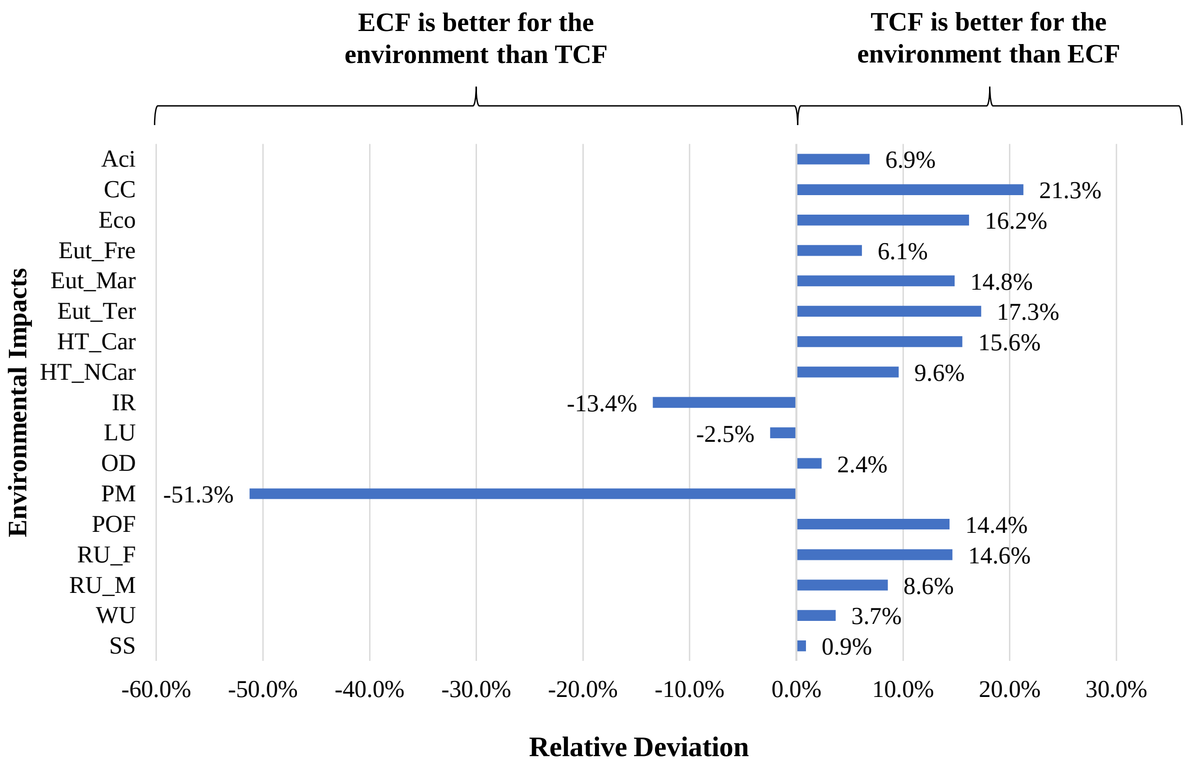
The characterized results of these impact categories are calculated using the characterization factors estimated by the most recommended methods to use in the European context (Zampori & Pant, 2019). These methods are presented in Table 5.3 together with the specific unit of each characterized result.

5.3.4 Step 4 – Conduct a deterministic impact assessment (S4)

In this study, the deterministic impact assessment was conducted in Microsoft Excel (Microsoft, 2021), considering the elementary input and output flows of both systems collected in Step 2 and the characterization, normalization, and weighting factors utilized by the PEF method selected in Step 3. The input parameters (see Figure 5.1) necessary to conduct this assessment were obtained through the SimaPro 8.4.0 software (PRéConsultants, 2021).

5.3.5 Step 5 – Analyze the deterministic results (S5)

The relative deviations obtained for each impact category consider in the PEF method by applying Equation 5.1 to the results of both systems in these categories are presented in Figure 5.4.



Acronyms: Elemental Chlorine Free (ECF), Total Chlorine Free (TCF), Acidification (Aci), Climate Change (CC), Ecotoxicity (Eco), Eutrophication_Freshwater (Eut_Fre), Eutrophication_Marine (Eut_Mar), Eutrophication_Terrestrial (Eut_Ter), Human Toxicity_Cancer (HT_Car), Human Toxicity_Non-cancer (HT_NCar), Ionising radiation (IR), Land Use (LU), Ozone Depletion (OD), Particulate Matter (PM), Photochemical Ozone Formation (POF), Resource Use_Fossils (RU_F), Resource Use_Minerals and Metals (RU_M), Water Use (WU), and Single Score (SS).

Figure 5.4 – Relative deviations obtained for each impact category and single score.

Looking into Figure 5.4, it can be observed that 13 out of the 16 impact categories present a positive RD while the remaining three impact categories present a negative RD. From Step 5 presented in the previous section, a positive RD means that, from an environmental perspective, the alternative system (i.e., TCF) is better than the base system (i.e., ECF). In contrast, a negative RD means that, from an environmental perspective, the alternative system (i.e., TCF) is worse than the base system (i.e., ECF). Hence, it can be concluded that switching from ECF to TCF will result in an improvement (i.e., reduction) of the following environmental impacts – Aci, CC, Eco, Eut_Fre, Eut_Mar, Eut_Ter, HT_Car, HT_NCar, OD, POF, RU_F, RU_M, and WU. From these impact categories, the one presenting the highest improvement (21.3%) is Climate Change. It can also be concluded that switching from ECF to TCF will result in a deterioration (i.e., increase) of the following environmental impacts – IR, LU, and PM. From these impact categories, the one presenting the highest deterioration (51.3%) is Particulate Matter. Since not all the relative deviations presented in Figure 5.4 are positive or negative, it is not possible to conclude which system is overall better for the environment. For this reason, an analysis of the single score of both systems was also conducted.

The outcome of producing 1 ton of bleached pulp using ECF is a total environmental impact of $1.25x10^{-01}$ Pt, while the outcome of the same process using TCF is a total environmental impact of $1.24x10^{-01}$ Pt. Using Equation 5.1, it can be concluded that the relative deviation between both systems is 0.9% (see Figure 5.4). Hence, it can be concluded that switching from ECF to TCF will result in an overall improvement of 0.9%. This small overall improvement indicates that this change may not be the most effective strategy when trying to decrease the environmental impact associated with the production of bleached pulp.

5.3.6 Question 1 – Are the characterization factors uncertain?

The report *Suggestions for updating the Product Environmental Footprint (PEF) method* by Zampori and Pant (2019) presents the classification of each characterization method according to their robustness (see Table 5.3). Robustness level "I" was assigned to the characterization methods (and resulting characterization factors) considered to have some uncertainty associated while robustness level "III" was assigned to the characterization methods considered to have considerable uncertainty associated, incompleteness and/or other shortcomings. Consequently, it can be concluded that the characterization factors utilized in the deterministic impact assessment conducted in this study are uncertain since they were estimated using characterization methods which have an overall robustness below 100% (see Table 5.3). Thus, an uncertainty analysis is essential to determine how the uncertainty of the characterization factors utilized in Step 4 might be affecting the LCA results and how robust are these results.

5.3.7 Step 6 – Assign a probability distribution to the uncertain parameters (S6)

From the two main approaches identified in Section 5.2 (see Step 6), the second was chosen in this study, which means that the characterization factors of all impact categories were taken into account in this step. A study by Santos et al. (2019b) analyzed the use of the first approach identified in Section

5.2 (see Step 6) by taking into account only the characterization factors of the most relevant impact categories. It was verified that it is critical to perform the uncertainty analysis holistically has this chapter does.

To assign a probability distribution to the uncertain characterization factors, the approach utilized by Gargalo et al. (2016) was followed. Accordingly, the probability distribution assigned to the characterization factors is the uniform distribution. Each characterization factor included in this study was assigned to one of three uncertainty classes. The first class was assigned to low uncertainty characterization factors classified with a robustness level I (Table 5.3). These characterization factors were assumed to have a 5% upper and lower bound around their standard values (i.e., deterministic value) (Sin, et al., 2009). The second class was assigned to medium uncertainty characterization factors classified with a robustness level II (Table 5.3). In this class, 25% upper and lower bounds around the standard values were assumed (Sin, et al., 2009). Finally, the third class was assigned to high uncertainty characterization factors from the remaining impact categories since these categories were classified with a robustness level III (Table 5.3), thus assuming upper and lower bounds equal to 50% of the standard values (Sin, et al., 2009). The probability distributions and respective parameters used to characterize each characterization factor are provided in Table 5.4.

Table 5.4 – Probability distributions assigned to the characterization factors of each impact category where s denotes the substances and c denotes the impact category.

Uncertainty classes	Impact categories	Probability distribution	Parameters
Class 1 (low uncertainty)	Climate Change, Ozone Depletion, and Particulate Matter	Uniform (a, b)	$a = (1 - 0.05) \times CF_{s,c}$ $b = (1 + 0.05) \times CF_{s,c}$
Class 2 (medium uncertainty)	Ionizing Radiation, Photochemical Ozone Formation, Acidification, Eutrophication (Terrestrial), Eutrophication (Freshwater), and Eutrophication (Marine)	Uniform (a, b)	$a = (1 - 0.25) \times CF_{s,c}$ $b = (1 + 0.25) \times CF_{s,c}$
Class 3 (high uncertainty)	Human Toxicity (Cancer), Human Toxicity (Non-cancer), Ecotoxicity (Freshwater), Land Use, Water Use, Resource Use (Minerals and Metals), and Resource Use (Fossils)	Uniform (a, b)	$a = (1 - 0.50) \times CF_{s,c}$ $b = (1 + 0.50) \times CF_{s,c}$

5.3.8 Step 7 – Generate random samples of the uncertain parameters (S7)

The sampling type selected was Latin Hypercube sampling because it usually leads to more precise random samples than Monte Carlo sampling (Huijbregts, 1998b). The stopping criteria considered were a convergence tolerance of 3% and a confidence level of 95%. Consequently, the simulation stops when the mean of the simulated single scores is within 3% of its actual value and is 95% of the time accurate.

5.3.9 Step 8 – Conduct a stochastic impact assessment (S8)

The deterministic impact assessment was conducted in Microsoft Excel (Microsoft, 2021). Thus, the stochastic impact assessment is performed using the @Risk software, the leading Monte Carlo simulation add-in for Excel (Palisade Corporation, 2016). The same inputs considered in Step 4 were considered in this step, except for the characterization factors. These were sampled at random from the probability distributions attributed (see Table 5.4). Given the characterization factors of the 16 impact categories, 44,726 inputs had to be generated in each iteration of the simulation. A total of 51 outputs were defined, including the characterized results of the impact categories and singles scores obtained for the two systems under analysis and the respective stochastic relative deviations. The Monte Carlo simulation ran for 1 minute and 23 seconds until the stopping criteria were met, which happened after 1,000 iterations.

5.3.10 Step 9 – Analyze the stochastic results (S9)

Since the LCA study performed in this work is a comparative LCA, the interpretation of stochastic results was accomplished by conducing the statistical hypothesis tests (Figure 5.2) in Python (Python Software Foundation, 2022) using a significance level of 0.05 (Ross, 2017). To identify the most appropriate statistical hypothesis tests, three assumptions were verified (Section 5.2 – Step 9):

- Independence of observations/variables: As previously explained in Section 5.2, the stochastic results involved in the statistical hypothesis tests identified in Figure 5.2 are independent;
- Normality of data: Since 1,000 iterations were conducted in this study (see Step 8), the sets of stochastic results are considered to be sufficiently large and this assumption does not need to be verified;
- Homogeneity of variance: The p-value obtained for the Levene's tests conducted to verify this assumption are presented in Table 5.5. Looking into this table it is possible to conclude, for example, that there is a statistical evidence that the variance of the two systems' stochastic Acidification results are equal (i.e., homogeneity of variance). In this case, a Student's t-test was conducted for the pairwise comparison between the two systems' stochastic Acidification results. On the other hand, there is a statistical evidence that the variance of the two systems' stochastic Climate Change results are different (i.e., no homogeneity of variance). In this case, a Welch's t-test was conducted for the pairwise comparison between the two systems' stochastic Climate Change results.

The p-value obtained for the Student's/Welch's t-tests conducted to perform the pairwise comparisons between the two systems' stochastic results are presented in Table 5.6. Looking into this table it is possible to conclude that the two systems studied were found to have significantly equal impact results for Land Use and Water Use.

Table 5.5 – P-value of the Levene's tests conducted.

ECF	**TCF**																
	Aci	CC	Eco	Eut_Fre	Eut_Mar	Eut_Ter	HT_Car	HT_NCar	IR	LU	OD	PM	POF	RU_F	RU_M	WU	**SS**
Aci	5.25x10^{-1}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CC	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eco	-	-	9.20x10^{-1}	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Fre	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Mar	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Ter	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-
HT_Car	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-
HT_NCar	-	-	-	-	-	-	-	9.55x10^{-3}	-	-	-	-	-	-	-	-	-
IR	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-
LU	-	-	-	-	-	-	-	-	-	3.37x10^{-1}	-	-	-	-	-	-	-
OD	-	-	-	-	-	-	-	-	-	-	6.05x10^{-1}	-	-	-	-	-	-
PM	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-
POF	-	-	-	-	-	-	-	-	-	-	-	-	7.53x10^{-2}	-	-	-	-
RU_F	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-
RU_M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.37x10^{-4}	-	-
WU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-
SS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00

Indicates a statistical evidence that the variance of the two systems' stochastic results are equal (i.e., homogeneity of variance). A Student's t-test is the most appropriate choice to conduct the pairwise comparison.

Indicates a statistical evidence that the variance of the two systems' stochastic results are different (i.e., no homogeneity of variance). A Welch's t-test is the most appropriate choice to conduct the pairwise comparison.

Acronyms: Elemental Chlorine Free (ECF), Total Chlorine Free (TCF), Acidification (Aci), Climate Change (CC), Ecotoxicity (Eco), Eutrophication_Freshwater (Eut_Fre), Eutrophication_Marine (Eut_Mar), Eutrophication_Terrestrial (Eut_Ter), Human Toxicity_Cancer (HT_Car), Human Toxicity_Non-cancer (HT_NCar), Ionizing radiation (IR), Land Use (LU), Ozone Depletion (OD), Particulate Matter (PM), Photochemical Ozone Formation (POF), Resource Use_Fossils (RU_F), Resource Use_Minerals and Metals (RU_M), Water Use (WU), and Single Score (SS).

Table 5.6 – P-value of the Student's/Welch's t-tests conducted.

ECF	**TCF**																
	Aci	CC	Eco	Eut_Fre	Eut_Mar	Eut_Ter	HT_Car	HT_NCar	IR	LU	OD	PM	POF	RU_F	RU_M	WU	**SS**
Aci	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CC	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eco	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Fre	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Mar	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-
Eut_Ter	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-
HT_Car	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-	-
HT_NCar	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-	-
IR	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	-
LU	-	-	-	-	-	-	-	-	-	5.80×10^{-2}	-	-	-	-	-	-	-
OD	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-
PM	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-
POF	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-	-
RU_F	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-
RU_M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-
WU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.92×10^{-1}	-
SS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.26×10^{-1}

(white box) Indicates a statistical evidence that the true means of the two systems' environmental impact are equal, i.e., the two systems have the same environmental impact.

(blue box) Indicates a statistical evidence that the true means of the two systems' environmental impact are different, i.e., the two systems do not have the same environmental impact.

Acronyms: Elemental Chlorine Free (ECF), Total Chlorine Free (TCF), Acidification (Aci), Climate Change (CC), Ecotoxicity (Eco), Eutrophication_Freshwater (Eut_Fre), Eutrophication_Marine (Eut_Mar), Eutrophication_Terrestrial (Eut_Ter), Human Toxicity_Cancer (HT_Car), Human Toxicity_Non-cancer (HT_NCar), Ionizing radiation (IR), Land Use (LU), Ozone Depletion (OD), Particulate Matter (PM), Photochemical Ozone Formation (POF), Resource Use_Fossils (RU_F), Resource Use_Minerals and Metals (RU_M), Water Use (WU), and Single Score (SS).

There is also statistical evidence that the true means of the two systems' single scores are equal (see Table 5.6). Thus, the two systems under analysis were found to have a significantly equal overall environmental impact. On the other hand, the two systems studied were found to have significantly different impact results for the remaining 14 impact categories (see Table 5.6). In these cases, the means of the two systems' stochastic results were compared to determine which system is better from an environmental perspective (see Figure 5.2). Table 5.7 presents the means of the two systems' stochastic results with the lowest mean of each result highlighted in green.

Table 5.7 – Means of the two systems' stochastic results and the percentiles of the stochastic relative deviations between both systems.

Statistics	μ_{ECF}	μ_{TCF}
Aci	4.98	4.64
CC	557.56	438.88
Eco	26298.39	22015.29
Eut_Fre	0.20	0.19
Eut_Mar	1.20	1.02
Eut_Ter	12.92	10.68
HT_Car	6.07E-07	5.12E-07
HT_NCar	9.84E-06	8.90E-06
IR	60.85	69.04
OD	8.23E-05	8.03E-05
PM	1.19E-04	1.80E-04
POF	3.67	3.14
RU_F	7171.14	6125.51
RU_M	1.96E-02	1.79E-02

Looking into Table 5.7 it is possible to conclude that the Total Chlorine Free technique has the lowest impact in 12 out of 14 impact categories and the highest impact on Ionizing radiation and Particulate Matter.

In summary, the results analyzed above indicate that switching from ECF to TCF is not the most effective strategy when trying to decrease the overall environmental impact associated with the production of 1 ton of bleached pulp since the two systems under analysis were found to have significantly equal single scores. However, the results also indicate that this switch in pulp bleaching technique is an effective strategy in terms of reducing different environmental issues as the two bleaching techniques analyzed were found to have significantly different results in 14 impact categories and the TCF technique had the lowest impact in 12 of these categories.

5.3.11 Step 10 – Compare the results (S10)

The comparison of the deterministic and stochastic results analyzed in Steps 5 and 9, respectively is presented in Table 5.8.

Table 5.8 – Comparison between the deterministic and stochastic results.

<table>
<tr><th rowspan="2">Deterministic Results</th><th colspan="3">Stochastic Results</th></tr>
<tr><th>High chance that the true mean of EI_ECF is lower than the true mean of EI_TCF – IR and PM</th><th>High chance that the true mean of EI_ECF is equal to the true mean of EI_TCF – LU, WU, and SS</th><th>High chance that the true mean of EI_ECF is higher than the true mean of EI_TCF – Aci, CC. Eco, Eut_Fre, Eut_Mar, Eut_Ter, HT_Car, HT_NCar, OD, POF, RU_F, and RU_M</th></tr>
<tr><td>$Aci\_ECF > Aci\_TCF$</td><td></td><td></td><td rowspan="8">The deterministic result is robust</td></tr>
<tr><td>$CC\_ECF > CC\_TCF$</td><td></td><td></td></tr>
<tr><td>$Eco\_ECF > Eco\_TCF$</td><td></td><td></td></tr>
<tr><td>$Eut\_Fre\_ECF > Eut\_Fre\_TCF$</td><td></td><td></td></tr>
<tr><td>$Eut\_Mar\_ECF > Eut\_Mar\_TCF$</td><td></td><td></td></tr>
<tr><td>$Eut\_Ter\_ECF > Eut\_Ter\_TCF$</td><td></td><td></td></tr>
<tr><td>$HT\_Car\_ECF > HT\_Car\_TCF$</td><td></td><td></td></tr>
<tr><td>$HT\_NCar\_ECF > HT\_NCar\_TCF$</td><td></td><td></td></tr>
<tr><td>$IR\_ECF < IR\_TCF$</td><td>The deterministic result is robust</td><td></td><td></td></tr>
<tr><td>$LU\_ECF < LU\_TCF$</td><td></td><td>The deterministic result is not robust</td><td></td></tr>
<tr><td>$OD\_ECF > OD\_TCF$</td><td></td><td></td><td></td></tr>
<tr><td>$PM\_ECF < PM\_TCF$</td><td>The deterministic result is robust</td><td></td><td></td></tr>
<tr><td>$POF\_ECF > POF\_TCF$</td><td></td><td></td><td rowspan="3">The deterministic result is robust</td></tr>
<tr><td>$RU\_F\_ECF > RU\_F\_TCF$</td><td></td><td></td></tr>
<tr><td>$RU\_M\_ECF > RU\_M\_TCF$</td><td></td><td></td></tr>
<tr><td>$WU\_ECF > WU\_TCF$</td><td></td><td>The deterministic result is not robust</td><td></td></tr>
<tr><td>$SS\_ECF > SS\_TCF$</td><td></td><td>The deterministic result is not robust</td><td></td></tr>
</table>

According to the comparison presented in Table 5.8, the identification of which system is better in each impact category, from an environmental perspective, is robust for all impact categories except Land Use and Water Use. On the other hand, the identification of which system is overall better, from an environmental perspective, is not robust since the deterministic and stochastic results do not match. While the deterministic single scores indicate that the TCF technique is overall better for the environment, the Welch's t-test conducted to compare the stochastic single scores indicate that the two pulp bleaching techniques have a significantly equal overall environmental impact.

5.4 Discussion

Life cycle assessment is commonly used by businesses and legislators as a decision support tool. Decisions made based on an LCA analysis will be better decisions if they take into account not only the LCA results but also the uncertainty in these results (Norris, 2002). Backing the reported LCA results with uncertainty information allows assessing the stability of these results and determining if decisions change when considering the underlying uncertainty. This type of information is helpful in a decision-making context, and it is one of the main reasons why uncertainty analysis in LCA is essential. Moreover, decision-makers have variable risk tolerances, so the information about uncertainty is desirable. Given the importance of taking into account uncertainty in the decision-making process, the methodology developed in this study presents a systematic procedure to incorporate uncertainty in LCA and determine the robustness of the LCA results. This methodology provides a clear path of how the uncertainty of the characterization factors could be integrated into LCA analysis through stochastic modeling using Monte Carlo simulation.

To conduct the Monte Carlo simulation, the uniform distribution was assigned to the characterization factors and the upper and lower bound of each characterization factor was established based on the robustness level attributed to the characterization methods (and resulting characterization factors) considered. This assignment was only possible due to the information provided on the report *Suggestions for updating the Product Environmental Footprint (PEF) method* which presents the classification of each characterization method according to their robustness. For the methodology presented in this study to be applied in other studies using an impact assessment method other than PEF (e.g., ReCiPe), it is necessary that all impact assessment methods include in their reports information regarding the overall robustness of the characterization methods considered. Furthermore, it would be very useful if, in addition to qualitative information on the robustness of the characterization methods, quantitative information was provided to allow the estimation of the upper and lower limits of the characterization factors (e.g., a 10% upper and lower bound around their standard values should be considered for the characterization factors estimated by characterization methods with a robustness level I). The next step would be for the impact assessment methods to identify which probability distribution best represents the uncertainty associated with each characterization factor. This would allow future studies to include these probability distributions instead of assigning the same probability distribution (e.g., uniform or lognormal) to all characterization factors due to lack of information. However, to reach this next step, a lot of research will be needed since there are hundreds of characterization factors. A study that presents a beginning in this research is the study conducted by Van Zelm and Huijbregts (2013) where the uncertainty associated with the data required to compute the characterization factors of chemicals for freshwater ecotoxicity was studied. The information presented in this study (van Zelm & Huijbregts, 2013) can be used to determine which probability distribution best represents the uncertainty of each characterization factor considered in the Freshwater Ecotoxicity category.

The methodology developed in this study focuses on the parameter uncertainty associated with the characterization factors utilized in an LCA. Some common sources of parameter uncertainty are the use of inaccurate or incomplete data in the Inventory Analysis and in the models used to compute the characterization, normalization, and weighting factors in the Impact Assessment (Huijbregts, 1998a). Even though this study focuses on the parameter uncertainty associated with the characterization factors used in the Impact Assessment step to address a research gap identified (see Introduction), the proposed methodology can be used considering the parameter uncertainty associated with other parameters utilized in an LCA (e.g., normalization factors). In this case, probability distributions should be attributed to all uncertain parameters. Besides parameter uncertainty, there are other types of uncertainty, such as uncertainty due to choices (i.e., scenario uncertainty) (Huijbregts, 1998a). The choices made when performing a life cycle assessment lead to uncertainty because different choices may generate different LCA outcomes. For example, a choice that leads to uncertainty in the Inventory Analysis is the choice of the functional unit. In the Impact Assessment, a choice that leads to uncertainty is the choice of characterization method to quantify the characterized result of each impact category, for example (Huijbregts, 1998a). One way for reducing uncertainty due to choices to an accepted level is the standardization of procedures, such as the guidelines provided by ISO in their *Environmental management – Life cycle assessment* series. Peer review can also be used to judge decisions on their merits. When standard procedures are not fully applicable, uncertainty due to choices may be made operational with the help of a nonparametric bootstrapping procedure (Huijbregts, et al., 2003). This procedure starts with identifying two or more alternatives for each choice and assigning a probability to each alternative that reflects the decision maker's preference for that alternative. The sum of probabilities assigned to the various alternatives, for each choice, must equal 1. During each bootstrap iteration, an alternative is randomly chosen for each choice, based on the defined probabilities (Efron & Tibshirani, 1991). This proposal for making uncertainty due to choices operational is easily integrated in the methodology presented in this study since the bootstrapping procedure resembles Monte Carlo simulation (i.e., the stochastic technique chosen).

The methodology developed in this study was applied to a case study related with micro-level decision support. However, this methodology is not case-specific and can be used in the different LCA applications, be it for a product or process design; identifying opportunities to decrease the environmental impact associated with a product’s life cycle; communicating to customers and other stakeholders of the life cycle’s environmental performance; and marketing purposes in the forms of environmental product declaration (EPD) and eco-labeling, for example (Tukker, 2000).

5.5 Conclusions

The inclusion of uncertainty analysis in life cycle assessment studies is still not standard in the literature, which is not surprising due to the increasing number of methodologies emerging for uncertainty treatment and the lack of consensus as to which methodology should be used. When included, uncertainty analysis focuses mostly on the Inventory Analysis step. This study's main goal was to help close this gap in the literature by developing an easily reproducible environmental assessment methodology that includes the uncertainty related with the characterization factors used in the third step of an LCA. This methodology incorporates both a traditional (deterministic) LCA and a stochastic LCA, where Monte Carlo simulation is used as the stochastic modeling technique. The application of the methodology to a case study where life cycle assessment is used for micro-level decision support can help decision-makers understand how to include uncertainty in their decision-making processes. The case study considered in this chapter compares two pulp bleaching techniques, Elemental Chlorine Free and Total Chlorine Free. The statistical hypothesis test conducted to compare the stochastic single scores of these two pulp bleaching techniques showed that switching from ECF to TCF will likely not lead to a decrease or increase in the overall environmental impact of the pulp bleaching operation. These results further reinforce what has been defended by the industry (i.e., there is no significant environmental difference between the two techniques), and it makes the arguments supporting their position more robust.

Although the methodology developed can be used in different LCA applications, this study only showed its use for micro-level decision support. Future studies should use the methodology for the remaining two LCA applications (macro-level decision support and accounting). Forthcoming research should also consider the application of the developed methodology to various impact assessment methods. This application could reveal which method has the least uncertainty associated when calculating the results of different impact categories and could help practitioners select the impact assessment method. Furthermore, the uncertainty of other parameters used in the Impact Assessment step, such as the normalization factors, should be investigated. Finally, a methodology that integrates both the uncertainty at the inventory analysis and impact assessment level should be carefully developed, bearing in mind that the additional data collection and calculations required to conduct such an in-depth uncertainty analysis would make carrying out an LCA study more complicated.

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6. Uncertainty Analysis – Multi Level

6.1 Introduction

There is an increasingly pressure from consumers for companies to reduce their environmental impacts (Deloitte, 2020). For this reason, companies that fail to adopt green practices will feel the impact on their economic performance. Besides this economic incentive, there is a growing concern among executives that the increasing number of climate-related events affecting populations and geographies will negatively affect their business operations. The pressure from consumers combined with the threats to their own businesses ensured that environmental sustainability has become a cornerstone of how executives manage their organizations (Deloitte, 2020). However, in this quest for environmental sustainability, companies should not only focus on the environmental impacts of their individual operations but also on the performance of their supply chains (Barbosa-Póvoa, et al., 2018). The integration of environmental criteria or concerns into supply chain management, including material sourcing, manufacturing process, delivery of the final product to the consumers, and end-of-life management of the product, is today a priority and gave rise to the field of green supply chain management (GSCM) (Bhattacharjee & Kishore, 2015).

Life cycle assessment (LCA) forms the backbone of the environmental debate in the field of green supply chain management (Seuring, 2013). Besides being used as a stand-alone decision support tool, LCA has been explored and combined with different approaches to support GSCM as highlighted in the study by Eskandarpour et al. (2015). In this review, the authors analyzed several papers in the field of sustainable supply chain network design, covering mathematical models that include at least two of the three dimensions of sustainable development (i.e., economic, environmental, and social). Almost half of the papers reviewed (44.8 %) integrated principles of LCA into their supply chain network design (SCND) models (Eskandarpour, et al., 2015). An example of an LCA-based SCND model is presented in the study conducted by Mota et al. (2018) where a multi-objective mixed integer linear programming model integrating several interconnected decisions was developed (Mota, et al., 2018), and in the study by Babazadeh et al. (2017) where a multi-objective possibilistic programming model for designing a second-generation biodiesel supply chain network considering total cost and environmental impact minimization was developed (Babazadeh, et al., 2017).

LCA is internationally standardized (ISO, 2006) and is comprised of four main steps. In the first step, *Goal and Scope Definition*, the LCA's goal, functional unit, and the boundaries of the system under analysis are established. This system refers to the object under study, which in the case of GSCM is the supply chain under analysis (EC-JRC-IES, 2010). The next step, *Inventory Analysis*, involves the quantification of the elementary flows in (e.g., resources taken from nature) and out (e.g., emissions into air, water, soil) of the system. In the third step, *Impact Assessment*, the inventory previously collected is converted into environmental impacts using characterization factors. These impacts can be added together to determine the overall environmental impact of the supply chain under study after being normalized and weighted using normalization and weighting factors, respectively. The fourth and last step, *Interpretation*, involves examining and interpreting the results of the LCA. In the case of green supply chain management, this last step includes identifying the most relevant environmental impacts associated with the supply chain under analysis and the supply chain processes that most contribute to these relevant impacts. The identification of the most relevant supply chain processes is key to develop an effective GSCM strategy for improving the overall environmental performance of the supply chain.

LCA, although being quite used to support GSCM, may give rise to an ineffective GSCM strategy when uncertainty is not properly considered (Huijbregts, 1998c). This is particularly critical given that uncertainty is always present in an LCA (Björklund, 2002). One source of this uncertainty is the large amount of data needed to determine the elementary input and output flows in the Inventory Analysis step and the different factors utilized in the Impact Assessment step. The uncertainty associated with this data causes the LCA parameters (i.e., inventory, characterization, normalization, and weighting factors) to also be uncertain and, consequently, causes uncertainty in the outcome results (Huijbregts, 1998a). To increase the confidence of the decision-makers in LCA results and on the GSCM strategy developed based on these results, parameter uncertainty should be taken into account when using LCA to support green supply chain management. Stochastic modelling has long been identified as a promising technique for integrating parameter uncertainty in life cycle assessments (Huijbregts, 1998a) with Monte Carlo simulation being the most used stochastic modelling approach in these assessments (Igos, et al., 2019). Instead of generating just a single estimate of results, the Monte Carlo simulation generates results with a wide range of possible outcomes represented through probability distributions, reflecting the combined parameter uncertainties (Palisade Corporation, 2016). The interpretation of results using uncertainty distributions is more challenging than interpreting single estimates of results. Hence, when applying Monte Carlo simulation in an LCA, there is a risk that the increased complexity of the LCA results will add confusion in the interpretation of these results. For this reason, it is also important to develop a clear guideline on how to present and interpret the results of a stochastic LCA. This guideline should aim at helping decision-makers form an opinion of how much confidence to have in the LCA results (Björklund, 2002).

