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Sustainable Supply Chain Design and Planning

A Case in the Cork Industry

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Declaração
Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration
I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

Cork has been an important material throughout history. Its range of physical properties means that it has several applications such as cork stoppers, building insulation and floor and wall coverings. The habitat of the cork oak is mainly located alongside the Mediterranean region, being Portugal the country that spearheaded the development of the cork industry and is currently the major exporter of cork goods. This work is carried out at Equipar, an industrial unit (IU) of Corticeira Amorim, world leader in the cork sector. In the sustainability context, the aim of this work is to holistically address and study the supply chain of Corticeira Amorim in relation to three aspects: economic, environment and social. Throughout this work, it is contextualized the cork industry, Corticeira Amorim and how the company looks into sustainability concerns. A literature review was performed to define what is a sustainable supply chain and infer which methodologies are best suited to assess it. Supply chain optimization in the context of TBL was the methodology chosen. The data used to characterize the supply chain is based on company-specific information and the literature. Results show that the main factor in economic and environmental terms is transportation, mainly due to the wide supply chain of Corticeira Amorim. In terms of social results, there was no trade-off that stood out. A sensitivity analysis is performed and confirms that the supply chain is robust to demand uncertainty.

Keywords: Sustainability; Optimization Model; Triple Bottom Line; Cork; Corticeira Amorim; Strategic/Tactical Planning.

Resumo

A gama de propriedades físicas da cortiça inclui aplicações tais como rolhas de cortiça, isolamento de edifícios e revestimentos de pavimentos e paredes. O habitat do sobreiro situa-se principalmente ao longo da região mediterrânica, sendo Portugal o país que liderou o desenvolvimento da indústria da cortiça e é atualmente o maior exportador de produtos de cortiça. Este trabalho é realizado na Equipar, uma unidade industrial da Corticeira Amorim, líder mundial no sector da cortiça. No contexto da sustentabilidade, o objetivo deste trabalho é abordar e estudar holisticamente a cadeia de fornecimento da Corticeira Amorim em relação a três aspetos: económico, ambiental e social. Ao longo deste trabalho, é contextualizada a indústria da cortiça, a Corticeira Amorim e a forma como a empresa encara as preocupações de sustentabilidade. Foi realizada uma revisão bibliográfica para definir o que é uma cadeia de fornecimento sustentável e inferir quais as metodologias mais adequadas para a avaliar. A otimização da cadeia de abastecimento no contexto da TBL foi a metodologia escolhida. Os dados utilizados para caracterizar a cadeia de abastecimento baseiam-se em informação específica da empresa e na literatura. Os resultados mostram que o principal fator em termos económicos e ambientais é o transporte, principalmente devido à ampla cadeia de abastecimento da Corticeira Amorim. Em termos de resultados sociais, não houve nenhuma contrapartida que se tenha destacado. É realizada uma análise de sensibilidade que confirma que a cadeia de abastecimento é robusta à incerteza da procura.

Palavras-chave: Sustentabilidade; Modelo de Otimização; *Triple Bottom Line*; Cortiça; Corticeira Amorim; Planeamento Estratégico-Tático.

Aknowledgements

I take this space to express my gratitude to all those who helped and accompanied me through this stage. I am so proud of the bonds that I have created throughout my student career and the work that I produced.

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This work has shown me that even if the situation we have in front of us is difficult and sometimes it seems insurmountable, there is always a way to overcome it and I realized that we always have someone to support us, especially in bad times.

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List of Acronyms and Abbreviations

APA – *Agência Portuguesa do Ambiente*

APCOR – *Associação Portuguesa da Cortiça*

AR – Article Review

BU – Business Unit

CA – *Corticeira Amorim*

CLSC – Closed Loop Supply Chain

CLT – Central Limit Theorem

CR – Cork Related

EPR – Extended Producer Responsibility

FSC – Forest Stewardship Council

GDP – Gross Domestic Growth

GHG – Greenhouse Gas

GRI – Global Reporting Initiative

GWP – Global Warming Potential

ILCD - International Reference Life Cycle Data System

ISO – International Standards Organization

IU – Industrial Unit

JIT – Just In Time

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA - Life Cycle Impact Assessment

NPV – Net Present Value

OR – Operational Research

PSILCA – Product Social Impact Life Cycle Assessment

RA – Medium thickness cork granules

RCT – Thicker cork granules

RL – Reverse Logistics

RN – Thinner cork granules

ROSA – Rate Optimal Steam Application

R&D – Research & Development

SA – Social Accountability

SC – Supply Chain

SDG – Strategic Development Goal

SETAC - Society of Environmental Toxicology and Chemistry

SHDB – Social Hotspot Database

SLCA – Social Life Cycle Assessment

SSC – Sustainable Supply Chain

TBL – Triple Bottom Line

TCA – 2, 4, 6 Trichloroanisol

UN – United Nations

UNEP – United Nations Environment Program

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1 Introduction

1.1 Contextualization

1.1.1 Contextualization of the Cork Industry

Cork, a 100% natural, reusable and recyclable material, is the bark of the cork oak. Its low density, high insulation capacity, impermeability and physical resistances give it a wide range of distinct applications that no technology has yet managed to emulate (APCOR 2020).

Portugal is the worldwide leader of cork exports with a 65% share. Despite having a vast percentage of its territory covered with cork oaks, Portugal is as well the major importer of cork, which it uses for processing and subsequent export. Portugal transforms 70% of the world's cork into final products (APCOR 2020).

The Iberian Peninsula, especially Portugal, have been pioneers in terms of taking advantage from cork throughout history. The use of cork stoppers and other cork products (e.g., cork flooring) dates from the 19th century in European countries (Portugal, Spain, United Kingdom, France) and the USA, but Portugal is the first country to recognize its importance and creates, in 1956, the Portuguese Cork Association. This would further develop the Portuguese cork industry (APCOR 2020).

Corticeira Amorim (CA) is created in this environment of growth of the cork industry and, in 150 years, has been its world leader. The company is responsible for almost 50% of cork national exports to 25.000 customers worldwide. This is due to the continuous investment in R&D projects enabling CA to introduce innovative products in the market and re-invent traditional products such as the cork stoppers (Corticeira Amorim 2020). Being a major player in the cork industry and markets, CA has a great deal of responsibility with regard to the sustainability of its business.

1.1.2 Sustainable Development, Circular Economy and Extended Producer Responsibility

In recent years, the concept of *Sustainable Development* has been growing. In 1987 was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). In this work, economic growth is stated as not being the sole factor to sustainability. Brundtland (1987) highlights that this growth can not endanger the environment and must not be based on the exploitation of others. Thus, three aspects must be respected in order to achieve sustainability: economic growth, environmental protection and social equity. Elkington (1997) analyzed the growing concern of these three main issues and was the first to recall them as the Triple Bottom Line (TBL) – the TBL is a framework which places the social and environmental aspects at the same level as the economical aspect in order to achieve sustainability.

To promote international cooperation and to align different countries within a single sustainability cause, in 2015, the United Nations member states adopted *The 2030 Agenda for Sustainable Development*. In this agenda 17 *Sustainable Development Goals* (SDGs) were defined. The SDGs cover subjects related to the ones included in the TBL. In order to illustrate how focused the SDG's are on the concept of sustainability, for instance, the 8th, 10th and 12th goals (respectively *Decent Work and Economic Growth*; *Reduced Inequalities*; *Responsible Consumption and Production*) are clearly aligned with it because they address the three pillars of the TBL (United Nations 2020). Moreover, SDGs are relevant for instilling responsibility for the achievement of these objectives into the business of companies, regardless of their sector or industry – the business decisions (e.g., supply chain decisions) that a company makes has to be driven by what the SDGs stand for and with relation to the TBL.

Another important concept in sustainability is that of Circular Economy. By applying a circular economy approach "*the value of products, materials and resources is maintained in the economy for as long as possible*", the waste generation is minimized and translated into economic, social and environmental gains (European Union 2020). The Circular Economy concept is considered to be transversal to the 6th SDG on energy, the 8th, the 11th on sustainable cities, the 12th, the 13th on climate change, the 14th on oceans and to the 15th on life and on land, that emphasizes its importance (United Nations 2018). Moreover, the United Nations recognize the need to make the "*transition from a linear to a circular economy*" – from a produce-use-discard model to a produce-use-revaluate-reuse one.

One of the existent policies within this matter is the Extended Producer Responsibility (EPR) policy, which holds producers responsible for the products' end-of-life. Consequently, producers are forced to rethink their products design and their supply chains (SCs) so as to minimize waste generation promoting recycling and the reusage of their end-of-life products (OECD 2019).

Within this context, CA has been supporting initiatives such as the collection of used cork stoppers (in specific designated locations throughout Portugal) to take advantage of the fact that cork stoppers are 100% recyclable (Green Cork 2019). Thus, the company is assuming the responsibility of its products and extending their lifecycle. With the view to ensure and possibly extend even further this responsibility, it is of paramount importance that the SC of CA is analyzed and optimized, so that its efficiency and sustainability are maximized.

1.1.3 Problem description

As already mentioned, CA has a great responsibility because it is one of the biggest and most innovative companies in the cork industry. Despite using 100% natural, reusable and recyclable core raw materials, investing only in R&D to face the market with eco-friendly products is not enough. It is essential that CA's SC is structured in such a way that minimizes social and environmental negative impacts and, at the same time, supports the company's economic growth and stability. The company's SC must therefore be analyzed with the aim to explore different solutions that adequately respond to economic, environmental and social issues and, overall, build more sustainable solutions. These solutions should also take into consideration the uncertainty in the SC regarding, for example, demand uncertainty, making sure that sufficient facility capacity is available in demand peak periods. In this line of thinking, the following questions are addressed:

- RQ1: How to design and plan a cork SC while ensuring the three pillars of the TBL?

To answer the previous question, one needs to answer first to the next three questions:

- RQ2: How to design and plan a cork SC while ensuring the economic pillar?
- RQ3: How to design and plan a cork SC while ensuring the environmental pillar?
- RQ4: How to design and plan a cork SC while ensuring the social pillar?

Furthermore, it is also important to consider:

- RQ5: How to ensure a holistic approach in the evaluation of the SC of Corticeira Amorim?
- RQ6: How to evaluate the trade-off between the supply chain sustainable objectives?

In this context, the research problem in this work concerns the design and planning of the SC of CA considering a trade-off between the three sustainability objectives. The SC under analysis is to encompass activities from the collection of cork (where forest management activities by the suppliers are to be analyzed for their sustainability) to the distribution of cork products and the collection of end-of-life products to revalue them.

1.2 Objectives

This work aims to describe the context of the problems under analysis, collect relevant data and gather the theoretical concepts and methodologies. Thus, the main objectives of this work are to:

1. Contextualize the research problem and motivation for the study;
2. Describe the CA's case-study and characterize its supply chain;
3. Perform a literature review on the relevant concepts, definitions and research methodologies, such as supply chain design and planning, supply chain sustainability, economic, environmental and social impact assessment, as well as identify existent research gaps;
4. Choose and adapting an optimization model to approach the model under study;
5. Perform an exhaustive data collection and define the necessary assumptions;
6. Develop recommendations for CA and provide insight on the SC under study;
7. Define a series of conclusions that need to be taken into account in future work.

1.3 Research Methodology

The methodology is defined and is illustrated in Figure 1.

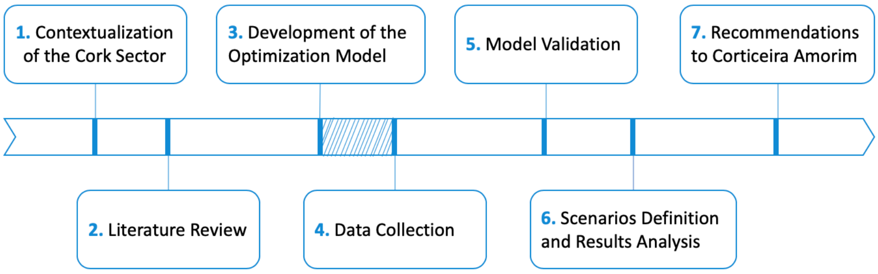

Figure 1 - Research Methodology

The first two have been already considered within the present document:

- **1. Contextualization of the Cork Sector: Corticeira Amorim** – A brief overview was given of the cork sector through the context of CA. In this phase it was described the problem that motivated this work and its objectives were defined. Moreover, concepts related to sustainability were addressed, such as circular economy and energy efficiency and how does CA achieve high environmental standards;
- **2. Literature Review** – In the literature were studied subjects namely: Defining Supply Chain; Contribution of OR to the associated decision processes; How the TBL has been addressed in a SC context. This structure tackles concepts such as CLSC, SSC, TBL, functional unit, system boundary, LCA methods, among others. In addition, the three pillars of the TBL were analyzed in detail to describe what is the current state of the literature of each pillar. After the state-of-the-art review, the work of Mota et. al (2018) was identified as the most promising to be the basis for the model developed.
- **3. Development of the Optimization Model** – Based on the characteristics of the characterized case-study and having as basis the work previously identified in the literature review, in this step a decision tool to support the design and planning of CA's SC in a sustainable way will be developed based);
- **4. Data Collection** – The fourth step involves the collection and treatment of data of CA's SC. The structure of the data collected should follow the required by the model that will be applied to the case in study. Assumptions due to data absence and procedures used to estimate data related to the SC costs, environmental and social impacts are also to be defined during this step. The third and fourth

steps interact between themselves (as depicted in Figure 1) because as data is being collected, assumptions need to be made, hence changing the way the model is developed;

- **5. Model Validation** – The model developed in the previous stage is applied to the data collected in the fourth stage. The results obtained serve as a baseline for comparison and evaluate potential improvements concerning the TBL;
- **6. Scenarios Definition and Results Analysis** – Different scenarios are to be defined and tested in order to find adequate solutions from which the decision-maker may choose to implement and satisfy its objectives. The model parameters are also subject to sensitivity analysis to test the robustness and feasibility of the results obtained;
- **7**. **Recommendations to Corticeira Amorim** – A set of recommendations are given to CA, based on the different scenarios previously found. These recommendations are at a strategic/tactical level and they may affect distinct aspects such as facility location, suppliers' selection, long and short-term inventory planning, among others. Moreover, the recommendations are going to take into considerations the three pillars of TBL, so that they are sustainable suggestions.

The first two steps have already been taken as part of the current work and can be found in chapters 2 and 3. The remaining steps will be developed in the dissertation

1.4 Dissertation Structure

The dissertation is divided into four chapters, which are presented below:

- **Chapter 1: Introduction** – It is described the context in which CA operates and the problem that triggers the implementation of this is introduced. This section covers the objectives of the present work;
- **Chapter 2: The Cork Sector: Corticeira Amorim, S.G.P.S., S.A.** – The company is described more thoroughly. In addition, the BUs that drive CA are introduced to provide context to the SC structure. Then, the sustainability approach of CA is exposed in order to contextualize to what extent is CA applying sustainable measures. On this line, subjects such as energy efficiency and circular economy are depicted uncovering the responsibility-driven policies employed by the company. Lastly, the SC of CA is described;
- **Chapter 3: Literature Review** – Concepts with regard to SC are explored (reverse logistics, sustainability and TBL). An overview on the operational research approaches applied to model SC sustainability is made. Research gaps are identified and it is selected the adequate methodologies to model the SC;
- **Chapter 4: Problem Definition and Model** – The model, its mathematical formulation and methodology followed described;
- **Chapter 5: Case study** – The main data points are described in a holistic approach as well as the assumptions made to deal with the complexity of the problem;
- **Chapter 6: Results and Discussion** – The results obtained from the optimization of each sustainability aspect are described. In addition, it is performed a sensitivity analysis centered in the uncertainty of demand and it is studied specific scenarios that tackle model parameters. Also, recommendations to the company are summed up;
- **Chapter 7: Conclusions and Future Work** – The main conclusions and possible considerations for future work are presented.

2 The Cork Sector: Corticeira Amorim, S.G.P.S., S.A.

The purpose of this chapter is to characterize the case study that will be addressed in this work. This chapter is divided into 6 sections, being the first an introduction to the company. Then, the primary products and services of the company businesses are presented. The third section gives an overview on the company approach to sustainability. The fourth section briefs on the cork stopper SC. The fifth exposes the SC of Equipar and in the last section it is depicted the chapter conclusions.

2.1 Characterization of Corticeira Amorim

The core raw material of CA is the cork. Its flexibility, durability, elasticity/compressibility and impermeability make this material a vital vector in the authenticity and value of their products. The cork oak covers over 23% of the Portugal's forest area and it is a tree that combats desertification, regulates the water cycle and stores carbon for long periods of time, fighting climate change (Corticeira Amorim, 2011).

Corticeira Amorim, S.G.P.S., S.A. has its headquarters in Mozelos, Santa Maria da Feira, Portugal and it is a holding company, currently valued at 1.3 billion euros, listed in Euronext Lisbon (Euronext Lisbon 2019). Being the world's largest cork products company, CA leads its sector as a role model to the economy and innovation of the cork industry. The company's activities started in 1870, in Vila Nova de Gaia, when António de Amorim started a business for the manual production of cork stoppers for Port wine (Corticeira Amorim 2019).

Throughout its 150 years of history, the company augmented its know-how regarding the cork industry and how to empower its raw materials into different applications, across multiple lines of businesses. This strategy of diversification is enhanced with the acquisition of various companies, driven by their motto "not a single market, not a single customer, not a single currency, not a single product" (Corticeira Amorim, 2018a).

CA's operational activity level is structured into five business units (Raw Materials, Cork Stoppers, Composite Cork, Cork Insulation and Floor and Wall Coverings). The company follows a management model based on the concept of a Strategic Holding Company. So, the parent company oversees the control of each BU, through the Executive Committee of CA. From Figure 2, the organizational structure is displayed.

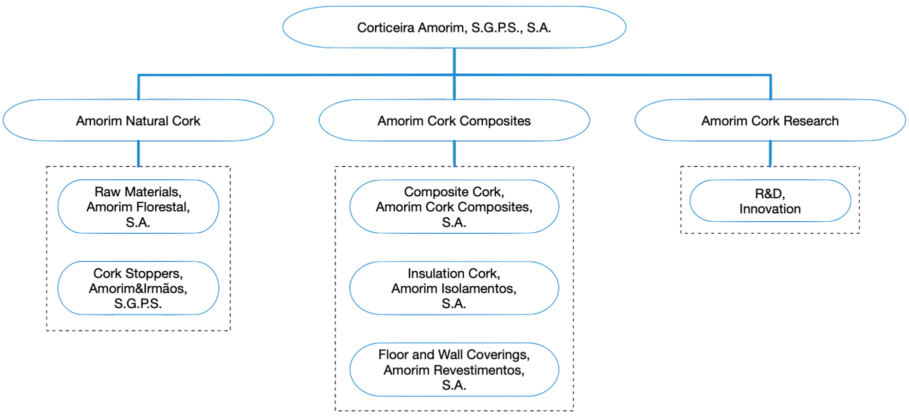

Figure 2 - Organizational chart of CA (Corticeira Amorim, 2018a)

The strategic alignment of the company and its BU's are enhanced through the use of the balance scorecard methodology. In this context, the Executive Committee is responsible for the approval of objectives and strategic initiatives (Corticeira Amorim, 2018b).

As shown in Figure 2, the company is divided in two main macro business areas (*Natural Cork* and *Cork Composites*), with the view to apply effectively the top-level strategy from CA. The *Amorim Cork Research* is a support branch of the company that helps it to keep a leading position in the market. In order to maintain that positioning, CA invests heavily in the R&D branch, creating new innovative products which increases its value chain (Corticeira Amorim, 2018b).

The company has been improving its financial stats as well, such as its net income which had a positive variation of 6% in 2018 when comparing to 2017. This positive result is in line with the overall approach that the company has in the market: create new products, technology breakthrough, gathering new clients and opportunities (Corticeira Amorim, 2018a).

CA has a wide variety of clients across the world and tends to create a lifelong relationship with its customers rather than one time sell. Its main clients are in industries as: Wine (e.g. use of cork stoppers for Gordon and MacPhail scotch whisky bottles), Construction and Infrastructure (e.g. products spotlighted in foreign initiatives such as the 2015 Turin Architecture Festival), Architecture and Design (e.g. products used in the Lisbon's Cruise Terminal), Aerospace (e.g. cork thermal protection products used by European Space Agency in their space shuttles), Transportation and Energy (e.g. cork used in projects like *EcoTrain* where the cork is applied to flooring, partitions and side panels), and Sport (e.g. cork is used in big wave surfer boards) (Corticeira Amorim 2019).

In relation to the Portuguese cork industry as a whole, 70% of national cork products have Europe as a final destination and 72% are products directed to the wine industry (to note in the next section, 69% of CA business volume are cork stopper related). 49% of the world's cork production is in Portugal (APCOR, 2018), albeit 34% of cork oaks are located in Portuguese territory (APCOR, 2018), implying that Portugal leverages well its cork resources, although it imports cork as well. So, it is clear that the Portuguese cork environment and a leading company as CA are vital subjects in this work.

2.2 Strategic Business Units: An overview

CA's deep knowledge in the cork industry and its core raw materials, built through research, development and innovation, has made possible to create and keep a wide portfolio, namely (Corticeira Amorim, 2018b):

- **BU Cork Stoppers** (business volume: 69%) – CA is the leader in the production and supply. There's a variety of natural and technical closures such as cork stoppers for wine, spirituous and effervescent wines. The company has its own distribution infrastructure, giving it a unique position in the supply of the ideal cork stopper for any wine segment;
- **BU Floor and Wall Coverings** (business volume: 14,2%) – The company is world leader in the production and distribution. By using green raw materials, these products follow sustainability values, ensuring better quality of life and sustainable flooring. The breakthrough in the acoustic and thermal insulation performance, is made possible by the constant investment in the R&D strategy;
- **BU Composite Cork** (business volume: 12,8%) – Activities focused in the production of granulates, agglomerates and cork composites. The solutions from this BU are used in different sectors of activity such as construction, the footwear industry, aerospace, railways, among others;
- **BU Insulation** (business volume: 1,4%) – Activities dedicated to the production of insulation materials. CA achieves high thermal, acoustic and anti-vibration insulation performance, using cork natural products, making these solutions sustainable. The BU has been selected more and more throughout the years for interior design due to the environmental concerns;
- **BU Raw Materials** (business volume: 2,6%) – This BU acts as a facilitator between the other BUs, by ensuring the optimization of the flow of raw materials. It eases the management of the cork value chain,

which extends to the entire company. In other words, this BU prepares and decides on the company's provisioning policy.

2.3 Corticeira Amorim: the sustainability approach

As mentioned previously, CA's core values are in line with sustainability and state their view to protect the natural environment. As their mission expresses, "*To add value to cork in a competitive, differentiated and innovative way, in **perfect harmony with Nature***", the company claims that their activities will do no harm to nature. Likewise, the company's vision states that: "*To remunerate the capital invested in an adequate and **sustained manner**, with differentiating factors at the level of product and service and with employees with a winning spirit*". In short, CA achieves a lead position in the market through differentiation and innovation, and claims that its approach is sustainable (Corticeira Amorim, 2018b).

Considering the materiality matrix (see Figure 3) presented in CA *Sustainability Report* (Corticeira Amorim, 2018b) it is possible to spot subjects that are important by the company and its stakeholders like circular economy, energy efficiency, environmental impact of the (cork) product, R&D need of investment, economic performance and promotion of the product (biodiversity and services of associated ecosystems). The issues highlighted in the materiality matrix (Figure 3) are those who will be featured in future initiatives, investment or strategic decisions from the company (Corticeira Amorim, 2018b). It is important to mention that if a subject is below the dashed line then it is of a higher priority to CA then to its stakeholders, and the opposite above the dashed line. Note that stakeholders are investors & shareholders (1), clients (2), employees (3), government (4), suppliers (5), media (6), NGO's & community (7), partners & civil society (8).

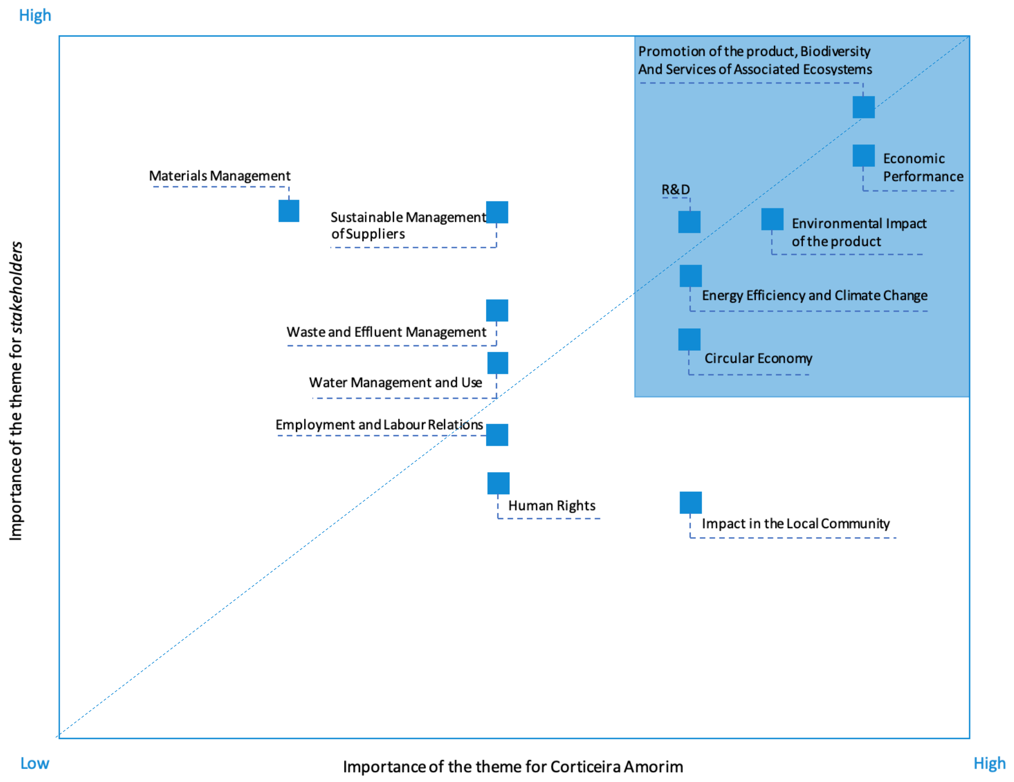

Figure 3 - Materiality Matrix [adapted from CA's 2018 Sustainability Report (Corticeira Amorim, 2018b)]

Sustainability is then a concern for both the company and their stakeholders, although different focuses exist. In the context of this work, where the objective is to construct of a more Sustainable SC, it is relevant to address issues as the **circular economy** approach performed by CA; how the company achieves **energy efficiency** and how it deals with **climate change**. Also, it is important to understand the **environmental impact** of the (cork) product, which will be described in sections 2.3.1 through 2.3.3 respectively. Other points of interest related to sustainability and how the company has been addressing them are summarized in section 2.3.4.

In relation to the issues that both stakeholders and the company prioritize (as observed in Figure 3), the company addresses them with a mindset focused on 12 out of 17 *Sustainable Development Goals* (SDG's) (Corticeira Amorim, 2018b), published by the *United Nations* (UN). The SDG's are:

- **(3) Good Health and Well-Being** – promotes safety at work and makes that a priority for its employees;
- **(4) Quality Education** – provides free trainings to its workers, with the view to help them improve their everyday job and to connect with the company's values;
- **(5) Gender Equality** – makes a point to offer equal opportunities for both genders;
- **(6) Clean Water and Sanitation** –applies measures to reduce water pollution like eliminating dumping and minimizing the release of chemicals and hazardous materials;
- **(7) Affordable and Clean Energy** – intends to augment their global rate of energy efficiency;
- **(8) Decent Work and Economic Growth** – success and good economic stats create a positive impact in local communities (e.g. the company supports local environmental institutions);
- **(9) Industry, Innovation and Infrastructure** – aims to modernize and rehabilitate their infrastructures to make them sustainable, with greater resource efficiency and adoption of clean and environmentally sound technologies and processes;
- **(11) Sustainable Cities and Communities** – aims to reduce per capita negative environmental impact in cities, by paying special attention to air quality and municipal waste management;
- **(12) Responsible Consumption and Production** – Circular Economy has been part of CA's strategy to achieve good environmental sustainability standards as well as power its business by taking advantage of residues that resulted from the SC processes;
- **(13) Climate Action** – aims for high energy efficiency and by exploring a core material that is 100% natural, CA helps to fight climate change;
- **(15) Life on Land** – CA intends to mobilize and increase the financial resources for the conservation and sustainable use of biodiversity and ecosystems;
- **(17) Partnership for the Goals** – CA is a leading company in the cork industry around the world. The company looks for possible partnerships and initiatives that might enhance the general public environmental awareness and the need to look for a more sustainable future.

In the next section, the subjects identified in Figure 3 or the most important and simultaneously related to the CA's SC, sustainability and the environment are further developed.