This study explores these challenges and presents an innovative methodology for integrating parameter uncertainty in an LCA conducted to assist green supply chain management. This methodology involves conducting a traditional deterministic LCA that does not consider uncertainty, a stochastic LCA, which considers the uncertainty associated with the inventory collected in the Inventory Analysis step and the characterization, normalization, and weighting factors used in the Impact Assessment step, and a comparison of both analyses. The stochastic modeling technique used is Monte Carlo simulation. The two main characteristics of the innovative methodology proposed in this study that differentiate it from other methodologies are the fact that it is:

- Multi-level – The proposed methodology considers the uncertainty associated with the parameters used in the Inventory Analysis and the Impact Assessment steps. Even though the need to consider uncertainty in the Impact Assessment step has been identified several years ago by Huijbregts (1998a) as a requirement to fully address uncertainty in an LCA (Huijbregts, 1998a), little attention has been given in the literature to the uncertainty associated with the parameters used in this step (Thies, et al., 2019). Furthermore, the development of a methodology that integrates both the uncertainty at the inventory analysis and impact assessment level was identified as a priority (Santos, et al., 2022b). By considering parameter uncertainty at multiple levels, the proposed methodology reduces the gap identified in the literature;
- Multi-purpose – The proposed methodology can be applied to any supply chain to support the development of a robust GSCM strategy. Besides being used in the field of green supply chain management, the proposed methodology can also be used in different LCA applications, such as the comparison of specific goods or services, which makes it valuable to both decision-makers and policy makers.

The remainder of this chapter is organized into four sections. Section 6.2 describes the methodology developed, including an in-depth description of its ten steps. Section 6.3 presents the case study used to illustrate the applicability of the proposed methodology. Section 6.4 presents a discussion of the stochastic results obtained and proposes which parameters should be the focus of future studies to improve the reliability of LCA results. Lastly, Section 6.5 presents the conclusions of this work, including highlights and limitations of the current study, and suggestions for future work.

6.2 Methodology

The proposed methodology for integrating parameter uncertainty in an LCA conducted to assist GSCM comprises 10 main steps divided into four main stages: Goal and Scope, Deterministic LCA, Stochastic LCA, and Results' Robustness. The work-flow describing the developed methodology is presented in Figure 6.1. Each of the four stages and associated steps are explained in detail below.

6.2.1 Goal and Scope

This first stage involves identifying the goal and scope of the life cycle assessment. It is comprised of two main steps: Step 1) Define the goal, functional unit, systems boundary, and impact categories and Step 2) Choose the characterization, normalization, and weighting methods.

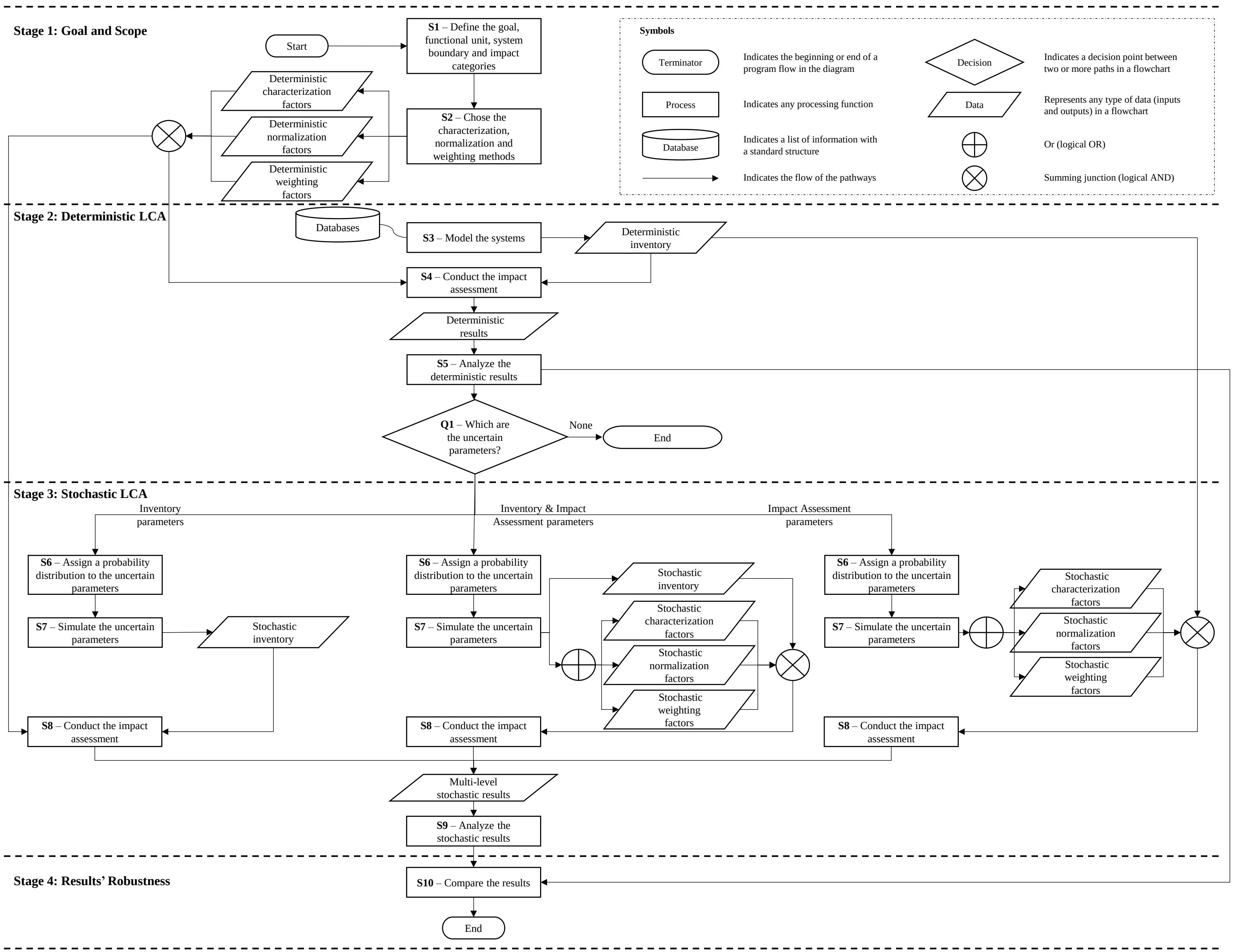


Figure 6.1 – Methodology for integrating parameter uncertainty in an LCA.

6.2.1.1 Step 1 – Define the goal, functional unit, systems boundary, and impact categories

During the goal definition the intended application of the LCA and the targeted audiences to whom the LCA results are to be communicated are identified (EC-JRC-IES, 2010). This study focuses on the application of LCA to assist green supply chain management. The results of an LCA developed to support GSCM are usually communicated internally to different supply chain partners.

One of the most important aspects of scope definition is defining the functional unit, which serves as a reference for the calculation of all elementary input and output flows in Inventory Analysis step. The functional unit should quantify the function(s) provided by the system under analysis. A supply chain is the sequence of processes involved in the production and distribution of a commodity. Thus, in LCAs conducted to support GSCM, the functional unit should be an amount of the commodity produced and distributed.

Another aspect of scope definition is defining the system's boundary which determines the stages and respective supply chain processes that will be considered in the LCA (EC-JRC-IES, 2010). Different system boundaries exist including gate-to-gate (i.e., only the processes involved in a single stage of the supply chain are considered) and cradle-to-grave (i.e., all supply chain processes from raw materials extraction to product disposal are considered) (Eskandarpour, et al., 2015). When the life cycle assessment is used to assist green supply chain management, the choice of a more restrictive system boundary (e.g., gate-to-gate) is not recommended since it could prevent the identification of the most relevant supply chain processes (in environmental terms), if these processes were located outside the boundary.

Scope definition also includes preparing the basis for the impact assessment, which starts with determining the environmental impact categories that should be covered by the LCA. Unless otherwise stated in the goal definition, the selection of impact categories must be comprehensive (i.e., cover all relevant environmental issues). The following impact categories shall be checked for relevance: Climate Change, Ozone Depletion, Acidification, Eutrophication, Human Toxicity, Ecotoxicity, Respiratory Inorganics, Ionizing Radiation, Photochemical Ozone Formation, Land Use, and Resource Depletion (minerals, fossil and renewable energy resources, water) (EC-JRC-IES, 2010).

6.2.1.2 Step 2 – Choose the characterization, normalizations, and weighting methods

The second step consists of selecting the characterization, normalizations, and weighting methods. For each impact category chosen in Step 1, the selected characterization method determines which characterization factors will be used as parameters to convert the inventory collected in Step 3 into characterized results. Consequently, one of the outputs of this step are the characterization factors of the different impact categories (Figure 6.1). The characterized result of each impact category is calculated through Equation 6.1.

$$C_i = \sum_s (INV_s \times CF_{s,i}) \quad (6.1)$$

where *i* denotes the impact category, *s* denotes the substance, *INV* is the inventory, *CF* is the characterization factor, and *C* is the characterized result of the impact category. Different characterization methods exist with the Product Environmental Footprint (PEF) being one of the most recent. This method was developed by the European Commission in cooperation with companies and sustainability experts with the aim of harmonizing future life cycle assessments in Europe (European Commission, 2021b). It considers 16 impact categories listed in Table 6.1 and adopts the most recommended methods to use in the European context as baseline characterization methods to assess the characterized results of the impact categories (Zampori & Pant, 2019). Each characterized result has a specific unit also presented in Table 6.1. It is important to notice that the PEF method considers the impact categories mentioned in Step 1 but it further details some of these impact categories. For example, the Resource Depletion impact category mentioned in Step 1 is divided into Water use, Resource use (minerals and metals), and Resource use (fossils) in Table 6.1. If the supply chain processes occur mostly in Europe, the Product Environmental Footprint should be chosen.

Normalization consists of expressing the results of the different impact categories in relation to a common reference and it is accomplished by dividing the characterized results of each impact category by the respective reference value (EC-JRC-IES, 2010). These reference values are also known as normalization basis or normalization factors and are determined by the normalization method chosen. Consequently, another output of this step are the normalization factors of the different impact categories (Figure 6.1). The normalized result of each impact category is calculated through Equation 6.2.

$$N_i = \frac{C_i}{NF_i} \quad (6.2)$$

where *NF* is the normalization factor and *N* is the normalized result of the impact category. There are two main approaches to normalization, namely internal normalization and external normalization (Pizzol, et al., 2017). When the life cycle assessment is conducted to assist green supply chain management, internal normalization cannot be selected since it can only be used in LCAs that compare two or more systems (Pizzol, et al., 2017). In external normalization, the reference values are external to the LCA and thus independent from the systems under analysis (Pizzol, et al., 2017). Different normalization methods exist for external normalization but the one adopted by the PEF method is global normalization due to the international nature of most supply chains (Sala, et al., 2017). Moreover, the *General Guide for LCA* recommends using as normalization factors the impact results per capita (i.e., per average citizen) in the selected region per year (EC-JRC-IES, 2010). Following this recommendation, the normalization factors suggested by the PEF method are the global impact results per capita for the year 2010 (Table 6.1). In this case, and for each impact category, the normalization factor represents the total impact of an average citizen of the world in 2010.

Weighting is usually accomplished by multiplying the (typically normalized) impact results of each impact category by the specific weighting factor. This weighting factor is intended to reflect the relative relevance of the different impact categories (EC-JRC-IES, 2010) and is determined by the weighting method chosen. Consequently, the third output of this step are the weighting factors of the different impact categories. The weighted result of each impact category is calculated through Equation 6.3.

$$W_i = N_i \times WF_i \tag{6.3}$$

where *WF* is the weighting factor and *W* is the weighted result of the impact category. There are four main approaches to weighting (Pizzol, et al., 2017): 1) distance to target (i.e., the impact results are weighted according to their proximity to a target); 2) panel weighting (i.e., the impact results are weighted based on the opinions of a group of people); 3) monetary weighting (i.e., the impact results are weighted according to their estimated economic value; and 4) binary weighting (i.e., the impact results are assigned either no weight or equal importance, based on criteria decided by the LCA practitioner). Each of these main approaches includes one or more weighting methods. For example, there are two weighting methods for binary weighting including equal weighting where all impact categories are assumed to have equal weight (weight equals one) and footprinting where one or more impact categories are selected (weight equals one) and the other categories are disregarded (weight equals zero) by the LCA practitioner.

6.2.2 Deterministic LCA

The next stage of the proposed methodology involves performing the LCA without considering the uncertainty associated with the parameters used in the Inventory Analysis and Impact Assessment steps. This stage is comprised of three main steps: Model the systems (S3); Conduct the impact assessment (S4); and Analyze the deterministic results (S5).

6.2.2.1 Step 3 – Model the systems

To model the supply chain under analysis, data gathered on the supply chain processes included within the systems boundary is used. The data collected on the different supply chain processes includes information regarding the amount per functional unit of each supply chain process (e.g., quantity of kilowatt-hours of electricity used) and the elementary input and output flows associated with an unitary amount of these processes (e.g., emissions to air associated with one kilowatt-hours of electricity used). These two types of information are combined to derive the elementary input and output flows associated with the amount per functional unit of all supply chain processes. The output of this step is then an inventory list of elementary flows and corresponding quantities (e.g., kilograms of carbon dioxide emitted) that quantitatively relate to the functional unit established in Step 1 (EC-JRC-IES, 2010).

6.2.2.2 Step 4 – Conduct the impact assessment

This step consists in converting the inventory collected in the previous step into characterized, normalized, and weighted results using the characterization, normalization, and weighting factors established by the characterization, normalization, and weighting methods selected in Step 2. The weighted results of the impact categories can be added together to calculate the supply chain's overall environmental impact (i.e., single score).

6.2.2.3 Step 5 – Analyze the deterministic results

The deterministic results' analysis conducted in this step depends on the goal of the LCA defined in Step 1. When the goal of the LCA is to support green supply chain management, this step must include the identification of the most relevant environmental impacts and supply chain processes (Zampori & Pant, 2019):

- Most relevant environmental impacts – The identification of the most relevant environmental impacts is made based on the deterministic normalized and weighted results of the different impact categories. The most relevant environmental impacts are identified considering all impact categories that cumulatively contribute at least 80% to the single score. At least three impact categories should be identified as the most relevant ones;
- Most relevant supply chain processes – The identification of the most relevant processes is made based on the deterministic characterized results of the different supply chain processes. For each of the most relevant impact categories identified, the most relevant processes are the ones that together contribute to at least 80% of the characterized result of each relevant impact categories identified.

The GSCM strategy should focus on improving the most relevant supply chain processes to reduce the most significant environmental impacts and, consequently, improve the overall environmental performance of the supply chain.

6.2.2.4 Question 1 – Which are the uncertain parameters?

Most life cycle assessments end after the analysis of the deterministic results without considering the impact that parameter uncertainty has on the results analyzed. However, given the diversity of parameters used in a life cycle assessment, it is likely that at least one of them is uncertain.

The uncertainty associated with the different LCA parameters (i.e., inventory, characterization, normalization, and weighting factors) is caused by the large amount of data needed to determine the input and output flows in the Inventory Analysis step and to calculate the characterization, normalization, and weighting factors utilized in the Impact Assessment step. Some sources of parameter uncertainty are empirical inaccuracy (i.e., the data used was obtained through imprecise measurements), unrepresentativity (i.e., the data used is incomplete or outdated), and lack of data (i.e., there is no data)

(Huijbregts, 1998a). The main reasons for parameter uncertainty are explained below for each of the different parameters used in an LCA:

- Inventory (*INV*) – A large amount of data is required to model the supply chain under the scope of the study. Data comes from a wide range of sources, which can be of differing quality, variability, and uncertainty (EC-JRC-IES, 2010). If some of the data used to model the supply chain is uncertain, then the inventory collected through this modelling will also be uncertain;
- Characterization factors (*CF*) – A large amount of data, which is not always available or is imprecise, is also required by the models which calculate the characterization factors (Huijbregts, 1998a). This lack of availability and quality of data is the cause of parameter uncertainty related with the characterization factors of each individual substance in each impact category. Table 6.1 provides the classification of each characterization method according to their robustness (EC-JRC-IES, 2011). Robustness level "I" was assigned to the characterization methods (and resulting characterization factors) considered to have some uncertainty associated while robustness level "III" was assigned to the characterization methods considered to have considerable uncertainty associated, incompleteness and/or other shortcomings. According to Table 6.1, energy-conversion related categories addressing climate change impacts are accompanied by considerably less uncertainties (robustness level "I") than the chemical-related categories addressing ecotoxicity (robustness level "III");
- Normalization factors (*NF*) – The normalization factors, also known as reference values, are determined by the normalization approach (i.e., internal or external) and associated normalization method selected. For external normalization and taking the global normalization method adopted by the PEF method as an example (Step 2), the reference values used to normalize the characterized results are the global impact results per capita for the year 2010. These normalization factors were calculated by Sala et al. (2017) based on the inventory covering both emissions into the environmental compartments (i.e., air, water and soil), and resources extracted on a global scale in 2010. For each impact category, this inventory was converted into a global impact result per capita using the respective characterization factors and dividing the overall impact result by the world population (Sala, et al., 2017). Consequently, the uncertainty associated with these normalization factors is the result of the combined uncertainty of the inventory collected on a global scale and the characterization factors used (Sala, et al., 2017). Accordingly, Sala et al. (2017) assessed the robustness of the global normalization factors per capita by considering three criteria: i) inventory coverage completeness, ii) inventory robustness, and iii) robustness of the characterization method (Sala, et al., 2017). To determine the overall robustness of the

global normalization factors per capita, the mathematical average of the three criteria was calculated using the strategy followed by Sala et al. (2018) and a scale from 1 to 0.1 (Sala, et al., 2018). This robustness is presented in Table 6.1 for each normalization factor. For example, a final robustness of 0.87 was determined for the Climate Change normalization factor (i.e., 8.10x103). To match the nomenclature used for the characterization factors, a robustness level "I" was assigned in this study to the normalization factors with the highest final robustness (i.e., between 1 and 0.8) while robustness level "III" was assigned in this study to the normalization factors with the lowest final robustness (i.e., between 0.2 and 0).

- Weighting factors (*WF*) – Similar to the normalization factors, the weighting factors are determined by the weighting approach and respective weighting method selected. In the case of the distance to target, panel weighting, and monetary weighting approaches, the weighting factors' uncertainty is mostly related with the translation into weights of policy-based targets, panel's opinion, and monetary valuation, respectively. For binary weighting where impact results are assigned either no weight (weight equals zero) or equal importance (weight equals one), there is no parameter uncertainty related to the weighting factors of each impact category since no data is required to determine the weights. However, this does not mean that binary weighting is the best approach. For example, applying a weight equal to zero to some impact categories means that those impacts are deliberately disregarded, even though they may be important (Pizzol, et al., 2017).

It is important to mention that even if the decision-maker determines that several parameters are uncertain, he/she might choose to not consider parameter uncertainty or to only consider the uncertainty associated with some parameters. In this case, the answer to Question 1 of the methodology should reflect this choice, which might be due to an assumption that parameter uncertainty does not greatly impact the results obtained, a lack of knowledge on how to deal with all uncertain parameters, or because dealing with all uncertain parameters requires an added effort that the decision-maker is not willing to make. However, it is advised that if several parameters are uncertain, the decision-maker takes into account this uncertainty. The next stage of the proposed methodology intends to help practitioners integrate parameter uncertainty in an LCA and interpret the results.

Table 6.1 – PEF impact categories with respective characterization methods and normalization factors classified according to their robustness (Zampori & Pant, 2019).

Impact Category	Acronym	Characterization			Normalization	
		Unit	Characterization method	Robustness	Normalization factors	Robustness
Climate Change	CC	kg CO_2 eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013 (IPCC, 2013))	I	$8.10x10^{3}$	0.87 (I)
Ozone Depletion	OD	kg CFC-11 eq.	Steady-state ODPs as in (WMO 2014 (World Meteorological Organisation (WMO), 2014) + integrations)	I	$5.36x10^{-2}$	0.60 (II)
Human Toxicity, Cancer	HT_Car	CTUh	USEtox model 2.1 (Fantke, et al., 2017)	III	$1.69x10^{-5}$	0.20 (III)
Human Toxicity, Non-cancer	HT_NCar	CTUh	USEtox model 2.1 (Fantke, et al., 2017)	III	$2.30x10^{-4}$	0.20 (III)
Particulate Matter	PM	disease incidence	PM method recomended by UNEP (UNEP (United Nations Environment Programme), 2016)	I	$5.95x10^{-4}$	0.87 (I)
Ionising radiation	IR	kBq U235 eq.	Human health effect model as developed by Dreicer et al. 1995 (Dreicer, et al., 1995) (Frischknecht, et al., 2000)	II	$4.22x10^{3}$	0.47 (II)
Photochemical Ozone Formation	POF	kg NMVOC eq.	LOTOS-EUROS model (Van Zelm, et al., 2008) as implemented in ReCiPe	II	$4.06Ex10^{1}$	0.53 (II)
Acidification	Aci	mol H+ eq.	Accumulated Exceedance (Seppälä, et al., 2006) (Posch, et al., 2008)	II	$5.56x10^{1}$	0.67 (II)
Eutrophication, Terrestrial	Eut_Ter	mol N eq.	Accumulated Exceedance (Seppälä, et al., 2006) (Posch, et al., 2008)	II	$1.77Ex10^{2}$	0.67 (II)
Eutrophication, Freshwater	Eut_Fre	kg P eq.	EUTREND model (Struijs, et al., 2009) as implemented in ReCiPe	II	$1.61x10^{0}$	0.47 (II)
Eutrophication, Marine	Eut_Mar	kg N eq.	EUTREND model (Struijs, et al., 2009) as implemented in ReCiPe	II	$1.95Ex10^{1}$	0.53 (II)
Ecotoxicity, Freshwater	Eco	CTUe	USEtox model 2.1 (Fantke, et al., 2017)	III	$4.27x10^{4}$	0.20 (III)
Land Use	LU	pt	Soil quality index based on LANCA (Beck, et al., 2010) (Bos, et al., 2016)	III	$8.20x10^{5}$	0.47 (II)
Water Use	WU	m3 eq.	Available WAter REmaining (AWARE) as recommended by UNEP (UNEP (United Nations	III	$1.15x10^{4}$	0.60 (II)

Impact Category	Acronym	Characterization			Normalization	
		Unit	Characterization method	Robustness	Normalization factors	Robustness
			Environment Programme), 2016)			
Resource Use, Minerals and Metals	RU_M	kg Sb eq.	CML 2002 (Guinée, et al., 2002) and van Oers et al. 2002 (Van Oers, et al., 2002)	III	$6.37\text{x}10^{-2}$	0.60 (II)
Resource Use, Fossils	RU_F	MJ	CML 2002 (Guinée, et al., 2002) and van Oers et al. 2002 (Van Oers, et al., 2002)	III	$6.50\text{x}10^{4}$	0.60 (II)

6.2.3 Stochastic LCA

The third stage of the proposed methodology involves performing the LCA considering the uncertainty associated with the parameters used in the Inventory Analysis and Impact Assessment steps. This stage is comprised of four main steps: Assign a probability distribution to the uncertain parameters (S6); Simulate the uncertain parameters (S7); Conduct the impact assessment (S8); and Analyze the stochastic results (S9).

6.2.3.1 Step 6 – Assign a probability distribution to the uncertain parameters

Monte Carlo simulation was chosen as the stochastic modeling technique in this study to deal with parameter uncertainty. The first step when conducting a Monte Carlo simulation is to assign probability distributions (e.g., uniform or normal) to the uncertain parameters. This assignment is dependent on the parameters that were considered uncertain in Question 1:

- Inventory – A probability distribution must be assigned to the uncertain data used to model the supply chain. In the ecoinvent database, the lognormal distribution is the most assigned probability distribution. This distribution is characterized by two parameters, namely the geometric mean (μ_g) and the geometric standard deviation (σ_g) (Muller, et al., 2014). For each data point used to model the supply chain, these two parameters must be defined. According to the ecoinvent approach, the geometric mean (μ_g) corresponds to the deterministic data point used to model the supply chain under analysis, while the geometric standard deviation (σ_g) is estimated based on a basic uncertainty factor and on additional uncertainty information. The basic uncertainty factors are determined by experts (Table C.8 available in the Supplementary Material) and reflect the fact that even "perfect" data is uncertain due to fluctuation over time, for example (ecoinvent, 2021). The additional uncertainty information is obtained using the Pedigree matrix approach (Weidema, et al., 2013). According to this approach, each data point is assessed based on five criteria – reliability, completeness, temporal correlation, geographical correlation, and further technological correlation (Table C.9 available in the Supplementary material). A score of 1 means that the data is of high quality regarding that criterion, while a score of 5 means the data quality for that criterion is low (Weidema, et al., 2013);

- Characterization factors – A probability distribution must be assigned to the characterization factors used. An approach that can be used for this assignment is the one utilized by Santos et al. (2022b) where a uniform distribution was attributed to each characterization factor (Santos, et al., 2022b). This distribution is characterized by two parameters, namely the minimum of the distribution (a) and the maximum of the distribution (b) (Muller, et al., 2014). For each characterization factor, these two parameters must be defined. Santos et al. (2022b) defined three classes of uncertainty for the characterization factors: Class 1 refers to 5% variation, Class 2 refers to 25% variation, and Class 3 refers to 50% variation around the reported standard values (i.e., deterministic value) of the characterization factors (Santos, et al., 2022b). The minimum and the maximum of the uniform distribution were calculated as follows: $a = (1 - \%variation) \times standard\ value$ and $b = (1 + \%variation) \times standard\ value$ (Santos, et al., 2022b);
- Normalization factors – A probability distribution must be assigned to the normalization factors used. The same approach as the one utilized by Santos et al. (2022b) for the characterization factors can be used;
- Weighting factors – Similarly to the normalization factors, the same approach as the one utilized by Santos et al. (2022b) can be used to assign a probability distribution to the weighting factors considered.

After assigning the probability distribution to the uncertain parameters, the next step is to simulate these parameters.

6.2.3.2 *Step 7 – Simulate the uncertain parameters*

During the Monte Carlo simulation, the uncertain parameters are sampled from the probability distributions defined in Step 6. Monte Carlo sampling and Latin Hypercube sampling are two statistical methods that can be used during a Monte Carlo simulation to generate samples of the uncertain parameters. In Monte Carlo sampling, the uncertain parameters are randomly sampled whereas in Latin Hypercube sampling, the probability distributions of uncertain parameters are divided into several non-overlapping intervals of equal probability. The random values of the uncertain parameters are then sampled from each interval according to the probability distribution within the interval which allows for a more stratified sampling (Palisade Corporation, 2016). Each time a different set of random values is generated is called an iteration. The number of random values that are sampled for each uncertain parameter depends on the number of iterations defined for the Monte Carlo simulation.

6.2.3.3 *Step 8 – Conduct the impact assessment*

As Step 4, this step of the methodology involves converting the collected inventory into environmental impacts. The input parameters used in this step are identified in Figure 6.1 and depend on the parameters that were considered uncertain in Question 1.Each sample of uncertain parameters generates a set of environmental impacts. Consequently, and contrary to Step 4, the output of this step is not a single estimate for each outcome, but instead a set of different estimates (i.e., stochastic results), reflecting the combined parameter uncertainty. For example, instead of obtaining a single value for the single score of the analyzed supply chain, as explained in Step 4, a set of single scores will be obtained for the supply chain under analysis.

6.2.3.4 *Step 9 – Analyze the stochastic results*

In the case of green supply chain management, the stochastic results' analysis requires the identification of the most relevant environmental impacts and supply chain processes. The identification of the most relevant environmental impacts is made based on the stochastic normalized and weighted results of the different impact categories, while the identification of the most relevant supply chain processes is made based on the stochastic characterized results of the different processes.

Different approaches have been applied when analyzing the results of stochastic LCA including conducting statistical hypothesis tests (Lesage, et al., 2018). In a statistical hypothesis test, a null hypothesis (H_0) is proposed, and the test may lead to the rejection or non-rejection of this hypothesis (Graybill, et al., 1998). To determine if the null hypothesis should be rejected or not, a probability value (p-value) is calculated and compared with a pre-established significance level (α) (Graybill, et al., 1998):

- p-value $\leq \alpha$: Reject the null hypothesis of the statistical test;
- p-value $> \alpha$: Fail to reject the null hypothesis of the statistical test.

The most chosen significance level (α) is 0.05 (Ross, 2017). To determine the most relevant environmental impacts and processes, several statistical hypothesis tests must be conducted (Figure 6.2).

There are different types of statistical hypothesis tests. To identify which statistical hypothesis test is the most appropriate, three assumptions must be verified (Graybill, et al., 1998):

- Independence of observations/variables: The observations/variables included in the test are not related. The stochastic results involved in the statistical hypothesis tests identified in Figure 6.2 are independent since the normalized and weighted stochastic results obtained for each impact category are not influenced by the normalized and weighted stochastic results obtained for the remaining impact categories. Moreover, the characterized stochastic results obtained for each supply chain process are not influenced by the characterized stochastic results obtained for the remaining processes;

- Normality of data: The data follows a normal distribution. In sufficiently large sets of sample data, this assumption does not need to be verified. Previous simulation studies show that "sufficiently large" is often under 100 data points (Lumley, et al., 2002). Hence, if the number of iterations established in Step 7 is greater than 100, the sets of normalized and weighted stochastic results obtained for each impact category and characterized stochastic results obtained for each supply chain process can be considered sufficiently large and this assumption does not need to be verified. On the other hand, if the number of iterations established in Step 7 is less than 100, this assumption should be verified using a statistical hypothesis test such as the Shapiro–Wilk test;
- Homogeneity of variance: The variance within each group being compared is similar among all groups. To verify this assumption, a statistical hypothesis test such as the Levene's test (Lim & Loh, 1996) should be utilized. Given the stochastic results involved in the statistical hypothesis tests identified in Figure 6.2, the Levene's tests should test 1) the null hypothesis that the variances of the normalized and weighted stochastic results of the different impact categories are equal ($H_0: \sigma_{Aci}^2 = \sigma_{CC}^2 = \cdots = \sigma_{WU}^2$) and 2) the null hypothesis that the variances of the characterized stochastic results of the different processes are equal ($H_0: \sigma_{Process1}^2 = \sigma_{Process2}^2 = \cdots$). For each Levene's test, a p-value lower or equal than the significance level defined indicates the rejection of the null hypothesis, i.e., statistical evidence that there is no homogeneity of variance. On the other hand, a p-value higher than the significance level defined indicates a failure to reject the null hypothesis, i.e., a statistical evidence that there is homogeneity of variance.

According to Figure 6.2, the first statistical hypothesis tests conducted to determine the statistically most relevant environmental impacts and supply chain processes should test the null hypothesis $H_0: \mu_{Aci} = \mu_{CC} = \cdots = \mu_{WU}$ and $H_0: \mu_{Process\ 1} = \mu_{Process\ 2} = \cdots$, respectively. These null hypotheses can be tested using the classic ANOVA test if the three assumptions mentioned above are verified or a Welch's ANOVA test if the assumption of homogeneity of variances is not verified (Liu, 2015), for example. When the p-value obtained for these statistical hypothesis tests is lower or equal to the significance level (i.e., p-value ≤ α), the next step involves making pairwise comparisons between the true means of the normalized and weighted results of the different impact categories and the true means of the characterized results of the supply chain processes. These pairwise comparisons can be made using a Tukey's post hoc test if the three assumptions mentioned above are verified or a Games-Howell post-hoc test if the assumption of homogeneity of variances is not verified, for example. On the other hand, when the p-value obtained for these statistical hypothesis tests is higher than the significance level (i.e., p-value > α), it can be concluded that the impact categories and supply chain processes have the same relevance. In this case, the GSCM strategy should focuses on the environmental impacts that stakeholders consider the most important and on any supply chain process.

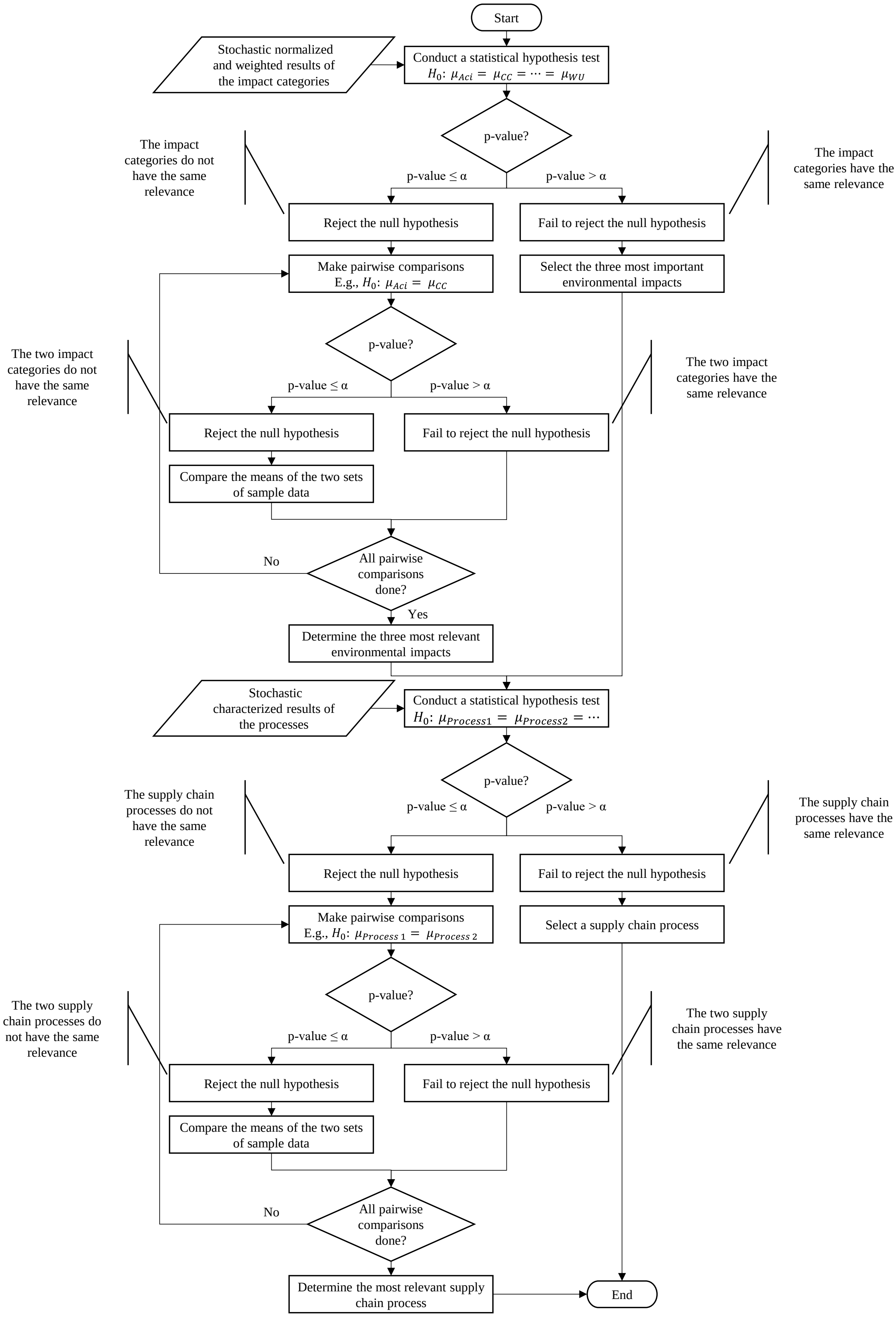


Figure 6.2 – Statistical hypothesis tests that must be conducted to determine the most relevant environmental impacts and supply chain processes.

6.2.4 Results' Robustness

The fourth and final stage of the proposed methodology involves one main step: Compare the results (S10). It is the comparison of the deterministic and stochastic results that will allow to determine the robustness of the LCA results obtained in the deterministic LCA.

6.2.4.1 Step 10 – Compare the results

The last step of the methodology involves comparing the deterministic and stochastic results. This comparison will allow determining how robust are the results obtained in the deterministic LCA are (Table 6.2).

Table 6.2 – Comparison between the deterministic and stochastic results where i = 1, …, I and j = 1, …, J denote two different results.

Deterministic Results	**Stochastic Results**		
	$\mu_i < \mu_j$ *High chance that the true mean of i is lower than the true mean of j.*	$\mu_i = \mu_j$ *High chance that the true mean of i is equal to the true mean of j.*	$\mu_i > \mu_j$ *High chance that the true mean of i is higher than the true mean of j.*
$i < j$	The deterministic result is robust	The deterministic result is not robust	The deterministic result is not robust
$i = j$	The deterministic result is not robust	The deterministic result is robust	The deterministic result is not robust
$i > j$	The conclusion result is not robust	The deterministic result is not robust	The deterministic result is robust

According to Table 6.2, deterministic results are considered robust when they point to the same conclusion as stochastic results.

6.3 Application of the Methodology

The cork industry is a forest-based industry of particular importance in Portugal since this country is the world's leading cork producer (Visit Portugal, 2013). A survey revealed that around 43% of the people surveyed consider that significant environmental damage is being caused by forest-based industries and 34% consider the forest sector to be responsible for at least moderate damage (FAO, 2007). For these reasons, it is important that companies from these industries look into the most relevant environmental impacts of their supply chains to identify the supply chain processes that most contribute to these relevant impacts. This will allow companies to study ways to prevent or mitigate the critical environmental issues identified. Hence, this section presents the application of the proposed methodology to a Portuguese forest supply chain, more specifically to the Portuguese natural cork stoppers supply chain since this is the most manufactured product by the Portuguese cork industry (NCSs) (ICNF, 2018).

6.3.1 Goal and Scope

The results of applying the first two steps of the methodology to the Portuguese natural cork stoppers (NCSs) supply chain are presented in Table 6.3.

The intended application of the life cycle assessment presented in this study (Table 6.3) is to provide informed recommendations on ways to prevent or mitigate the critical environmental impacts identified for the Portuguese NCSs supply chain. The results of this LCA are directed towards the different supply chain partners who should implement the recommendations provided. One ton of natural cork stoppers was chosen as a functional unit (Table 6.3). This functional unit relates to the main function of the supply chain under analysis which is to produce and distribute Portuguese natural cork stoppers (Section 6.2 – Step 1). A cradle-to-grave system boundary was selected to ensure that all supply chain processes were included in the analysis. The use of a broad system boundary is important since the most relevant supply chain processes may be located in different stages of the supply chain (ISO, 2015). To make the LCA presented in this study as comprehensive as possible and to guarantee that all relevant environmental issues were taken into account, all impact categories identified in Section 6.2 – Step 1 were chosen (Table 6.3).

Table 6.3 – Results of applying Steps 1 and 2 of the methodology to the Portuguese natural cork stoppers supply chain.

Step	Application
Step 1 – Define the goal, functional unit, system boundary, and impact categories	<u>Goal</u> – Provide informed recommendations on ways to prevent or mitigate the critical environmental impacts identified for the Portuguese natural cork stoppers supply chain. <u>Functional unit</u> – One ton of natural cork stoppers. <u>System boundary</u> – Cradle-to-grave. <u>Impact categories</u> – Climate Change, Ozone Depletion, Acidification, Eutrophication, Human Toxicity, Ecotoxicity, Respiratory Inorganics, Ionizing Radiation, Photochemical Ozone Formation, Land Use, and Resource Depletion (minerals, fossil and renewable energy resources, water).
Step 2 – Choose the characterization, normalization, and weighting methods	<u>Characterization methods</u> – The characterization methods adopted by the PEF method (Table 6.1). <u>Normalization method</u> – Global normalization as adopted by the PEF method (Table 6.1). <u>Weighting method</u> – Equal weighting, i.e., all impact categories have equal weight (weight equals one).

The characterization methods adopted by the Product Environmental Footprint method were selected in this study (Table 6.3) since most of the Portuguese NCSs supply chain processes occur in Europe

(Section 6.2 – Step 2) together with the global normalization method as adopted by this method (Table 6.3) due to the international nature of the Portuguese NCSs supply chain (Section 6.2 – Step 2). The weighting method selected in this study is equal weighting because the other weighting approaches cause the weighting factors to be uncertain mostly due to the translation into weights of policy-based targets, panel's opinion, and monetary valuation (Section 6.2 – Question 1). By assuming that all impact categories have equal weight, this study allows to better analyze the effects of parameter uncertainty related with the inventory, characterization factors and normalization factors utilized in the LCA without worrying about the parameter uncertainty related to the weighting factors.

6.3.2 Deterministic LCA

The results of applying Steps 3 to 5 of the methodology to the Portuguese natural cork stoppers supply chain are presented in Table 6.4.

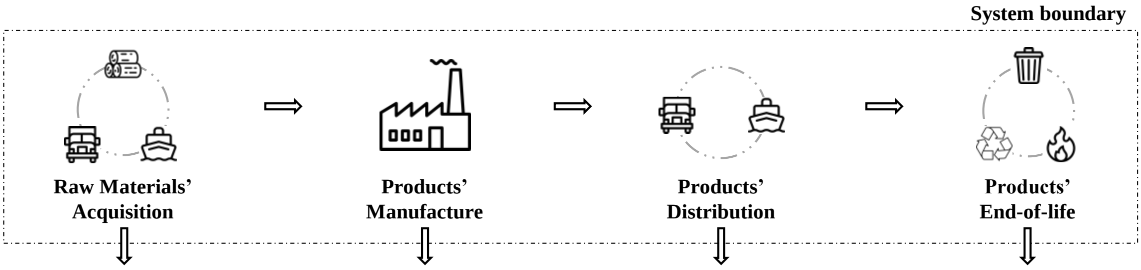
Table 6.4 – Results of applying Steps 3 to 5 of the methodology to the Portuguese natural cork stoppers supply chain.

Step	Application
Step 3 – Model the systems	The Portuguese natural cork stoppers supply chain was modelled in the SimaPro 8.4.0 software (PRéConsultants, 2021) using data collected for all supply chain processes.
Step 4 – Conduct the impact assessment	An environmental model was developed in Microsoft Excel (Microsoft, 2021) to conduct the impact assessment.
Step 5 – Analyze the deterministic results	The most relevant environmental impacts (Figure 6.4) and supply chain processes (Figure 6.5) are: 1. Ecotoxicity – Sludge treatment (Products' Manufacture); 2. Land Use – Cork harvesting (Raw Materials' Extraction); 3. Resource Use (Fossils) – Natural gas use (Products' Manufacture), Electricity use (Products' Manufacture), Coating powder use (Products' Manufacture), and Transportation, national origin, lorry (Raw Materials' Extraction).

To model the Portuguese natural cork stoppers supply chain, data was collected regarding the life cycle stages and respective processes included within the system boundary. Given that the system's boundary defined in Step 1 was cradle-to-grave, it was necessary to collect data describing the processes included in four life cycle stages: Raw Materials' Acquisition, Products' Manufacture, Products'

Distribution, and Products' End-of-Life. As previously explained in the methodology, the data collected on the different supply chain processes includes information regarding (Section 6.2 – Step 3):

- The amount per functional unit of each supply chain process which in this study was collected from different sources, the main one being the study carried out by Demertzi et al. (2016) (Demertzi, et al., 2016). Figure 6.3 presents the amount per functional unit of most Portuguese NCS supply chain processes. All data regarding the amount per functional unit of each supply chain process and the data sources used are presented in the Supplementary Material (Table C.1 to C.7);
- The elementary input and output flows associated with an unitary amount of these processes which in this study were obtained through the ecoinvent database (ecoinvent, 2021).



Process	Amount per FU
Cork harvesting	5.00E+03 kg
Transportation, national origin, lorry	1.71E+06 kg.km
Transportation, national origin, ship	0.00E+00 kg.km
Transportation, international origin, lorry	1.49E+05 kg.km
Transportation, international origin, ship	3.55E+04 kg.km

Process	Amount per FU
Electricity use	1.23E+03 kWh
Lubricating oil use	1.32E+01 kg
Paraffin use	1.48E+01 kg
Sulfur dioxide use	1.00E+00 kg
…	…

Process	Amount per FU
Transportation, domestic market, lorry	1.70E+05 kg.km
Transportation, domestic market, ship	6.12E+04 kg.km
Transportation, international market, lorry	5.43E+04 kg.km
Transportation, international market, ship	1.99E+05 kg.km

Process	Amount per FU
Landfilling	6.75E+02 kg
Incineration	1.58E+02 kg
Recycling	1.67E+02 kg

Figure 6.3 – Amount per functional unit (FU) of most Portuguese NCS supply chain processes.

The collected data regarding the amount per functional unit of each supply chain process and the elementary input and output flows associated with an unitary amount of these processes were used to model the Portuguese natural cork stoppers supply chain in the SimaPro 8.4.0 software (PRéConsultants, 2021).

To conduct the impact assessment, an environmental model was developed in Microsoft Excel (Table 6.4). The inputs of this model are the inventory obtained after the Portuguese natural cork stoppers supply chain was modelled in SimaPro, the characterization and normalization factors obtained by selecting the PEF 3.0 method available in this software, and the weighting factors equal to one for all impact categories. The outputs of this model were the deterministic characterized, normalized, and weighted results associated with the supply chain under analysis.

Due to the goal of the life cycle assessment presented in this study (Table 6.3), the interpretation of deterministic results focuses on the identification of the most relevant environmental impacts and the supply chain processes that most contribute to these relevant impacts (Table 6.4).

Figure 6.4 presents the deterministic normalized and weighted results of the different impact categories. From the analysis of this figure, it is possible to conclude that the normalized and weighted results of the Ecotoxicity and Land Use impact categories cumulatively contribute to 83.78% of the total environmental impact. However, as previously mentioned (Section 6.2 – Step 5), at least three impact categories should be identified as the most relevant ones. For this reason, Resource Use (Fossils) is also considered a relevant environmental impact.

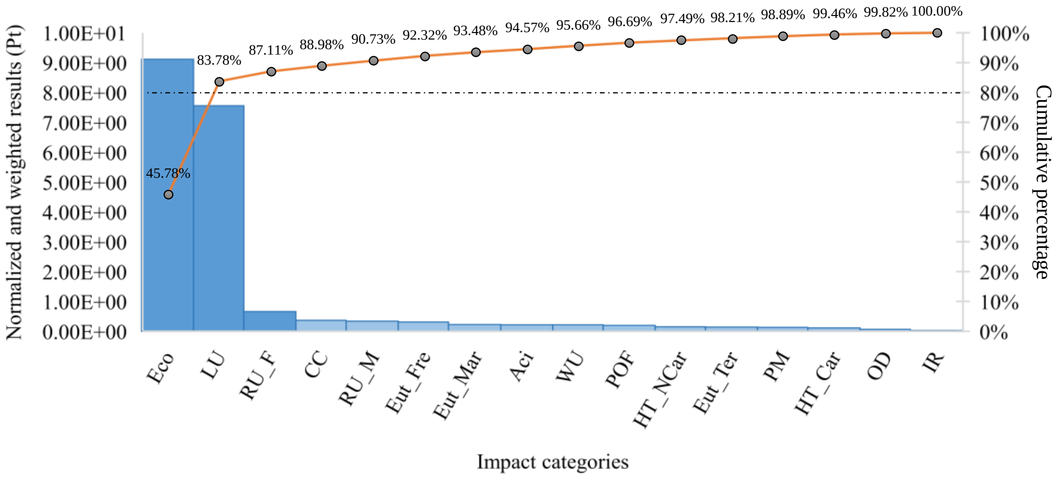


Figure 6.4 – Deterministic normalized and weighted results of the different impact categories.

Figure 6.5 presents the contribution (based on deterministic characterized results) of the different supply chain processes to the three most relevant environmental impacts. In this figure, the supply chain processes that together contribute to at least 80% of the characterized result of each relevant impact category are highlighted.

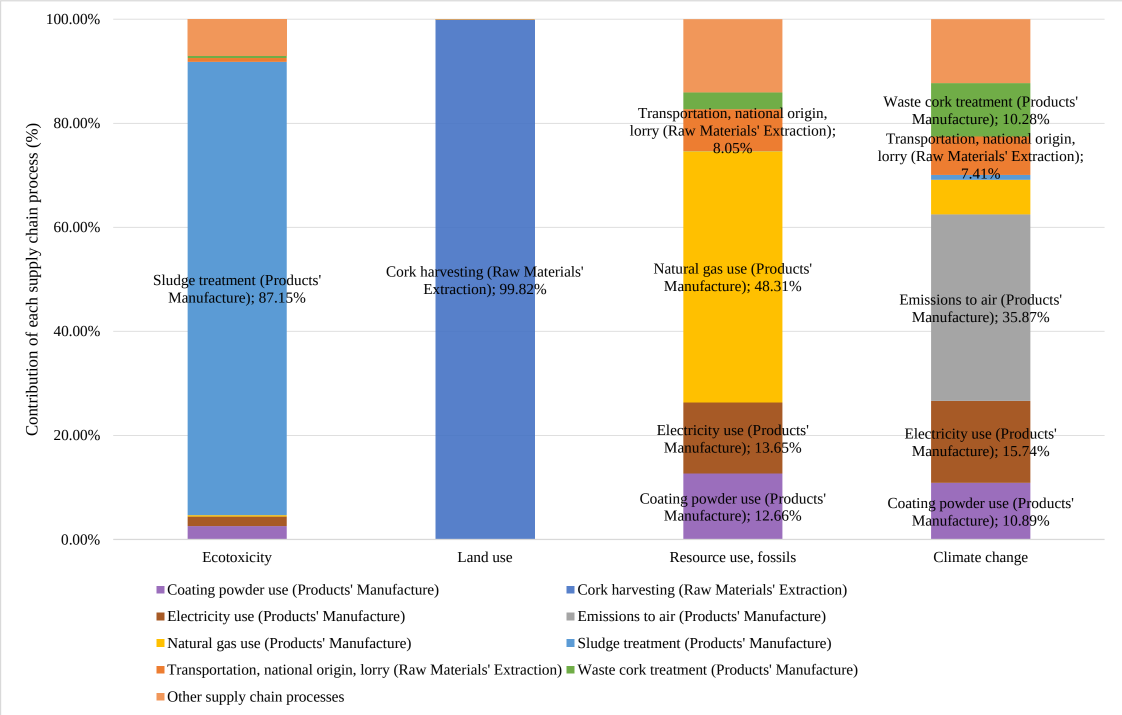


Figure 6.5 – Contribution (based on deterministic characterized results) of the different supply chain processes.

Looking into Figure 6.5, it is possible to conclude that "Sludge treatment" is the most relevant supply chain process associated with Ecotoxicity since the treatment of the sludge generated during the manufacture of natural cork stoppers contributes 87.15% to the characterized result of this impact category. Following the same rationale, "Cork harvesting" is the most relevant supply chain process associated with Land Use since the harvesting of cork from *Quercus suber* trees (commonly called the cork oak) contributes 99.82% to the characterized result of this impact category. Lastly, for the third most relevant environmental impact, Resource Use (Fossils), the most relevant supply chain processes are "Natural gas use", "Electricity use" and "Coating powder use" from the Products' Manufacture life cycle stage, and "Transportation, national origin, lorry" from the Raw Materials' Extraction life cycle stage. Together these four supply chain processes contribute 82.67% to the characterized result of the Resource Use (Fossils) impact category.

In the deterministic life cycle assessment presented, several data sources were used to model the Portuguese natural cork stoppers supply chain in Step 3 and the characterization and normalization methods chosen in Step 2 have an overall robustness below 100% (Table 6.1). Consequently, different parameters used in this assessment are uncertain, namely the inventory, characterization, and normalization factors. Thus, the application of the stochastic LCA analysis is justified (Question 1 of the methodology). The weighting factors are not considered uncertain since equal weighting was the weighting method selected and, as previously explained (Section 6.2 – Question 1), there is no parameter uncertainty associated with this weighting method since no data is required to determine the weights (i.e., all weights are equal to one).

6.3.3 Stochastic LCA

The results of applying Steps 6 to 9 of the methodology to the Portuguese natural cork stoppers supply chain is presented in Table 6.5.

Following the approach utilized by the ecoinvent database, the probability distribution assigned to the uncertain data used to model the Portuguese natural cork stoppers supply chain is the lognormal distribution. For each data point used, the two parameters that characterized this distribution, namely the geometric mean (μ_g) and the geometric standard deviation (σ_g), were defined (Section 6.2 – Step 6). The geometric mean corresponds to the deterministic value used to determine the inventory in the deterministic LCA while the geometric standard deviation is determined based on the basic uncertainty factor and additional uncertainty information attributed to each data point (Section 6.2 – Step 6). For example, in the case of the Products' distribution life cycle stage (Table C.5 available in the Supplementary Material) a geometric mean of 1.70×10^5 kgkm was attributed to "Transport, domestic market, lorry". For the geometric standard deviation, a basic uncertainty parameter of 2.00 was attributed to "Transport, domestic market, lorry" since this is the basic uncertainty parameter associated with transport services (Table C.8 available in the Supplementary material) and the following scores regarding the additional uncertainty information were attributed: 2 – reliability, 2 – completeness, 1 – temporal correlation, 1 – geographical correlation, and 1 – further technological correlation (Table C.9 available in the Supplementary material). A score of 2 was given to completeness (i.e., representative data from >50% of the sites relevant for the market considered), for example, since not all markets to which natural cork stoppers are distributed were considered (i.e., only exporting countries that contributed more than 1% to the total exports were considered).

Table 6.5 – Results of applying Steps 6 to 9 of the methodology to the Portuguese natural cork stoppers supply chain.

Step	Application
Step 6 – Assign a probability distribution to the uncertain parameters	The following distributions were assigned to the uncertain parameters: • Inventory – Lognormal (μ_g, σ_g) • Characterization factors – Uniform (a, b) • Normalization factors – Uniform (a, b)
Step 7 – Simulate the uncertain parameters	Statistical method – Latin Hypercube sampling Stopping criteria – 50,000 iterations
Step 8 – Conduct the impact assessment	The environmental model developed in Microsoft Excel (Step 4) and the @Risk software were used to conduct the impact assessment.
Step 9 – Analyze the stochastic results	The statistically most relevant environmental impacts and supply chain processes are: 1. Land Use – Cork harvesting (Raw Materials' Extraction); 2. Resource Use (Fossils) – Natural gas use (Products' Manufacture); 3. Climate Change – Emissions to air (Products' Manufacture).

Following the approach utilized by Santos et al. (2022b), the probability distribution assigned to the characterization factors and normalization factors is the uniform distribution. For each characterization and normalization factor used, the two parameters that characterized this distribution, namely the minimum (a) and a maximum (b) value, were defined (Section 6.2 – Step 6). Three uncertainty classes were distinguished, and each characterization and normalization factor included in the analysis was assigned to a certain class depending on the knowledge available in the literature. The first class was assigned to low uncertainty characterization and normalization factors classified with a robustness of level I (Table 6.1). In this class, the minimum and maximum values were defined as 5% lower and upper bound around the standard values (i.e., deterministic value), respectively (Santos, et al., 2022b). The second class was assigned to medium uncertainty characterization and normalization factors classified with a robustness of level II (Table 6.1). In this class, the minimum and maximum values were defined as 25% lower and upper bound around the standard values, respectively (Santos, et al., 2022b). Finally, the third class was assigned to high uncertainty characterization and normalization factors classified with a robustness of level III (Table 6.1). In this class, the minimum and maximum values were defined as 50% lower and upper bound around the standard values, respectively. The probability distributions and respective parameters used to characterize each characterization and normalization factor considered are provided in Table 6.6 and Table 6.7, respectively.

Table 6.6 – Probability distributions assigned to the characterization factors of each impact category.

Uncertainty classes	Impact categories	Probability distribution	Parameters
Class 1 (low uncertainty)	Climate Change, Ozone Depletion, and Particulate Matter	Uniform (a, b)	$a = (1 - 0.05) \times CF_{s,c}$ $b = (1 + 0.05) \times CF_{s,c}$
Class 2 (medium uncertainty)	Ionising Radiation, Photochemical Ozone Formation, Acidification, Eutrophication (Terrestrial), Eutrophication (Freshwater), and Eutrophication (Marine)	Uniform (a, b)	$a = (1 - 0.25) \times CF_{s,c}$ $b = (1 + 0.25) \times CF_{s,c}$
Class 3 (high uncertainty)	Human Toxicity (Cancer), Human Toxicity (Non-cancer), Ecotoxicity (Freshwater), Land Use, Water Use, Resource Use (Minerals and Metals), and Resource Use (Fossils)	Uniform (a, b)	$a = (1 - 0.50) \times CF_{s,c}$ $b = (1 + 0.50) \times CF_{s,c}$

Table 6.7 – Probability distributions assigned to the normalization factors of each impact category.

Uncertainty classes	Impact categories	Probability distribution	Parameters
Class 1 (low uncertainty)	Climate Change and Particulate Matter	Uniform (a, b)	$a = (1 - 0.05) \times NF_c$ $b = (1 + 0.05) \times NF_c$
Class 2 (medium uncertainty)	Ozone Depletion, Ionising Radiation, Photochemical Ozone Formation, Acidification, Eutrophication (Terrestrial), Eutrophication (Freshwater), Eutrophication (Marine), Land Use, Water Use, Resource Use (Minerals and Metals), and Resource Use (Fossils)	Uniform (a, b)	$a = (1 - 0.25) \times NF_c$ $b = (1 + 0.25) \times NF_c$
Class 3 (high uncertainty)	Human Toxicity (Cancer), Human Toxicity (Non-cancer), and Ecotoxicity (Freshwater)	Uniform (a, b)	$a = (1 - 0.50) \times NF_c$ $b = (1 + 0.50) \times NF_c$

In this study, the Latin Hypercube sampling was selected because it usually leads to more precise random samples than Monte Carlo sampling (Huijbregts, 1998b) and a total of 50,000 iterations were defined as the stopping criteria for the simulation (Table 6.5).

The impact assessment was conducted using the environmental model developed in Microsoft Excel (Table 6.4) and the @Risk software (Table 6.5), a Monte Carlo simulation add-in for Excel (Palisade Corporation, 2016). The inputs of the environmental model are the inventory, characterization factors, and normalization factors sampled at random in Step 7 and the same weighting factors utilized in Step 4 since these parameters were not considered uncertain (Question 1). A total of 134,938 inputs were generated in each iteration of the simulation. The outputs of this model are similar to the ones defined in Step 4 and include the stochastic characterized, normalized, and weighted results associated with the supply chain under analysis. The Monte Carlo simulation ran for 10 hours, 42 minutes, and 47 seconds. Due to the goal of the life cycle assessment presented (Table 6.3), the interpretation of stochastic results focuses on the identification of the statistically most relevant environmental impacts and supply chain processes (Table 6.5). This identification was accomplished by conducing statistical hypothesis tests (Figure 6.2) in Python (Python Software Foundation, 2022). The significance level defined for these tests was 0.05 (Section 6.2 – Step 9). As previously explained in Section 6.2, three assumptions were verified to identify which statistical hypothesis tests are the most appropriate:

- Independence of observations/variables: The stochastic results involved in the statistical hypothesis tests identified in Figure 6.2 are independent (Section 6.2 – Step 9);
- Normality of data: Since 50,000 iterations were conducted in this study (Table 6.5), the sets of stochastic results are considered to be sufficiently large and this assumption does not need to be verified (Section 6.2 – Step 9);
- Homogeneity of variance: Since a p-value of zero was obtained for all Levene's tests conducted (Section 6.2 – Step 14), which is lower than the significance level defined (0.05), it can be concluded that there is no homogeneity of variance among the stochastic results involved in the statistical hypothesis tests identified in Figure 6.2.

The first null hypothesis identified in Figure 6.2 to determine the statistically most relevant environmental impacts ($H_0\colon \mu_{Aci} = \mu_{CC} = \cdots = \mu_{WU}$) was tested using Welch's ANOVA since the data violates the assumption of homogeneity of variances (Section 6.2 – Step 9). A p-value of zero (i.e., lower than the significance level defined) was obtained in this first statistical hypothesis test which indicates a statistical evidence that the true means of the normalized and weighted results of the impact categories are different. Thus, it can be concluded that the impact categories do not have the same relevance (Figure 6.2). For this reason, the next step in the interpretation of stochastic results is to make pairwise comparisons between the true means of the normalized and weighted results of the different impact categories (Figure 6.2). Since the data violates the assumption of homogeneity of variances, these pairwise comparisons were made using the Games-Howell post-hoc test (Section 6.2 – Step 9). The p-value obtained for each pairwise comparison is presented in Table 6.8.

Table 6.8 – P-value of the Games-Howell test conducted to compare the true means of the normalized and weighted stochastic results of the different impact categories.

i	*j*																**Mean (Pt)**	**CV**
	Aci	CC	Eco	Eut_Fre	Eut_Mar	Eut_Ter	HT_Car	HT_NCar	IR	LU	OD	PM	POF	RU_F	RU_M	WU		
Aci	-	0.001	0.900	0.900	0.900	0.900	0.001	0.900	0.001	0.001	0.001	0.211	0.900	0.001	0.001	0.900	0.18	27.09
CC	-	-	0.900	0.900	0.900	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.900	0.37	9.78
Eco	-	-	-	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	15.02	151.94
Eut_Fre	-	-	-	-	0.900	0.621	0.014	0.472	0.008	0.001	0.020	0.227	0.900	0.001	0.025	0.900	0.28	49.64
Eut_Mar	-	-	-	-	-	0.900	0.416	0.900	0.371	0.001	0.461	0.804	0.900	0.023	0.497	0.900	0.28	73.88
Eut_Ter	-	-	-	-	-	-	0.138	0.900	0.039	0.001	0.251	0.900	0.900	0.001	0.342	0.900	0.13	45.76
HT_Car	-	-	-	-	-	-	-	0.900	0.900	0.001	0.900	0.570	0.010	0.001	0.900	0.900	0.04	62.94
HT_NCar	-	-	-	-	-	-	-	-	0.900	0.001	0.900	0.900	0.900	0.001	0.900	0.900	0.10	82.67
IR	-	-	-	-	-	-	-	-	-	0.001	0.900	0.205	0.003	0.001	0.900	0.900	0.04	0.81
LU	-	-	-	-	-	-	-	-	-	-	0.001	0.001	0.001	0.001	0.001	0.001	7.55	0.49
OD	-	-	-	-	-	-	-	-	-	-	-	0.766	0.020	0.001	0.900	0.900	0.05	61.29
PM	-	-	-	-	-	-	-	-	-	-	-	-	0.663	0.001	0.889	0.900	0.09	46.90
POF	-	-	-	-	-	-	-	-	-	-	-	-	-	0.001	0.030	0.900	0.18	42.39
RU_F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.001	0.900	0.63	3.98
RU_M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.900	0.05	50.47
WU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	1997.78

p-value > 0.05	Indicates a statistical evidence that the true means of the normalized and weighted results of two impact categories are equal, i.e., the two impact categories have the same relevance.
p-value ≤ 0.05	Indicates a statistical evidence that the true means of the normalized and weighted results of two impact categories are not equal, i.e., the two impact categories do not have the same relevance.

According to the Games-Howell test conducted (Table 6.8), the three statistically most relevant impact categories associated with the Portuguese natural cork stoppers supply chain are:

- Land Use – The true mean of the normalized and weighted result of Land Use is (statistically) significantly different than the true mean of the normalized and weighted results of all the other impact categories except for the Ecotoxicity (see the results within the green border in Table 6.8). Interestingly, the true mean of the normalized and weighted result of Ecotoxicity is (statistically) equal to the true mean of the normalized and weighted results of all other impact categories. This can be explained by the high variability of the normalized and weighted stochastic results obtained for this impact category (see coefficient of variation presented in Table 6.8). Consequently, predictions regarding the relative importance of the Ecotoxicity impact category are not reliable. Looking into Table 6.8, it can be concluded that the mean obtained for the Land Use impact category (i.e., 7.55 Pt) is higher than the mean obtained for the other impact categories. Hence, Land Use is the most relevant impact category;
- Resource Use (Fossils) – The true mean of the normalized and weighted result of Resource Use (Fossils) is (statistically) significantly different than the true mean of the normalized and weighted results of all the other impact categories with the exception of the Ecotoxicity (for reasons discussed in the previous point) and Water Use (see the results within the brown border in Table 6.8). The true mean of the normalized and weighted result of Water Use is (statistically) equal to the true mean of the normalized and weighted results of all the other impact categories except for the Land Use. Once again, this can be explained by the high variability of the normalized and weighted stochastic results obtained for this impact category (see coefficient of variation presented in Table 6.8). Consequently, predictions regarding the relative importance of the Water Use impact category are not reliable. Looking into Table 6.8, it can be concluded that the mean obtained for Resource Use (Fossils) (i.e., 0.63 Pt) is higher than the mean obtained for the other impact categories except for Land Use. Hence, Resource Use (Fossils) is the second most relevant impact category;
- Climate Change – The true mean of the normalized and weighted result of Climate Change is (statistically) significantly different than the true mean of the normalized and weighted results of all the other impact categories with the exception of Eutrophication (Freshwater), Eutrophication (Marine), Ecotoxicity, and Water Use (see the results within the orange border in Table 6.8). Even though the Games-Howell test could not find enough evidence to reject the null hypothesis that the true means of the normalized and weighted results of Climate Change and Eutrophication (Freshwater)/(Marine) are equal, one of these categories obtained higher values during the Monte Carlo simulation. Figure 6.6 presents the relative frequencies of the normalized and weighted stochastic results obtained for

Climate Change, Eutrophication (Freshwater), and Eutrophication (Marine). In 92.51% of the iterations conducted, the normalized and weighted stochastic result of Climate Change was higher than 0.07 Pt while in 89.05% and 81.38% of the iterations conducted, the normalized and weighted stochastic result of Eutrophication (Freshwater) and Eutrophication (Marine), respectively, were lower than 0.07 Pt. Hence, it can be concluded that Climate Change is the third most relevant impact category.