2.3.1 Circular Economy

CA has acknowledged the opportunity of *Circular Economy* sustainable-economic potential, being a primary strategy applied by the company.

Figure 4 illustrates the cork transformation process, adopted by CA (Corticeira Amorim, 2018b). Bear in mind that it is considered **two tiers** of the cork SC: the **first tier** concerns the SC stages since cork harvesting until the production of the products shown in Figure 4 (these products cannot be originated from cork circular economy); the **second tier** regards all the SC stages that give origin to cork products that use by-products, generated in both tiers, as their raw material.

In the first tier, as shown in Figure 4, there can be two types of the cork raw material: *Amadia* and *Falca*. Depending on the type of cork, different products such as natural cork stoppers (if the cork harvested from the cork oak has enough thickness), footwear and sporting goods (made from *Amadia*) and decorative items (made from *Falca*) are produced. From the processes to generate these products, the **first tier of by-products** (see Figure 4) is originated. These are cork waste or dust that result from production stages; cork waste resulting directly from cork harvesting (depicted in Figure 4 by the arrow between "The Core Raw Material - Cork" and "Cork granulates", in the middle).

CA investment in R&D and technological breakthrough gave the company the chance to add value to the **first tier of by-products**. These are used to form cork granulates (see Figure 4) which in turn will be used by CA's BUs: to create cork stoppers, insulation panels, coverings and composite materials. The production stages in these BUs, will lead to the **second tier of by-products**. These are mainly cork dust that will be treated as biomass or regranulates.

The majority of the **by-products from both tiers** (see Figure 4) are recycled or reused. Some are regranulated and reenter the Insulation, Coverings and Composite Materials BUs (it must be clarified that the BU Cork Stoppers does not use regranulates due to quality issues). The rest is used as a fuel (biomass) to generate energy that CA will exploit to power itself.

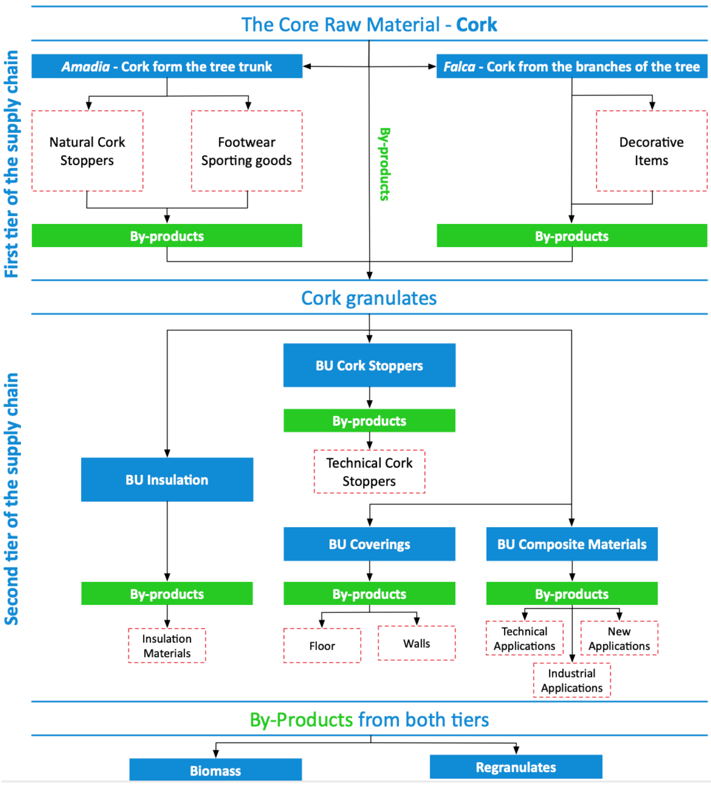

Figure 4 - Cork transformation process into different ends. A Red square means that it is a final product; The processes which re-adds value to the by-products are represented by their use to Biomass and Regranulates (Corticeira Amorim, 2018b)

In this work, circular economy, recycling and environmental stability are pertinent concepts. Therefore, it must be highlighted the recycling and value that CA adds to its by-products and why these two aspects are vital to the company's business.

Cork recycling

One of the advantages of recycling cork is the fact that this material incorporates carbon captured by the cork oak, keeping the CO_2 locked during the entire life of the product. So, with the extension of the cork life cycle, through recycling, the CO_2 emissions are delayed. After being used for the first time, the cork stoppers are collected, treated and then shredded. Afterwards, the resultant cork dust is transformed into cork granulates, returning to integrate the productive processes of the Insulation, Coverings and Composite Agglomerates BUs. Bear in mind that the Cork Stoppers BU cannot utilize granulates originated from recycling due to quality issues, further highlighting the importance of the investment in R&D, by contributing to the creation of the other BUs.

The company supports several initiatives for the collection and recycling of cork stoppers, since 2008 in Portugal:

- **Green Cork** (Portugal) – Partnership between CA and Quercus that promotes the collection of cork stoppers and the financing to plant native trees. The collection is aimed to the final customer to take its cork stoppers to a specific collection point (Green Cork 2019);
- **ReCork** (North America) – CA is a member of the biggest partner network to recover cork. A partner acts as a collection point where people can leave their cork stoppers and thereafter, they are sent to recycling facilities across the continent (ReCork 2019);

Other initiatives have spread to other parts of the world (e.g. Canada, South Africa, France, United Kingdom). The problem is that the recycling of cork products is mainly supported by the volunteering of the general public and the goodwill manifested by various companies such as CA. There is not a logistics system to improve the rate at which the cork products are being recycled like with plastic, carton and glass. These initiatives are essential to change the approach (possibly implying a lot of investment in research to create such system). In 2018, 478 tons of cork were recycled through these initiatives, where 87% were cork stoppers and 13% other cork products, in Portugal (Corticeira Amorim, 2018b).

Valuation of the by-products

CA does not consider the by-products (represented in Figure 4) as a waste, recovering them. The by-products go through a set of processes where they are shredded, in order to form the cork dust. This cork dust can either be recycled into recycled granulates, or used as an energy source to biomass (Corticeira Amorim, 2018b).

As shown in Table 1, in 2018, 90% of the total waste generated was recovered and only 10% was disposed of to landfills (Corticeira Amorim, 2018b).

Table 1 - Distribution of recovered and eliminated waste (tons) (Corticeira Amorim, 2018b)

	2018	2017	2016
Hazardous Industrial Waste	373	282	249
Recovered	237	170	116
Eliminated	135	112	134
Non-Hazardous Industrial Waste	10 059	8 544	9 559
Recovered	9 114	7 811	8 683
Eliminated	945	733	876
Total Recovered	9 351 *(90%)*	7 981 *(90%)*	8 799 *(90%)*
Total Eliminated	1 080 *(10%)*	845 *(10%)*	1 010 *(10%)*
Total	10 432	8 826	9 808

With the view to maximize the value added from waste, CA has implemented new technologies and projects in order to maintain a closed-loop SC:

- **Project *Recupera*** - consisted in the incorporation of cutting surpluses in new cork composites. The company avoided 600 ton/year of composite cork waste, to be sent to a landfill and 700 ton/year of natural fibers to be used in cork agglomerations processes (Corticeira Amorim, 2018b);
- **Development of a new Underlay** - based in cork composites that are previously recycled and treated and then used as a raw material to this new underlay (Corticeira Amorim, 2018b).

These projects are a clear example of what can be represented by the *Regranulates* box from Figure 4. In addition, these types of projects show how CA is deeply engaged with the goal of maintaining a SC that minimizes the waste or other scrap products to be disposed in the end of their life cycle. This is possible by constant R&D investment and continuously adapting the SC to enable the reverse logistics of such waste.

In the context of this work, this information is significant because it shows a clear trend that the company follows in relation to the percentage of waste recovered. In addition, the waste recovered is going to re-enter the SC in the production stages (see section 2.4) or used as a biomass energy source (see next section)

2.3.2 Energy efficiency and climate change

More than 685 companies work in the cork sector in Portugal and 40 million cork stoppers are being produced every day (APCOR, 2018). To power this sector energy consumption is essential. In line with the energy related SDG's, CA applies continuous improvement to its energy efficiency and implements disruptive technologies that guarantees high yields in cork and energy usage.

The company uses two macro indicators to monitor its performance on these areas: one to assess the company's energetic standings (*Energy Intensity*) and the other regards to climate change/carbon emissions (*Carbon Intensity*). It must be taken into consideration what are the system's boundaries by which these indicators are being calculated, due to possible biased results that may not mirror the reality. The source used in this section does not specify what do the boundaries englobe (in terms of the system's inflows and outflows). Nevertheless, the following information detailed in the next subsection are relevant in the sense that there can be found some improvements that need to be applied in the CA's SC.

Energy consumption and Emissions

CA is a company that, due to its size, has to use macro perspectives regarding its energy overall consumption (*Energy Intensity*) and emissions (*Carbon Intensity*). In the following two tables, it is displayed the energy consumption mix and distribution of the company's CO_2 emissions.

From Table 2, it is clear that 65% of CA energy usage comes from Biomass. When comparing to the Portuguese scenario that value is approximately 17% (APA 2019). This is mainly due to the company utilizing cork dust, resulting from its processes, as an energy source (Corticeira Amorim, 2018b).

Table 2 - Energy consumption mix (in GJ) and Energy Intensity (Corticeira Amorim, 2018b)

Type of energy source	2018	2017	2016
Biomass	1 051 116 *(65,67%)*	943 946 *(65,67%)*	878 934 *(65,00%)*
Electricity	485 272 *(30,32%)*	410 738 *(28,58%)*	391 392 *(28,94%)*
Natural Gas	58 254 *(3,64%)*	73 050 *(5,08%)*	74 161 *(5,48%)*
Diesel	5 628 *(0,35%)*	9 339 *(0,65%)*	7 450 *(0,55%)*
Gasoline	411 *(0,03%)*	236 *(0,02%)*	332 *(0,02%)*
Energy Intensity	2 160	2 161	2 142

Energy Intensity consists in the energy spent per monetary value (e.g. GJ/M€ sold). In the three years displayed in Table 2, there is a clear trend in the usage of the various energy sources. Moreover, the data presented, although its sources are not specified, clearly shows the company's business reality and will serve as a point-of-comparison in the present work – the real data shown in the table and the output results of this work may trigger SC decisions (e.g. if the output results state that the company can consume 70% of its energy from biomass sources, seeing the data presented in Table 2, the present work may advise decision makers to change the SC in line with the output results).

The use of energy are related to the total emissions in terms of CO_2 (displayed in Table 3), which have risen since 2016 as the business activity has increased and consequently the share of the electricity usage (Corticeira Amorim, 2018b).

Table 3 - Distribution of the company's emissions (in t CO2) and Carbon Intensity (Corticeira Amorim, 2018b)

Type of energy source	2018	2017	2016
Electricity	63 355 *(91,28%)*	53 624 *(89,30%)*	51 098 *(89,02%)*
Natural Gas	3 734 *(5,38%)*	4 135 *(6,89%)*	4 198 *(7,31%)*
Diesel	1 963 *(2,83%)*	1 682 *(2,80%)*	1 610 *(2,80%)*
Propane Gas	355 *(0,51%)*	589 *(0,98%)*	470 *(0,82%)*
Gasoline	2 *(~0,00%)*	17 *(0,03%)*	24 *(0,04%)*
Carbon Intensity	92,1	88,9	89,5

Carbon Intensity consists in the carbon emitted to the atmosphere per monetary value (t CO_2/M€ sold). The same conclusions as those obtained in Table 2, there is a clear trend in the emissions of the various energy sources. Again, although the sources are not specified, the data explicitly depicts that electricity is the main contributor to the carbon emissions. This data will be compared to the results of the present work and may imply considerations in SC decision-making (e.g., if the output results achieve a considerably lower carbon intensity, decisions makers may be inclined to implement the SC decisions that allow that result).

2.3.3 Environmental Impact of the product

Despite the cork being a natural material, the production of cork products incurs in using other resources and its environmental impact has to be assessed. Thereby, the inventory of input and outflows of energy and material used during the cork life cycle and the system's boundary have to be defined.

Regarding inputs, they are related to energy (mainly electricity, fuel to power transportation and natural gas), water, organic composites (citric acid, silicone oil, paraffin) and inorganic as well (NaOH, H_2O_2, SO_2). In relation to outputs, they consist on by-products, finished products, wastewater, cork residues and sludge (Demertzi, Silva, Neto, Dias, & Arroja, 2016). The previous materials come from different stages of the cork life cycle and will influence the environmental assessment of cork products.

The environmental impact can be assessed in impact categories such as climate change (CC), ozone depletion (OD), acidification (A), human toxicity cancer (and non-cancer) effects (HTC & HTNC), photochemical ozone formation (POF), terrestrial eutrophication (TE), freshwater eutrophication (FEu), marine eutrophication (ME), freshwater ecotoxicity (FE) and mineral and fossil depletion (MFRD). The 1st stage of the cork SC (forest management) is crucial because it dominates the impact in six of the categories above (OD, POF, A, TE, ME and MFRD), due to fuel usage (Demertzi et al., 2016; González-García, Dias, & Arroja, 2013).

In this work it will be designed a boundary to the SC system of CA and, based on this, evaluate what impact assessment categories to use. The previous information will be taken into consideration as a starting point and what kind of results can be expected from the various SC stages.

On the importance of this assessment and regarding the carbon footprint, CA has a product called *Neutrocork* (Cork Stopper) that is used in bottles of wine considered to have a certain complexity. PwC has conducted a study to assess the carbon footprint of this product. The conclusion was that the footprint is negative, -1,8g CO_2 per cork stopper (Corticeira Amorim, 2018b). The system's boundary was not specified, so the results, although positive and aligned with other sources, may be biased.

The problem is that many companies publish their "sustainability reports", but do not explain in detail how they are recovering specific information like this one related to the carbon footprint. It is true that cork products can lock away CO_2 for a long period of time, providing a beneficial effect on the environment, but the processes that transform raw cork into a cork product must be part of these studies. Therefore, there is still room for improvement when publishing these reports where it must be displayed the considered assumptions with the same degree of significance as the results, something that will be done throughout this work.

2.3.4 Other points of interest

As can be inferred from the materiality matrix (Figure 3), there are other issues related to the company's sustainability approach. Although their priority is lower compared to the previous addressed these are also a regular target of the company's sustainable policies. Examples are as follow (Corticeira Amorim, 2018b):

- **Water Management and Use** – Water is especially relevant for the Raw Materials, Cork Stoppers and Insulation Cork BUs, which are responsible for 86% of the total water used by CA. Thus, several policies have been implemented by the company enhancing efficient water management (e.g. Installation of innovative equipment or technologies to reduce consumption);
- **Employment and Labor Relations** – The labor force is vital to ensure the company's success. CA invests in its workers through training (technical and behavioral aspects), ensuring their working rights, balancing the number of male/female workers ratio and constantly checking whether there is a wage discrepancy gap between female and male workers;
- **Sustainable Management of Suppliers** – Cork is the major element in CA's business, hence cork procurement and supplier selection are vital to the company. In line with this, CA promotes forest certification to producers, including the *Forest Stewardship Council* (FSC) certification. A supplier with the FSC certification has implemented, for example, new cork production techniques through improved installation irrigation processes, with the aim of increasing the quality and quantity of cork, so as to ensure the sustainability of its business;
- **Human Rights** – Again, the labor force is important to the well-being of the company. Until now, CA has not identified cases of discrimination, nor risks of occurrence of child labor, forced or compulsory labor or restrictions on the freedom of association and unionization in any of the activities and operations carried out in its SC.

The above issues are relevant in this work as they will help prioritize which sustainability concerns are pertinent to be addressed.

Although, CA has demonstrated serious concerns about the sustainability of its business, these concerns need to be addressed from an integrated SC perspective, which will be done in the context of this work. One of CA's most important IUs has been selected to carry out this type of approach, which is described in the next sections of this chapter.

2.4 The Cork Stopper Supply Chain

In the literature, the work of Demertzi et al. (2015), González-García et al. (2013) and Rives, Fernández-Rodríguez, Rieradevall, & Gabarrell (2012) the *Cork Stopper Supply Chain* described is very similar to the SC of CA. In Figure 5 a simplified version of the cork stopper SC is displayed and it is interpreted within a system's boundary to assess its SC stages (Demertzi et al., 2016; González-García et al., 2013; Rives, Fernández-Rodríguez, Rieradevall, & Gabarrell, 2012).

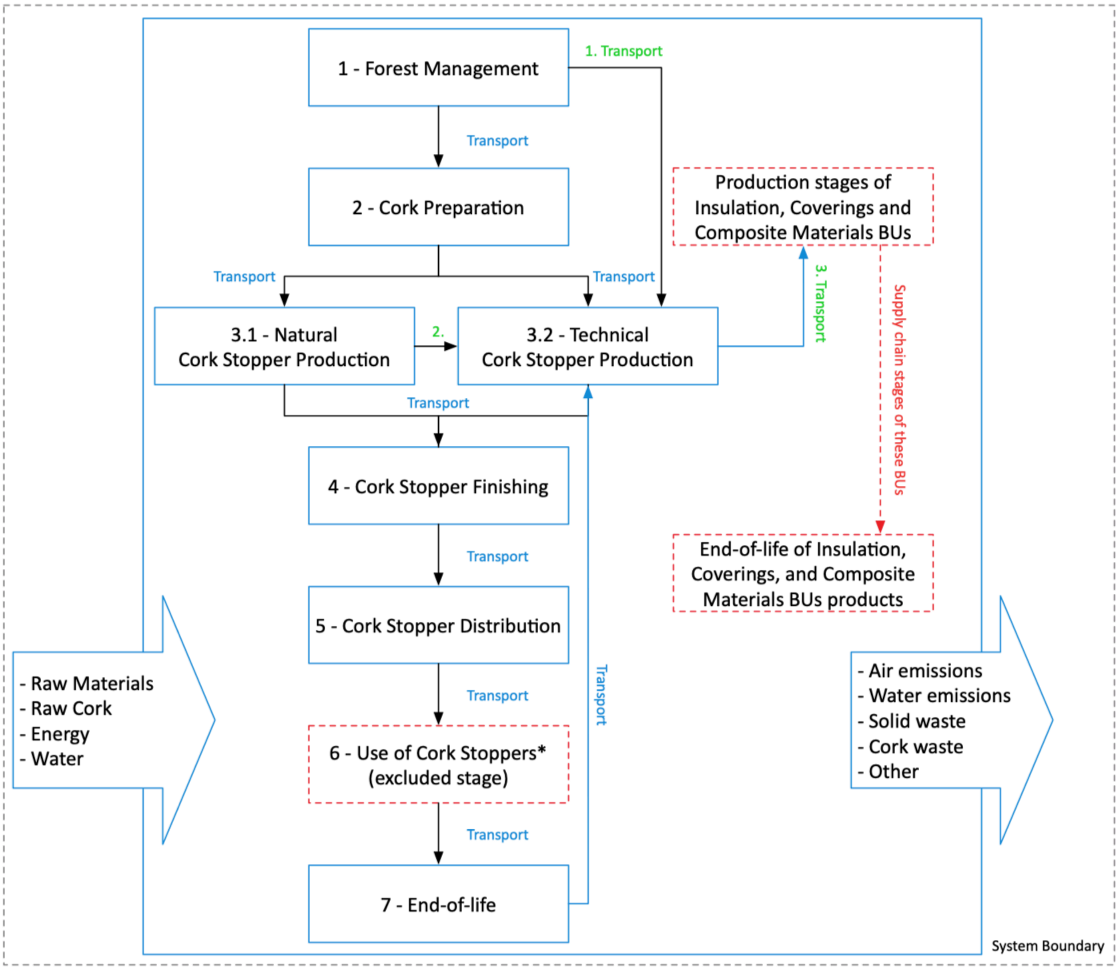

Figure 5 - Simplified Supply Chain of Cork Stoppers. Red figures are not considered in the context of this work. Blue arrows indicate that transport is a reverse logistics operation. Green "transport" means that they are defined in the text below. [Demertzi, Silva, et al. (2015), González-García et al. (2013), Rives, Fernández-Rodríguez, Rieradevall, & Gabarrell (2012)]

From Figure 5 it is highlighted the fact that there are two main types of cork stoppers: **technical** and **natural**. The differences in the SC of both types are minimal, being slightly different in the production stage (*Stage 3 – Cork Stopper Production* from Figure 5). These differences are depicted below.

The processes within each stage of Figure 5 are described in the work of Demertzi et al. (2016), González-García et al. (2013), Rives, Fernández-Rodríguez, Rieradevall, & Gabarrell (2012) and are the same ones CA uses in its SC. Then 7 stages have been identified:

- **Stage 1 – Forest Management** which includes operations like <u>stand establishment</u> (cut-over clearing, ripping, planting, fertilization and dead plants substitution), <u>stand management</u> (spontaneous vegetation cleaning, pruning and thinning), <u>cork stripping</u> (manual cork extraction, transport of the slabs, cleaning of the spontaneous vegetation and pruning) and <u>field recovery</u> (cutting of the tree at the end of its life which is approximately 170 years);
- **Stage 2 – Cork Preparation** which includes planks <u>pile establishment</u> (the extracted cork is manually put into piles), <u>first stabilization</u> (the cork piles are left at an open-air area until they achieve the required moisture), <u>planks boiling</u> (immersion of cork planks in clean boiling water), <u>second stabilization</u> (resting of the planks in order to flatten) and <u>scalding</u> (2nd boiling). Additionally, there is a <u>manual selection</u> of the planks with the appropriate characteristics to produce natural cork stoppers and the rejected ones are sent to the production of technical cork stoppers;

- **Stage 3.1 – Natural Cork Stopper Production** which includes slicing (cork planks are cut into strips), punching (perforation of the cork strips with a drill), pre-drying (to lower humidity), rectification (to obtain final dimensions), aspiration (removal of cork dust), selection (manual/automated), washing (disinfection), drying (to lower humidity), deodorization (to clean the cork stopper's surface), coloring and packaging (in line with the specifications of the client);
- **Stage 3.2 – Technical Cork Stopper Production** which includes grinding (to obtain the cork granulate), extrusion (mechanical compaction and thermal processing of the granulate), molding (a mixture of glue and granules is pressed), gluing (gluing of cork discs to the body of cork stoppers), pre-drying (to lower humidity), rectification (to obtain final dimensions), aspiration (removal of cork dust), selection (manual/automated), washing (disinfection), drying (to lower humidity), deodorization (to clean the cork stopper's surface), coloring and packaging (in line with the specifications of the client);
- **Stage 4 – Cork Stopper Finishing** which includes dusting (removal of dust), branding (optional; depends on the client's needs), printing (similar to branding; a symbol than the brand is printed; depends on the client's needs), surface treatment (to assure an easier insertion/extraction of the cork stoppers in the bottle) and packaging (in line with the specifications of the client);
- **Stage 5 – Cork Stopper Distribution** which represents the outbound transportation from the factory into bottling centers (or clients) across the world;
- **Stage 6 – Use of Cork Stoppers** which represents the usage of the product. In the context of this work, it is the single excluded stage due to the granularity of the product, in other words, cork stoppers are used by millions of end-users with a meaningless impact;
- **Stage 7 – End-of-life** products can have three types of destination: incineration, landfill or recycling.

All the "transport" flows in Figure 5 are performed by third-party logistics. Regarding the three specific flows in Figure 5 (depicted in green), they are described as:

- **1. Transport** – While harvesting the cork there is a coarser visual filtration of cork that will not have enough quality from the outset to produce natural cork stoppers. This cork is sent directly to IUs that produce technical cork stoppers;
- **2. Transport** – The cork residues that result from the cork punching (see *Stage 3.1* above) are sent to IUs that produce technical cork stoppers. Otherwise, they would be used to biomass;
- **3. Transport** – The grinding unit of IUs that produce technical cork stoppers is responsible for recycling cork products at their end-of-life. The unit shreds the used products, forming the regranulates (see Figure 4), and sends them to the Insulation, Coverings and Composite Materials BUs.

Exposing the differences between **technical** and **natural cork stoppers** is relevant due to CA having IUs that produce technical and/or natural cork stoppers and thus show a holistic view of the SC of the company. For the purpose of this work, in the next section, it is given a specific example of Equipar IU that produces technical cork stoppers, which will be the focus of the dissertation.

2.5 Supply Chain of Equipar: Amorim&Irmãos, S.A., Industrial Unit Coruche

In Equipar the phase *Cork Stopper Production* is the **Stage 3.2 – Technical Cork Stopper Production**. In here it is **used cork granulates to produce technical cork stoppers instead of cork planks to produce natural cork stoppers**. Referring back to Figure 5, this IU is focused in the *Stage 3.2 – Technical Cork Stopper Production* and *Stage 4 - Cork Stopper Finishing* phase.

As mentioned, Equipar produces **technical** cork stoppers which are originated from cork granulates (see Figure 4). In addition, Equipar is one of the many IUs across the CA's SC, and in this case, it supplies other BUs with cork granulates. Figure 6 is a strategic point of view of Equipar and provides an overview to the processes that occur there.

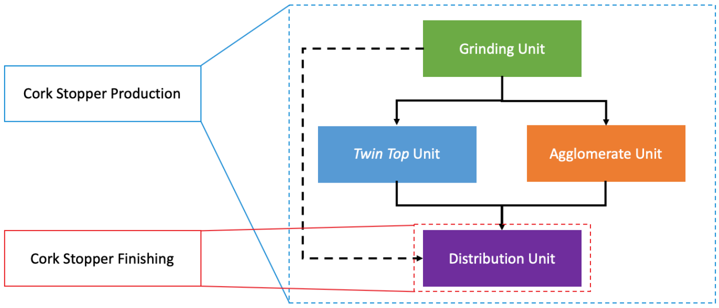

Figure 6 - Equipar Cork Production Unit: a strategic point of view

Regarding the production units within Equipar:

- **Grinding Unit** – The inputs used in this unit are residues resulted from *Punching* (that come from other IUs that produce natural cork stoppers), defective cork disks and mainly cork planks after the scalding process (95% comes from *Stage 2* and 5% of this process is done indoors). This unit produces three types of granulates, **RCT** (used in champagne bottles cork stoppers), **RA** (utilized in still wines cork stoppers), **RN** (used also in still wine bottles cork stoppers), in descending order of diameter;
- **Agglomerate Unit** – This unit can have as inputs any type of granulates mentioned earlier. In this unit the granulates are glued together in a process called *Extrusion* into rolls of cork (called *sticks*), which then are cut down (with approaximetly the dimensions of a cork stopper) to a basket. The rest of the industrial processes are described in the previous section;
- ***Twin Top* Unit** – This unit can have as inputs any type of granulates mentioned earlier. The main difference to the previous IU is that before the production of cork sticks, the granulate is mixed with a special glue, unloaded for molds, pressed, followed by a passage through a heater and then the cork bodies are stabilized – this process is called *Molding*. After the *Extrusion*/*Molding* there is an additional process called *Gluing*, where natural cork discs are glued to the ends of the cork bodies (these disks are bought from Amorim Florestal);
- **Distribution Unit** – In this unit the cork stoppers may be *Branded* (at the request of the client), *Surface Treatment* (application of a lubricant and sealant to facilitate bottling, sealing and extraction of the stopper) and, as stated previously, *Coloring* (at the request of the client) and *Packaging*. From this unit, the cork stoppers/cork granulate leave Equipar to supply other IUs/clients.

Table 4 presents a summary of types of inputs/outputs and highlights the major difference between the production units *Agglomerate* and *Twin Top*. The distinction is that in the *Agglomerate* unit the processes *Molding* and *Gluing* are not required. The rest of the processes described in the *Stage 3.2 – Technical Cork Stopper Production* section 2.4 are the same for both units.

Table 4 - Summary of the production only phases

Production Phase	Types of inputs	Types of product outputs	Extrusion	Molding	Gluing
Grinding Unit	Cork residues, defective cork disks, cork planks, end-of-life products	Granulates: RCT, RA, RN	-	-	-
Agglomerate Unit	Granulates: RCT, RA, RN	Technical agglomerate cork stoppers	Yes	No	No
***Twin Top* Unit**	Granulates: RCT, RA, RN	Technical *twin top* cork stoppers (cork disk at the edges)	Yes	Yes	Yes

Before the granulates reach the Agglomerate and *Twin Top* units they have to go through the **ROSA** treatment (Rate Optimal Steam Application). It is a heat treatment by application of water vapor ensuring the elimination of **TCA** (2, 4, 6 Trichloroanisol) responsible for giving the wine an undesirable taste (Demertzi et al., 2016). This process is harder with greater grain size (e.g. it is a harder process to apply in RCT granulates rather that RA).

Equipar operates in a *Just in Time* (JIT) system producing and supplying products only when needed. Thus, the operations described must run smoothly in order to prevent bottlenecks. Regarding that, the IU Director explained that if a bottleneck exists it is at the *Packaging* and/or *Extrusion* processes, but that it is not yet studied. So, if the IU runs at almost full capacity there is a low probability of errors or disruptions in the production/finishing stages.