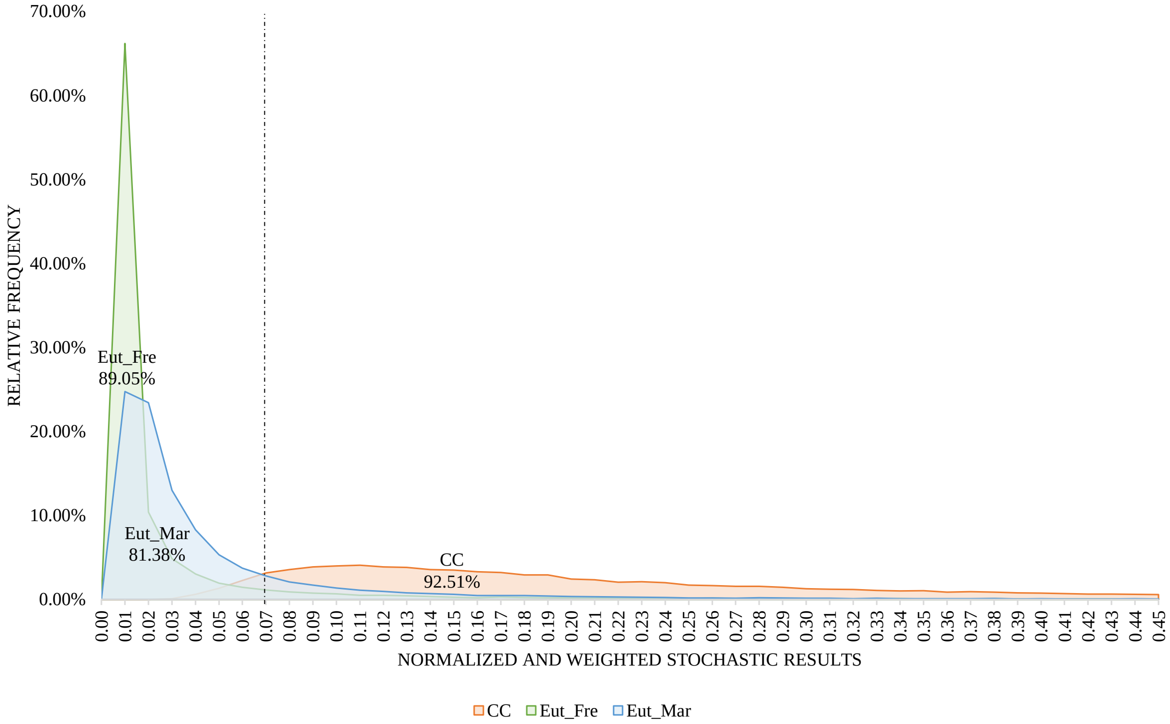


Figure 6.6 – Relative frequencies of the normalized and weighted stochastic results obtained for Climate Change, Eutrophication (Freshwater), and Eutrophication (Marine).

For each of the three statistically most relevant environmental impacts previously identified, the first null hypothesis identified in Figure 6.2 to determine the statistically most relevant supply chain processes (H_0: $\mu_{Process\ 1} = \mu_{Process\ 2} = \cdots$) was tested using Welch's ANOVA since the data violates the assumption of homogeneity of variances (Section 6.2 – Step 9). A p-value of zero (i.e., lower than the significance level defined) was obtained for the three Welch's ANOVA tests which indicates statistical evidence that the true means of the characterized results of the different processes are different. Thus, it can be concluded that the supply chain processes do not have the same relevance (Figure 6.2). For this reason, the next step is to make pairwise comparisons between the true means of the characterized results of the different processes (Figure 6.2). Since the data violates the assumption of homogeneity of variances, these pairwise comparisons were made using the Games-Howell post-hoc test (Section 6.2 – Step 9). The p-value obtained for each pairwise comparison is presented in Table 6.9 (Land Use), Table 6.10 (Resource Use, Fossils), and Table 6.11 (Climate Change) .

Table 6.9 – P-value of the Games-Howell test conducted to compare the true means of the characterized results of different processes in the Land Use impact category.

i	*j* Coating powder use (Products' Manufacture)	Cork harvesting (Raw Materials' Extraction)	Transportation, national origin, lorry (Raw Materials' Extraction)	**Mean (Pt)**	**CV**
Coating powder use (Products' Manufacture)	-	1.00E-03	8.08E-01	1.75E+03	39.49
Cork harvesting (Raw Materials' Extraction)	-	-	1.00E-03	6.18E+06	0.27
Transportation, national origin, lorry (Raw Materials' Extraction)	-	-	-	1.30E+03	118.63

p-value > 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are equal, i.e., the two processes have the same relevance.
p-value ≤ 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are not equal, i.e., the two processes do not have the same relevance.

Table 6.10 – P-value of the Games-Howell test conducted to compare the true means of the characterized results of different processes in the Resource Use (Fossils) impact category.

i	*j* Coating powder use (Products' Manufacture)	Electricity use (Products' Manufacture)	Natural gas use (Products' Manufacture)	Transportation, national origin, lorry (Raw Materials' Extraction)	**Mean (MJ)**	**CV**
Coating powder use (Products' Manufacture)	-	1.00E-03	1.00E-03	1.00E-03	5.20E+03	1.48
Electricity use (Products' Manufacture)	-	-	1.00E-03	1.00E-03	6.33E+03	2.57
Natural gas use (Products' Manufacture)	-	-	-	1.00E-03	1.86E+04	1.19
Transportation, national origin, lorry (Raw Materials' Extraction)	-	-	-	-	1.94E+03	2.76

p-value > 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are equal, i.e., the two processes have the same relevance.
p-value ≤ 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are not equal, i.e., the two processes do not have the same relevance.

Table 6.11 – P-value of the Games-Howell test conducted to compare the true means of the characterized results of different processes in the Climate Change impact category.

i \ *j*	Coating powder use (Products' Manufacture)	Electricity use (Products' Manufacture)	Emissions to air (Products' Manufacture)	Transportation, national origin, lorry (Raw Materials' Extraction)	Waste cork treatment (Products' Manufacture)	**Mean (kg CO_2 eq.)**	**CV**
Coating powder use (Products' Manufacture)	-	1.00E-03	1.00E-03	1.00E-03	1.00E-03	3.41E+02	1.44
Electricity use (Products' Manufacture)	-	-	1.00E-03	1.00E-03	1.00E-03	5.12E+02	2.36
Emissions to air (Products' Manufacture)	-	-	-	1.00E-03	1.00E-03	1.19E+03	1.17
Transportation, national origin, lorry (Raw Materials' Extraction)	-	-	-	-	1.00E-03	1.52E+02	2.53
Waste cork treatment (Products' Manufacture)	-	-	-	-	-	1.63E+02	3.56

p-value > 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are equal, i.e., the two processes have the same relevance.
p-value ≤ 0.05	Indicates a statistical evidence that the true means of the characterized results of two processes are not equal, i.e., the two processes do not have the same relevance.

According to the Games-Howell tests conducted, the three statistically most relevant supply chain processes are:

- Cork harvesting (Land Use) – The true mean of the characterized result of “Cork harvesting” is (statistically) significantly different than the true mean of the characterized results of other processes (see the results within the green border in Table 6.9). Looking into Table 6.9, it can be concluded that the mean obtained for the characterized result of this process (i.e., 6.18E+06 Pt) is higher than the mean obtained for the other supply chain processes. Hence, it can be concluded that “Cork harvesting” is the statistically most relevant supply chain process associated with Land USe. According to this conclusion, to reduce the most relevant environmental issue associated with the Portuguese natural cork stoppers supply chain, the occupation of land with *Quercus suber* trees (commonly called the cork oak) should be better managed. This improved management can be accomplished by increasing the number of trees per hectare or reducing the time between each harvest. These changes would result in more cork generated from the occupation of the same area during the same amount of time (Santos, et al., 2021);

- Natural gas use (Resource Use, Fossils) – The true mean of the characterized result of "Natural gas use" is (statistically) significantly different than the true mean of the characterized results of other processes (see the results within the brown border in Table 6.10). Looking into Table 6.10, it can be concluded that the mean obtained for the characterized result of this process (i.e., 1.86E+04 MJ) is higher than the mean obtained for the other supply chain processes. Hence, it can be concluded that "Natural gas use" is the statistically most relevant supply chain process associated with Resource Use (Fossils). According to this conclusion, to reduce the second most relevant environmental issue associated with the Portuguese natural cork stoppers supply chain, companies that manufacture natural cork stoppers should consider substituting natural gas for renewable energy sources since these are not dependent on fossil fuels;
- Emissions to air (Climate Change) – The true mean of the characterized result of "Emissions to air" is (statistically) significantly different than the true mean of the characterized results of other processes (see the results within the orange border in Table 6.11). Looking into Table 6.11, it can be concluded that the mean obtained for the characterized result of this process (i.e., 1.19E+03 kg CO_2 eq.) is higher than the mean obtained for the other supply chain processes. Hence, it can be concluded that "Emissions to air" is the statistically most relevant supply chain process associated with Climate Change. According to this conclusion, to reduce the third most relevant environmental issue associated with the Portuguese natural cork stoppers supply chain, companies that manufacture natural cork stoppers should consider the establishment of systems to monitor and control emissions and install chemical recovery systems to capture chemicals in exhaust gases (U.K. Government, 2020).

6.3.4 Results' Robustness

Table 6.12 presents the comparison between the deterministic and stochastic results analyzed in Step 5 and Step 9, respectively. According to this comparison, the identification of the most relevant environmental impacts presented in the deterministic LCA (Step 5) is not robust since it does not match the statistically most relevant environmental impacts identified in the stochastic LCA (Step 9) when considering parameter uncertainty. This might explain why the Product Environmental Footprint method indicates that at least three impact categories should be identified as the most relevant ones (Section 6.2 – Step 5) to ensure that, even considering parameter uncertainty, the most relevant impact categories are included. On the other hand, the identification of the most relevant supply chain processes presented in the deterministic LCA (Step 5) is robust since it matches the statistically most relevant supply chain processes identified in the stochastic LCA (Step 9).

Table 6.12 – Comparison between the deterministic and stochastic results.

Deterministic Results	Stochastic Results	
	The statistically most relevant environmental impacts are Land Use, Resource Use (Fossils), and Climate Change (Table 6.8)	The statistically most relevant processes are Cork harvesting (LU), Natural gas use (RU_F), and Emissions to air (CC) (Table 6.9 to Table 6.11)
Most relevant environmental impacts are Ecotoxicity, Land Use, and Resource Use (Fossils) (Figure 6.4)	The deterministic result is not robust	-
Most relevant processes are Cork harvesting (LU), Natural gas use (RU_F), and Emissions to air (CC) (Figure 6.5)	-	The deterministic result is robust

For the supply chain under analysis, it can be inferred that the identification of the most relevant environmental impacts is the most affected by parameter uncertainty since this was the result not considered robust. Normalized and weighted results are used to determine the most relevant environmental impacts while characterized results are used to determine the most relevant processes. Hence, more parameters are involved when determining the most relevant environmental impacts which explains why it is the most affected by parameter uncertainty. For this reason, an effort should be made to improve the reliability of the normalized and weighted results of the different impact categories.

6.4 Discussion

Three additional Monte Carlo simulations were conducted to determine which uncertain parameter (i.e., inventory, characterization factors or normalization factors) most affects the normalized and weighted stochastic results obtained for each impact categories. In each of these additional simulations, only one of the uncertain parameters was simulated. Recall that the weighting factors were not simulated since these were not considered uncertain in this study.

Table 6.13 presents the coefficient of variation (CV) obtained for each impact category in each of the three additional simulations. The CV is a unit-free statistic that can be used to compare the variability of the data from two or more distinct sets of sample data. This statistic is calculated by dividing the standard deviation by the mean. The higher the coefficient of variation, the greater the dispersion between the data points.

For all impact categories, the highest coefficient of variation (highlighted in red) was obtained in the simulation where the inventory was the only parameter considered uncertain. Hence, to improve the reliability of the normalized and weighted results of the different impact categories, the data used to model the supply chain under analysis must be of the best quality. After the inventory, the uncertain parameter (characterization factors or normalization factors) which causes the greatest variation in the normalized and weighted results of the different impact categories varies between impact categories (Table 6.13). For five impact categories (LU, OD, RU_F, RU_M, and WU), the characterization and normalization factors were not considered to have the same robustness (Table 6.1). In this case, the uncertain parameter (characterization factors or normalization factors) with the highest robustness caused the least variation in the normalized and weighted results of these five impact categories. For example, for the category Land Use, the characterization factors were included in Class 3 (high uncertainty) while the normalization factor was included in Class 2 (medium uncertainty) (Table 6.1). Consequently, the lowest coefficient of variation (highlighted in green) was obtained in the simulation where the normalization factor was the only parameter considered uncertain. For this impact category, improving the estimation of the characterization factors should also be a priority to improve the reliability of the normalized and weighted result obtained.

Table 6.13 – Coefficient of variation obtained for each impact category in each of the three additional simulations.

Impact Categories	**Inventory**	**Characterization Factors**	**Normalization Factors**
Aci	$2.80x10^{1}$	$7.50Ex10^{-2}$	$1.44x10^{-1}$
CC	$9.97x10^{0}$	$3.19x10^{-3}$	$2.89x10^{-2}$
Eco	$1.62x10^{2}$	$2.58x10^{-1}$	$2.89x10^{-1}$
Eut_Fre	$4.44x10^{1}$	$1.18x10^{-1}$	$1.44x10^{-1}$
Eut_Mar	$7.19x10^{1}$	$5.80x10^{-2}$	$1.44x10^{-1}$
Eut_Ter	$5.50x10^{1}$	$8.23x10^{-2}$	$1.44x10^{-1}$
HT_Car	$7.01x10^{1}$	$1.02x10^{-1}$	$3.07x10^{-1}$
HT_NCar	$1.18x10^{2}$	$6.88x10^{-2}$	$2.97x10^{-1}$
IR	$7.66x10^{-1}$	$1.00x10^{-1}$	$1.77x10^{-1}$
LU	$3.32x10^{-1}$	$2.91x10^{-1}$	$1.44x10^{-1}$
OD	$5.83x10^{1}$	$2.57x10^{-2}$	$1.47x10^{-1}$
PM	$4.55x10^{1}$	$1.45x10^{-2}$	$2.89x10^{-2}$
POF	$4.30x10^{1}$	$6.67x10^{-3}$	$1.44x10^{-1}$
RU_F	$3.92x10^{0}$	$1.86x10^{-1}$	$1.44x10^{-1}$
RU_M	$5.14x10^{1}$	$2.67x10^{-1}$	$1.44x10^{-1}$
WU	$2.00x10^{3}$	$1.04x10^{2}$	$1.44x10^{-1}$

(red)	Highest CV
(yellow)	Intermediate CV
(green)	Lowest CV

For the other eleven impact categories, the characterization and normalization factors were considered to have the same robustness (Table 6.1). In this case, the simulation where the normalization factors were the only parameter considered uncertain resulted in the second highest coefficient of variation (highlighted in yellow). For these impact categories, improving the estimation of the normalization factor should also be a priority to improve the reliability of the normalized and weighted results obtained.

6.5 Conclusions

Life cycle assessment is frequently used to support green supply chain management, either as a stand-alone decision support tool or in combination with different approaches. Given that parameter uncertainty is always present in an LCA, due to the large amount of data needed in the Inventory Analysis and Impact Assessment steps, it is crucial that this uncertainty is considered when using LCA to assist green supply chain management. Only by considering parameter uncertainty can a robust GSCM strategy be developed. This study proposes an innovative multi-level methodology for integrating parameter uncertainty in LCA. This methodology is valuable to both decision-makers and policy makers since it can be used not only in the field of green supply chain management, but also in other LCA applications. It is also of value to academics conducting research in life cycle assessment since the developed methodology addresses one of the current gaps and challenges for LCA, i.e., uncertainty, identified by Finkbeiner et al. (2014) (Finkbeiner, et al., 2014).

To illustrate how the proposed methodology can be used, this study also presents the application of this methodology to the Portuguese natural cork stoppers supply chain. Detailed analysis of the results revealed that the identification of the most relevant environmental impacts is the most affected by parameter uncertainty. For this reason, an effort should be made to improve the reliability of the normalized and weighted results of the different impact categories. The priority for this improvement is to ensure that the data used to model the supply chain under analysis is of the best quality possible. Furthermore, for four impact categories (LU, RU_F, RU_M, and WU) improving the estimation of the characterization factors should also be a priority while for the remaining 12 impact categories the focus should be on improving the estimation of the normalization factors.

Future studies should illustrate the application of the methodology to other supply chains to determine whether the identification of the most relevant environmental impacts is in fact the most affected conclusion by parameter uncertainty and whether the inventory collected is the parameter which most affects this conclusion, followed by the normalization factors. Future studies should also illustrate the application of the methodology in other LCA applications such as the comparison of products.

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7. Conclusions and Future Research

The fields of sustainable supply chain management and sustainable forest supply chains have received increasing attention in recent years. Thus, the present thesis intends to be an asset to assist sustainable forest supply chains management by presenting a roadmap based on the life cycle assessment approach to guide robust sustainable forest supply chains management. This roadmap includes a detailed approach on how the LCA methodology can be used to analyze the environmental and social performance of forest supply chains, an environmental and social LCA analysis of three specific forest supply chains, and provides managerial insights for forest products' manufactures and other supply chain partners to assist them in improving the environmental and social performance of their activities and, consequently, improve the environmental and social performance of their supply chain. Moreover, it includes a multi-level methodology for integrating parameter uncertainty into the environmental and social analysis of supply chains to support the development of a robust sustainable supply chain management strategy.

The most relevant contributions of this doctoral thesis are presented below together with the main limitations of the work conducted and future research that can be carried out based on these limitations.

7.1 Main Contribution

Throughout this thesis, several contributions were made, each of which is listed in the corresponding chapter. In summary, the main contributions of this doctoral thesis are:

- A systematic review of literature that considers forest supply chains and at least one of the sustainability dimensions to understand how the sustainability of different forest supply chains has been assessed in different studies. This review is significantly different from other reviews in the field as it considers different types of forest supply chains (while other reviews focus on biomass supply chains) and classifies the reviewed studies according to several criteria rarely considered such as stakeholders' involvement in the supply chain's assessment process;
- An environmental and social life cycle assessments of three forest supply chains to illustrate how the environmental and social performance of these supply chains should be analyzed. The results of these assessments can be used by companies from the forest sector to benchmark the environmental and social performance of their supply chain;
- The identification of the most relevant potential environmental/social impacts associated with the three forest supply chains analyzed and the most relevant forest supply chain processes to determine whether there is commonality. The most relevant potential environmental/social impacts and supply chain processes are key to develop an effective strategy for enhancing the overall environmental and social performance of forest supply chains;

- The proposal of a set of recommendations for different forest supply chain partners, such as forest products' manufactures, to assist them in improving their environmental and social performance and, consequently, the environmental and social performance of their supply chains;
- The development of an innovative methodology with clear guidelines on how to integrate in a life cycle assessment the uncertainty associated with the parameters used in the *Inventory Analysis* and the *Impact Assessment* steps of an LCA. It provides an easily reproducible systematic procedure to address the uncertainty related to LCA parameters. This methodology will contribute to an increase on the rate of LCA studies that report uncertainty analysis;
- The application of the aforementioned methodology to two case studies. By applying the developed methodology to different case studies, this doctoral thesis shows how the methodology can be used as part of the decision-making process and how it can assist decision-makers to have robust LCA results and, consequently, more informed decisions. Besides being used in the field of sustainable supply chain management, the proposed methodology can also be used in different LCA applications, such as the comparison of specific goods or services, which makes it valuable to decision-makers, policy makers, and also academics conducting research in life cycle assessment.

7.2 Limitation and Future Work

This doctoral thesis is composed by a set of research developments that were peer reviewed by international journals' reviewers and the scientific committee of different international conferences. However, like all scientific works, there are limitations associated with the work conducted throughout this thesis that must be overcome in future works.

The main limitation of the literature review conducted is a consequence of the systematic methodology followed and relates to the fact that not all studies which consider forest supply chains and at least one of the sustainability dimensions were reviewed due to the keywords and database selected. Nevertheless, the overall results obtained in this review can be extrapolated because they are in agreement with previous reviews in the area namely the one conducted by Cambero and Sowlati (2014). Given that this review revealed LCA is the most used methodology to analyze the environmental aspects associated with forest supply chains and is also a promising approach to analyze the social aspects associated with these supply chains, as future work it would be interesting to conduct a literature review focused specifically on LCA application to different forest supply chains to identify specific research gaps.

In the case of the environmental and social life cycle assessments of three forest supply chains, the main limitation is mostly related to some of the assumptions made in the *Inventory Analysis* step. For example, it was assumed that the end-of-life destinations of natural cork stoppers are similar to the end-of-life destinations of particle boards due to lack of information regarding the end-of-life of cork products. Wood and cork have different components and, consequently, some of the emissions that depend on the composition of the waste are different. Notwithstanding, these assumptions did not significantly affect the results obtained. Future research should extend the environmental and social analysis conducted to include more forest supply chains. This will allow determining whether the conclusions hold for other products or regions. For example, relevant potential environmental/social impacts common across different forest supply chains should always be included in future LCA studies considering forest products.

Concerning the methodology developed for integrating parameter uncertainty into LCA studies, the main limitation is mostly associated with its application. Even though this methodology can be applied to both environmental and social life cycle assessments, its applicability was demonstrated using case studies focused on traditional life cycle assessment since this analysis is at a much higher level of operationalization than social life cycle assessment. Future studies should illustrate the application of the developed methodology in social life cycle assessments. In addition, this doctoral thesis only showed the use of this methodology to support micro-level decisions using the *Product Environmental Footprint* method. Forthcoming research should illustrate the use of the developed methodology in other LCA applications, such as macro-level decision support and accounting, and should also consider the application of this methodology to various impact assessment methods. This application could reveal which method has the least uncertainty associated when calculating potential impacts and could help practitioners select the impact assessment method. Finally, one of the parameters used in the Impact Assessment step was not consider uncertain in this doctoral thesis (i.e., weighting factors). Consequently, the uncertainty of these parameters should be investigated in future research.

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Appendix A. Supplementary Material for Chapter 3

A.1. Environmental Assessment

This appendix presents the data used to model the three life cycles.

Raw Materials' Extraction

Table A.1 – Quantity of each tree species in each subregion of Portugal.

Source	System 1 (*Eucalyptus globulus*)		System 2 (*Quercus suber*)		System 3 (*Pinus pinaster*)	
	Thousand hectares	Percentage	Thousand hectares	Percentage	Thousand hectares	Percentage
Subregions	**845.01**	**100.00%**	**719.94**	**100.00%**	**713.25**	**100.00%**
Alto Minho	25.45	3.01%	0.13	0.02%	24.28	3.40%
Alto Tâmega	0.97	0.11%	0	0.00%	39.54	5.54%
Área Metropolitana do Porto	63.78	7.55%	0	0.00%	11.63	1.63%
Ave	18.38	2.18%	0	0.00%	13	1.82%
Cávado	19	2.25%	0.08	0.01%	13.92	1.95%
Douro	2.68	0.32%	0.97	0.13%	36.27	5.09%
Tâmega e Sousa	29.63	3.51%	0.03	0.00%	16.31	2.29%
Terras de Trás-os-Montes	4.23	0.50%	14.56	2.02%	24.92	3.49%
Beira Baixa	65.24	7.72%	20.94	2.91%	72.54	10.17%
Beiras e Serra da Estrela	7.15	0.85%	4.33	0.60%	61.42	8.61%
Médio Tejo	71.04	8.41%	15.49	2.15%	51.81	7.26%
Oeste	36.48	4.32%	0.57	0.08%	17.26	2.42%
Região de Aveiro	56.62	6.70%	0	0.00%	18.89	2.65%
Região de Coimbra	119.58	14.15%	0.05	0.01%	87.77	12.31%
Região de Leiria	50.13	5.93%	0.13	0.02%	66.92	9.38%
Viseu Dão Lafões	33.5	3.96%	0.1	0.01%	83.36	11.69%
Área Metropolitana de Lisboa	12.52	1.48%	18.21	2.53%	13.54	1.90%
Alentejo Central	21.78	2.58%	179.85	24.98%	0.97	0.14%
Alentejo Litoral	53.92	6.38%	148.99	20.69%	29.66	4.16%
Alto Alentejo	43.59	5.16%	113.92	15.82%	11.72	1.64%
Baixo Alentejo	12.3	1.46%	73.24	10.17%	0.75	0.11%
Lezíria do Tejo	68.01	8.05%	93.36	12.97%	12	1.68%
Algarve	29.03	3.44%	34.99	4.86%	4.77	0.67%

Table A.2 – Quantity of raw material sourced from the different subregions for each of the three systems.

Source	System 1		System 2		System 3	
	Quantity of pulpwood (m^3)	Distance by truck (km)	Quantity of raw cork (kg)	Distance by truck (km)	Quantity of roundwood (m^3)	Distance by truck (km)
Subregions	**1721.43**	**4150.60**	**14649.29**	**4764.00**	**436.37**	**4810.60**
Alto Minho	51.85	195.00	2.65	81.90	14.85	200.00
Alto Tâmega	1.98	241.00	0.00	154.00	24.19	152.00
Área Metropolitana do Porto	129.93	120.00	0.00	0.00	7.12	124.00
Ave	37.44	179.00	0.00	57.70	7.95	174.00
Cávado	38.71	178.00	1.63	58.20	8.52	183.00
Douro	5.46	186.00	19.74	98.70	22.19	97.10
Tâmega e Sousa	60.36	151.00	0.61	42.20	9.98	145.00
Terras de Trás-os-Montes	8.62	289.00	296.27	211.00	15.25	200.00
Beira Baixa	132.91	137.00	426.09	255.00	44.38	171.00
Beiras e Serra da Estrela	14.57	138.00	88.11	234.00	37.58	125.00
Médio Tejo	144.72	95.50	315.19	202.00	31.70	182.00
Oeste	74.32	169.00	11.60	270.00	10.56	255.00
Região de Aveiro	115.34	63.40	0.00	69.30	11.56	84.90
Região de Coimbra	243.61	0.00	1.02	120.00	53.70	91.60
Região de Leiria	102.12	74.10	2.65	183.00	40.94	163.00
Viseu Dão Lafões	68.25	91.60	2.03	124.00	51.00	0.00
Área Metropolitana de Lisboa	25.51	203.00	370.54	309.00	8.28	290.00
Alentejo Central	44.37	244.00	3659.57	361.00	0.59	341.00
Alentejo Litoral	109.84	312.00	3031.64	419.00	18.15	399.00
Alto Alentejo	88.80	172.00	2318.04	290.00	7.17	260.00
Baixo Alentejo	25.06	344.00	1490.28	442.00	0.46	431.00
Lezíria do Tejo	138.55	137.00	1899.68	244.00	7.34	224.00
Algarve	59.14	431.00	711.97	538.00	2.92	518.00

Table A.3 – Inventory data for the life cycle stage Raw Materials' Extraction considered in System 1.

Input/Output	Quantity	Unit
Input		
Resources		
Carbon dioxide, in air	1.97E+03	kg
Energy, gross calorific value, in biomass	2.92E+04	MJ
Wood, hard, standing	1.10E+00	m^3
Occupation, forest, intensive	5.81E+02	m2a
Transformation, from forest, intensive	5.81E+00	m^2
Transformation, to forest, intensive	5.81E+00	m^2
Materials/Fuels		
Diesel	6.48E+01	MJ
Lubricating oil	3.00E-01	kg
Power sawing	2.50E-01	hr
Transport, truck	1.14E+05	kgkm
Output		
Product		
Pulpwood	1.00	m^3
Emissions to air		
Carbon dioxide, biogenic	3.28E+02	kg
Dinitrogen monoxide	1.97E-03	kg
Methane, biogenic	2.87E-01	kg
Particulates, < 2.5 um	9.90E-01	kg
Particulates, > 10 um	6.60E-01	kg
Particulates, > 2.5 um, and < 10um	8.25E-01	kg

Table A.4 – Inventory data for the life cycle stage Raw Materials' Extraction considered in System 2.

Input/Output	Quantity	Unit
Input		
Resources		
Carbon dioxide, in air	1.08E+01	kg
Energy, gross calorific value, in biomass	1.17E+02	MJ
Wood, hard, standing	6.01E-03	m^3
Occupation, forest, intensive	6.83E+01	m2a
Transformation, from forest, intensive	6.83E-01	m^2
Transformation, to forest, intensive	6.83E-01	m^2
Materials/Fuels		
Transport, truck	3.51E+02	kgkm
Output		
Product		
Raw cork	1.00	kg

Table A.5 – Inventory data for the life cycle stage Raw Materials' Extraction considered in System 3.

Input/Output	Quantity	Unit
Input		
Resources		
Carbon dioxide, in air	8.88E+02	kg
Energy, gross calorific value, in biomass	1.00E+04	MJ
Wood, hard, standing	1.00E+00	m^3
Occupation, forest, intensive	2.29E+03	m2a
Transformation, from forest, intensive	2.29E+01	m^2
Transformation, to forest, intensive	2.29E+01	m^2
Materials/Fuels		
Diesel	1.58E+01	MJ
Lubricating oil	1.27E-01	kg
Power sawing,	1.06E-01	hr
Transport, truck	7.51E+04	kgkm
Output		
Product		
Roundwood	1.00	m^3

Products' Manufacture

Table A.6 – Inventory data for the life cycle stage Products' Manufacture considered in System 1.

Input/Output	Quantity	Unit
Input		
Resources		
Water, cooling	3.61E-02	m^3
Water	4.99E-02	m^3
Materials/Fuels		
Alkylketene dimer sizing agent	2.00E-03	kg
Aluminium sulfate, powder	1.35E-05	kg
Calcium carbonate	9.42E-05	kg
Carbon dioxide, liquid	1.14E-03	kg
Chemical, inorganic	3.14E-05	kg
Chemical, organic	2.52E-03	kg
Chlorine dioxide	3.12E-04	kg
Diesel	7.19E-06	kg
Digester sludge	-1.10E-04	kg
Electricity	4.01E-01	kWh
Hard coal	7.02E-03	kg
Heavy fuel oil	2.87E-02	kg
Hydrochloric acid	3.39E-05	kg
Hydrogen peroxide	4.41E-03	kg
Kaolin	1.19E-01	kg
Light fuel oil	6.75E-05	kg
Lignite briquettes	7.89E-02	MJ
Lime	1.19E-01	kg
Magnesium oxide	6.58E-05	kg
Magnesium sulfate	2.46E-03	kg
Malusil	4.62E-05	kg
Methanol	1.25E-03	kg
Natural gas	4.37E-02	m^3
Nitrogen, liquid	1.30E-04	kg
Oxygen, liquid	1.39E-02	kg
Ozone, liquid	8.06E-06	kg
Potato starch	3.80E-02	kg
Pulpwood	3.25E-03	m^3
Quicklime	5.04E-03	kg
Sodium chlorate, powder	1.44E-02	kg
Sodium chloride, powder	2.30E-04	kg
Sodium hydroxide	2.23E-02	kg
Sodium hypochlorite	5.46E-06	kg
Sodium sulfate	1.24E-05	kg
Sulfur	2.92E-08	kg
Sulfur dioxide, liquid	1.14E-03	kg
Sulfuric acid	1.78E-02	kg

Input/Output	Quantity	Unit
Output		
Product		
UWF paper	1	kg
Emissions to air		
Carbon dioxide	1.87E+00	kg
Carbon monoxide	6.84E-03	kg
Nitrogen oxides	1.76E-03	kg
Particulates	1.00E-03	kg
Sulfur dioxide	5.26E-04	kg
Other emissions	1.58E-03	kg
Radioactive materials	4.35E-04	kBq
Water	2.19E-02	m^3
Emissions to water		
Chemical Oxygen Demand	1.72E-02	kg
Dissolved Organic Carbon	6.36E-03	kg
Total Organic Carbon	6.36E-03	kg
Suspended solids	1.19E-03	kg
Water	6.41E-02	m^3
Other emissions	1.43E-03	kg
Waste to treatment		
Ash	2.54E-03	kg
Limestone residue	5.83E-04	kg
Municipal solid waste	1.53E-02	kg
Wood ash mixture	2.74E-02	kg
Sludge	9.15E-03	kg
Other wastes	9.61E-04	kg

Table A.7 – Inventory data for the life cycle stage Products' Manufacture considered in System 2.

Input/Output	Quantity	Unit
Input		
Resources		
Water	2.18E-01	m^3
Materials/Fuels		
Anticorrosive	1.74E-04	kg
Antifouling mix	1.74E-04	kg
Citric acid	6.30E-03	kg
Electricity	4.94E+00	kWh
Enzyme catalyst for H2O2	4.00E-04	kg
Ethyl alcohol	4.30E-02	L
H2O2	3.36E-01	kg
Lubricating oil	6.20E-02	L
NaCl	3.50E-03	kg
NaHSO4	6.30E-03	kg
NaOH	1.40E-01	kg
Natural gas	2.01E+00	m^3
Paint	5.00E-04	kg
Paraffin	5.90E-02	kg
Raw cork	2.00E+01	kg
Silicone oil	1.20E-02	kg
SO2	4.00E-03	kg
Water based coverings	2.00E-01	kg
Output		
Product		
Natural cork stoppers	4	kg
Emissions to air		
Carbon dioxide	4.33E+03	g
Nitrogen oxides	5.71E+00	g
Carbon monoxide	2.24E+00	g
NMVOC	1.77E+00	g
Methane	7.71E-02	g
Other emissions	2.32E-01	g
Waste to treatment		
Cork residues	1.60E+01	kg
Sludge	5.34E-01	kg
Wastewater	1.14E-01	m^3

Table A.8 – Inventory data for the life cycle stage Products' Manufacture considered in System 3.

Input/Output	Quantity	Unit
Input		
Resources		
Water, cooling	6.13E-02	m^3
Water	1.95E-03	m^3
Materials/Fuels		
Aluminium sulfate	1.55E+00	kg
Chemical, organic	3.84E-01	kg
Electricity	1.03E+02	kWh
Heat, natural gas	1.97E+02	MJ
Heat, heavy fuel oil	2.47E+01	MJ
Heat, light fuel oil	2.22E+01	MJ
Lubricating oil	2.49E-01	kg
Melamine formaldehyde resin	9.76E+00	kg
Methylene diphenyl diisocyanate	3.19E+00	kg
Paraffin	2.99E+00	kg
Phenolic resin	1.20E+00	kg
Roundwood	1.71E+00	m^3
Tap water	1.74E+02	kg
Urea formaldehyde resin	4.43E+01	kg
Urea, as N	1.93E-01	kg
Output		
Product		
Particle board	1.00	m^3
Emissions to air		
Carbon dioxide	1.68E+02	kg
NMVOC	4.01E-01	kg
Carbon monoxide	3.29E-01	kg
Nitrogen oxides	1.98E-01	kg
Formaldehyde	9.13E-02	kg
Other emissions	1.74E-01	kg
Waste to treatment		
Biowaste	4.76E+00	kg
Hazardous waste	8.29E-02	kg
Wastewater	7.03E-02	m^3
Wood ash mixture	7.84E-01	kg
Waste wood	2.68E+02	kg

Products' Distribution

Table A.9 – Quantities and distances considered for the life cycle stage Products' Distribution given the domestic markets of the three systems.

Market	Share	System 1		System 2		System 3	
		Quantity of UWF paper (kg)	Distance by truck (km)	Quantity of natural cork stoppers (kg)	Distance by truck (km)	Quantity of particle boards (m^3)	Distance by truck (km)
Domestic Market	**100%**	**41,886.77**	**4,150.60**	**2,685.80**	**4764.00**	**129.92**	**4810.60**
Alto Minho	2.44%	1023.39	195.00	65.62	81.90	3.17	200.00
Alto Tâmega	0.94%	393.51	241.00	25.23	154.00	1.22	152.00
Área Metropolitana do Porto	17.56%	7354.67	120.00	471.59	0.00	22.81	124.00
Ave	4.25%	1778.18	179.00	114.02	57.70	5.52	174.00
Cávado	4.09%	1714.47	178.00	109.93	58.20	5.32	183.00
Douro	2.05%	857.54	186.00	54.99	98.70	2.66	97.10
Tâmega e Sousa	4.32%	1809.55	151.00	116.03	42.20	5.61	145.00
Terras de Trás-os-Montes	1.17%	491.25	289.00	31.50	211.00	1.52	200.00
Beira Baixa	0.89%	372.28	137.00	23.87	255.00	1.15	171.00
Beiras e Serra da Estrela	2.36%	986.56	138.00	63.26	234.00	3.06	125.00
Médio Tejo	2.20%	922.34	95.50	59.14	202.00	2.86	182.00
Oeste	3.62%	1515.39	169.00	97.17	270.00	4.70	255.00
Região de Aveiro	3.70%	1548.22	63.40	99.27	69.30	4.80	84.90
Região de Coimbra	4.59%	1923.34	0.00	123.33	120.00	5.97	91.60
Região de Leiria	2.94%	1231.54	74.10	78.97	183.00	3.82	163.00
Viseu Dão Lafões	2.67%	1118.68	91.60	71.73	124.00	3.47	0.00
Área Metropolitana de Lisboa	28.16%	11795.22	203.00	756.32	309.00	36.59	290.00
Alentejo Central	1.66%	696.90	244.00	44.69	361.00	2.16	341.00
Alentejo Litoral	0.98%	409.32	312.00	26.25	419.00	1.27	399.00
Alto Alentejo	1.18%	495.35	172.00	31.76	290.00	1.54	260.00
Baixo Alentejo	1.26%	529.56	344.00	33.96	442.00	1.64	431.00
Lezíria do Tejo	2.47%	1034.33	137.00	66.32	244.00	3.21	224.00
Algarve	4.50%	1885.17	431.00	120.88	538.00	5.85	518.00

Table A.10 – Quantities and distances considered for the life cycle stage Products' Distribution given the international markets of System 1.

Market	Share	Quantity of UWF paper (kg)	Distance by truck (km)	Distance by ship (km)
International Market	**83.08 %**	**405,391.88**	**18,050.00**	**29,180.11**
France	12.74%	62165.29	1586.00	-
Germany	10.93%	53333.33	2633.00	-
United States of America	10.07%	49136.93	110.00	5985.66
Turkey	9.56%	46648.37	397.00	4215.15
Spain	8.67%	42305.58	529.00	-
Italy	7.77%	37914.00	2361.00	-
United Kingdom	4.92%	24007.32	91.00	1783.48
Egypt	4.41%	21518.76	185.00	4533.70
Algeria	3.88%	18932.60	50.00	1587.16
Netherlands	2.83%	13809.09	2083.00	-
Belgium	1.82%	8880.76	1909.00	-
Morocco	1.72%	8392.80	135.00	824.14
Switzerland	1.45%	7075.33	1861.00	-
Saudi Arabia	1.24%	6050.63	474.00	10250.82
Greece	1.07%	5221.10	3646.00	-

Table A.11 – Quantities and distances considered for the life cycle stage Products' Distribution given the international markets of System 2.

Market	Share	Quantity of natural cork stoppers (kg)	Distance by truck (km)	Distance by ship (km)
International Market	**93.47%**	**228.12**	**10,566.00**	**70,564.90**
United States of America	25.91%	63.23	75.00	5956.03
France	25.38%	61.94	1588.00	-
Spain	10.38%	25.33	604.00	-
Italy	8.44%	20.60	2363.00	-
Mexico	4.29%	10.47	394.00	8502.53
United Kingdom	3.83%	9.35	57.00	1674.21
Chile	3.76%	9.18	125.00	12739.91
Germany	3.03%	7.39	2635.00	-
Australia	2.95%	7.20	285.00	19868.26
Argentina	2.42%	5.91	45.00	10106.36
South Africa	1.57%	3.83	532.00	11717.60
Switzerland	1.51%	3.69	1863.00	-

Table A.12 – Quantities and distances considered for the life cycle stage Products' Distribution given the international markets of System 3.

Market	Share	Quantity sold of particle boards (cubic meters)	Distance by truck (km)	Distance by ship (km)
International Market	**93.70%**	**87.89**	**7,632.00**	**8,450.68**
Spain	55.88%	52.41	601.00	-
United Kingdom	20.65%	19.37	179.00	1674.21
Morocco	8.52%	7.99	216.00	824.14
Ireland	2.27%	2.13	140.00	1420.48
France	2.22%	2.08	1495.00	-
Israel	1.62%	1.52	189.00	4531.84
Italy	1.51%	1.42	2270.00	-
Germany	1.03%	0.97	2542.00	-

Products' End-of-Life

Table A.13 – Quantities considered in System 1 for the life cycle stage Products' End-of-Life.

End-of-life	Quantity of UWF paper (kg)
Recycling	349,247.14
Combustion with energy recovery	355,01.92
Landfill	145,091.35

Table A.14 – Quantities considered in System 2 for the life cycle stage Products' End-of-Life.

End-of-life	Quantity of natural cork stoppers (kg)
Recycling	488.58
Combustion with energy recovery	464.15
Landfill	1,977.12

Table A.15 – Quantities considered in System 3 for the life cycle stage Products' End-of-Life.

End-of-life	Quantity of particle boards (cubic meters)
Recycling	42.61
Combustion with energy recovery	40.48
Landfill	172.45

A.2. Economic Assessment

This appendix presents the economic assessment of the three products.

Table A.16 – Net present value considered in System 1.

Year	Quantity (kg)	Product Sales (€)	EBITDA (€)	Net Present value (€)
1	-	-	-	-
2	-	-	-	-
…	…	…	…	…
11	-	-	-	-
12	-	-	-	-
13	5519.17	3604.70	760.59	636.46
14	5519.17	3604.70	760.59	627.80
…	…	…	…	…
107	5519.17	3604.70	760.59	175.49
108	5519.17	3604.70	760.59	173.10
Total	**529,840.41**	**-**	**-**	**34,213.09**

Table A.17 – Net present value considered in System 2.

Year	Quantity (kg)	Product Sales (€)	EBITDA (€)	Net Present value (€)
1	-	-	-	-
2	-	-	-	-
…	…	…	…	…
42	-	-	-	-
43	-	-	-	-
44	46.51	170.69	15.19	8.31
45	46.51	170.69	15.19	8.20
…	…	…	…	…
105	46.51	170.69	15.19	3.60
106	46.51	170.69	15.19	3.55
Total	**2,929.86**	**-**	**-**	**353.13**

Table A.18 – Net present value considered in System 3.

Year	Quantity (m^3)	Product Sales (€)	EBITDA (€)	Net Present value (€)
1	-	-	-	-
2	-	-	-	-
…	…	…	…	…
39	-	-	-	-
40	-	-	-	-
41	2.80	621.49	79.55	45.35
42	2.80	621.49	79.55	0.03
…	…	…	…	…
119	2.80	621.49	79.55	79.55
120	2.80	621.49	79.55	79.55
Total	**223.72**	**-**	**-**	**6,093.68**

Appendix B. Supplementary Material for Chapter 4

B.1. Primary Data

This appendix presents the primary data used to model the three supply chains under study considering the four life cycle stages included within the systems' boundary defined: Raw Material Acquisition, Manufacturing, Distribution, and End-of-Life.

Please consider the following abbreviations when consulting this appendix.

Regions: PRT – Portugal, AGR – Algeria, ARG – Argentina, AUS – Australia, AUT – Austria, BEL – Belgium, BRA – Brazil, BGR – Bulgaria, CAN – Canada, CHL – Chile, CHN – China, COL – Colombia, CYP – Cyprus, DNK – Denmark, EGY – Egypt, FIN – Finland, FRA – France, DEU – Germany, GRC – Greece, HUN – Hungary, IND – India, IRL – Ireland, ISR – Israel, ITA – Italy, JPN – Japan, JOR – Jordan, KWT – Kuwait, LVA – Latvia, LTU – Lithuania, LUX – Luxembourg, MYS – Malaysia, MEX – Mexico, MAR – Morocco, NLD – Netherlands, PER – Peru, POL – Poland, RUS – Russia Federation, SAU – Saudi Arabia, SVK – Slovakia, ZAF – South Africa, KOR – South Korea, ESP – Spain, SWE – Sweden, CHE – Switzerland, TWN – Taiwan, THA – Thailand, TTO – Trinidad and Tobago, TUN – Tunisia, TUR – Turkey, UGA – Uganda, ARE – United Arab Emirates, GBR – United Kingdom, USA – United States of America, VNM – Vietnam, XAC – South Central Africa

Portuguese UWF paper supply chain

Table B.1 – Inventory data for the life cycle stage Raw Material Acquisition (Pulpwood = 3.25 m^3).

Process	Quantity	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [4][5][6]
Pulpwood harvesting	3.25E+00 [7]	m3	6.55E+01 [8]	frs	PRT 83.16%, FRA 0.85%, ESP 14.96%, USA 0.91%
Transportation, national origin, lorry	3.05E+05	kgkm	6.08E+01 [9][2]	otp	PRT 100.00%
Transportation, national origin, ship	3.49E+04	kgkm	4.47E-01 [9][2]	wtp	PRT 100.00%
Transportation, international origin, lorry	2.50E+05	kgkm	4.98E+01 [9][2]	otp	FRA 14.46%, ESP 84.47%, USA 1.07%
Transportation, international origin, ship	1.45E+05	kgkm	1.86E+00 [9][2]	wtp	USA 100%

[1] All costs collected in this study were converted into dollars for the year of 2011 since the SHDB considers 2011 as a reference year. This conversion was accomplished by exchanging the euros into dollars [1] and then adjusting this result for inflation to determine the value of those dollars in 2011 [2].

[2] For all transportation included in this study, it was considered that each kilogram transported per kilometer cost, in 2005, around 1.40E-04 euros [9] (i.e. $ 2.00E-04 in 2011 [1][2]) using road transportation and around 9.00E-06 euros [9] (i.e. $ 1.28E-05 in 2011 [1][2]) using maritime transportation.

Table B.2 – Inventory data for the life cycle stage Manufacturing (Sulfate Pulp = 35.00 kg).

Process	Quantity [10][11]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [12][13][14][6]
Aluminum sulfate production	1.35E-02	kg	2.32E-02	crp	PRT 39.37%, BEL 4.66%, CHN 1.82%, FRA 0.87%, NLD 1.88%, ESP 47.05%, TUR 4.24%
Calcium carbonate production	9.42E-02	kg	1.71E-01	crp	PRT 39.37%, BEL 2.29%, FRA 7.50%, DEU 3.21%, ITA 3.80%, ESP 41.21%, VNM 1.55%
Chlorine dioxide production	3.12E-01	kg	8.66E-01	crp	PRT 39.37%, FRA 13.35%, ESP 43.80%, SWE 2.81%
Diesel production	7.19E-03	kg	1.00E-02	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%,FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64%, ESP 48.20%, ARE 1.03%
Electricity production	1.07E+00	kWh	1.42E-01	ely	PRT 92.50%, ESP 7.50%
Heavy fuel oil extraction	4.88E-01	kg	2.84E-01	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%,FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64%, ESP 48.20%, ARE 1.03%
Hydrochloric acid production	3.39E-02	kg	3.07E-02	crp	PRT 39.37%, BEL 5.85%, FRA 1.52%, DEU 3.17%, NLD 4.24%, ESP 40.19, SWE 5.65%
Hydrogen peroxide production	1.76E-01	kg	6.15E-02	crp	PRT 39.37%, BEL 8.40%, FRA 2.15%, ISR 4.88%, NLD 9.14%, ESP 29.32%, GBR 6.49%
Light fuel oil extraction	6.75E-02	kg	8.01E-02	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%,FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64%, ESP 48.20%, ARE 1.03%
Lime production	5.25E-03	kg	3.18E-04	crp	PRT 90.40%, ITA 0.16%, ESP 9.32%
Magnesium oxide production	6.58E-02	kg	1.23E-01	nmm	PRT 90.40%, AUT 0.15%, BEL 0.11%, CHN 0.60%, GRC 0.86%, NLD 1.10%, ESP 6.06%, GBR 0.47%
Magnesium sulfate production	5.79E-03	kg	5.71E-03	crp	PRT 39.37%, CHN 2.75%, DEU 24.06%, GRC 3.51%, IND 4.58%, ITA 0.78%, ESP 24.08%
Malusil production	4.62E-02	kg	1.47E-01	crp	PRT 39.37%, BEL 2.53%, BRA 1.32%, FRA 16.44%, DEU 7.05%, ITA 5.04%, LUX 0.99%, NLD 0.64%, POL 5.54%, ESP 18.84%, GBR 1.55%
Natural gas extraction, high pressure	8.90E-01	m3	1.23E+00	gas	ESP 100%
Oxygen production, liquid	5.03E-01	kg	7.61E-02	crp	PRT 39.37%, ITA 3.86%, ESP 56.38%
Ozone production, liquid	8.06E-03	kg	2.03E-03	crp	PRT 39.37%, AUT 1.32%, BEL 0.95%, DNK 3.29%, FRA 1.92%, DEU 8.75%, IRL 0.82%, ITA 13.59%, MYS 0.84%, NLD 3.43%, ESP 24.77%, USA 0.78%
Quicklime production	6.56E-02	kg	7.12E-03	nmm	PRT 90.40%, FRA 0.14%, ESP 9.46%
Sodium chlorate production	1.08E-01	kg	1.73E+00	crp	PRT 39.37%, CAN 11.79%, FRA 31.09%, ESP 17.25%
Sodium hydroxide production	5.54E-01	kg	6.15E-01	crp	PRT 39.37%, BEL 5.98%, CHN 3.48%, FRA 6.85%, KWT 2.39%, NLD 3.51%, POL 9.90%, RUS 12.91%, ESP 12.68%, SWE 0.62%, TWN 0.65%, GBR 1.25%
Sodium hypochlorite production	5.46E-03	kg	1.87E-02	crp	PRT 39.37%, BEL 4.29%, CHN 12.57%, FRA 5.89%, DEU 10.65%, ITA 1.64%, ESP 12.87%, GBR 12.41%
Sodium sulfate production	1.24E-02	kg	1.88E-02	crp	PRT 39.37%, BEL 5.32%, BGR 16.44%, FRA 5.24%, DEU 7.24%, ESP 13.35%, TUR 12.60%
Sulfur production	2.92E-05	kg	1.33E-05	crp	PRT 39.37%, IND 55.21%, ESP 4.71%
Sulfur dioxide production	1.58E-03	kg	5.56E-03	crp	PRT 39.37%, CHN 0.65%, FRA 18.64%, DEU 3.36%, IND 2.97%, ITA 2.73%, NLD 1.12%, ESP 29.45%
Sulfuric acid production	4.00E-01	kg	7.85E-01	crp	PRT 39.37%, BEL 1.25%, FRA 0.99%, ESP 54.33%, GBR 3.38%
Water supply	1.01E+00	m3	1.86E+00	wtr	PRT 100.00%

Table B.3 – Inventory data for the life cycle stage Manufacturing (UWF Paper = 1000 kg).

Process	Quantity [7]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [12][13][14][6]
Alkylketene dimer sizing agent production	2.00E+00	kg	3.63E+00	crp	PRT 39.37%, AUT 26.62%, BEL 1.62%, CHN 3.53%, DEU 5.87%, ITA 3.17%, ESP 15.58%, SWE 2.83%
Carbon dioxide production, liquid	1.14E+00	kg	1.72E-01	crp	PRT 39.37%, CHN 2.13%, FRA 1.21%, ESP 54.96%
Electricity production	4.00E+02	kWh	5.32E+01	ely	PRT 92.50%, ESP 7.50%
Hard coal mining	7.02E+00	kg	4.53E-01	coa	COL 1.71%, ITA 1.16%, NLD 1.25%, ESP 94.20%
Heavy fuel oil extraction	2.82E+01	kg	1.64E+01	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%,FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64%, ESP 48.20%, ARE 1.03%
Hydrogen peroxide production	4.23E+00	kg	1.48E+00	crp	PRT 39.37%, BEL 8.40%, FRA 2.15%, ISR 4.88%, NLD 9.14%, ESP 29.32%, GBR 6.49%
Kaolin mining	1.19E+02	kg	2.30E+02	nmm	PRT 90.40%, FRA 0.32%, DEU 0.29%, MAR 0.12%, ESP 1.54%, GBR 6.91%, USA 0.27%
Lignite briquettes mining	7.89E+01	MJ	2.52E+00	coa	PRT 82.67%, POL 13.69%, ESP 3.63%
Lime mining	1.19E+02	kg	7.20E+00	nmm	PRT 90.40%, ITA 0.16%, ESP 9.32%
Magnesium sulfate production	2.45E+00	kg	2.42E+00	crp	PRT 39.37%, CHN 2.75%, DEU 24.06%, GRC 3.51%, IND 4.58%, ITA 0.78%, ESP 24.08%
Methanol production	1.25E+00	kg	1.41E+00	crp	PRT 39.37%, NLD 1.04%, ESP 2.89%, TTO 54.76%, USA 1.71%
Natural gas extraction, high pressure	4.28E+01	m3	1.57E+01	gas	ESP 100%
Nitrogen production, liquid	1.30E-01	kg	1.97E-02	crp	PRT 39.37%, ESP 59.46%, USA 0.81%
Oxygen production, liquid	1.34E+01	kg	2.03E+00	crp	PRT 39.37%, ITA 3.86%, ESP 56.38%
Potato starch production	3.80E+01	kg	1.46E+02	ofd	PRT 72.05%, BEL 1.36%, DNK 4.15%, FRA 1.11%, DEU 3.96%, NLD 14.51%, ESP 4.77%
Quicklime production	4.97E+00	kg	5.39E-01	nmm	PRT 90.40%, FRA 0.14%, ESP 9.46%
Sodium chlorate production	1.43E+01	kg	2.29E+02	crp	PRT 39.37%, CAN 11.79%, FRA 31.09%, ESP 17.25%
Sodium chloride production	2.30E-01	kg	8.35E-01	crp	PRT 39.37%, DNK 0.65%, FRA 1.82%, ISR 2.48%, NLD 22.48%, ESP 17.47%, TUN 1.29%, GBR 12.86%
Sodium hydroxide production	2.17E+01	kg	2.41E+01	crp	PRT 39.37%, BEL 5.98%, CHN 3.48%, FRA 6.85%, KWT 2.39%, NLD 3.51%, POL 9.90%, RUS 12.91%, ESP 12.68%, SWE 0.62%, TWN 0.65%, GBR 1.25%
Sulfur dioxide production	1.14E+00	kg	4.02E+00	crp	PRT 39.37%, CHN 0.65%, FRA 18.64%, DEU 3.36%, IND 2.97%, ITA 2.73%, NLD 1.12%, ESP 29.45%
Sulfuric acid production	1.74E+01	kg	3.42E+01	crp	PRT 39.37%, BEL 1.25%, FRA 0.99%, ESP 54.33%, GBR 3.38%
Water supply	8.50E+01	m3	1.57E+02	wtr	PRT 100.00%

Table B.4 – Inventory data for the life cycle stage Distribution.

Process	Quantity	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration
Transportation, domestic market, lorry	1.32E+04	kgkm	2.64E+00 [9][2]	otp	PRT 100.00%
Transportation, domestic market, ship	5.04E+03	kgkm	6.47E-02 [9][2]	wtp	PRT 100.00%
Transportation, international market, lorry	8.47E+05	kgkm	1.69E+02 [9][2]	otp	AGR 0.20%, BEL 4.41%, EGY 1.02%, FRA 22.66%, DEU 33.08%, ITA 18.44%, JOR 0.24%, MEX 0.68%, MAR 0.33%, NLD 8.07%, ESP 4.80%, CHE 2.50%, TUN 0.08%, TUR 1.88%, GBR 0.61%, USA 0.98%
Transportation, international market, ship	1.20E+06	kgkm	1.53E+01 [9][2]	wtp	AGR 4.60%, EGY 17.67%, JOR 3.83%, MEX 9.63%, MAR 1.43%, TUN 2.18%, TUR 14.16%, GBR 8.53%, USA 37.96%

Table B.5 – Inventory data for the life cycle stage End-of-Life.

Process	Quantity [15][3]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [6]
Landfilling	2.74E+02	kg	1.49E+01 [16][4]	wtr	PRT 8.06%, AGR 3.47%, BEL 1.96%, EGY 4.66%, FRA 12.11%, DEU 10.65%, ITA 6.62%, JOR 1.01%, MEX 1.35%, MAR 2.08%, NLD 3.28%, ESP 7.69%, CHE 1.14%, TUN 1.14%, TUR 4.02%, GBR 5.72%, USA 7.59%
Incineration	6.70E+01	kg	2.55E+00 [17][4]	wtr	PRT 8.06%, AGR 3.47%, BEL 1.96%, EGY 4.66%, FRA 12.11%, DEU 10.65%, ITA 6.62%, JOR 1.01%, MEX 1.35%, MAR 2.08%, NLD 3.28%, ESP 7.69%, CHE 1.14%, TUN 1.14%, TUR 4.02%, GBR 5.72%, USA 7.59%
Recycling	6.59E+02	kg	6.51E+01 [18][4]	wtr	PRT 8.06%, AGR 3.47%, BEL 1.96%, EGY 4.66%, FRA 12.11%, DEU 10.65%, ITA 6.62%, JOR 1.01%, MEX 1.35%, MAR 2.08%, NLD 3.28%, ESP 7.69%, CHE 1.14%, TUN 1.14%, TUR 4.02%, GBR 5.72%, USA 7.59%

[3] According to information provided by the Environmental Protection Agency, it was assumed that 65.9% of UWF paper is recycled, 6.7% is incinerated, and 27.4% is landfilled [15].

[4] The cost of disposing UWF paper was assumed to be on average, in 2020, around 5.62E-02 euros per kilogram landfilled [16] (i.e. $ 5.44E-02 in 2011 [1][2]), 3.93E-02 euros per kilogram incinerated [17] (i.e. $ 3.81E-02 in 2011 [1][2]), and 1.02E-01 euros per kilogram recycled [18] ($ 9.88E-02 in 2011 [1][2]).

Table B.6 – Source of Pulpwood and Destination of UWF Paper.

Source of Pulpwood and Destination of UWF Paper	Pulpwood (3.25 m3)				UWF Paper (1 ton)			
	Share [4][5]	Quantity (m3)[5]	Distance by truck (km)[6]	Distance by ship (km)[6]	Share	Quantity (kg)	Distance by truck (km)[6]	Distance by ship (km)[6]
Domestic	**83.16% [19]**	**2.70**	**4240.60**	**2594.65**	**8.06% [20]**	**80.60**	**4240.60**	**2594.65**
Alto Minho	2.47%	0.08	195.00	-	0.18%	1.81	195.00	-
Cávado	1.85%	0.06	178.00	-	0.32%	3.17	178.00	-
Ave	1.79%	0.06	179.00	-	0.32%	3.24	179.00	-
Área Metropolitana do Porto	6.20%	0.20	120.00	-	1.35%	13.51	120.00	-
Alto Tâmega	0.09%	0.00	241.00	-	0.07%	0.68	241.00	-
Tâmega e Sousa	2.88%	0.09	151.00	-	0.33%	3.27	151.00	-
Douro	0.26%	0.01	186.00	-	0.15%	1.50	186.00	-
Terras de Trás-os-Montes	0.41%	0.01	289.00	-	0.08%	0.85	289.00	-
Oeste	3.54%	0.12	169.00	-	0.28%	2.80	169.00	-
Região de Aveiro	5.50%	0.18	63.40	-	0.28%	2.84	63.40	-
Região de Coimbra	11.62%	0.38	0.00	-	0.34%	3.40	0.00	-
Região de Leiria	4.87%	0.16	74.10	-	0.22%	2.23	74.10	-
Viseu Dão-Lafões	3.25%	0.11	91.60	-	0.20%	1.98	91.60	-
Beira Baixa	6.34%	0.21	137.00	-	0.06%	0.63	137.00	-
Médio Tejo	6.90%	0.22	95.50	-	0.18%	1.83	95.50	-
Beiras e Serra da Estrela	0.69%	0.02	138.00	-	0.17%	1.67	138.00	-
Área Metropolitana de Lisboa	1.22%	0.04	203.00	-	2.23%	22.32	203.00	-
Alentejo Litoral	5.24%	0.17	312.00	-	0.07%	0.73	312.00	-
Baixo Alentejo	1.20%	0.04	344.00	-	0.09%	0.91	344.00	-
Lezíria do Tejo	6.61%	0.21	137.00	-	0.19%	1.86	137.00	-
Alto Alentejo	4.24%	0.14	172.00	-	0.08%	0.83	172.00	-
Alentejo Central	2.12%	0.07	244.00	-	0.12%	1.20	244.00	-
Algarve	2.82%	0.09	431.00	-	0.34%	3.44	431.00	-
Região Autónoma dos Açores	0.35%	0.01	45.00	1479.75	0.19%	1.90	45.00	1479.75
Região Autónoma da Madeira	0.71%	0.02	45.00	1114.90	0.20%	1.99	45.00	1114.90
International	**16.72% [6]**	**0.54**	**2225.00**	**5985.66**	**74.47% [6]**	**744.72**	**14619.00**	**34267.56**
France	0.85%	0.03	1586.00	-	12.11%	121.09	1586.00	-
Germany	-	-	-	-	10.65%	106.47	2633.00	-
Spain	14.96%	0.49	529.00	-	7.69%	76.86	529.00	-
United States of America	0.91%	0.03	110.00	5985.66	7.59%	75.85	110.00	5985.66
Italy	-	-	-	-	6.62%	66.20	2361.00	-
United Kingdom	-	-	-	-	5.72%	57.19	91.00	1783.48
Egypt	-	-	-	-	4.66%	46.61	185.00	4533.70
Turkey	-	-	-	-	4.02%	40.18	397.00	4215.15
Algeria	-	-	-	-	3.47%	34.66	50.00	1587.16
Netherlands	-	-	-	-	3.28%	32.82	2083.00	-
Morocco	-	-	-	-	2.08%	20.78	135.00	824.14
Belgium	-	-	-	-	1.96%	19.58	1909.00	-
Mexico	-	-	-	-	1.35%	13.52	429.00	8522.90
Switzerland	-	-	-	-	1.14%	11.40	1861.00	-
Tunisia	-	-	-	-	1.14%	11.40	59.00	2283.52
Jordan	-	-	-	-	1.01%	10.11	201.00	4531.84
Total	**99.88%**	**3.25**	**6465.60**	**8580.32**	**82.53%**	**825.31**	**18859.60**	**36862.21**

[5] The quantity of pulpwood in cubic meters was converted to kilograms considering 820 kg/m^3 [28].

[6] The distance between the UWF paper manufacturing facility located in *Região de Coimbra* [26] and the Source of Pulpwood/Destination of UWF Paper was determined using Google Maps platform [24] when only road transportation was considered (e.g. Spain) and a Sea and Inland Routing tool [25] when both road and maritime transportation was considered (e.g. United States of America). For the international location points, the capitals were used.

Portuguese natural cork stoppers supply chain

Table B.7 – Inventory data for the life cycle stage Raw Material Acquisition (Cork = 5000 kg).

Process	Quantity	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [4][5][6]
Cork harvesting	5.00E+03 [21]	kg	7.36E+03 [8]	frs	PRT 97.27%, ITA 0.81%, ESP 1.76%, USA 0.12%
Transportation, national origin, lorry	1.71E+06	kgkm	3.41E+02 [9][2]	otp	PRT 100%
Transportation, national origin, ship	0.00E+00	kgkm	0.00E+00 [9][2]	wtp	-
Transportation, international origin, lorry	1.49E+05	kgkm	2.98E+01 [9][2]	otp	ITA 63.98%, ESP 35.72%, USA 0.30%
Transportation, international origin, ship	3.55E+04	kgkm	4.55E-01 [9][2]	wtp	USA 100%

Table B.8 – Inventory data for the life cycle stage Manufacturing (Cork Planks = 3500 kg).

Process	Quantity [21]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [13][14][6]
Electricity production	2.58E+02	kWh	3.43E+01	ely	PRT 92.50%, ESP 7.50%
Natural gas extraction, high pressure	2.36E+02	m3	8.65E+01	gas	ESP 100%
Water supply	2.40E+01	m3	4.44E+01	wtr	PRT 100.00%

Table B.9 – Inventory data for the life cycle stage Manufacturing (NCS Production = 1050 kg).

Process	Quantity [21]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [12][13][14][6]
Electricity production	4.38E+02	kWh	5.82E+01	ely	PRT 92.50%, ESP 7.50%
Lubricating oil production	1.32E+01	kg	1.11E+02	crp	PRT 39.37%, BEL 10.69%, FRA 39.89%, DEU 2.61%, ITA 4.61%, NLD 2.24%
Natural gas extraction, high pressure	2.66E+02	m3	9.73E+01	gas	ESP 100%
Sodium hydroxide production	3.50E+01	kg	3.88E+01	crp	PRT 39.37%, BEL 5.98%, CHN 3.48%, FRA 6.85%, KWT 2.39%, NLD 3.51%, POL 9.90%, RUS 12.91%, ESP 12.68%, SWE 0.62%, TWN 0.65%, GBR 1.25%
Hydrogen peroxide production	8.40E+01	kg	2.94E+01	crp	PRT 39.37%, BEL 8.40%, FRA 2.15%, ISR 4.88%, NLD 9.14%, ESP 29.32%, GBR 6.49%
Sodium hydrogen sulfate production	1.58E+00	kg	3.92E+00	crp	PRT 39.37%, FRA 1.29%, DEU 3.52%, ITA 1.12%, NLD 1.73%, KOR 25.74%, ESP 14.16%, GBR 12.72%
Citric acid production	1.58E+00	kg	4.13E+00	crp	PRT 39.37%, AUT 15.16%, BEL 12.51%, CHN 12.42%, FRA 0.65%, DEU 1.65%, IRL 1.66%, ITA 1.01%, NLD 0.96%, ESP 10.59%, SWE 1.17%, THA 2.61%
Potato starch production	1.00E-01	kg	3.83E-01	ofd	PRT 72.05%, BEL 1.36%, DNK 4.15%, FRA 1.11%, DEU 3.96%, NLD 14.51%, ESP 4.77%
Sodium chloride production	8.75E-01	kg	3.18E+00	crp	PRT 39.37%, DNK 0.65%, FRA 1.82%, ISR 2.48%, NLD 22.48%, ESP 17.47%, TUN 1.29%, GBR 12.86%
Ethanol production	8.49E+00	kg	1.63E+01	crp	PRT 39.37%, CYP 7.04%, FRA 8.25%, ITA 0.99%, ESP 33.86%, TUR 9.95%
Coating powder production	5.00E+01	kg	1.26E+02	crp	PRT 39.37%, AUT 26.62%, BEL 1.62%, CHN 3.53%, DEU 5.87%, ITA 3.17%, ESP 15.58%, SWE 2.83%
Water supply	3.06E+01	m3	5.66E+01	wtr	PRT 100.00%

Table B.10 – Inventory data for the life cycle stage Manufacturing (NCS Finishing = 1000 kg).