As mentioned, Equipar encompasses only *Stage 3.2* and *Stage 4*. The other stages of the SC are performed by other companies of Group Amorim.

The SC outside of Equipar will be covered in this work (mapping suppliers, clients and the sidelines of the global SC of Equipar). Data that characterizes the SC will be covered as well (e.g., product demand; operational costs).

2.6 Chapter Conclusions

From this chapter it can be concluded that CA has a great deal of responsibility for being one the global leaders in the cork industry. The company thrives in investment in R&D and innovation. This innovation is often connected to the growing concern about the environment and is translated in the development of more eco-friendly solutions (e.g., *Development of a new Underlay*) and promoting initiatives related to circular economy (e.g., *Project Recupera*).

For the purpose of this work, the SC of CA was described with Equipar as being the IU responsible for the *Stage 3.2 – Technical Cork Stopper Production* and *Stage 4 – Cork Stopper Finishing*. As previously stated, the SC of CA covers stages from forest management to the end-of-life of the cork product. Being a fully integrated SC, CA recognizes its economic, environmental and social responsibility, because it outlines its objectives based on the SDG's (Corticeira Amorim, 2018b).

In order to design the most appropriate methodology in the course of this work, a literature review is performed to assess how concepts such as SC and sustainability are being addressed by authors.

3 Literature Review

In this chapter a literature review is performed on relevant SC concepts, on how these have been addressed in the context of Operational Research (OR), and how sustainability has been explored in a SC context. The current chapter is divided into four sub-sections being the first an overview of SC definitions and how the concept evolved into the sustainable supply chain concept today. The second subsection is relative to how OR has been contributing to the decision processes within Sustainable Supply Chain (SSC). Next, it is briefly addressed how sustainability through the Triple-Bottom-Line (TBL) has been modelled in SC studies. The final subsection presents the chapter conclusions.

3.1 Sustainable Supply Chains

Supply Chain Management has been appearing in the literature since the beginning of the 1980's, a time when firms realized that building close relationships with their suppliers and efficiently managing the company's inflows (e.g., raw materials) and outflows (e.g., finished products) was a growing need.

In 1996, SC was defined to be centered in three main stages: procurement, production and distribution (Thomas e Griffin 1996) – showing the first signs of recognition of how complex a SC and its decisions can become. Later on, in 2001 (Lambert, Stock e Ellram 1998) a **Supply Chain** (SC) is generally referred as "*the alignment of firms that bring products or services to market* (…) *that includes manufacturer, suppliers, transporters, warehouses, wholesalers, retailers, other intermediaries and even customers themselves"*. This is a very simple and direct approach to define "supply chain", since it does not highlight the complex interactions between the different so-called "supply chain" entities.

In 2001, the importance of the various interactions within the SC was evidenced and were described as "*a set of three or more entities directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer*" - where different levels of complexity exist depending on the size of the SC (Mentzer, et al. 2001). So, from these key concepts it is possible to deduce others related to SC: strategic planning (e.g. warehouse allocation); tactical planning (e.g. flow planning); operations planning (e.g. daily production planning) (Mihai Felea & Irina Albăstroiu, 2013). The previous concepts serve to show the generic and hierarchical structure of the decision approach to a SC (Strategic, Tactical and Operational decisions). An improved SC approach, that took into account the complex relationships between SC entities, was identified by Mihai Felea & Irina Albăstroiu (2013).

In the context of economic growth powered the development of more ambitious companies that wanted to take advantage of the positive economical scale environment. But, the increasing expansion and complexity of SCs diverted the general attention to other problems such as the increasing amounts of waste created by SCs. At the same time the society environmental mindset had been developing as well and pressured governments to implement green policies that indirectly controlled the waste created. For instance, the **Extended Producer Responsibility** (EPR) is a government policy that assigns companies the financial/physical responsibility for the post-consumer phase of their products. Companies faced this policy with the gradual introduction of environmental objectives in their SC models (e.g. a company develops a model where it re-collects post-consumer products and recycles them, extending the product lifecycle of its product) (OECD 2019). This new environmental concern divided the concept "supply chain" into two:

- **Forward Supply Chain** – The forward SC is a "*network of facilities and distribution options that performs the functions of procurement* (…), *transformation of materials into intermediate and finished products,* *and the distribution* (…) *to customers*"(Kannan, Sasikumar, & Devika, 2010). This concept is a one-way approach to SC – transforming raw materials into finished products and shipping them to customers;

- **Reverse Supply Chain** – The chain "*focuses on the backward flow of materials from customer to supplier* (…) *with the goals of maximizing value from the returned item or minimizing the total reverse logistics cost*" (Kannan et al., 2010) – a definition that gives emphasis to the economic advantage of performing reverse logistics . A similar approach is that **Reverse Logistics** (RL) is the "*term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes a relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials, and disposal*" (Jamshidi 2011) – in this definition, RL is stated as the ensemble of activities needed to do the disposal of hazardous materials as well as of the products that can be recycled or reused. The latter definition is an improvement from the first definition because RL can be either used to re-add value to post-consumer products and extend their lifecycle or to ensure the correct and efficient disposal of end-life-products.

Throughout the years, with the need to achieve high economic and environmental standards, the previous concepts gave birth to **Closed Loop Supply Chain** (CLSC) – "*design, planning and operation aim to maximize value creation over the entire life cycle of a product, pursuing a dynamic recovery of the product value from different types and volumes of returns*" (Barbosa-Póvoa, da Silva, & Carvalho, 2018). Basically, a CLSC consists of both forward and reverse SC where the forward SC consists on the movement of goods from the upstream suppliers to the downstream customers and the reverse from downstream customers to upstream recycling centers, revaluation facilities (e.g. giving used goods another purpose), re-integration in the manufacturer's production lines (Kannan et al., 2010).

The inclination towards economic and environmental concerns slowly became to encompass the social pillar as well – decision-makers added the social aspect as an important concern at the same level of the economic and environmental, giving rise to the **Triple Bottom Line** (TBL) concept. The TBL is a framework which places the social and environmental aspects at the same level as the economical aspect. Elkington (1997) addressed the issues related to the feasibility of maintaining the growing global economy in which society depends to move forward. In addition, the economy depends on the global ecosystem, whose health is represented by the "*Bottom Line*" – Social, Environment and Economical bottom lines. These three aspects add complexity to the sustainability challenge due to being subject to external pressures which in turn might increase their unpredictability and may provoke a reaction from the company (e.g. an unexpected political crisis changes the social scenario and the company must react to it).

Elkington (1997) recognizes the sustainability concept development that went from the economical point of view to the TBL. As the concept evolved, the business environment needs also to change in a modernized direction. The author focuses, for instance, on how *Company Values*, *Partnerships* and *Markets* will have to adapt to respect the TBL and be sustainable:

- **Company Values** – The author states the clear change from "*hard values*" (higher importance of the financial aspect) to "*soft values*" (social aspect). Personal integrity, respect for employees and environmental awareness are three additional examples regarding the current trend of "*soft values*" (Elkington, 1997);
- **Partnerships** - With the view to achieve good TBL performance "*new types of economic, social, and environmental partnerships are needed*" whereby "*long-standing enemies must shift from mutual*

subversion to new forms of symbiosis" (Elkington, 1997) – meaning that to achieve the objectives of the TBL, the business environment has to cooperate. Elkington (1997) states that this cooperation is crucial to meet sustainability;

- **Markets** – The traditional approach where the company's products competed head-on with another's is out of date. The business ecosystem will develop as a biological ecosystem – "*the focus now is not just on a given company, but on its entire environment*" (Elkington, 1997). As in *Partnerships*, companies will need to cooperate by sharing visions, form alliances and managing complex relationships. A business intercepts several types of industries and thus it needs outside expertise to thrive.

These points are examples of how to address the TBL and how complex it is. Only through distinct businesses working together (to combine different expertise) and applying a *softer* vision of the business (from "the product needs to be financially advantageous" to "the product needs to provide financial stability to the company and not harm the environment and the society") can the balance be achieved by a company. This breakthrough can be witnessed with the growing awareness of authors to include the TBL in their research (examples of papers described in 3.2.2) – thus, to be "sustainable", it is vital to encompass three pillars: Economic, Environmental and Social.

From the application of the TBL concept to SC resulted the definition of the **Sustainable Supply Chain** (SSC), described as "*complex network systems that involve diverse entities that manage the products from suppliers to customers and their associated returns, accounting for social, environmental and economic impacts*" (Barbosa-Póvoa et al., 2018) – it can be stated as the explicit consideration of the environmental and social impacts is the SSC.

3.2 Sustainable Supply Chains and Operation Research

Barbosa-Póvoa et al. (2018) made a state-of-the-art review of the new opportunities and current research trends regarding SSC with an OR perspective. In this paper a sample of 220 papers was used, and it was analyzed according to two main issues: (1) how OR has been contributing to decision processes within SSC (strategic vs tactical vs operational decisions); (2) how the TBL has been modelled (e.g., optimization models, simulation models, among others). The main conclusions of this paper are considered and summarized in the following sections.

To complement the work and methodology followed by Barbosa-Póvoa et al. (2018), recently published papers in OR (after 2016) are included in this review as well. The review was further strengthened with TBL assessment and optimization related works with particular focus on LCA and SLCA methodologies.

3.2.1 Contribution of OR to SC decision processes

In order to do a first screening of the researched papers, they were separated into groups. The criteria used was "how does this paper contribute to the decision process", generating three distinct groups: **strategic decisions** – it addresses long-term planning and represents a decision from the executive management level of a company; **tactical decisions** – it addresses short-term planning and deals with inventory, demand and supply management; **operational decisions** – it addresses demand fulfillment, production scheduling and weekly planning (a combination between the previous concepts was also considered – e.g. strategic-tactical paper). Most publications addressed a strategic (145) or strategic-tactical (59) decisions and only two papers addressed the three decision levels, being the study of economic and environmental pillars the main trend. In relation to the majority of the literature, within a strategic decision level, network design (inventory positioning, production allocation, facility design) emerges as the top researched issue. The reason for the operational level is relatively less researched when compared to strategic or tactical level is due to the computational effort to do the level of detail and the decision integration of operational decisions (Barbosa-Póvoa et al., 2018).

It should be noted that to define and model an SSC it is necessary to integrate several decisions (strategic and/or tactical and/or operational) as decision variables. Taking into consideration the data recovered and represented in chapter 2, in the context of this work the decisions that appear to be most relevant are (1) supplier's selection, (2) technology selection, (3) intermodal transportation, (4) inventory planning at a strategic and tactical level and (5) defining final destination of end-of-life products. Regarding these decisions, some authors identified them as research gaps in the literature: (2) technology selection (e.g. for different production technologies) and (3) intermodal transportation, in the context of CLSC design (Boukherroub, Ruiz, Guinet, & Fondrevelle, 2015; Brandenburg, Govindan, Sarkis, & Seuring, 2014; Eskandarpour, Dejax, Miemczyk, & Péton, 2015; Seuring, 2013; Seuring & Müller, 2008; Taticchi, Garengo, Nudurupati, Tonelli, & Pasqualino, 2014); (1) supplier's selection and (4) inventory planning have been identified as research gaps, specially if it is a CLSC design and planning problem (Barbosa-Póvoa et al., 2018). Regarding the (5) final destination of end-of-life products, if it is related to cork products, only one paper have been found to address the subject, that is not related to SC design and planning (Demertzi, Dias, Matos, & Arroja, 2015).

The five decisions introduced above are considered research gaps in the literature hence the present work have a significant contribution potential to the literature.

3.2.2 How the TBL has been modelled

The TBL has been recurrently mentioned in the literature. There are distinct metrics for each goal (economic, environmental and social pillars). In Table 5, Table 6 and Table 8 an overview of how these goals have been addressed in the literature using OR techniques is given, based on the work of Barbosa-Póvoa et al. (2018). In each metric uncovered, it is given an example of its application to understand how authors are approaching problems within each goal/metric.

Economic Goal

From Table 5 one can see that cost (59% of analyzed papers address this goal), profit (25%), NPV (9%) and risk (7%) are the metrics chosen by authors to module the *Economic Goal*. The OR models used are optimization (73%), simulation (12%) and others such as statistics, decision analysis or data analysis.

Table 5 - Literature overview of the Economic Goal (Barbosa-Póvoa et al., 2018)

	Metrics most used	OR models used
Economic Goal	Min. of cost (59%)	Optimization (~73%) Simulation (~12%) Others (~15%)
	Max. of profit (25%)	
	Max. of NPV (9%)	
	Min. of Risk (7%)	

The *Economic Goal* is the most researched across the literature (Barbosa-Póvoa et al., 2018). The narrow number of metrics used (displayed in Table 5) are a sign that this goal is easily described by a single concept/metric. For instance, (Liotta, Stecca, & Kaihara, 2015) treats **Cost** as a parameter in the objective function to optimize freight flows between SC entities; (Garg, Kannan, Diabat, & Jha, 2015) maximizes **Profit** is maximized to assess the economical aspect of an electric goods CLSC; (Ashayeri, Ma, & Sotirov, 2014) maximizes **NPV** in an MIP problem that seeks optimal capacity allocation; (Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2018) uses **NPV** in a multi-objective MILP programming model that takes into account the three TBL goals and is intended to be a decision support tool for the design and planning of SSCs; (Moghaddam, 2015) minimizes **Risk** through the use of an economic risk metric associated with the supplier not supplying the correct quantity or quality required of raw materials.

The examples above emphasize the fact that the *Economic Goal* is usually modelled with one single metric for one single economic objective function. On the other hand, most of the authors that address risk, combine it along another metric like Moghaddam (2015). Generally speaking, risk is used as a parameter arbitrarily defined in an objective function that is minimized – that parameter intends to model an unexpected event (e.g., a supplier that ships raw materials with $X\%$ of them being defective on average).

In addition, when SC network is dynamic (it can change throughout the problem modulation), NPV is the indicator preferred by authors (Barbosa-Póvoa et al., 2018). So, to design different scenarios to a given SC problem, the NPV metric is the most suitable. The paper from Mota, Gomes, Carvalho, & Barbosa-Povoa (2019) is an example where this approach is followed.

This line of the TBL has been a focus of companies since the beginning, due to the natural need of making a business profitable, hence maximize profits and minimize costs is treated as a vital requirement to the survival of a company.

Environmental Goal

From Table 6, CO_2 emissions (24,5% of analyzed papers address this goal), GHG emissions (16,8%), LCA assessment (16,1%), Waste (14,3%), GWP (9,1%), Climate Change (9,1%), Recycling (8%) and others such as Biodiversity and Renewable Energies are the metrics chosen by authors to model the *Environmental Goal*. The OR models used are optimization (70%), simulation (8,5%), statistics (8%) and others such as data analysis or decision analysis.