Process	Quantity [21]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [12][14][6]
Electricity production	5.39E+02	kWh	7.16E+01	ely	PRT 92.50%, ESP 7.50%
Printing ink production	1.25E-01	kg	2.28E-01	crp	PRT 39.37%, FRA 4.67%, DEU 12.24%, ITA 8.08%, NLD 16.76%, ESP 8.83%, CHE 0.73%, TUR 1.42%, GBR 5.94%
Polydimethylsiloxane production	3.00E+00	kg	3.92E+01	crp	PRT 39.37%, BEL 1.31%, CHN 1.80%, FRA 2.81%, DEU 12.36%, HUN 0.72%, ITA 1.73%, NLD 10.31%, ESP 25.59%, GBR 2.43%, USA 0.76%
Paraffin production	1.48E+01	kg	2.38E+01	p_c	PRT 82.67%, BEL 0.53%, CHN 3.23%, DEU 1.42%, IND 0.34%, ITA 0.19%, MYS 2.16%, NLD 0.29%, ZAF 2.60%, ESP 5.92%
Sulfur dioxide production	1.00E+00	kg	3.53E+00	crp	PRT 39.37%, CHN 0.65%, FRA 18.64%, DEU 3.36%, IND 2.97%, ITA 2.73%, NLD 1.12%, ESP 29.45%

Table B.11 – Inventory data for the life cycle stage Distribution.

Process	Quantity	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration
Transportation, domestic market, lorry	1.70E+05	kgkm	3.40E+01 [9][2]	otp	PRT 100.00%
Transportation, domestic market, ship	6.12E+04	kgkm	7.86E-01 [9][2]	wtp	PRT 100.00%
Transportation, international market, lorry	5.43E+04	kgkm	1.08E+01 [9][2]	otp	ARG 0.06%, AUS 0.89%, CHL 0.62%, FRA 49.69%, DEU 8.47%, ITA 24.95%, MEX 1.28%, ZAF 0.72%, ESP 7.61%, CHE 3.21%, GBR 0.30%, USA 2.21%
Transportation, international market, ship	1.99E+05	kgkm	2.56E+00 [9][2]	wtp	ARG 3.87%, AUS 16.82%, CHL 17.22%, MEX 7.50%, ZAF 4.30%, GBR 2.41%, USA 47.88%

Table B.12 – Inventory data for the life cycle stage End-of-Life.

Process	Quantity [15][7]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [6]
Landfilling	6.75E+02	kg	3.67E+01 [16][8]	wtr	PRT 93.59%, ARG 0.08%, AUS 0.17%, CHL 0.27%, FRA 1.70%, DEU 0.17%, ITA 0.57%, MEX 0.18%, ZAF 0.07%, ESP 0.68%, CHE 0.09%, GBR 0.29%, USA 1.60%
Incineration	1.58E+02	kg	6.02E+00 [17][7]	wtr	PRT 93.59%, ARG 0.08%, AUS 0.17%, CHL 0.27%, FRA 1.70%, DEU 0.17%, ITA 0.57%, MEX 0.18%, ZAF 0.07%, ESP 0.68%, CHE 0.09%, GBR 0.29%, USA 1.60%
Recycling	1.67E+02	kg	8.25E+00 [22][7]	wtr	PRT 93.59%, ARG 0.08%, AUS 0.17%, CHL 0.27%, FRA 1.70%, DEU 0.17%, ITA 0.57%, MEX 0.18%, ZAF 0.07%, ESP 0.68%, CHE 0.09%, GBR 0.29%, USA 1.60%

[7] Since there is no information available regarding the end-of-life destination of natural cork stoppers, the same end-of-life destinations and percentages considered for particleboards were assumed. Accordingly, it was assumed that 16.7% of natural cork stoppers is recycled, 15.8% is incinerated, and 67.5% is landfilled [15].

[8] The cost of disposing natural cork stoppers was assumed to be on average, in 2020, around 5.62E-02 euros per kilogram landfilled [16] (i.e. $ 5.44E-02 in 2011), 3.93E-02 euros per kilogram incinerated [17] (i.e. $ 3.81E-02 in 2011), and 5.10E-02 euros per kilogram recycled [22] ($ 4.94E-02 in 2011).

Table B.13 – Source of Cork and Destination of Natural Cork Stoppers.

Source of Cork and Destination of NCS	Cork (5000 kg)				Natural Cork Stoppers (1 ton)			
	Share [4][5]	**Quantity (kg)**	**Distance by truck (km)[9]**	**Distance by ship (km)[9]**	**Share**	**Quantity (kg)**	**Distance by truck (km)[9]**	**Distance by ship (km)[9]**
Domestic	**97.27% [19]**	**4863.46**	**4784.00**	**2713.18**	**93.59% [20]**	**935.91**	**4784.00**	**2713.18**
Alto Minho	0.02%	0.88	81.90	-	2.10%	21.03	81.90	-
Cávado	0.01%	0.54	58.20	-	3.68%	36.78	58.20	-
Ave	0.00%	0.00	57.70	-	3.76%	37.58	57.70	-
Área Metropolitana do Porto	0.00%	0.00	0.00	-	15.69%	156.86	0.00	-
Alto Tâmega	0.00%	0.00	154.00	-	0.79%	7.87	154.00	-
Tâmega e Sousa	0.00%	0.20	42.20	-	3.80%	38.00	42.20	-
Douro	0.13%	6.55	98.70	-	1.74%	17.40	98.70	-
Terras de Trás-os-Montes	1.97%	98.36	211.00	-	0.98%	9.82	211.00	-
Oeste	0.08%	3.85	270.00	-	3.25%	32.49	270.00	-
Região de Aveiro	0.00%	0.00	69.30	-	3.30%	32.98	69.30	-
Região de Coimbra	0.01%	0.34	120.00	-	3.95%	39.53	120.00	-
Região de Leiria	0.02%	0.88	183.00	-	2.59%	25.91	183.00	-
Viseu Dão-Lafões	0.01%	0.68	124.00	-	2.30%	22.97	124.00	-
Beira Baixa	2.83%	141.46	255.00	-	0.74%	7.36	255.00	-
Médio Tejo	2.09%	104.64	202.00	-	2.12%	21.21	202.00	-
Beiras e Serra da Estrela	0.59%	29.25	234.00	-	1.94%	19.43	234.00	-
Área Metropolitana de Lisboa	2.46%	123.02	309.00	-	25.92%	259.22	309.00	-
Alentejo Litoral	20.13%	1006.48	419.00	-	0.85%	8.49	419.00	-
Baixo Alentejo	9.90%	494.76	442.00	-	1.06%	10.62	442.00	-
Lezíria do Tejo	12.61%	630.68	244.00	-	2.16%	21.61	244.00	-
Alto Alentejo	15.39%	769.57	290.00	-	0.96%	9.61	290.00	-
Alentejo Central	24.30%	1214.95	361.00	-	1.39%	13.92	361.00	-
Algarve	4.73%	236.37	538.00	-	4.00%	39.97	538.00	-
Região Autónoma dos Açores	0.00%	0.00	10.00	1507.53	2.21%	22.12	10.00	1507.53
Região Autónoma da Madeira	0.00%	0.00	10.00	1205.65	2.31%	23.13	10.00	1205.65
International	**2.69%[6]**	**134.60**	**3042.00**	**5956.03**	**5.87% [6]**	**58.72**	**10566.00**	**70564.90**
France	-	-	-	-	1.70%	16.98	1588.00	-
United States of America	0.12%	5.95	75.00	5956.03	1.60%	16.01	75.00	5956.03
Spain	1.76%	88.24	604.00	-	0.68%	6.83	604.00	-
Italy	0.81%	40.40	2363.00	-	0.57%	5.73	2363.00	-
United Kingdom	-	-	-	-	0.29%	2.86	57.00	1674.21
Chile	-	-	-	-	0.27%	2.69	125.00	12739.91
Mexico	-	-	-	-	0.18%	1.76	394.00	8502.53
Germany	-	-	-	-	0.17%	1.74	2635.00	-
Australia	-	-	-	-	0.17%	1.69	285.00	19868.26
Switzerland	-	-	-	-	0.09%	0.94	1863.00	-
Argentina	-	-	-	-	0.08%	0.76	45.00	10106.36
South Africa	-	-	-	-	0.07%	0.73	532.00	11717.60
Total	**99.96%**	**4998.06**	**7826.00**	**8669.21**	**99.46%**	**994.63**	**15350.00**	**73278.08**

[9] The distance between the natural cork stoppers manufacturing facility located in *Área Metropolitana do Porto* [26] and the Source of Cork/Destination of NCS was determined using Google Maps platform [24] when only road transportation was considered (e.g. Spain) and a Sea and Inland Routing tool [25] when both road and maritime transportation was considered (e.g. United States of America). For the international location points, the capitals were used.

Portuguese particleboards supply chain

Table B.14 – Inventory data for the life cycle stage Raw Material Acquisition (Roundwood = 2.53 m^3).

Process	Quantity	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [4][5][6]
Roundwood harvesting	2.53E+00 [23]	m3	6.35E+01 [8]	frs	PRT 94.63%, AUT 0.09%, BRA 0.23%, FIN 0.09%, DEU 0.19%, LTU 0.21%, ESP 3.88%, SWE 0.58%
Transportation, national origin, lorry	1.79E+05	kgkm	3.58E+01 [9][2]	otp	PRT 100%
Transportation, national origin, ship	9.84E+03	kgkm	1.26E-01 [9][2]	wtp	PRT 100%
Transportation, international origin, lorry	8.07E+04	kgkm	1.61E+01 [9][2]	otp	AUT 3.75%, BRA 4.67%, FIN 5.75%, DEU 7.55%, LTU 11.38%, ESP 36.57%, SWE 30.34%
Transportation, international origin, ship	2.33E+04	kgkm	2.99E-01 [9][2]	wtp	BRA 100%

Table B.15 – Inventory data for the life cycle stage Manufacturing (Particleboards = 1000 kg).

Process	Quantity [23]	Unit	Costs_2011 ($) [1][2][1]	GTAP Sector [3]	Supply chain configuration [12][13][14][6]
Aluminum sulfate production	2.29E+00	kg	3.93E+00	crp	PRT 39.37%, BEL 4.66%, CHN 1.82%, FRA 0.87%, NLD 1.88%, ESP 47.05%, TUR 4.24%
Electricity production	1.52E+02	kWh	2.02E+01	ely	PRT 92.50%, ESP 7.50%
Natural gas extraction, heat	2.91E+02	MJ	2.68E+00	gas	ESP 100%
Heavy fuel oil extraction, heat	3.66E+01	MJ	5.52E-01	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%, FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64, ESP 48.20%, ARE 1.03%
Light fuel oil extraction, heat	3.30E+01	MJ	9.65E-01	p_c	BEL 11.26%, BRA 1.34%, CHN 3.97%, EGY 1.49%, FRA 2.24%, GRC 1.06%, ITA 1.74%, NLD 9.04%, RUS 11.41%, SAU 3.64, ESP 48.20%, ARE 1.03%
Lubricating oil production	3.68E-01	kg	3.11E+00	crp	PRT 39.37%, BEL 10.69%, FRA 39.89%, DEU 2.61%, ITA 4.61%, NLD 2.24%
Melamine formaldehyde resin production	1.45E+01	kg	2.46E+01	crp	PRT 39.37%, BEL 1.70%, DNK 2.69%, EGY 1.79%, FRA 1.57%, DEU 42.19%, ITA 2.30%, ESP 7.54%
Methylene diphenyl diisocyanate production	4.72E+00	kg	2.13E+01	crp	PRT 39.37%, BEL 1.67%, CHN 1.24%, FRA 7.48%, DEU 1.72%, ESP 48.34%
Paraffin production	4.43E+00	kg	7.14E+00	p_c	PRT 82.67%, BEL 0.53%, CHN 3.23%, DEU 1.42%, IND 0.34%, ITA 0.19%, MYS 2.16%, NLD 0.29%, ZAF 2.60%, ESP 5.92%
Phenolic resin production	1.77E+00	kg	4.83E+00	crp	PRT 39.37%, BEL 25.62%, BRA 1.90%, FRA 1.95%, DEU 0.62%, IND 1.58%, NLD 3.23%, POL 4.37%, KOR 4.64%, ESP 15.78%
Urea formaldehyde resin production	6.57E+01	kg	1.92E+02	crp	PRT 39.37%, DEU 24.98%, ITA 7.80%, ESP 25.12%, SWE 1.09%
Urea production, as N	2.86E-01	kg	3.87E-01	crp	PRT 39.37%, AGR 4.67%, DEU 15.09%, LVA 1.84%, NLD 1.35%, POL 1.43%, RUS 2.66%, SVK 1.09%, ESP 32.07%
Water supply	3.52E-01	m3	6.50E-01	wtr	PRT 100%

Table B.16 – Inventory data for the life cycle stage Distribution.

Process	**Quantity**	**Unit**	**Costs_2011 ($) [1][2][1]**	**GTAP Sector [3]**	**Supply chain configuration**
Transportation, domestic market, lorry	1.27E+05	kgkm	2.54E+01 [9][2]	otp	PRT 100%
Transportation, domestic market, ship	3.81E+04	kgkm	4.89E-01 [9][2]	wtp	PRT 100%
Transportation, international market, lorry	2.08E+05	kgkm	4.15E+01 [9][2]	otp	FRA 6.19%, DEU 5.26%, IRL 0.68%, ITA 8.29%, MAR 3.54%, NLD 6.44%, ESP 62.63%, GBR 6.97%
Transportation, international market, ship	1.78E+05	kgkm	2.28E+00 [9][2]	wtp	IRL 8.09%, MAR 15.78%, GBR 76.13%

Table B.17 – Inventory data for the life cycle stage End-of-Life.

Process	**Quantity [15][10]**	**Unit**	**Costs_2011 ($) [1][2][1]**	**GTAP Sector [3]**	**Supply chain configuration [6]**
Landfilling	6.75E+02	kg	3.67E+01 [16][11]	wtr	PRT 60.93%, FRA 0.86%, DEU 0.43%, IRL 1.01%, ITA 0.76%, MAR 3.40%, NLD 0.67%, ESP 21.64%, GBR 8.08%
Incineration	1.58E+02	kg	6.02E+00 [17][10]	wtr	PRT 60.93%, FRA 0.86%, DEU 0.43%, IRL 1.01%, ITA 0.76%, MAR 3.40%, NLD 0.67%, ESP 21.64%, GBR 8.08%
Recycling	1.67E+02	kg	8.25E+00 [22][10]	wtr	PRT 60.93%, FRA 0.86%, DEU 0.43%, IRL 1.01%, ITA 0.76%, MAR 3.40%, NLD 0.67%, ESP 21.64%, GBR 8.08%

[10] According to information provided by the Environmental Protection Agency, it was assumed that 16.7% of particleboards is recycled, 15.8% is incinerated, and 67.5% is landfilled [15].

[11] The cost of disposing particleboards was assumed to be on average, in 2020, around 5.62E-02 euros per kilogram landfilled [16] (i.e. $ 5.44E-02 in 2011), 3.93E-02 euros per kilogram incinerated [17] (i.e. $ 3.81E-02 in 2011), and 5.10E-02 euros per kilogram recycled [22] ($ 4.94E-02 in 2011).

Table B.18 – Source of Roundwood and Destination of Particleboards.

Source of Roundwood and Destination of Particleboards	Roundwood (2.53 m3)				Particleboards (1 ton)			
	Share [4][5]	Quantity (m3)[12]	Distance by truck (km)[13]	Distance by ship (km)[13]	Share	Quantity (kg)	Distance by truck (km)[13]	Distance by ship (km)[13]
Domestic	**94.63% [19]**	**2.39**	**5062.60**	**2594.65**	**60.93%[20]**	**609.28**	**5062.60**	**2594.65**
Alto Minho	3.20%	0.08	200.00	-	1.37%	13.69	200.00	-
Cávado	1.83%	0.05	183.00	-	2.39%	23.95	183.00	-
Ave	1.71%	0.04	174.00	-	2.45%	24.47	174.00	-
Área Metropolitana do Porto	1.53%	0.04	124.00	-	10.21%	102.12	124.00	-
Alto Tâmega	5.21%	0.13	152.00	-	0.51%	5.13	152.00	-
Tâmega e Sousa	2.15%	0.05	145.00	-	2.47%	24.74	145.00	-
Douro	4.78%	0.12	97.10	-	1.13%	11.33	97.10	-
Terras de Trás-os-Montes	3.28%	0.08	200.00	-	0.64%	6.39	200.00	-
Oeste	2.27%	0.06	255.00	-	2.12%	21.15	255.00	-
Região de Aveiro	2.49%	0.06	84.90	-	2.15%	21.47	84.90	-
Região de Coimbra	11.56%	0.29	91.60	-	2.57%	25.73	91.60	-
Região de Leiria	8.82%	0.22	163.00	-	1.69%	16.87	163.00	-
Viseu Dão-Lafões	10.98%	0.28	0.00	-	1.50%	14.95	0.00	-
Beira Baixa	9.56%	0.24	171.00	-	0.48%	4.79	171.00	-
Médio Tejo	6.83%	0.17	182.00	-	1.38%	13.81	182.00	-
Beiras e Serra da Estrela	8.09%	0.20	125.00	-	1.26%	12.65	125.00	-
Área Metropolitana de Lisboa	1.78%	0.05	290.00	-	16.88%	168.75	290.00	-
Alentejo Litoral	3.91%	0.10	399.00	-	0.55%	5.53	399.00	-
Baixo Alentejo	0.10%	0.00	431.00	-	0.69%	6.91	431.00	-
Lezíria do Tejo	1.58%	0.04	224.00	-	1.41%	14.07	224.00	-
Alto Alentejo	1.54%	0.04	260.00	-	0.63%	6.25	260.00	-
Alentejo Central	0.13%	0.00	341.00	-	0.91%	9.06	341.00	-
Algarve	0.63%	0.02	518.00	-	2.60%	26.02	518.00	-
Região Autónoma dos Açores	0.12%	0.00	126.00	1479.75	1.44%	14.40	126.00	1479.75
Região Autónoma da Madeira	0.54%	0.01	126.00	1114.90	1.51%	15.06	126.00	1114.90
International	**5.27%[6]**	**0.13**	**18060.00**	**7987.68**	**36.85% [6]**	**368.53**	**9433.00**	**3918.83**
Spain	3.88%	0.10	601.00	-	21.64%	216.38	601.00	-
United Kingdom	-	-	-	-	8.08%	80.80	179.00	1674.21
Morocco	-	-	-	-	3.40%	34.03	216.00	824.14
Ireland	-	-	-	-	1.01%	10.12	140.00	1420.48
France	-	-	-	-	0.86%	8.60	1495.00	-
Italy	-	-	-	-	0.76%	7.58	2270.00	-
Netherlands	-	-	-	-	0.67%	6.72	1990.00	-
Sweden	0.58%	0.01	3359.00	-	-	-	-	-
Brazil	0.23%	0.01	1292.00	7987.68	-	-	-	-
Lithuania	0.21%	0.01	3538.00	-	-	-	-	-
Germany	0.19%	0.00	2542.00	-	0.43%	4.30	2542.00	-
Austria	0.09%	0.00	2591.00	-	-	-	-	-
Finland	0.09%	0.00	4137.00	-	-	-	-	-
Total	**99.89%**	**2.53**	**23122.60**	**10582.33**	**97.78%**	**977.81**	**14495.60**	**6513.48**

[12] The quantity of roundwood in cubic meters was converted to kilograms considering 500 kg/m3 [29].

[13] The distance between the particleboards manufacturing facility located in *Viseu Dão-Lafões* [26] and the Source of Roundwood/Destination of Particleboards was determined using Google Maps platform [24] when only road transportation was considered (e.g. Spain) and a Sea and Inland Routing tool [25] when both road and maritime transportation was considered (e.g. Brazil). For the international location points, the capitals were used.

B.2. Supply chain models

This appendix presents the model developed for the three supply chains analyzed.

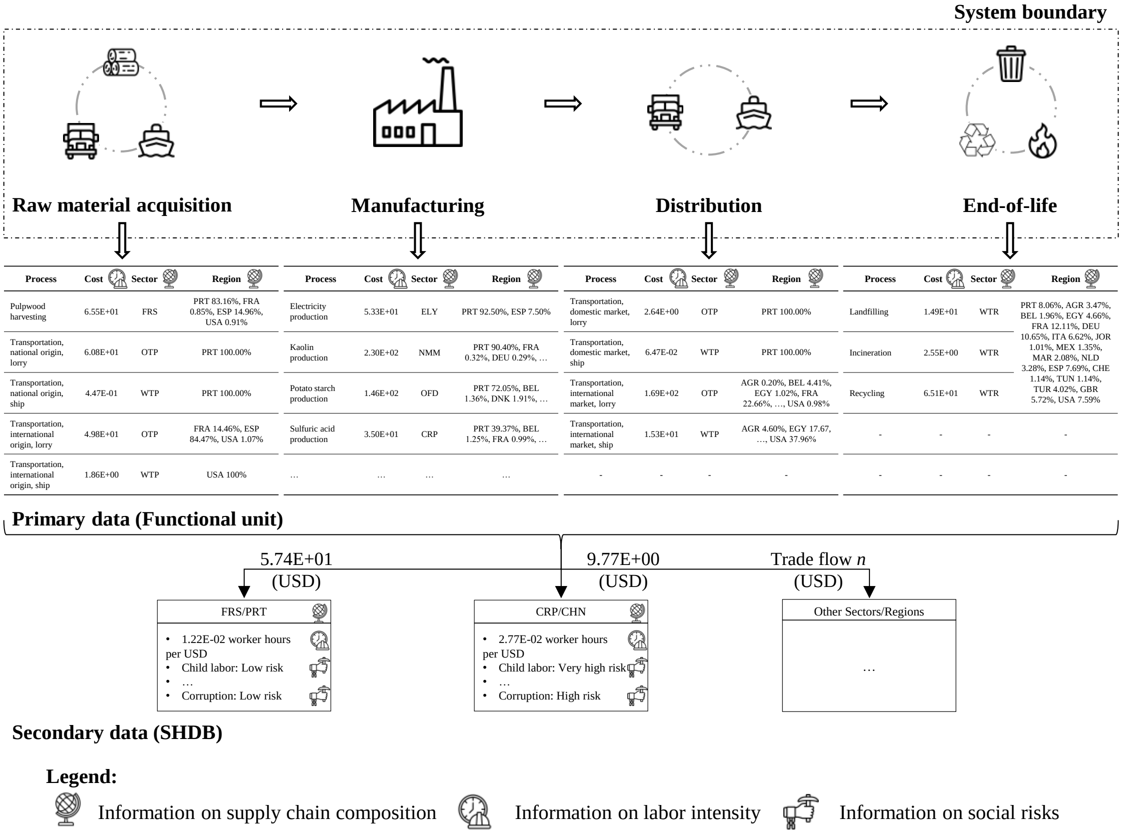

Figure B.1 – Portuguese UWF paper supply chain model.

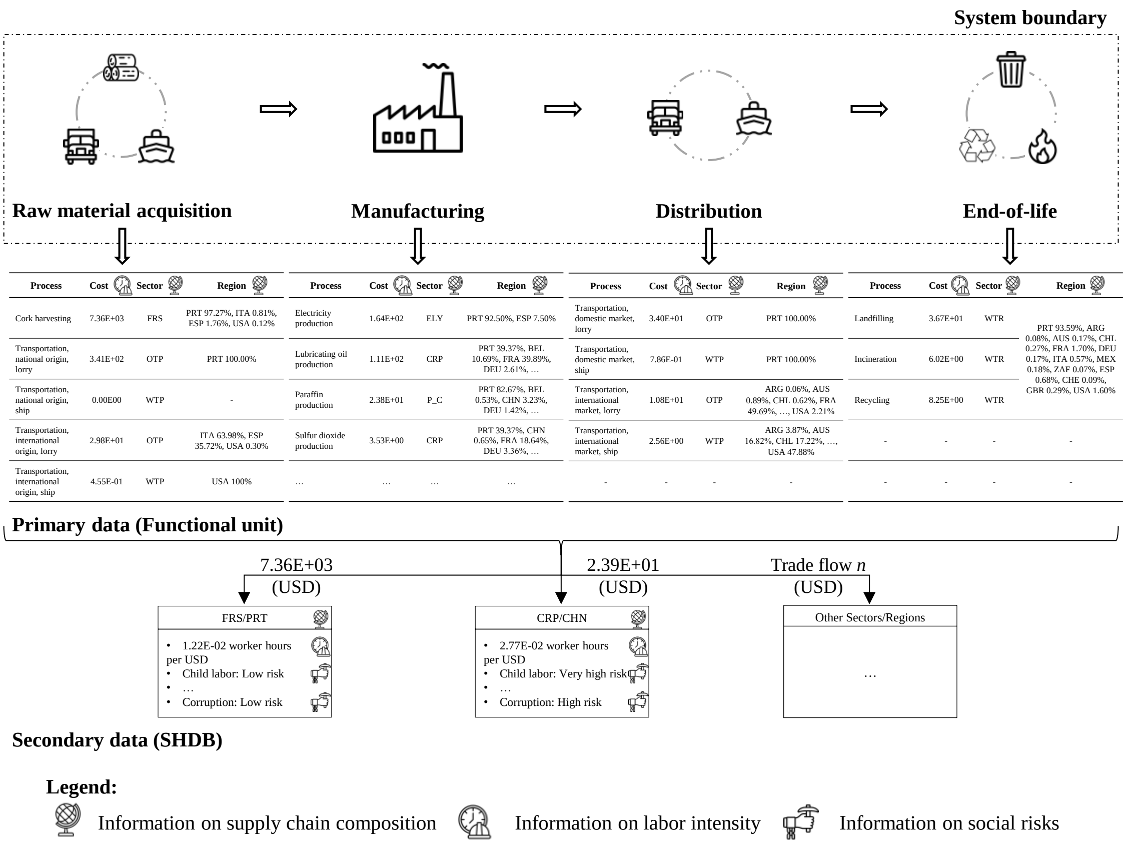

Figure B.2 – Portuguese natural cork stoppers supply chain model.

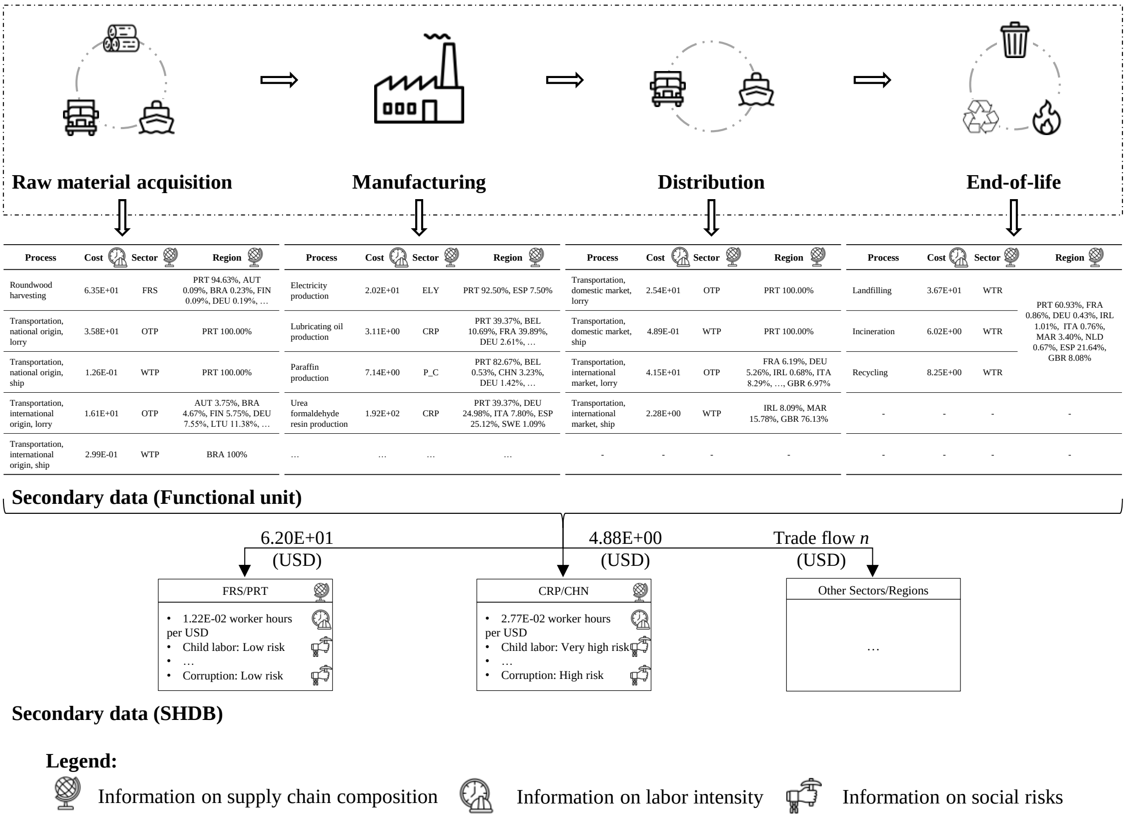

Figure B.3 – Portuguese particleboards supply chain model.

B.3. Social issues

This appendix presents the characterized, normalized and weighted results obtained for the three supply chains.

Table B.19 – Characterized, normalized, and weighted results obtained for each of the three supply chains.