Table 6 - Literature overview of the Environmental Goal (Barbosa-Póvoa et al., 2018)

	Metrics most used	OR models used
Environmental Goal	Min. of CO_2 emissions (24,5%)	Optimization (~70%) Simulation (~8,5%) Statistics (~8%) Others (~14,5%)
	Min. of GHG emissions (16,8%)	
	LCA assessment (16,1%)	
	Min. of waste (14,3%)	
	Min. of GWP (9,1%)	
	Min. of Climate Change (9,1%)	
	Max. of Recycling (8%)	

Regarding the *Environmental Goal* it can be concluded that the majority of the research developed focuses in just one or two metrics at a time (e.g. using only CO_2 emissions to address the environmental aspect). For instance, (Hernández-Calderón et al., 2016) minimizes **CO_2 emissions** through the maximization of tax credit, in Algae-based Biorefinaries; (Giarola, Zamboni, & Bezzo, 2012) minimizes **GHG emissions** through an LCA approach in an MILP model that seek to optimize the environmental and economic aspects; (Cucchiella, D'Adamo, & Gastaldi, 2013) minimizes **Waste** diverted to landfills in order to be used as an energy source, in a problem where the economic and environmental benefits are assessed; (Chaabane, Ramudhin, & Paquet, 2012) expresses **GWP** for each activity of the SC in terms of carbon dioxide equivalent (CO_2e) which is then minimized; (Accorsi, Cholette, Manzini, Pini, & Penazzi, 2016) uses an LP model to optimize the infrastructure, agriculture, and logistics costs and balances CO_2 emissions, the latter in an holistic perspective related to **Climate Change**; (Igarashi, Yamada, Gupta, Inoue, & Itsubo, 2016) minimizes end-of-life assembly products disassembly costs, leaning towards higher **Recycling** and CO_2 saving rates. In contrast, (Mota et al., 2018) uses the software SimaPro to characterize the environmental aspect of the problem. The authors selected, a *consequential* **LCA methodology** due to being aimed to study environmental consequences of possible changes between alternative systems and it is typically linked with policy making - see Table 7 for further topic development.

This *Goal* is as well quite developed – there is a relevant diversity of metrics used and distinct examples of their application such as inclusion of parameters in the objective function, multi-objective programming, optimization models and a relatively new concept, the use of LCA. Despite the fact that in the economic area choosing one of the metrics presented is most of the times enough to assess the economic performance of a given system, in the environmental aspect it is needed to address more indicators in order to have a holistic view of the system.

The **Life Cycle Assessment** (LCA) has shown to be the most suitable methodology to this end. It can be described as "*a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use*" (Muralikrishna e Manickam 2017). So, the LCA assesses the environmental impacts from the entire lifecycle of a given product or process, using multiple impact categories.

With the view to apply the LCA methodology, the international standards ISO 14040:2006 (rules for conducting an LCA) and 14044:2006 (requirements for conducting an LCA) have to be respected (The International Standards Organisation, 2006).

Usually, an LCA study follows four steps (see Figure 7 for the LCA framework representation):

- (1) **Goal and Scope definition phase -** Defines the reasons why the LCA is being executed, the product and its life cycle and a description of the boundaries of the system (the depth and level of detail of an LCA can differ);

- (2) **Life Cycle Inventory analysis** (**LCI** or inventory analysis phase) – The inventory of inflows and outflows associated to a product, service or process are assessed (ex. use of electricity in GJ). The data collected is necessary to meet the goals defined in (1);
- (3) **Life Cycle Impact Assessment** (**LCIA** or impact assessment phase) - The environmental impacts are classified, evaluated and translated into environmental impact categories. In addition, LCIA provides additional information that helps to assess a given system's LCI;
- (4) **Interpretation phase** - As the name implies, the results from (2) and (3) are summarized and interpreted. This phase will provide a basis for recommendations or decision-making in line with (1).

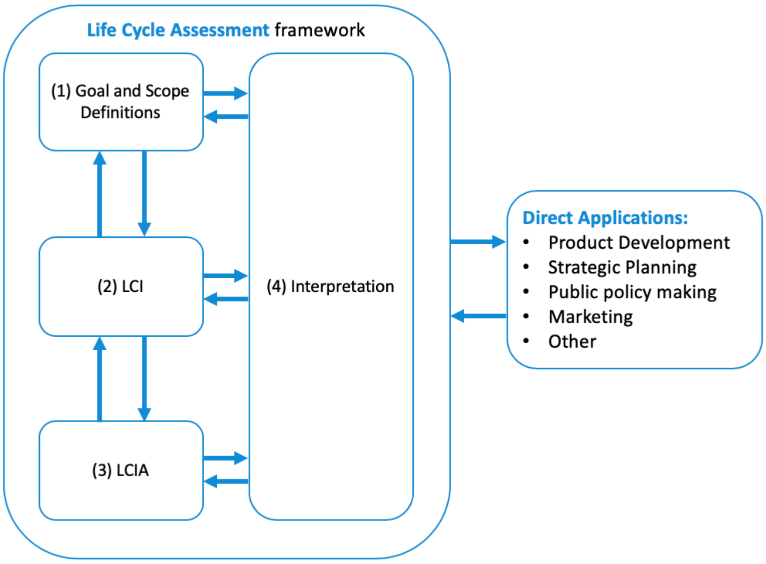

Figure 7 - LCA framework [adapted from The International Standards Organisation, (2006)]

With respect to the *(1) Goal and Scope Definitions* the **functional unit** and the **system boundary** must be defined. These two concepts are vital to perform the LCA because, if changed, the impact assessment and its interpretation can change substantially. The concepts are thus defined:

- **Functional Unit** – It "*defines the quantification of the identified functions (performance characteristics) of the product*". Its main purpose "*is to provide a reference to which the inputs and outputs are related*", ensuring comparability on a common basis to the LCA results (The International Standards Organisation, 2006). The system's inflows and outflows are given in relation to the functional unit. For instance, to produce 1 egg (functional unit) company A spends 1L of water and 0,2Kg of chicken feed; on the other hand, company B spends 1,1L of water and 0,19Kg of chicken feed → company A and B are comparable because there is a common basis between them, the 1 egg;
- **System boundary** – It "*defines the unit processes to be included in the system*". The choice of elements/processes/stages within the system depends on the criteria defined in *(1) Goal and Scope Definitions* → "*The criteria used in setting the system boundary are important for the degree of confidence in the results*" (The International Standards Organisation, 2006). Defining the system boundary is an iteration process, so what is initially designed may be altered throughout the LCA application.

As exposed in the previous chapter, results from environmental studies can be biased by the incorrect way of delineating the boundary of the system (e.g., putting outside the boundary the disposal phase of end-life products) or the non-optimal definition of the functional unit (e.g., appoint an irrelevant product as a functional unit that does not reflect the inputs and outputs of the system). Thus, these two concepts should be available with the view to have a better critical viewpoint about the problem.

Depending on the method used in an LCA assessment (e.g., *Eco-99* vs *ReCiPe* vs *IPCC*) the metrics utilized can consider different environmental hazards like freshwater eutrophication or carbon emitted to the atmosphere. According to Barbosa-Póvoa et al. (2018) the most suitable method to use is the *ReCiPe* due to it being a direct development from *Eco-99* (problem-oriented approach) and *CML* method (damage-oriented approach) – the *CML* defines the impact categories at the *midpoint* level; the *Eco-99* translates those into three impact categories at the *endpoint* level (Goedkoop et al., 2009; Leitão, 2016). In addition, *ReCiPe* method was directly compared with several LCIA methods with the view to assess which one was the most complete in terms of impact categories covered (European Commission, 2011). It has been concluded, that *ReCiPe* method is the most complete and suitable LCIA method for the assessment of the potential environmental impacts of products and processes to use in the European environment (European Commission, 2011; Mota, Carvalho, Gomes, & Barbosa-Póvoa, 2019).

Figure 8 summarizes the *ReCiPe* method. "LCI result" is an example of a given system's inventory to demonstrate the method dynamic. In the case of the *ReCiPe* method there is a midpoint and endpoint approach – **Midpoint** represents the *Environmental Mechanisms* (e.g., Ozone Depletion or Climate Change) which in turn will translate into impact categories; **Endpoint** categories refer to the subsequent damage (e.g., damage to Human Health or Ecosystems Species). However, in Figure 8 it can be observed that the *ReCiPe* method has *Midpoints impact categories* without any *Environmental Mechanisms* to include them in the *Endpoint categories* (e.g., Algae Growth or Water Use) – this is due to the incompleteness of the method, reinforcing the fact that there is still room to develop it. Despite this, it is still the most complete method according to what was stated earlier.

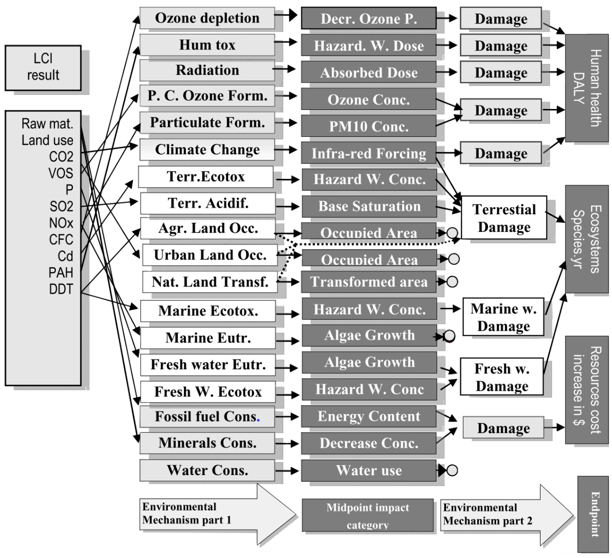

Figure 8 - ReCiPe method (Goedkoop et al., 2009)

In Figure 9, the LCIA methods' typical structure is further detailed. **Classification** - the inventory from the LCI is sorted into classes or impact categories (e.g. CO_2 → Climate Change); **Characterization** – convert an assigned LCI analyzes result to the common unit of the category indicator; **Normalization** (optional) calculation of the magnitude of each category indicator results relative to reference information; **Weighting** (optional) for each impact category a given weight is given in order to calculate a single score of a given system (Mota et al., 2019; The International Standards Organisation, 2006). All of these stages depend on the LCIA method used.

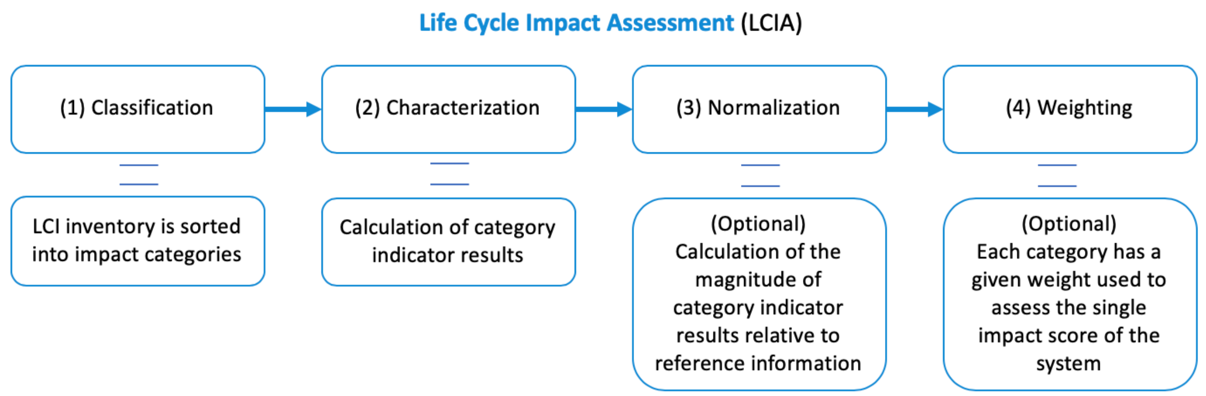

Figure 9 - LCIA scheme (Mota, Carvalho, Gomes, & Barbosa-Povoa, 2019; The International Standards Organisation, 2006)

Similar to the *Eco-99* method, the *ReCiPe* method also incorporates uncertainty in the form of different cultural perspectives (Goedkoop et al., 2009; Leitão, 2016):

- **Individualist** (I) – It is based on types of impact that are undisputed on a shorter time-window (100 years or less), i.e. substances are included if their impacts are proven;
- **Hierarchist** (H) – It is based on a longer time-window, i.e. substances are included if there is consensus about their impacts;
- **Egalitarian** (E) – It considers a longer time-window as well and even the types of impact that are not yet fully established (an indication of the effects of substances are included).

The perspective *Hierarchist* is generally applied and accepted by the scientific community (Goedkoop & Spriemsma, 2001; Leitão, 2016).

In Table 7 it is displayed various examples of LCA applications.

Table 7 - LCA application examples

Authors	Why was the LCA applied?	LCA method	Description of the application
(Brunet, Guillén-Gosálbez, & Jiménez, 2012)	Used to determine the environmental performance of biotechnical facilities in a multi-objective problem	Eco-99	The environmental and economic performance are quantified and optimized.
(Rives, Fernandez-Rodriguez, Rieradevall, & Gabarrell, 2011)	Used to assess the environmental profile of the production of natural cork stoppers, in Catalonia, Spain.	CML 2001	LCA is encompasses in Figure 5 (except for forest management). The LCA assesses the environmental profile of four different companies, so that their impact can be compared.
(González-García et al., 2013)	Used to assess different environmental scenarios of Portuguese cork woodlands.	CML 2001	The environmental profile resulting from forest management stage were assessed using LCA. Two distinct scenarios were compared (Tagus valley VS Alentejo).
(Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2015)	Utilized to tackle the environmental aspect of a SC design case of a Portuguese battery and producer and distributor.	ReCiPe	The environmental aspect is assessed in a paper where the TBL is taken into consideration. Different scenarios (given distinct objectives such as minimizing cost or environmental impact) are compared.
(Demertzi, Dias, et al., 2015)	Used to evaluate different waste management strategies for natural cork stoppers, in Portugal.	IPCC	LCA is used in the disposal stage and considers different scenarios for distinct waste management alternatives: incineration, landfilling and recycling.