Impact subcategories	UWF Paper			Natural cork stoppers			Particleboards		
	Charact. (MRH eq.)	Normal.	Weigh. (Pt)	Charact. (MRH eq.)	Normal.	Weigh. (Pt)	Charact. (MRH eq.)	Normal.	Weigh. (Pt)
Wage Assessment	2.37E+02	4.31E+02	4.31E+02	7.58E+02	1.38E+03	1.38E+03	7.72E+01	1.40E+02	1.40E+02
Poverty	3.29E+02	5.97E+02	5.97E+02	6.86E+02	1.25E+03	1.25E+03	1.14E+02	2.07E+02	2.07E+02
Child Labor	3.29E+02	5.98E+02	5.98E+02	9.60E+02	1.75E+03	1.75E+03	1.28E+02	2.32E+02	2.32E+02
Forced Labor	4.58E+02	8.33E+02	8.33E+02	1.11E+03	2.01E+03	2.01E+03	1.61E+02	2.92E+02	2.92E+02
Excessive Working Time	5.08E+02	9.24E+02	9.24E+02	9.86E+02	1.79E+03	1.79E+03	1.67E+02	3.03E+02	3.03E+02
Freedom of Association	6.90E+02	1.25E+03	1.25E+03	1.70E+03	3.09E+03	3.09E+03	2.29E+02	4.16E+02	4.16E+02
Migrant Labor	1.01E+03	1.83E+03	1.83E+03	4.07E+03	7.39E+03	7.39E+03	3.33E+02	6.05E+02	6.05E+02
Social Benefits	2.02E+02	3.67E+02	3.67E+02	3.30E+02	5.99E+02	5.99E+02	5.56E+01	1.01E+02	1.01E+02
Labor Laws	1.64E+02	2.98E+02	2.98E+02	3.40E+02	6.18E+02	6.18E+02	5.18E+01	9.42E+01	9.42E+01
Discrimination	4.56E+02	8.29E+02	8.29E+02	9.59E+02	1.74E+03	1.74E+03	1.46E+02	2.65E+02	2.65E+02
Unemployment	3.70E+02	6.72E+02	6.72E+02	8.76E+02	1.59E+03	1.59E+03	1.28E+02	2.33E+02	2.33E+02
Occupational Toxics & Hazards	5.58E+02	5.58E+03	5.58E+03	2.33E+03	2.33E+04	2.33E+04	1.92E+02	1.92E+03	1.92E+03
Injuries & Fatalities	9.11E+02	9.11E+03	9.11E+03	3.04E+03	3.04E+04	3.04E+04	2.51E+02	2.51E+03	2.51E+03
Indigenous Rights	1.90E+02	7.59E+02	7.59E+02	4.61E+02	1.85E+03	1.85E+03	6.42E+01	2.57E+02	2.57E+02
Gender Equity	3.29E+02	1.32E+03	1.32E+03	6.95E+02	2.78E+03	2.78E+03	1.01E+02	4.05E+02	4.05E+02
High Conflict Zones	5.36E+02	2.14E+03	2.14E+03	1.37E+03	5.49E+03	5.49E+03	1.83E+02	7.30E+02	7.30E+02
Non-Communicable Diseases	1.29E+02	5.17E+02	5.17E+02	2.92E+02	1.17E+03	1.17E+03	4.01E+01	1.60E+02	1.60E+02
Communicable Diseases	2.02E+02	8.10E+02	8.10E+02	6.54E+02	2.62E+03	2.62E+03	7.26E+01	2.90E+02	2.90E+02
Legal System	3.13E+02	3.13E+03	3.13E+03	5.00E+02	5.00E+03	5.00E+03	9.06E+01	9.06E+02	9.06E+02
Corruption	5.48E+02	5.48E+03	5.48E+03	1.22E+03	1.22E+04	1.22E+04	1.80E+02	1.80E+03	1.80E+03
Access to Drinking Water	2.10E+02	8.40E+02	8.40E+02	7.19E+02	2.88E+03	2.88E+03	9.30E+01	3.72E+02	3.72E+02
Access to Sanitation	2.62E+02	1.05E+03	1.05E+03	8.57E+02	3.43E+03	3.43E+03	1.01E+02	4.04E+02	4.04E+02
Children Out of School	4.00E+02	1.60E+03	1.60E+03	1.50E+03	5.98E+03	5.98E+03	1.60E+02	6.38E+02	6.38E+02
Access to Hospital Beds	4.48E+02	1.79E+03	1.79E+03	1.31E+03	5.25E+03	5.25E+03	1.49E+02	5.94E+02	5.94E+02
Smallholder vs Commercial Farms	3.42E+02	1.37E+03	1.37E+03	1.39E+03	5.58E+03	5.58E+03	1.14E+02	4.54E+02	4.54E+02
Total	-	**4.41E+04**	**4.41E+04**	-	**1.31E+05**	**1.31E+05**	-	**1.43E+04**	**1.43E+04**

B.4. Processes and Regions

This appendix presents the analysis conducted to identify the social hotspots associated with each of the three supply chains considering the four life cycle stages included within the systems' boundary defined: Raw Material Acquisition, Manufacturing, Distribution, and End-of-Life.

Portuguese UWF paper supply chain

Table B.20 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Raw Material Acquisition (Pulpwood = 3.25 m^3).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Pulpwood harvesting, Portugal	1.63E+01	1.79%	1.29E+01	2.32%	4.60E+00	0.84%	1.94E+00	0.62%	6.07E+00	1.13%
Pulpwood harvesting, France	1.92E-01	0.02%	1.26E-01	0.02%	1.45E-01	0.03%	9.01E-02	0.03%	1.31E-01	0.02%
Pulpwood harvesting, Spain	4.34E+00	0.48%	2.20E+00	0.39%	1.09E+00	0.20%	8.49E-01	0.27%	3.32E+00	0.62%
Pulpwood harvesting, USA	2.37E-01	0.03%	7.77E-02	0.01%	6.55E-02	0.01%	9.72E-02	0.03%	3.40E-01	0.06%
Transportation, lorry, Portugal	4.26E+01	4.67%	3.48E+01	6.25%	3.47E+01	6.33%	8.25E+00	2.63%	2.66E+01	4.96%
Transportation, ship, Portugal	2.35E-01	0.03%	2.31E-01	0.04%	2.73E-01	0.05%	8.07E-02	0.03%	2.02E-01	0.04%
Transportation, lorry, France	1.37E+00	0.15%	1.57E+00	0.28%	1.96E+00	0.36%	1.10E+00	0.35%	1.43E+00	0.27%
Transportation, lorry, Spain	1.27E+01	1.39%	1.07E+01	1.92%	1.52E+01	2.77%	7.50E+00	2.40%	1.75E+01	3.27%
Transportation, lorry, USA	4.47E-01	0.05%	9.75E-02	0.02%	1.78E-01	0.03%	1.55E-01	0.05%	4.29E-01	0.08%
Transportation, USA	1.38E+00	0.15%	3.74E-01	0.07%	5.42E-01	0.10%	5.20E-01	0.17%	1.48E+00	0.28%
Total	**7.97E+01**	**8.75%**	**6.31E+01**	**11.32%**	**5.88E+01**	**10.72%**	**2.06E+01**	**6.57%**	**5.75E+01**	**10.74%**

Table B.21 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (Sulfate Pulp = 35.00 kg).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Chlorine dioxide production, Portugal	1.64E-01	0.02%	1.29E-01	0.02%	1.31E-01	0.02%	5.64E-02	0.02%	1.16E-01	0.02%
Chlorine dioxide production, France	2.61E-02	0.00%	2.91E-02	0.01%	3.12E-02	0.01%	2.07E-02	0.01%	2.79E-02	0.01%
Chlorine dioxide production, Spain	1.35E-01	0.01%	1.18E-01	0.02%	1.33E-01	0.02%	8.99E-02	0.03%	1.66E-01	0.03%
Chlorine dioxide production, Sweden	3.00E-03	0.00%	4.80E-03	0.00%	4.25E-03	0.00%	2.87E-03	0.00%	6.17E-03	0.00%
Electricity production, Portugal	6.20E-02	0.01%	3.90E-02	0.01%	3.72E-02	0.01%	1.46E-02	0.00%	3.73E-02	0.01%
Electricity production, Spain	2.29E-03	0.00%	2.04E-03	0.00%	2.67E-03	0.00%	1.51E-03	0.00%	3.49E-03	0.00%
Natural gas extraction, high pressure, Spain	2.30E+00	0.25%	2.49E+00	0.45%	7.01E+00	1.28%	2.71E+00	0.86%	4.92E+00	0.92%
Water supply, Portugal	3.68E+00	0.40%	1.48E+00	0.27%	2.24E-01	0.04%	1.37E-01	0.04%	5.64E-01	0.11%
Other processes and regions	1.54E+00	0.17%	1.54E+00	0.28%	1.83E+00	0.33%	9.99E-01	0.32%	1.67E+00	0.31%
Total	**7.91E+00**	**0.87%**	**5.83E+00**	**1.05%**	**9.40E+00**	**1.72%**	**4.03E+00**	**1.29%**	**7.51E+00**	**1.40%**

Table B.22 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (UWF Paper = 1000 kg).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Electricity production, Portugal	2.32E+01	2.55%	1.46E+01	2.62%	1.39E+01	2.54%	5.47E+00	1.75%	1.40E+01	2.61%
Electricity production, Spain	8.57E-01	0.09%	7.65E-01	0.14%	9.99E-01	0.18%	5.64E-01	0.18%	1.31E+00	0.24%
Kaolin mining, Portugal	1.13E+02	12.40%	7.14E+01	12.81%	5.23E+01	9.55%	2.19E+01	6.99%	5.20E+01	9.71%
Kaolin mining, France	1.90E-01	0.02%	1.82E-01	0.03%	1.71E-01	0.03%	1.18E-01	0.04%	1.55E-01	0.03%
Kaolin mining, Germany	1.92E-01	0.02%	1.56E-01	0.03%	1.60E-01	0.03%	8.63E-02	0.03%	2.29E-01	0.04%
Kaolin mining, Morocco	3.42E-02	0.00%	3.90E-01	0.07%	2.40E-01	0.04%	7.91E-01	0.25%	2.16E-01	0.04%
Kaolin mining, Spain	1.17E+00	0.13%	9.62E-01	0.17%	1.16E+00	0.21%	6.84E-01	0.22%	1.47E+00	0.27%
Kaolin mining, UK	3.98E+00	0.44%	5.41E+00	0.97%	3.26E+00	0.59%	2.97E+00	0.95%	3.83E+00	0.72%
Kaolin mining, USA	5.57E-01	0.06%	1.15E-01	0.02%	1.17E-01	0.02%	1.53E-01	0.05%	4.88E-01	0.09%
Potato starch production, Portugal	8.12E+01	8.91%	5.45E+01	9.77%	5.37E+01	9.80%	3.10E+01	9.91%	4.36E+01	8.14%
Potato starch production, Belgium	7.52E-01	0.08%	8.90E-01	0.16%	2.83E+00	0.52%	1.48E+00	0.47%	2.01E+00	0.38%
Potato starch production, Denmark	2.68E+00	0.29%	1.98E+00	0.36%	2.92E+00	0.53%	2.11E+00	0.67%	2.28E+00	0.43%
Potato starch production, France	4.81E-01	0.05%	4.43E-01	0.08%	5.97E-01	0.11%	3.83E-01	0.12%	4.76E-01	0.09%
Potato starch production, Germany	1.98E+00	0.22%	1.79E+00	0.32%	3.31E+00	0.60%	1.84E+00	0.59%	3.36E+00	0.63%
Potato starch production, Netherlands	6.49E+00	0.71%	6.58E+00	1.18%	1.55E+01	2.83%	7.82E+00	2.50%	1.36E+01	2.54%
Potato starch production, Spain	4.12E+00	0.45%	3.07E+00	0.55%	4.32E+00	0.79%	2.69E+00	0.86%	4.60E+00	0.86%
Sodium chlorate production, Portugal	4.33E+01	4.75%	3.41E+01	6.12%	3.47E+01	6.32%	1.49E+01	4.76%	3.07E+01	5.74%
Sodium chlorate production, Canada	7.46E+00	0.82%	4.82E+00	0.86%	7.67E+00	1.40%	6.05E+00	1.93%	1.32E+01	2.46%
Sodium chlorate production, France	1.61E+01	1.77%	1.79E+01	3.21%	1.92E+01	3.50%	1.27E+01	4.06%	1.72E+01	3.21%
Sodium chlorate production, Spain	1.40E+01	1.54%	1.23E+01	2.21%	1.38E+01	2.52%	9.36E+00	2.99%	1.73E+01	3.24%
Water supply, Portugal	3.11E+02	34.11%	1.25E+02	22.46%	1.89E+01	3.45%	1.16E+01	3.69%	4.77E+01	8.90%
Other processes and regions	4.15E+01	4.56%	4.49E+01	8.06%	5.95E+01	10.86%	3.05E+01	9.73%	5.04E+01	9.42%
Total	**6.74E+02**	**73.98%**	**4.03E+02**	**72.20%**	**3.09E+02**	**56.43%**	**1.65E+02**	**52.74%**	**3.20E+02**	**59.77%**

Table B.23 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Distribution.

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Legal System**		**High Conflict Zones**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Transportation, lorry, Portugal	1.85E+00	0.20%	1.51E+00	0.27%	1.51E+00	0.27%	3.58E-01	0.11%	1.15E+00	0.22%
Transportation, ship, Portugal	3.40E-02	0.00%	3.34E-02	0.01%	3.95E-02	0.01%	1.17E-02	0.00%	2.92E-02	0.01%
Transportation, lorry, Algeria	2.19E-02	0.00%	6.34E-01	0.11%	3.24E-01	0.06%	1.33E+00	0.42%	3.07E-01	0.06%
Transportation, lorry, Belgium	2.08E+00	0.23%	2.22E+00	0.40%	2.73E+00	0.50%	1.85E+00	0.59%	2.38E+00	0.45%
Transportation, lorry, Egypt	1.29E+01	1.42%	4.42E+00	0.79%	1.80E+01	3.28%	1.78E+01	5.68%	1.79E+01	3.34%
Transportation, lorry, France	7.32E+00	0.80%	8.35E+00	1.50%	1.04E+01	1.90%	5.85E+00	1.87%	7.62E+00	1.42%
Transportation, lorry, Other regions	3.86E+01	4.23%	3.01E+01	5.40%	4.97E+01	9.06%	2.52E+01	8.05%	4.57E+01	8.53%
Transportation, ship, Algeria	8.13E-02	0.01%	1.05E+00	0.19%	6.37E-01	0.12%	2.17E+00	0.69%	5.71E-01	0.11%
Transportation, ship, Egypt	1.31E+01	1.44%	4.93E+00	0.88%	1.87E+01	3.41%	1.81E+01	5.78%	1.83E+01	3.41%
Transportation, ship, Jordan	4.35E+00	0.48%	1.13E-01	0.02%	4.47E+00	0.81%	1.11E-01	0.04%	1.01E+00	0.19%
Transportation, ship, Mexico	8.76E+00	0.96%	1.30E+00	0.23%	1.18E+01	2.15%	5.91E+00	1.89%	5.99E+00	1.12%
Transportation, ship, Other regions	6.24E+00	0.69%	2.82E+00	0.50%	5.81E+00	1.06%	3.92E+00	1.25%	6.79E+00	1.27%
Total	**9.53E+01**	**10.47%**	**5.75E+01**	**10.31%**	**1.24E+02**	**22.63%**	**8.26E+01**	**26.39%**	**1.08E+02**	**20.11%**

Table B.24 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage End-of-Life.

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Legal System**		**High Conflict Zones**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Landfilling, Portugal	2.38E+00	0.26%	9.58E-01	0.17%	1.45E-01	0.03%	8.84E-02	0.03%	3.65E-01	0.07%
Landfilling, Algeria	1.13E-04	0.00%	6.26E-01	0.11%	2.69E-01	0.05%	1.34E+00	0.43%	2.68E-01	0.05%
Landfilling, Belgium	8.33E-02	0.01%	5.91E-02	0.01%	3.35E-02	0.01%	3.27E-02	0.01%	4.20E-02	0.01%
Landfilling, Egypt	6.34E-01	0.07%	6.37E-01	0.11%	2.62E+00	0.48%	2.60E+00	0.83%	2.61E+00	0.49%
Landfilling, France	5.30E-01	0.06%	4.76E-01	0.09%	2.54E-01	0.05%	2.46E-01	0.08%	2.98E-01	0.06%
Landfilling, Other regions	6.12E+00	0.67%	2.40E+00	0.43%	5.11E+00	0.93%	3.05E+00	0.97%	4.14E+00	0.77%
Incineration, Portugal	4.07E-01	0.04%	1.64E-01	0.03%	2.48E-02	0.00%	1.51E-02	0.00%	6.24E-02	0.01%
Incineration, Algeria	1.93E-05	0.00%	1.07E-01	0.02%	4.60E-02	0.01%	2.30E-01	0.07%	4.59E-02	0.01%
Incineration, Belgium	1.43E-02	0.00%	1.01E-02	0.00%	5.74E-03	0.00%	5.60E-03	0.00%	7.20E-03	0.00%
Incineration, Egypt	1.08E-01	0.01%	1.09E-01	0.02%	4.48E-01	0.08%	4.45E-01	0.14%	4.46E-01	0.08%
Incineration, France	9.08E-02	0.01%	8.14E-02	0.01%	4.35E-02	0.01%	4.22E-02	0.01%	5.10E-02	0.01%
Incineration, Other regions	1.05E+00	0.12%	4.11E-01	0.07%	8.74E-01	0.16%	5.22E-01	0.17%	7.09E-01	0.13%
Recycling, Portugal	1.04E+01	1.14%	4.19E+00	0.75%	6.33E-01	0.12%	3.86E-01	0.12%	1.59E+00	0.30%
Recycling, Algeria	4.93E-04	0.00%	2.73E+00	0.49%	1.17E+00	0.21%	5.86E+00	1.87%	1.17E+00	0.22%
Recycling, Belgium	3.64E-01	0.04%	2.58E-01	0.05%	1.47E-01	0.03%	1.43E-01	0.05%	1.84E-01	0.03%
Recycling, Egypt	2.77E+00	0.30%	2.78E+00	0.50%	1.14E+01	2.08%	1.13E+01	3.62%	1.14E+01	2.13%
Recycling, France	2.32E+00	0.25%	2.08E+00	0.37%	1.11E+00	0.20%	1.08E+00	0.34%	1.30E+00	0.24%
Recycling, Other regions	2.68E+01	2.94%	1.05E+01	1.88%	2.23E+01	4.07%	1.33E+01	4.26%	1.81E+01	3.38%
Total	**5.40E+01**	**5.93%**	**2.86E+01**	**5.12%**	**4.67E+01**	**8.51%**	**4.08E+01**	**13.02%**	**4.28E+01**	**7.99%**

Portuguese natural cork stoppers supply chain

Table B.25 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Raw Material Acquisition (Cork = 5000 kg).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Migrant Labor		Children Out of School	
	Value	%	Value	%	Value	%	Value	%	Value	%
Cork harvesting, Portugal	2.14E+03	70.48%	1.70E+03	73.07%	6.05E+02	49.70%	2.89E+03	71.08%	9.29E+02	62.11%
Cork harvesting, Italy	2.01E+01	0.66%	1.06E+01	0.46%	8.87E+00	0.73%	1.73E+01	0.43%	3.80E+00	0.25%
Cork harvesting, Spain	5.76E+01	1.89%	2.92E+01	1.25%	1.44E+01	1.19%	1.52E+01	0.37%	5.21E+00	0.35%
Cork harvesting, USA	3.49E+00	0.11%	1.14E+00	0.05%	9.65E-01	0.08%	5.16E+00	0.13%	4.74E-01	0.03%
Transportation, lorry, Portugal	2.39E+02	7.85%	1.95E+02	8.38%	1.95E+02	16.00%	4.32E+02	10.63%	2.09E+02	14.00%
Transportation, ship, Portugal	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Transportation, lorry, Italy	3.10E+00	0.10%	4.87E+00	0.21%	6.74E+00	0.55%	8.49E+00	0.21%	3.23E+00	0.22%
Transportation, lorry, Spain	3.20E+00	0.11%	2.70E+00	0.12%	3.84E+00	0.32%	4.54E+00	0.11%	2.82E+00	0.19%
Transportation, lorry, USA	7.49E-02	0.00%	1.63E-02	0.00%	2.98E-02	0.00%	7.94E-02	0.00%	1.82E-02	0.00%
Transportation, ship, USA	3.37E-01	0.01%	9.15E-02	0.00%	1.33E-01	0.01%	3.95E-01	0.01%	7.65E-02	0.01%
Total	**2.47E+03**	**81.22%**	**1.95E+03**	**83.54%**	**8.35E+02**	**68.59%**	**3.37E+03**	**82.96%**	**1.15E+03**	**77.15%**

Table B.26 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (Cork Planks = 3500 kg).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Migrant Labor		Children Out of School	
	Value	%	Value	%	Value	%	Value	%	Value	%
Electricity production, Portugal	1.50E+01	0.49%	9.42E+00	0.40%	8.98E+00	0.74%	1.77E+01	0.43%	8.80E+00	0.59%
Electricity production, Spain	5.53E-01	0.02%	4.93E-01	0.02%	6.44E-01	0.05%	6.67E-01	0.02%	3.82E-01	0.03%
Natural gas extraction, high pressure, Spain	1.53E+01	0.50%	1.65E+01	0.71%	4.65E+01	3.82%	5.72E+01	1.41%	4.12E+01	2.76%
Water supply, Portugal	8.77E+01	2.89%	3.54E+01	1.52%	5.35E+00	0.44%	5.33E+01	1.31%	1.27E+01	0.85%
Total	**1.19E+02**	**3.90%**	**6.18E+01**	**2.65%**	**6.15E+01**	**5.05%**	**1.29E+02**	**3.17%**	**6.31E+01**	**4.22%**

Table B.27 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (NCS Production = 1050 kg).

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Migrant Labor**		**Children Out of School**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Electricity production, Portugal	2.54E+01	0.84%	1.60E+01	0.69%	1.52E+01	1.25%	3.00E+01	0.74%	1.49E+01	1.00%
Electricity production, Spain	9.38E-01	0.03%	8.37E-01	0.04%	1.09E+00	0.09%	1.13E+00	0.03%	6.49E-01	0.04%
Lubricating oil production, Portugal	2.10E+01	0.69%	1.66E+01	0.71%	1.68E+01	1.38%	3.08E+01	0.76%	1.48E+01	0.99%
Lubricating oil production, Belgium	2.51E+00	0.08%	3.49E+00	0.15%	4.82E+00	0.40%	5.26E+00	0.13%	2.76E+00	0.18%
Lubricating oil production, France	1.00E+01	0.33%	1.12E+01	0.48%	1.20E+01	0.98%	1.27E+01	0.31%	7.34E+00	0.49%
Lubricating oil production, Germany	6.79E-01	0.02%	6.94E-01	0.03%	7.46E-01	0.06%	7.95E-01	0.02%	4.01E-01	0.03%
Lubricating oil production, Italy	1.20E+00	0.04%	1.49E+00	0.06%	1.63E+00	0.13%	2.28E+00	0.06%	8.29E-01	0.06%
Lubricating oil production, Netherlands	4.50E-01	0.01%	5.88E-01	0.03%	8.14E-01	0.07%	8.78E-01	0.02%	4.35E-01	0.03%
Natural gas extraction, high pressure, Spain	1.72E+01	0.57%	1.86E+01	0.80%	5.23E+01	4.30%	6.43E+01	1.58%	4.64E+01	3.10%
Coating powder production, Portugal	2.38E+01	0.78%	1.88E+01	0.81%	1.91E+01	1.57%	3.49E+01	0.86%	1.68E+01	1.12%
Coating powder production, Austria	7.95E+00	0.26%	7.23E+00	0.31%	6.98E+00	0.57%	7.88E+00	0.19%	6.70E+00	0.45%
Coating powder production, Belgium	4.31E-01	0.01%	5.99E-01	0.03%	8.26E-01	0.07%	9.01E-01	0.02%	4.73E-01	0.03%
Coating powder production, China	4.61E-01	0.02%	1.77E+01	0.76%	1.18E+01	0.97%	1.20E+01	0.30%	1.11E+01	0.74%
Coating powder production, Germany	1.73E+00	0.06%	1.77E+00	0.08%	1.90E+00	0.16%	2.03E+00	0.05%	1.02E+00	0.07%
Coating powder production, Italy	9.34E-01	0.03%	1.16E+00	0.05%	1.27E+00	0.10%	1.78E+00	0.04%	6.46E-01	0.04%
Coating powder production, Spain	6.98E+00	0.23%	6.12E+00	0.26%	6.86E+00	0.56%	7.94E+00	0.20%	3.99E+00	0.27%
Coating powder production, Sweden	4.40E-01	0.01%	7.04E-01	0.03%	6.24E-01	0.05%	7.73E-01	0.02%	3.12E-01	0.02%
Water supply, Portugal	1.12E+02	3.68%	4.51E+01	1.94%	6.82E+00	0.56%	6.79E+01	1.67%	1.62E+01	1.08%
Other processes and regions	3.91E+01	1.29%	4.48E+01	1.92%	5.05E+01	4.15%	6.56E+01	1.61%	3.01E+01	2.01%
Total	**2.73E+02**	**8.98%**	**2.13E+02**	**9.16%**	**2.12E+02**	**17.44%**	**3.50E+02**	**8.60%**	**1.76E+02**	**11.76%**

Table B.28 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (NCS Finishing = 1000 kg).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Migrant Labor		Children Out of School	
	Value	%	Value	%	Value	%	Value	%	Value	%
Electricity production, Portugal	3.13E+01	1.03%	1.97E+01	0.84%	1.88E+01	1.54%	3.69E+01	0.91%	1.84E+01	1.23%
Electricity production, Spain	1.16E+00	0.04%	1.03E+00	0.04%	1.35E+00	0.11%	1.39E+00	0.03%	7.99E-01	0.05%
Printing ink production, Portugal	4.30E-02	0.00%	3.39E-02	0.00%	3.45E-02	0.00%	6.30E-02	0.00%	3.03E-02	0.00%
Printing ink production, France	2.41E-03	0.00%	2.67E-03	0.00%	2.87E-03	0.00%	3.04E-03	0.00%	1.76E-03	0.00%
Printing ink production, Germany	6.52E-03	0.00%	6.66E-03	0.00%	7.16E-03	0.00%	7.64E-03	0.00%	3.85E-03	0.00%
Printing ink production, Italy	4.30E-03	0.00%	5.33E-03	0.00%	5.85E-03	0.00%	8.20E-03	0.00%	2.97E-03	0.00%
Printing ink production, Netherlands	6.89E-03	0.00%	9.01E-03	0.00%	1.25E-02	0.00%	1.34E-02	0.00%	6.66E-03	0.00%
Printing ink production, Spain	7.15E-03	0.00%	6.27E-03	0.00%	7.03E-03	0.00%	8.13E-03	0.00%	4.09E-03	0.00%
Printing ink production, Switzerland	3.66E-04	0.00%	4.62E-04	0.00%	4.97E-04	0.00%	5.23E-04	0.00%	2.99E-04	0.00%
Printing ink production, Turkey	1.72E-03	0.00%	1.43E-03	0.00%	4.03E-03	0.00%	2.68E-03	0.00%	1.95E-03	0.00%
Printing ink production, UK	2.68E-03	0.00%	3.98E-03	0.00%	3.19E-03	0.00%	6.30E-03	0.00%	1.83E-03	0.00%
Paraffin production, Portugal	3.99E+00	0.13%	6.35E+00	0.27%	3.28E+01	2.70%	3.58E+01	0.88%	2.96E+01	1.98%
Paraffin production, Belgium	1.61E-02	0.00%	2.20E-02	0.00%	6.81E-02	0.01%	6.34E-02	0.00%	2.77E-02	0.00%
Paraffin production, China	6.41E-02	0.00%	1.28E+00	0.06%	1.60E+00	0.13%	1.63E+00	0.04%	1.45E+00	0.10%
Paraffin production, Germany	4.60E-02	0.00%	7.31E-02	0.00%	2.14E-01	0.02%	1.95E-01	0.00%	9.64E-02	0.01%
Paraffin production, India	9.95E-03	0.00%	5.73E-02	0.00%	1.16E-01	0.01%	1.56E-01	0.00%	6.12E-02	0.00%
Paraffin production, Italy	9.15E-03	0.00%	2.05E-02	0.00%	3.92E-02	0.00%	4.30E-02	0.00%	2.11E-02	0.00%
Paraffin production, Malaysia	3.86E-01	0.01%	9.27E-01	0.04%	1.15E+00	0.09%	1.34E+00	0.03%	2.58E-01	0.02%
Paraffin production, Netherlands	1.01E-02	0.00%	1.59E-02	0.00%	3.33E-02	0.00%	3.12E-02	0.00%	1.02E-02	0.00%
Paraffin production, South Africa	2.88E-02	0.00%	6.92E-02	0.00%	8.05E-01	0.07%	8.30E-01	0.02%	7.25E-01	0.05%
Paraffin production, Spain	2.10E-01	0.01%	2.35E-01	0.01%	1.01E+00	0.08%	1.38E+00	0.03%	1.10E+00	0.07%
Other processes and regions	1.52E+01	0.50%	1.65E+01	0.71%	1.66E+01	1.37%	2.35E+01	0.58%	1.20E+01	0.80%
Total	**5.25E+01**	**1.73%**	**4.63E+01**	**1.99%**	**7.47E+01**	**6.14%**	**1.03E+02**	**2.54%**	**6.46E+01**	**4.32%**

Table B.29 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Distribution.

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Migrant Labor**		**Children Out of School**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Transportation, lorry, Portugal	2.38E+01	0.78%	1.95E+01	0.83%	1.94E+01	1.59%	4.30E+01	1.06%	2.09E+01	1.39%
Transportation, ship, Portugal	4.13E-01	0.01%	4.06E-01	0.02%	4.79E-01	0.04%	9.04E-01	0.02%	4.57E-01	0.03%
Transportation, lorry, Argentina	3.65E-02	0.00%	6.91E-03	0.00%	3.37E-02	0.00%	3.36E-02	0.00%	1.05E-03	0.00%
Transportation, lorry, Austria	4.27E-02	0.00%	2.08E-02	0.00%	1.69E-02	0.00%	8.67E-02	0.00%	2.58E-02	0.00%
Transportation, lorry, Chile	1.26E-01	0.00%	2.11E-02	0.00%	3.44E-02	0.00%	9.37E-02	0.00%	8.57E-02	0.01%
Transportation, lorry, France	1.03E+00	0.03%	1.17E+00	0.05%	1.46E+00	0.12%	1.51E+00	0.04%	8.32E-01	0.06%
Transportation, lorry, Other regions	1.90E+00	0.06%	1.35E+00	0.06%	2.67E+00	0.22%	2.67E+00	0.07%	1.00E+00	0.07%
Transportation, ship, Argentina	5.06E-01	0.02%	9.63E-02	0.00%	4.67E-01	0.04%	4.66E-01	0.01%	1.49E-02	0.00%
Transportation, ship, Austria	1.54E-01	0.01%	1.08E-01	0.00%	1.34E-01	0.01%	3.75E-01	0.01%	1.41E-01	0.01%
Transportation, ship, Chile	4.11E-01	0.01%	1.82E-01	0.01%	3.79E-01	0.03%	5.10E-01	0.01%	3.24E-01	0.02%
Transportation, ship, Mexico	1.14E+00	0.04%	1.69E-01	0.01%	1.52E+00	0.13%	7.90E-01	0.02%	4.00E-02	0.00%
Transportation, ship, Other regions	9.29E-01	0.03%	2.97E-01	0.01%	5.17E-01	0.04%	1.24E+00	0.03%	3.46E-01	0.02%
Total	3.04E+01	1.00%	2.33E+01	1.00%	2.71E+01	2.23%	5.17E+01	1.27%	2.41E+01	1.61%

Table B.30 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage End-of-Life.

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Migrant Labor**		**Children Out of School**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Landfilling, Portugal	6.80E+01	2.24%	2.74E+01	1.18%	4.14E+00	0.34%	4.13E+01	1.02%	9.83E+00	0.66%
Landfilling, Argentina	1.15E-01	0.00%	2.20E-02	0.00%	1.07E-01	0.01%	1.06E-01	0.00%	4.15E-03	0.00%
Landfilling, Austria	1.58E-02	0.00%	1.22E-02	0.00%	9.33E-03	0.00%	3.46E-02	0.00%	1.13E-02	0.00%
Landfilling, Chile	1.16E-01	0.00%	1.81E-02	0.00%	2.07E-02	0.00%	8.05E-02	0.00%	7.80E-02	0.01%
Landfilling, France	1.83E-01	0.01%	1.64E-01	0.01%	8.77E-02	0.01%	9.66E-02	0.00%	5.51E-02	0.00%
Landfilling, Other regions	8.88E-01	0.03%	3.40E-01	0.01%	5.04E-01	0.04%	8.21E-01	0.02%	1.46E-01	0.01%
Incineration, Portugal	1.11E+01	0.37%	4.49E+00	0.19%	6.79E-01	0.06%	6.77E+00	0.17%	1.61E+00	0.11%
Incineration, Argentina	1.88E-02	0.00%	3.61E-03	0.00%	1.76E-02	0.00%	1.74E-02	0.00%	6.79E-04	0.00%
Incineration, Austria	2.58E-03	0.00%	2.00E-03	0.00%	1.53E-03	0.00%	5.67E-03	0.00%	1.85E-03	0.00%
Incineration, Chile	1.90E-02	0.00%	2.97E-03	0.00%	3.39E-03	0.00%	1.32E-02	0.00%	1.28E-02	0.00%
Incineration, France	3.00E-02	0.00%	2.69E-02	0.00%	1.44E-02	0.00%	1.58E-02	0.00%	9.04E-03	0.00%
Incineration, Other regions	1.46E-01	0.00%	5.57E-02	0.00%	8.25E-02	0.01%	1.35E-01	0.00%	2.39E-02	0.00%
Recycling, Portugal	1.53E+01	0.50%	6.16E+00	0.26%	9.31E-01	0.08%	9.28E+00	0.23%	2.21E+00	0.15%
Recycling, Argentina	2.58E-02	0.00%	4.95E-03	0.00%	2.41E-02	0.00%	2.39E-02	0.00%	9.31E-04	0.00%
Recycling, Austria	3.54E-03	0.00%	2.74E-03	0.00%	2.10E-03	0.00%	7.78E-03	0.00%	2.54E-03	0.00%
Recycling, Chile	2.60E-02	0.00%	4.07E-03	0.00%	4.65E-03	0.00%	1.81E-02	0.00%	1.75E-02	0.00%
Recycling, France	4.11E-02	0.00%	3.69E-02	0.00%	1.97E-02	0.00%	2.17E-02	0.00%	1.24E-02	0.00%
Recycling, Other regions	2.00E-01	0.01%	7.63E-02	0.00%	1.13E-01	0.01%	1.85E-01	0.00%	3.28E-02	0.00%
Total	**9.62E+01**	**3.17%**	**3.88E+01**	**1.67%**	**6.77E+00**	**0.56%**	**5.89E+01**	**1.45%**	**1.41E+01**	**0.94%**

Portuguese particleboards supply chain

Table B.31 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Raw Material Acquisition (Roundwood = 2.53 m³).