Table 7 - LCA application examples (Continued)

(Günther, Kannegiesser, & Autenrieb, 2015)	Utilized to cover the environmental aspect of an electrical vehicle CLSC in a multi-objective problem.	Not stated	The LCA encompasses all stages in the SC (even the use stage). It is considered only some environmental metrics such as CO_2 emissions, meaning that the impact computed is not that extensive.
(Demertzi, Garrido, Dias, & Arroja, 2015)	Used to assess the environmental performance of a cork floating floor.	ILCD guidelines	The LCA englobes all stages from Figure 5 (except for forest management) and considers only two scenarios for the end-of-life stage. The SC environmental profile is computed.
(Bairamzadeh, Pishvaee, & Saidi-Mehrabad, 2016)	Utilized to tackle the environmental aspect of a Bioethanol SC under uncertainty, in a multi-objective problem.	Eco-99	The LCA considered a three-echelon SC. The problem at hand takes into account the TBL and for each sustainability pillar an objective function is assigned. Different solutions are designed given different constraint boundaries.
(Demertzi et al., 2016)	Used to evaluate environmental impact from the production of natural cork stoppers, in Portugal.	Not stated	LCA is applied to all stages depicted in Figure 5 (except for the usage). The authors defined different scenarios for each stage and studied their environmental profile.

From Table 7, two types of examples can be highlighted: (1) cork related papers that provide an environmental analyzes of the cork SC; (2) papers that tackle the environmental optimization in the design and plan of a SC. The research gap on the design and planning of the cork SC, while considering holistic approaches to the environmental aspect, will be further explored in chapter 3.3.1.

Generally speaking, the previous papers show that LCA methods are being used by authors to optimize the environmental performance/impact of a given SC of a product or process. Then that impact can be compared to the economic and social aspects creating a multi-objective approach to a problem. Additionally, that impact can be capitalized into defining several SC design and planning decisions that a decision-maker can choose to apply. Another application is to assess environmental impacts between different scenarios in order to compare them and conclude which ones are the most hazardous.

Although, in Table 7 all of the examples that included multi-objective approach of the problem are in line with the three pillars of sustainability of the TBL, in the literature that is quite rare. For instance, in the 220 papers reviewed by Barbosa-Póvoa et al. (2018), only 45 addressed the TBL. 178 out of 220 papers are related to optimization problems which 36 address the TBL – there is a great potential to address all aspects of the TBL.

Social Goal

From Table 8, Job Creation (38% of analyzed papers address this goal), Safety (25%), Health (16%) and other such as Poverty, Nr of Working Hours, Discrimination and Satisfaction are the metrics chosen by authors to model the *Social Goal*. The OR models used are optimization (60%), decision analysis (14%), statistics (6%) and others such as statistics or data analysis.

Table 8 - Literature overview of the Social Goal (Barbosa-Póvoa et al., 2018)

	Metrics most used	OR models used
Social Goal	Max. of job creation (38%)	Optimization (~60%) Decision analysis (~14%) Statistics (~6%) Others (~20%)
	Max. of safety (25%)	
	Max. of health (16%)	

Examples of the metrics application include the following: (Ziolkowska, 2014) translates **Job Creation** into a parameter that is maximized in the objective function, in an optimization LP model that approaches the three lines of the TBL; (Boukherroub et al., 2015) models **Safety** as minimizing layoffs and distance travelled (both decision variables) to production sites, in a multi-objective programming model that addresses the TBL; (Chen & Andresen, 2014) assesses **Health** by the an incident rate (it accounts for number of illnesses and injuries) which is minimized in the context of a multi-objective programming model that addresses the TBL; (Mota et al., 2018) addresses **Job Creation** - the social objective gives preference to the SC entities and activities in regions with lower GDP. So, the social objective function maximizes the GDP index which uses the number of jobs created as a parameter. These four examples feature the TBL, but not in a holistic way (e.g. the social aspect is assessed by using one or two metrics, providing a potential limited of the social line of the problem).

The fact that the *Social Goal* is often modelled as an objective with a single metric (examples from Table 8), usually a narrower point of view of the social aspect is made. The literature about the social aspect is also quite recent (the examples in Table 8 reinforce that fact) and seems that will follow the trend of the *Environmental Pillar*: relatively diverse literature that, most of the times, focus solely in one or two (social) metrics. Thus, similar to the *Environmental Goal*, in order to have a broader view of the social aspects, SLCA appears as a promising methodology to follow in future research (Kühnen & Hahn, 2017).

As Garrido (2017) states, "*SLCA draws its origins in environmental life-cycle assessment*" and it was "*conceived as a social complement to ELCA*" when the concept was first introduced in literature. **Social Life Cycle Assessment** (SLCA) provides a "*holistic, systemic, and rigorous tool to understand social issues that may arise in the value chains of products and services sustaining human life today*" (Garrido, 2017). The SLCA tries to measure how a specific product, process or service impacts, positively or negatively, stakeholders (local communities, workers or consumers). The main difference to LCA is that SLCA has social metrics instead of environmental ones (Benoît et al., 2010).

Social related information is more difficult to collect due to sometimes being an intangible concept open to interpretation like safety or discrimination. On the other hand, tangible concepts like working hours or medium wage can be hard to gather since that is sensible information which companies don't want to release. Thus, authors resort to online databases that have this kind of information but may be inaccurate. **Social Hotspot Database** (SHDB) or the **Product Social Impact Life Cycle Assessment** (PSILCA) are examples of these databases that allow authors to remove research barriers.

In Table 9 it is displayed various examples of SLCA applications or the usage of social indicators.

Table 9 - Social LCA application or social indicators usage examples (Kühnen & Hahn, 2017)

Authors	Description of the application	Guidelines	Categories used	Social aspect approaches
(Pishvaee, Razmi, & Torabi, 2014)	Optimization of the social aspect in a medical and syringe SC; The 3 objectives of the TBL are considered.	UNEP/SETAC	(1) human rights, (2) labor practices, (3) consumer issues, (4) fair operating practices, (5) community involve. and develop.	It is applied an SLCA. The chosen social indicators are treated directly as model parameters, which will feed an objective function to be optimized.
(Mota et al., 2015)	Social aspect optimization in a company that produces and sell batteries; The 3 objectives of the TBL are considered.	GRI	(1) labor practices, (2) decent work – these are social indicators	It is used social indicators instead of an SLCA. It only uses social guidelines (GRI) to provide social indicators to compute the social objective function.
(Miret, Chazara, Montastruc, Negny, & Domenech, 2016)	Social aspect optimization in the design of a bioethanol green SC; The 3 objectives of the TBL are considered.	It does not follow any known guidelines	(1) jobs creation – this is a social indicator	It is used social indicators instead of an SLCA. The social aspect is tackled through the maximization of jobs created.
(Meyer, Campanella, Corsano, & Montagna, 2019)	Social aspect optimization in the design of a forest SC; The economic and social aspects are considered.	It does not follow any known guidelines	(1) generated jobs, (2) unemployment rate, (3) nr of local inhabitants – these are social indicators	It is used social indicators instead of an SLCA. The authors outlined indicators that are intertwined with the Argentinian forest SC of the problem.

By analyzing Table 9, Pishvaee, Razmi, & Torabi (2014) has been found to be the only paper to tackle the social aspect with an SLCA in a SC design and planning problem, making it a rare methodology used in the literature.

In the context of the SLCA, for each social category there are several qualitative and quantitative indicators. There are published guidelines from which a researcher can retrieve the most suited social indicators to apply in its research. Those guidelines are, for instance, GRI, UNEP/SETAC, UN SDG's and SA 8000 (Kühnen & Hahn, 2017). The difference between these is how much coverage they give to each category (Pishvaee et al., 2014).

The examples depicted in Table 9 show that the use of SLCA is recent and it is still a research gap and, as previously stated , the most complete way to address an SSC problem is to address all three goals from the TBL. In line with that, authors use multi-objective programming to assess the impact of the three lines combined. However, the environmental and specially the social aspect has been assessed with narrow methodologies that use only one or two combined metrics (Miret et al., 2016; Mota et al., 2015). So, to have a broader approach, authors that address the environmental line are beginning to use an LCA methodology. On the other hand, the SLCA application in this kind of SSC problems are still being left apart, making it a significant research opportunity. This research gap is discussed in the next sections.

3.3 Research Gaps Cork SSC design and planning

In line with the problem defined and the research questions addressed in the *1.3 Problem Description* section, the research gaps highlighted in this section are related to the cork SC design and planning, assessment performed in the context of the TBL and the use of holistic methodologies in the environmental and social aspects. The purpose of this work is to address these research gaps.

3.3.1 Cork SC design and planning

From the literature review, it was not found a paper that addressed the cork SC design and planning. Although, some authors addressed forest wood and biomass SCs. For instance, Cambero & Sowlati (2014) performed a literature review on forest biomass SC and how it was optmized – it was concluded that the majority of the literature did an economic optimization and only a small amount of papers addressed the other two sustainability pillars; Santos, Carvalho, Barbosa-Póvoa, Marques, & Amorim (2019) performed a similar review on forest wood SC and how is was optimized – it was concluded that the majority of the literature did an economic and economic-environmental optimization and only a small amount addressed the social aspect and/or the environmental one. What this means is that there is a significant gap related to the SC design and planning optimization that takes into account the three pillars of sustainability.

In the literature of cork related SC (see Table 11) all of the articles do only an environmental analysis of the cork SC and not a design and planning of it, which represents a gap in the literature. Such studies mainly use an LCA methodology. In relation to the work of Barbosa-Póvoa et al. (2017), the same conclusion can be taken – none of the 220 papers address the cork SC design and planning.

In Table 10 an overview of literature of the cork SC design and planning is performed, as well the contribution of this work to it is identified.

Table 10 - Overview of the literature of cork SC design and planning

		Cork SC Stages Covered						
Authors	TBL Pillars addressed	Forest Manag.	Prep.	Stopper Prod.	Finishing	Distrib.	Use	End-of-life
(Cambero & Sowlati, 2014)	Economic Environmental Social	No	No	No	No	No	No	No
(Santos et al., 2019)	Economic Environmental Social	No	No	No	No	No	No	No
(Barbosa-Póvoa et al., 2018)	Economic Environmental Social	No	No	No	No	No	No	No
The present work	Economic Environmental Social	Yes	Yes	Yes	Yes	Yes	No	Yes

3.3.2 TBL assessment

In the literature regarding the assessment of the three pillars of TBL, there are some papers that address the cork SC. However, it is always the case that it is an environmental assessment (see Table 11).

In order to expand the point of view on the evaluation of the TBL, two articles review topics similar to cork (Cambero & Sowlati, 2014; Santos, Carvalho, Barbosa-Póvoa, Marques, & Amorim, 2019). Cambero & Sowlati (2014) performed a literature review on forest biomass SC and what pillars of the TBL were assessed – from all papers reviewed (64), 22 were related to an economic assessment, 28 environmental and only 4 addressed fully the TBL; Santos, Carvalho, Barbosa-Póvoa, Marques, & Amorim (2019) performed a similar review on forest wood SC and what pillars of the TBL were assessed – from all papers reviewed (104), 30 were related to an economic assessment, 23 environmental, 30 economic-environmental, 1 environmental-social, 2 economic-social and 18 addressed fully the TBL. By analyzing the distribution of papers it is possible to understand that the economic and environmental aspects are relatively well addressed in the literature unlike the social aspect. In addition, none of the total reviewed papers (168) addressed cork related SC and the social aspect was featured in a few papers, which suggests other two research gaps.

In Table 11 it is given an overview of the literature of the TBL assessment, as well as the contribution of the present work to it. Moreover, in Table 11 the column "Type" defines if the paper is an "AR" – "Article Review" in which it is performed a review of many research papers like Barbosa-Póvoa et al. (2018) did; "CR" – "Cork Related" in which the research perfomed is related with cork.

Table 11 - Overview of the literature of the TBL assessment

			Cork SC Stages Covered						
Authors	**TBL Pillars addressed**	**Type**	**Forest Manag.**	**Prep.**	**Stopper Prod.**	**Finishing**	**Distrib.**	**Use**	**End-of-life**
(Cambero & Sowlati, 2014)	Economic Environmental Social	AR	No	No	No	No	No	No	No
(Santos et al., 2019)	Economic Environmental Social	AR	No	No	No	No	No	No	No
(Rives et al., 2011)	Environmental	CR	No	Yes	Yes	Yes	Yes	No	Yes
(Rives, Fernández-Rodríguez, et al., 2012)	Environmental	CR	No	Yes	Yes	Yes	Yes	No	Yes
(González-García et al., 2013)	Environmental	CR	Yes	No	No	No	No	No	No
(Demertzi, Dias, et al., 2015)	Environmental	CR	No	No	No	No	No	No	Yes
(Demertzi, Garrido, et al., 2015)	Environmental	CR	No	Yes	Yes	Yes	Yes	No	No
(Demertzi et al., 2016)	Environmental	CR	Yes[1]	Yes	Yes	Yes	Yes	No	No
The present work	Economic Environmental Social	CR	Yes	Yes	Yes	Yes	Yes	No	Yes

3.3.3 TBL optimization

As stated previously in this chapter, in order to approach the SSC with a more holistic point-of-view, methodologies such as LCA and SLCA have been found to be the most suitable.

Three article reviews (Barbosa-Póvoa et al., 2018; Cambero & Sowlati, 2014; Santos et al., 2019) reviewed 178, 35 and 84 papers respectively that do sustainability pillar optimization in the SC design and planning context – papers that potentially need to choose a methodology to treat the environmental and social aspects. In Table 12 an overview of the usage of holistic methodologies in the literature is depicted.

[1] It adapts the results from González-García et al. (2013) in relation to forest management.

Table 12 - Overview of the usage of holistic methodologies in the literature

Authors	Green SC related	Nr of papers that address environmental aspect	Environmental LCA	Nr of papers that address social aspect	Social SLCA
(Cambero & Sowlati, 2014)	Yes	7 out of 35	1	3 out of 35	0
(Santos et al., 2019)	Yes	54 out of 84	3	8 out of 84	0
(Barbosa-Póvoa et al., 2018)	No	141 out of 178	44	36 out of 178	0

Regarding the research gaps on the usage of more holistic methodologies, by analyzing Table 12, one can conclude that (1) the use of the LCA to tackle the environmental aspect is still quite underdeveloped in the literature specially if it is related to Green SC; (2) the social aspect is being overlooked by the research community - no author has ever utilized the SLCA to address this aspect. Thereby, the present work will implement methodologies found to be more holistic to address the sustainability pillars of the TBL.

3.4 Chapter conclusions

From the literature review performed it can be seen that SSC have been mainly treated using optimization models where the economic aspect is the main driver. The environmental aspect is often combined with the economic aspect and the social aspect is seldom addressed. When it is, it is because the research paper addresses all three pillars of sustainability, which is rare in the literature. Let alone there is no author that has already addressed the SC design and planning of a cork SSC, making this a highly significant gap.