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Roundwood harvesting, Portugal	1.80E+01	7.16%	1.43E+01	7.43%	5.07E+00	2.82%	2.14E+00	2.36%	6.70E+00	3.67%
Roundwood harvesting, Austria	2.46E-02	0.01%	1.32E-02	0.01%	1.10E-02	0.01%	6.39E-03	0.01%	1.64E-02	0.01%
Roundwood harvesting, Brazil	3.52E-01	0.14%	1.46E-01	0.08%	1.40E+00	0.77%	1.48E-01	0.16%	7.00E-01	0.38%
Roundwood harvesting, Finland	7.33E-03	0.00%	9.44E-03	0.00%	8.22E-03	0.00%	4.28E-03	0.00%	1.20E-02	0.01%
Roundwood harvesting, Germany	4.16E-02	0.02%	3.36E-02	0.02%	2.47E-02	0.01%	1.62E-02	0.02%	5.05E-02	0.03%
Roundwood harvesting, Lithuania	2.53E-01	0.10%	2.52E-01	0.13%	6.67E-02	0.04%	5.67E-02	0.06%	5.46E-02	0.03%
Roundwood harvesting, Spain	1.09E+00	0.44%	5.54E-01	0.29%	2.74E-01	0.15%	2.14E-01	0.24%	8.35E-01	0.46%
Roundwood harvesting, Sweden	3.39E-02	0.01%	4.64E-02	0.02%	2.58E-02	0.01%	1.84E-02	0.02%	6.46E-02	0.04%
Transportation, lorry, Portugal	2.51E+01	9.99%	2.05E+01	10.67%	2.05E+01	11.36%	4.86E+00	5.36%	1.57E+01	8.57%
Transportation, ship, Portugal	6.64E-02	0.03%	6.52E-02	0.03%	7.70E-02	0.04%	2.28E-02	0.03%	5.70E-02	0.03%
Transportation, lorry, Austria	1.58E-01	0.06%	1.58E-01	0.08%	1.56E-01	0.09%	9.98E-02	0.11%	1.91E-01	0.10%
Transportation, lorry, Brazil	9.26E-01	0.37%	3.94E-01	0.21%	3.64E+00	2.02%	4.12E-01	0.45%	1.84E+00	1.01%
Transportation, lorry, Finland	1.82E-01	0.07%	2.71E-01	0.14%	2.68E-01	0.15%	1.41E-01	0.16%	3.17E-01	0.17%
Transportation, lorry, Germany	3.29E-01	0.13%	2.68E-01	0.14%	3.25E-01	0.18%	1.53E-01	0.17%	4.06E-01	0.22%
Transportation, lorry, Lithuania	5.12E-01	0.20%	1.70E+00	0.88%	9.12E-01	0.51%	6.19E-01	0.68%	6.16E-01	0.34%
Transportation, lorry, Spain	1.77E+00	0.71%	1.50E+00	0.78%	2.13E+00	1.18%	1.05E+00	1.16%	2.46E+00	1.34%
Transportation, lorry, Sweden	6.78E-01	0.27%	9.84E-01	0.51%	9.44E-01	0.52%	5.95E-01	0.66%	1.34E+00	0.73%
Transportation, ship, Brazil	3.22E-01	0.13%	1.51E-01	0.08%	1.25E+00	0.69%	1.62E-01	0.18%	6.40E-01	0.35%
Total	**4.98E+01**	**19.85%**	**4.13E+01**	**21.50%**	**3.70E+01**	**20.57%**	**1.07E+01**	**11.82%**	**3.19E+01**	**17.50%**

Table B.32 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Manufacturing (Particleboards = 1000 kg).

Processes and Regions	**Injuries & Fatalities**		**Occupational Toxics & Hazards**		**Corruption**		**Legal System**		**High Conflict Zones**	
	Value	%	Value	%	Value	%	Value	%	Value	%
Electricity production, Portugal	8.84E+00	3.52%	5.56E+00	2.89%	5.30E+00	2.94%	2.08E+00	2.30%	5.32E+00	2.91%
Electricity production, Spain	3.26E-01	0.13%	2.91E-01	0.15%	3.80E-01	0.21%	2.15E-01	0.24%	4.97E-01	0.27%
Melamine formaldehyde resin production, Portugal	4.64E+00	1.85%	3.66E+00	1.90%	3.72E+00	2.06%	1.60E+00	1.77%	3.30E+00	1.81%
Melamine formaldehyde resin production, Belgium	8.81E-02	0.04%	1.22E-01	0.06%	1.69E-01	0.09%	1.09E-01	0.12%	1.55E-01	0.08%
Melamine formaldehyde resin production, Denmark	1.38E-01	0.06%	1.62E-01	0.08%	1.50E-01	0.08%	9.61E-02	0.11%	2.01E-01	0.11%
Melamine formaldehyde resin production, Egypt	8.96E-01	0.36%	4.15E-01	0.22%	1.27E+00	0.71%	1.19E+00	1.32%	1.24E+00	0.68%
Melamine formaldehyde resin production, France	8.72E-02	0.03%	9.69E-02	0.05%	1.04E-01	0.06%	6.89E-02	0.08%	9.31E-02	0.05%
Melamine formaldehyde resin production, Germany	2.42E+00	0.97%	2.48E+00	1.29%	2.66E+00	1.48%	1.57E+00	1.73%	3.39E+00	1.86%
Melamine formaldehyde resin production, Italy	1.32E-01	0.05%	1.64E-01	0.09%	1.80E-01	0.10%	1.20E-01	0.13%	2.13E-01	0.12%
Melamine formaldehyde resin production, Spain	6.59E-01	0.26%	5.78E-01	0.30%	6.48E-01	0.36%	4.39E-01	0.48%	8.13E-01	0.45%
Urea formaldehyde resin production, Portugal	3.63E+01	14.46%	2.86E+01	14.88%	2.91E+01	16.14%	1.25E+01	13.81%	2.58E+01	14.12%
Urea formaldehyde resin production, Germany	1.12E+01	4.47%	1.15E+01	5.97%	1.23E+01	6.85%	7.25E+00	8.00%	1.57E+01	8.60%
Urea formaldehyde resin production, Italy	3.50E+00	1.40%	4.34E+00	2.26%	4.77E+00	2.65%	3.18E+00	3.51%	5.64E+00	3.09%
Urea formaldehyde resin production, Spain	1.72E+01	6.84%	1.50E+01	7.82%	1.69E+01	9.37%	1.14E+01	12.62%	2.12E+01	11.60%
Urea formaldehyde resin production, Sweden	2.57E-01	0.10%	4.11E-01	0.21%	3.64E-01	0.20%	2.46E-01	0.27%	5.30E-01	0.29%
Water supply, Portugal	1.28E+00	0.51%	5.18E-01	0.27%	7.83E-02	0.04%	4.78E-02	0.05%	1.97E-01	0.11%
Other processes and regions	1.49E+01	5.94%	1.64E+01	8.51%	2.74E+01	15.22%	1.11E+01	12.22%	2.13E+01	11.67%
Total	**1.03E+02**	**40.99%**	**9.03E+01**	**46.96%**	**1.05E+02**	**58.56%**	**5.32E+01**	**58.75%**	**1.06E+02**	**57.81%**

Table B.33 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage Distribution.

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Transportation, lorry, Portugal	1.78E+01	7.08%	1.45E+01	7.56%	1.45E+01	8.05%	3.44E+00	3.80%	1.11E+01	6.08%
Transportation, ship, Portugal	2.57E-01	0.10%	2.52E-01	0.13%	2.98E-01	0.17%	8.82E-02	0.10%	2.21E-01	0.12%
Transportation, lorry, France	4.90E-01	0.20%	5.59E-01	0.29%	6.98E-01	0.39%	3.92E-01	0.43%	5.10E-01	0.28%
Transportation, lorry, Germany	5.91E-01	0.24%	4.81E-01	0.25%	5.82E-01	0.32%	2.75E-01	0.30%	7.28E-01	0.40%
Transportation, lorry, Ireland	6.26E-02	0.02%	7.41E-02	0.04%	7.93E-02	0.04%	4.78E-02	0.05%	7.88E-02	0.04%
Transportation, lorry, Italy	5.60E-01	0.22%	8.78E-01	0.46%	1.21E+00	0.67%	6.85E-01	0.76%	1.08E+00	0.59%
Transportation, lorry, Other regions	8.95E+00	3.57%	1.06E+01	5.49%	1.19E+01	6.61%	1.10E+01	12.18%	1.35E+01	7.37%
Transportation, ship, Ireland	4.81E-02	0.02%	5.07E-02	0.03%	6.59E-02	0.04%	4.03E-02	0.04%	6.28E-02	0.03%
Transportation, ship, Morocco	4.14E-02	0.02%	5.38E-01	0.28%	3.25E-01	0.18%	1.11E+00	1.22%	2.91E-01	0.16%
Transportation, ship, UK	3.95E-01	0.16%	5.40E-01	0.28%	4.83E-01	0.27%	3.71E-01	0.41%	4.62E-01	0.25%
Total	**2.92E+01**	**11.63%**	**2.85E+01**	**14.81%**	**3.01E+01**	**16.74%**	**1.75E+01**	**19.30%**	**2.80E+01**	**15.33%**

Table B.34 – Characterized results and contribution of the different processes and regions to the relevant impact categories considering the life cycle stage End-of-Life.

Processes and Regions	Injuries & Fatalities		Occupational Toxics & Hazards		Corruption		Legal System		High Conflict Zones	
	Value	%	Value	%	Value	%	Value	%	Value	%
Landfilling, Portugal	4.43E+01	17.64%	1.78E+01	9.28%	2.70E+00	1.50%	1.65E+00	1.82%	6.79E+00	3.72%
Landfilling, France	9.27E-02	0.04%	8.32E-02	0.04%	4.44E-02	0.02%	4.31E-02	0.05%	5.21E-02	0.03%
Landfilling, Germany	3.40E-02	0.01%	2.70E-02	0.01%	1.41E-02	0.01%	9.10E-03	0.01%	3.67E-02	0.02%
Landfilling, Ireland	1.72E-01	0.07%	1.32E-01	0.07%	5.42E-02	0.03%	3.98E-02	0.04%	9.44E-02	0.05%
Landfilling, Italy	1.12E-01	0.04%	8.77E-02	0.05%	6.03E-02	0.03%	4.44E-02	0.05%	1.19E-01	0.07%
Landfilling, Other regions	5.08E+00	2.03%	5.00E+00	2.60%	2.49E+00	1.38%	4.83E+00	5.32%	5.22E+00	2.86%
Incineration, Portugal	7.25E+00	2.89%	2.92E+00	1.52%	4.42E-01	0.25%	2.70E-01	0.30%	1.11E+00	0.61%
Incineration, France	1.52E-02	0.01%	1.36E-02	0.01%	7.28E-03	0.00%	7.06E-03	0.01%	8.54E-03	0.00%
Incineration, Germany	5.57E-03	0.00%	4.42E-03	0.00%	2.31E-03	0.00%	1.49E-03	0.00%	6.01E-03	0.00%
Incineration, Ireland	2.81E-02	0.01%	2.17E-02	0.01%	8.88E-03	0.00%	6.52E-03	0.01%	1.55E-02	0.01%
Incineration, Italy	1.83E-02	0.01%	1.44E-02	0.01%	9.87E-03	0.01%	7.27E-03	0.01%	1.96E-02	0.01%
Incineration, Other regions	8.33E-01	0.33%	8.20E-01	0.43%	4.08E-01	0.23%	7.91E-01	0.87%	8.56E-01	0.47%
Recycling, Portugal	9.94E+00	3.96%	4.01E+00	2.08%	6.06E-01	0.34%	3.70E-01	0.41%	1.53E+00	0.84%
Recycling, France	2.08E-02	0.01%	1.87E-02	0.01%	9.98E-03	0.01%	9.68E-03	0.01%	1.17E-02	0.01%
Recycling, Germany	7.63E-03	0.00%	6.06E-03	0.00%	3.17E-03	0.00%	2.04E-03	0.00%	8.24E-03	0.00%
Recycling, Ireland	3.86E-02	0.02%	2.97E-02	0.02%	1.22E-02	0.01%	8.94E-03	0.01%	2.12E-02	0.01%
Recycling, Italy	2.51E-02	0.01%	1.97E-02	0.01%	1.35E-02	0.01%	9.97E-03	0.01%	2.68E-02	0.01%
Recycling, Other regions	1.14E+00	0.46%	1.12E+00	0.58%	5.60E-01	0.31%	1.08E+00	1.20%	1.17E+00	0.64%
Total	**6.91E+01**	**27.54%**	**3.22E+01**	**16.73%**	**7.45E+00**	**4.13%**	**9.18E+00**	**10.12%**	**1.71E+01**	**9.37%**

B.5. Sectors and Regions

This appendix presents the analysis conducted to identify the sectors/regions that most contribute to the social hotspots identified for each of the three supply chains.

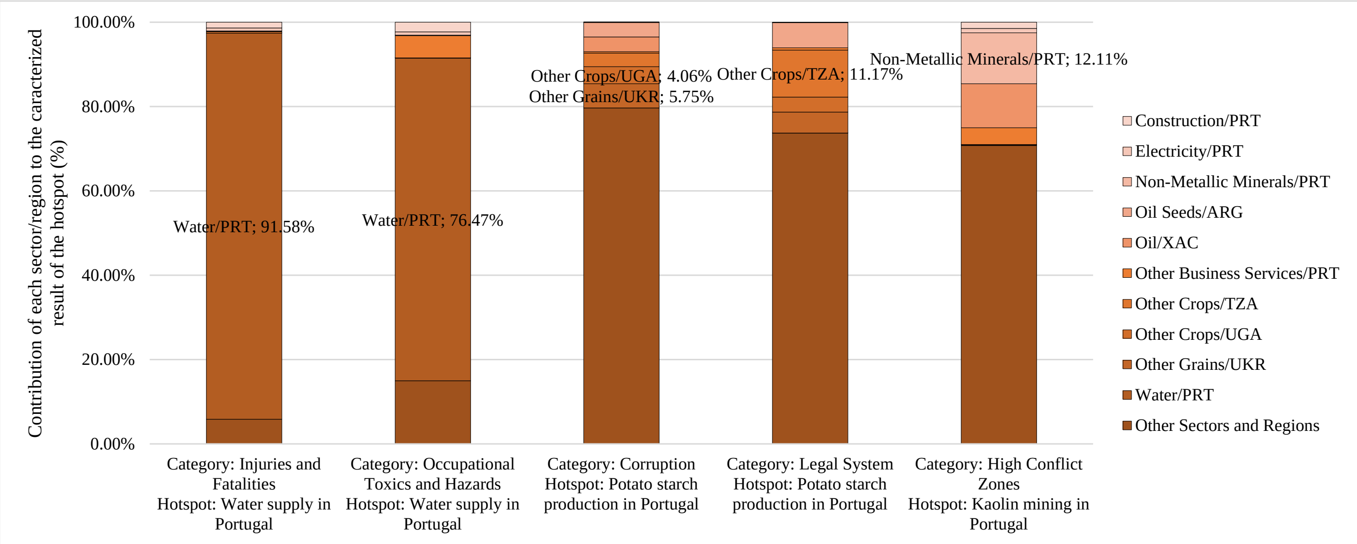

Figure B.4 – *Contribution of different sectors/regions to the characterized result of the three social hotspots identified for the five most relevant impact categories associated with the Portuguese UWF paper supply chain.*

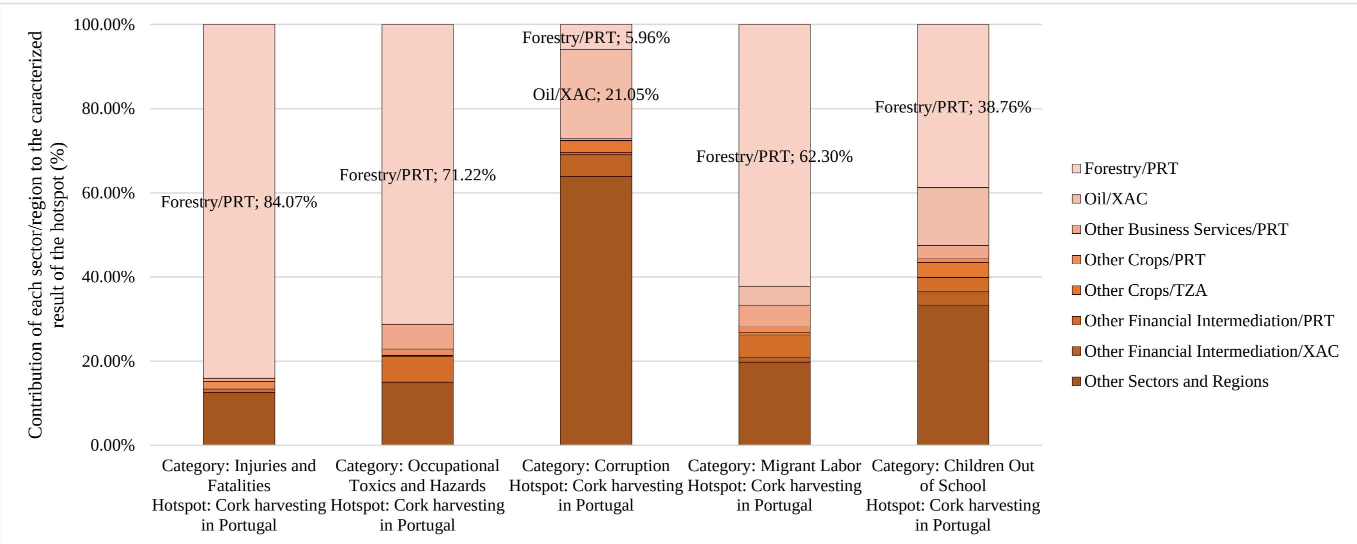

Figure B.5 – *Contribution of different sectors/regions to the characterized result of the three social hotspots identified for the five most relevant impact categories associated with the Portuguese natural cork stoppers supply chain.*

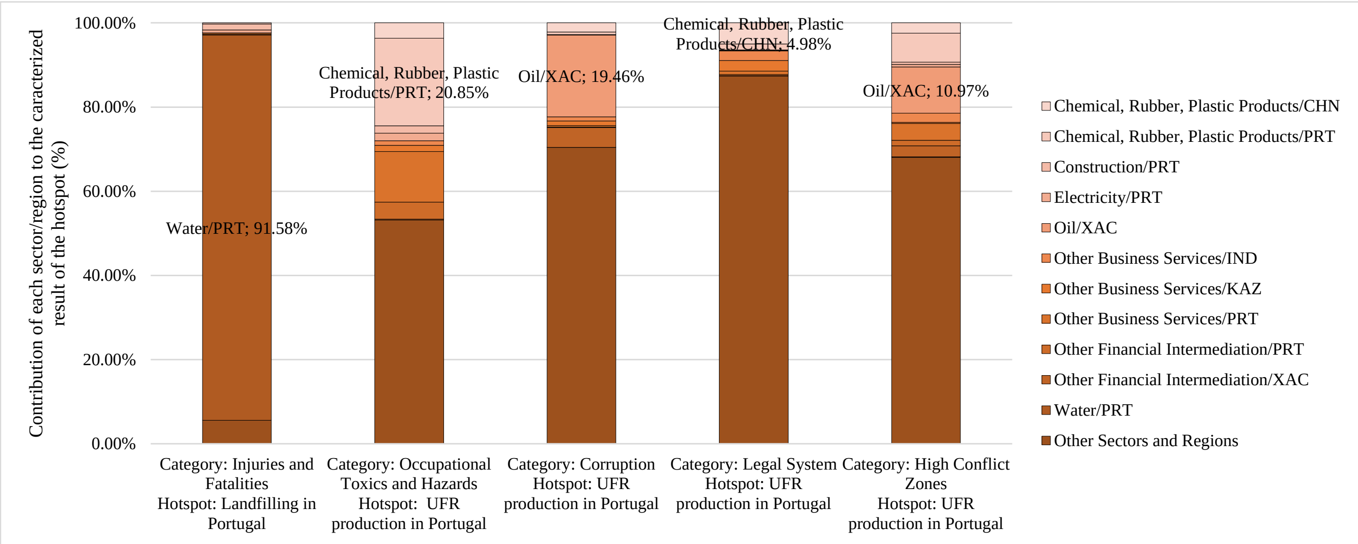

Figure B.6 – *Contribution of different sectors/regions to the characterized result of the three social hotspots identified for the five most relevant impact categories associated with the Portuguese particleboards supply chain.*

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Appendix C. Supplementary Material for Chapter 6

C.1. Data

This appendix presents the data regarding the amount per functional unit of each supply chain process used to model the Portuguese natural cork stoppers supply chain.

Table C.1 – Data for the life cycle stage Raw Materials' Extraction (Cork = 5000 kg).

Process	Amount per FU	Uncertainty			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Input					
Cork harvesting	5.00E+03 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Transportation, national origin, lorry	1.71E+06[14] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, national origin, ship	0.00E+00[1] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, international origin, lorry	1.49E+05[1] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, international origin, ship	3.55E+04[1] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)

Table C.2 – Data for the life cycle stage Products' Manufacture (Cork Planks = 3500 kg).

Process	Amount per FU	Uncertainty			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Input					
Electricity use	2.58E+02 kWh [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Natural gas use	2.36E+02 m^3 [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Water use	2.40E+01 m^3 [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Output					
Emissions to air					
Carbon dioxide	5.09E+05 g	Lognormal	1.17	1.05	(3,4,2,1,2)
Nitrogen oxides	6.71E+02 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Carbon monoxide	2.63E+02 g	Lognormal	5.03	5.00	(3,4,2,1,2)
NMVOC	2.09E+02 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Methane	9.07E+00 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Other emissions	2.73E+01 g	Lognormal	-	-	-
Cork residues treatment	1.50E+03 kg	Lognormal	1.13	1.05	(1,4,2,1,2)
Sludge treatment	1.22E+02 kg	Lognormal	1.13	1.05	(1,4,2,1,2)
Wastewater treatment	2.33E+01 m^3	Lognormal	1.13	1.05	(1,4,2,1,2)

[14] The amount per FU was calculated using the quantities and distances available in Table A.7.

Table C.3 – Data for the life cycle stage Products' Manufacture (Natural Cork Stoppers Production = 1050 kg).

Process	Amount per FU	Uncertainty			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Input					
Electricity use	4.38E+02 kWh [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Lubricating oil use	1.32E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Natural gas use	2.66E+02 m^3 [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Sodium hydroxide use	3.50E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Hydrogen peroxide use	8.40E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Sodium hydrogen sulfate use	1.58E+00 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Citric acid use	1.58E+00 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Potato starch use	1.00E-01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Sodium chloride use	8.75E-01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Ethanol use	8.49E+00 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Coating powder use	5.00E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Water use	3.06E+01 m^3 [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Output					
Emissions to air					
Carbon dioxide	5.72E+05 g	Lognormal	1.17	1.05	(3,4,2,1,2)
Nitrogen oxides	7.55E+02 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Carbon monoxide	2.96E+02 g	Lognormal	5.03	5.00	(3,4,2,1,2)
NMVOC	2.35E+02 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Methane	1.02E+01 g	Lognormal	1.54	1.50	(3,4,2,1,2)
Other emissions	3.07E+01 g	Lognormal	-	-	-
Cork residues treatment	2.45E+03 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Sludge treatment	1.11E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Wastewater treatment	5.18E+00 m^3 [1]	Lognormal	1.13	1.05	(1,4,2,1,2)

Table C.4 – Data for the life cycle stage Products' Manufacture (Natural Cork Stoppers Finishing = 1000 kg).

Process	Amount per FU	Uncertainty			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Input					
Electricity use	5.39E+02 kWh [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Printing ink use	1.25E-01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Polydimethylsiloxane use	3.00E+00 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Paraffin use	1.48E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Sulfur dioxide use	1.00E+00 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)
Output					
Cork residues treatment	5.00E+01 kg [1]	Lognormal	1.13	1.05	(1,4,2,1,2)

Table C.5 – Data for the life cycle stage Products' Distribution.

Process	**Amount per FU**	**Uncertainty**			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Transportation, domestic market, lorry	1.70E+05[15] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, domestic market, ship	6.12E+04[2] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, international market, lorry	5.43E+04[2] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)
Transportation, international market, ship	1.99E+05[2] kgkm	Lognormal	2.00	2.0	(2,2,1,1,1)

Table C.6 – Data for the life cycle stage Products' End-of-Life.

Process	**Amount per FU**	**Uncertainty**			
		Distribution	2SD	Basic Uncertainty	Pedigree Matrix
Landfilling	6.75E+02[16] kg	Lognormal	1.13	1.05	(1,1,2,5,2)
Combustion with energy recovery	1.58E+02[3] kg	Lognormal	1.13	1.05	(1,1,2,5,2)
Recycling	1.67E+02[3] kg	Lognormal	1.13	1.05	(1,1,2,5,2)

[15] The amount per FU was calculated using the quantities and distances available in Table A.7.

[16] Since there is no information available regarding the end-of-life destination of natural cork stoppers, the end-of-life destinations and respective percentages available for wood products were assumed. Accordingly, it was assumed that 16.7% of natural cork stoppers are recycled, 15.8% are incinerated, and 67.5% are landfilled [2].

Table C.7 – Source of Cork and Destination of Natural Cork Stoppers (NCS).

Source of Cork and Destination of NCS	Cork (5000 kg)				Natural Cork Stoppers (1 ton)			
	Share [3][4]	Quantity (kg)	Distance by truck (km)[17]	Distance by ship (km)[4]	Share [3][4]	Quantity (kg)	Distance by truck (km)[4]	Distance by ship (km)[4]
Domestic	**97.27% [5]**	**4863.46**	**4784.00**	**2713.18**	**93.59% [6]**	**935.91**	**4784.00**	**2713.18**
Alto Minho	0.02%	0.88	81.90	-	2.10%	21.03	81.90	-
Cávado	0.01%	0.54	58.20	-	3.68%	36.78	58.20	-
Ave	0.00%	0.00	57.70	-	3.76%	37.58	57.70	-
Área Metropolitana do Porto[18]	0.00%	0.00	0.00	-	15.69%	156.86	0.00	-
Alto Tâmega	0.00%	0.00	154.00	-	0.79%	7.87	154.00	-
Tâmega e Sousa	0.00%	0.20	42.20	-	3.80%	38.00	42.20	-
Douro	0.13%	6.55	98.70	-	1.74%	17.40	98.70	-
Terras de Trás-os-Montes	1.97%	98.36	211.00	-	0.98%	9.82	211.00	-
Oeste	0.08%	3.85	270.00	-	3.25%	32.49	270.00	-
Região de Aveiro	0.00%	0.00	69.30	-	3.30%	32.98	69.30	-
Região de Coimbra	0.01%	0.34	120.00	-	3.95%	39.53	120.00	-
Região de Leiria	0.02%	0.88	183.00	-	2.59%	25.91	183.00	-
Viseu Dão-Lafões	0.01%	0.68	124.00	-	2.30%	22.97	124.00	-
Beira Baixa	2.83%	141.46	255.00	-	0.74%	7.36	255.00	-
Médio Tejo	2.09%	104.64	202.00	-	2.12%	21.21	202.00	-
Beiras e Serra da Estrela	0.59%	29.25	234.00	-	1.94%	19.43	234.00	-
Área Metropolitana de Lisboa	2.46%	123.02	309.00	-	25.92%	259.22	309.00	-
Alentejo Litoral	20.13%	1006.48	419.00	-	0.85%	8.49	419.00	-
Baixo Alentejo	9.90%	494.76	442.00	-	1.06%	10.62	442.00	-
Lezíria do Tejo	12.61%	630.68	244.00	-	2.16%	21.61	244.00	-
Alto Alentejo	15.39%	769.57	290.00	-	0.96%	9.61	290.00	-
Alentejo Central	24.30%	1214.95	361.00	-	1.39%	13.92	361.00	-
Algarve	4.73%	236.37	538.00	-	4.00%	39.97	538.00	-
Região Autónoma dos Açores	0.00%	0.00	10.00	1507.53	2.21%	22.12	10.00	1507.53
Região Autónoma da Madeira	0.00%	0.00	10.00	1205.65	2.31%	23.13	10.00	1205.65
International	**2.69% [7]**	**134.60**	**3042.00**	**5956.03**	**5.87% [7]**	**58.72**	**10566.00**	**70564.90**
France	-	-	-	-	1.70%	16.98	1588.00	-
United States of America	0.12%	5.95	75.00	5956.03	1.60%	16.01	75.00	5956.03
Spain	1.76%	88.24	604.00	-	0.68%	6.83	604.00	-
Italy	0.81%	40.40	2363.00	-	0.57%	5.73	2363.00	-
United Kingdom	-	-	-	-	0.29%	2.86	57.00	1674.21
Chile	-	-	-	-	0.27%	2.69	125.00	12739.91
Mexico	-	-	-	-	0.18%	1.76	394.00	8502.53
Germany	-	-	-	-	0.17%	1.74	2635.00	-
Australia	-	-	-	-	0.17%	1.69	285.00	19868.26
Switzerland	-	-	-	-	0.09%	0.94	1863.00	-
Argentina	-	-	-	-	0.08%	0.76	45.00	10106.36
South Africa	-	-	-	-	0.07%	0.73	532.00	11717.60
Total	**99.96%**	**4998.06[19]**	**7826.00**	**8669.21**	**99.46%**	**994.63[6]**	**15350.00**	**73278.08**

[17] The distance between the natural cork stoppers manufacturing facility and the Source of Cork/Destination of NCS was determined using Google Maps platform [8] when only road transportation was considered (e.g., Spain) and a Sea and Inland Routing tool [9] when both road and maritime transportation was considered (e.g., United States of America). For the international location points, the capitals were used.

[18] It was assumed that the one ton (i.e., functional unit) of NCS is manufactured in the *Área Metropolitana do Porto* subregion since this is the Portuguese subregion where most natural cork stoppers factories are located [10].

[19] The total amount of cork is not 5000 kilograms (Table A.1) because only countries that contributed more than 1% to the total imports of cork were considered. Similarly, the total amount of NCS is not 1 ton (Table A.4) because only countries that contributed more than 1% to the total exports of natural cork stoppers were considered.

C.2. Basic uncertainty factors and Pedigree matrix

This appendix presents the basic uncertainty factors and pedigree matrix utilized in ecoinvent version 3.

Table C.8 – Default basic uncertainty applied to intermediate and elementary exchanges when no sampled data are available; c: combustion emissions; p: process emissions; a: agricultural emissions.

Input/Output Group	C	P	A
Demand of:			
Thermal energy, electricity, semi-finished products, working material, waste treatment services	1.05	1.05	1.05
Transport services (tkm)	2.00	2.00	2.00
Infrastructure	3.00	3.00	3.00
Resources:			
Primary energy carriers, metals, salts	1.05	1.05	1.05
Land use, occupation	1.50	1.50	1.50
Land use, transformation	2.00	2.00	2.00
Pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds (NH4, PO4, NO3, Cl, Na etc.)		1.50	
Individual hydrocarbons, PAH		3.00	
Heavy metals		5.00	1.80
Pesticides			1.50
NO_3, PO_4			1.50
Pollutants emitted to soil:			
Oil, hydrocarbon total		1.50	
Heavy metals		1.50	1.50
Pesticides			1.45
Pollutants emitted to air:			
CO_2	1.05	1.05	
SO_2	1.05		
NMVOC total	1.50		
NO_X, N_2O	1.50		1.40
CH_4, NH_3	1.50		1.20
Individual hydrocarbons	1.50	2.00	
PM > 10	1.50	1.50	
PM10	2.00	2.00	
PM2.5	3.00	3.00	
Polycyclic aromatic hydrocarbons (PAH)		3.00	
CO, heavy metals		5.00	
Inorganic emissions, others		1.50	
Radionuclides (e.g., Radon-222)		3.00	

Table C.9 – Pedigree matrix used to assess the quality of data sources, modified from Weidema (1998) [11].

Criterion score	1	2	3	4	5 (default)
Reliability	Verified[20] data based on measurements[21]	Verified data partly based on assumptions **or** non-verified data based on measurement	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered **or** >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered **or** some sites but from shorter periods	Representativeness unknown or data from a small number of sites **and** from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from area with slightly similar production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale **or** from different technology

[20] Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources.

[21] Includes calculated data (e.g. emissions calculated from inputs to an activity), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score would be 2 or 3.

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