In the context of this work and considering the case-study described in chapter 2, the aim is to design possible scenarios or courses of action that the company may implement with the view to achieve a more SSC. To do so it appears that an optimization model is the most appropriate methodology to explore. This is due to being able to deal with great amounts of data, being conducive to scenario design hence analyzes and sensitivity analyses which ease the process to find different solutions taking into consideration different objectives/priorities.

Considering the published literature, the work of Mota et. al (2018) can be taken as the basis for this work. This because Mota et. al (2018) developed a tool that focuses on strategic-tactical problems which support the use of aggregated data so as to allow the modeling of the problems such as: SC design, production/remanufacturing planning, inventory planning, supply planning, purchasing planning, transportation network planning and product recovery planning, while exploring TBL objetives.

Although this work is based on the previous work mentioned, a series of improvements were done specially in the social aspect where it will be applied a SLCA methodology perspective, providing a more holistic view of this aspect. As for the environmental aspect, the environmental impact of each stage depicted in Figure 5 will be first analyzed and, if one stands out, a more detailed view of that stage is given (incurring in the model extension). This detailed view will allow a better understanding of why that stage is the most environment impactful and my revert in better SC decision making.

In conclusion, the present work will allow the development of strategies for SSC design and planning in the cork industry.

4 Problem Definition and Model Formulation

Section 4.1 presents the problem definition. Next, the mathematical formulation of the developed SSC design and planning model for the Cork Industry in the context of Equipar/CA is presented in **section 4.2**. **Section 4.3** resumes the conclusions for this chapter.

4.1 Problem Definition

As previously mentioned, this work intends to model the SC of CA in the context of Equipar. The model will help decision-makers in the SC design and planning, as well as contextualizing its decisions in the light of sustainability values. Additionally, the application of holistic methodologies ensures that the SC decisions are properly justified.

The SC of CA is complex due to having a wide range of distinct final products, from small grain size granulate (RN) to Technical Cork Stoppers. These products differ in the granulate used, manufacturing processes and the number of cork disks (an input from the Raw Materials BU). Moreover, CA produces recycled granulates that dispatches to other BUs.

For the purpose of this work there are four considered main products. There are Technical Cork Stopper without and with two cork disks (*Aglo* and *Twin* respectively), Small Grain Size Granulate (RN) and Recycled Granulate (*oCork*). To cover the set of different products, this work models such complexity in the production stages, by directly modelling the different productions units displayed in Figure 6 in section 2.4.

The SC includes suppliers (differing in supply capacity and FSC certification, introduced later in this work), different types of transport modes (truck and boat) and warehouses to rent (the model selects the optimal locations) and Equipar as the sole industrial unit.

As in Figure 10, suppliers provide raw materials that are sent directly to Equipar or a facility that produces the cork disks. Then, Equipar produces final products given their demand that may be transported to warehouses (if available/needed) or final customers/markets. The reverse flow has two possible options: incineration and recycling. Figure 10 shows a graphical representation of the CA's SC structure and specific flows. In Figure 10 it is not represented the incineration of cork waste created because of production stages, due to lack of space in the Figure.

Figure 10 is a simplified structure of the SC. The Figure provides a strategic approach to the SC and an overview how Equipar is included in it, which is aligned with the scope of the present work.

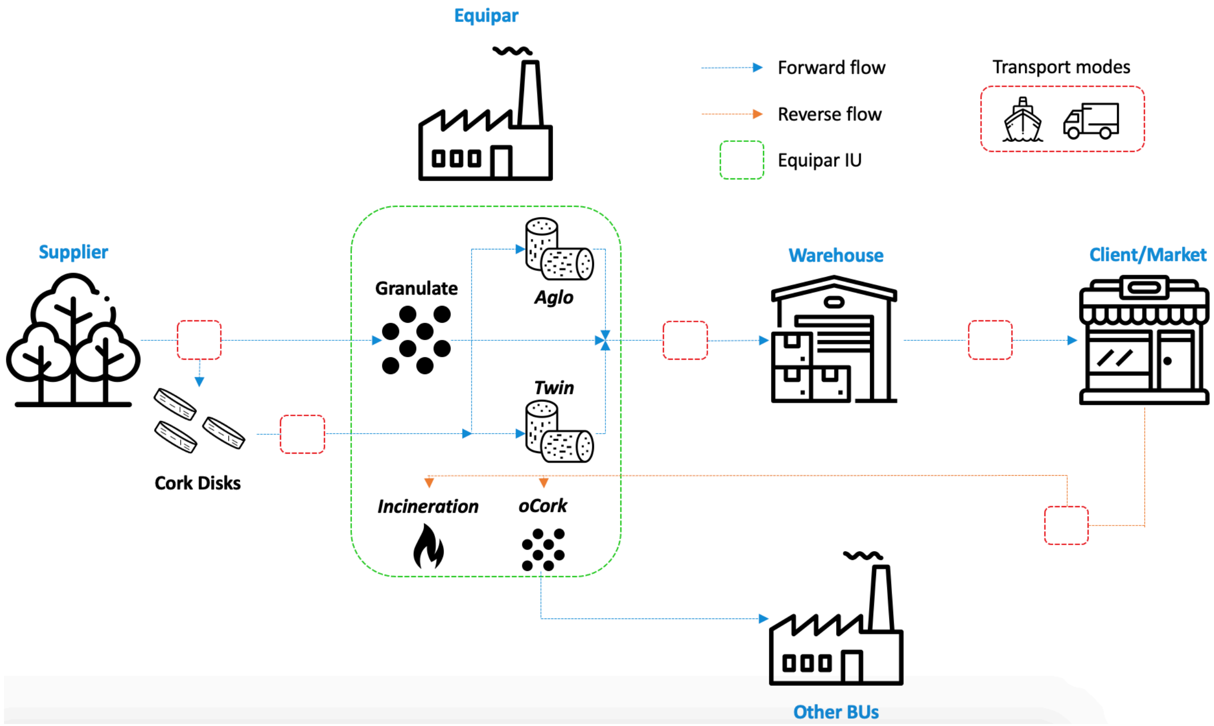

Figure 10 - Example structure of the CA's SC in the context of Equipar

Thus, the SC requires raw materials (and intermediate products such as cork disks), origin and destination entities (e.g., suppliers and warehouses), technologies to fulfill production needs and transportation modes (e.g., plane, boat and truck). The problem can be summarized as follows:

Given:

- A SC structure with pre-determined flows and interaction between entities and existing or potentially new geographical locations, which compose the SC network;
- The supply and production capacities;
- A set of all available production and remanufacturing technologies;
- The bill of materials of products being produced, remanufactured and respective resources needed;
- The demand of products being produced;
- The distance between all points and entities;
- A transportation network and means available;
- A fixed time horizon;
- The economic valorization of incinerated recovered products;
- The initial inventory levels;
- The contracted capacity of each outsourced transportation mode.

Determine:

- The network configuration, in terms of which warehouses to open and which suppliers to procure;
- The transportation network structure, specific flows to take and the optimal mix of modes to use;
- The optimal production and remanufacturing levels and technologies to be selected;
- The share of energy to be used between public network and in-house generation from biomass sources (incineration of recovered products);
- The total cost of the SC structure;

- The total Environmental Impact of the SC;
- The total Social Impact of the SC.

In order to:

- Maximize Net Present Value – Studied through maximizing the NPV of the SC in a 5-year period;
- Minimize Environmental Impact – Studied through minimizing the SC Environmental Impact, which is measured through the *ReCiPe* LCIA method;
- Maximize Social Benefit – Studied through maximizing the benefit of the SC of CA in the locations where the company operates.

4.2 Mathematical Formulation

The current chapter describes the mathematical formulation. First, the clarification of the model assumptions that had to be made is presented. Then, it is introduced the indexes, sets and decision variables used. After that, the general constraints are exposed while highlighting some of the most important parameters. Lastly, the objective functions are presented.

The convention adopted and being used throughout the section is: **(1)** indexes are expressed by lower-case characters in variables, sets and parameters; **(2)** sets are represented by a capital letter accompanied by a descriptive subscript; **(3)** parameters start with the lower-case character "*p*" and **(4)** variables with an upper-case. Within general variables, **(4.1)** binary variables are expressed in Greek letters accompanied by the respective subscripts. The convention used for the objective functions is based on the abbreviations of what they actually represent (e.g., *DP* – Depreciation Rate; *NE* – Net Earnings).

4.2.1 Model Assumptions

Section 3.4 clarifies that, although the work of Mota et. al (2018) will be the basis for the optimization model, several modifications and assumptions need to be considered.

The Cork Industry competitive environment and wide range of players make the information available to use in the model restrict and dealt with care to prevent model inaccuracy. Thus, a few assumptions had to be performed. The assumptions are as follow:

- **Social Objective Function** – Although, economic and environmental objective function will approach a holistic point-of-view of the SC, the Social Objective Function will mostly tackle the component of the SC where CA has physical infrastructure and its own workers (Production Facility and Warehouses) as well as the supplier side. This corresponds to the supply, preparation, production, finishing and distribution stages;
- **Production Stages** – The flows depicted earlier are a simpler version of the technical cork stoppers production system, in order to soothe the computational effort of the model. The production and stock levels are driven by demand and it is assumed that ruptures in inventory never occur. In addition, it is assumed that preparation stage has always enough capacity to supply the Production Facility with treated cork. It is not considered the cork disks (as shown in Figure 10) because in the industrial complex where Equipar is located, there is a unit focused solely on the preparation stage that supplies Equipar that product;

- **Finishing Stage** – It is assumed that are two packaging options. In the first option it is used bulk bags (with neglegible environmental impacts) and the cork stoppers are not customized; the other option it is used cardboard boxes and plastic and the cork stoppers are customized;
- **Distribution Stage** – It is assumed that the warehouses are rented by CA to store final and recovered products. The inventory levels are determined by the demand and production capacity. The warehouse locations are pre-determined by the major logistic centers of each region that has CA's clients, due to the distribution stage being completely outsourced by several logistics companies;
- **End-of-life Stage** – It is considered three options: (1) incineration, (2) landfill and (3) send the remanufactured products to other CA industrial units. Options (1) and (2) are driven by SC decision-making regarding the three modal objectives. Option (3) is an optional decision, since this option acts as a bonus to the business performed by the specific case of Equipar;
- **Parameters in general** – Due to privacy concerns, most of the parameters are estimated given different assumptions.

4.2.2 Indexes and sets

Let $\boldsymbol{I}$ be the set of locations where entities are established or potentially located (suppliers, Equipar IU, warehouses, seaports and clients). Let $\boldsymbol{i} = (1,2,\dots,n)$ be the index that indicates these locations, represented graphically as subscribed to in parameters or variables, whenever these are intended for specific entities. In addition, $\boldsymbol{j} = (1,2,\dots,n)$ can be used as an additional location that interacts with location $\boldsymbol{i}$. The several types of entities are divided into subsets, defined as $\boldsymbol{I} = \boldsymbol{I_{sup}} \cup \boldsymbol{I_{Facility}} \cup \boldsymbol{I_w} \cup \boldsymbol{I_{port}} \cup \boldsymbol{I_c}$, where $\boldsymbol{I_{sup}}$ denotes the suppliers, $\boldsymbol{I_{Facility}}$ the IU, $\boldsymbol{I_w}$ the warehouses, $\boldsymbol{I_{port}}$ the seaports and $\boldsymbol{I_c}$ the clients. The IU represents a subset the subset $\boldsymbol{I_{Facility}} = \boldsymbol{I_{grind}} \cup \boldsymbol{I_{prod}} \cup \boldsymbol{I_{dist}}$.

As stated, $\boldsymbol{F}$ represent the set of all connections. $\boldsymbol{F_{NET}}$ relates to all possible and allowed connections between entity locations. Moreover, the following structure is used: $\boldsymbol{F_{IN_{i,m}}}$ and $\boldsymbol{F_{OUT_{i,m}}}$ represent the flows of materials/products $\boldsymbol{m}$ (defined below) from (*OUT*) or into (*IN*) location $\boldsymbol{i}$. Connections between continents are defined as well, where entities from different entities may not directly connected (e.g., Lisbon and Mexico City).

Let $\boldsymbol{N}$ represent the set of all nodes. $\boldsymbol{N_{NET}}$ relates to all possible and allowed nodes in each entity location. Moreover, the following structure is used: $\boldsymbol{N_{i,m}}$ represents the node where material/product $\boldsymbol{m}$ can be present at entity location $\boldsymbol{i}$.

Let $\boldsymbol{A}$ be the set of transportation modes to use and $\boldsymbol{a} = (1,2,\dots,n)$ be the index that indicates these modes. The types of transportation modes are divided into subsets, defined as $\boldsymbol{A} = \boldsymbol{A_{truck}} \cup \boldsymbol{A_{boat}}$, $\boldsymbol{A_{truck}}$ representing trucks (roads), $\boldsymbol{A_{boat}}$ boats (maritime) respectively.

Let $\boldsymbol{T}$ be the set of time periods and $\boldsymbol{t} = (1,2,\dots,n)$ be the index that defines them. The set $\boldsymbol{T}$ can be divided into subsets as $\boldsymbol{T} = \boldsymbol{T_{first}} \cup \boldsymbol{T_{other}} \cup \boldsymbol{T_{last}}$ where $\boldsymbol{T_{first}}$ corresponds to the first time period and $\boldsymbol{T_{other}}$ to the remaining time periods except for $\boldsymbol{T_{last}}$ that represents the last time period. There is only one-time level considered which is the weekly basis.

Let $\boldsymbol{G}$ be the set of technologies to choose from and $\boldsymbol{g} = (1,2,\dots,n)$ be the index that defines them. Technologies are divided between production and remanufacturing subsets, defined as $\boldsymbol{G} = \boldsymbol{G_{pr}} \cup \boldsymbol{G_{rem}}$ respectively.

Let $\boldsymbol{M}$ be the set of materials/products and $\boldsymbol{m} = (1,2,\dots,n)$ be the index that defines them. With the view to ease the production and remanufacturing processes in Equipar IU, various subsets were created $\boldsymbol{M} = \boldsymbol{M_{rm}} \cup \boldsymbol{M_{ip}} \cup \boldsymbol{M_{fp}} \cup \boldsymbol{M_{rp}} \cup \boldsymbol{M_{wp}}$ where $\boldsymbol{M_{rm}}$ denotes the raw materials, $\boldsymbol{M_{ip}}$ the intermediate products, $\boldsymbol{M_{fp}}$ the finished products, $\boldsymbol{M_{rp}}$ the recovered products and $\boldsymbol{M_{wp}}$ the waste products. In addition, the specifications of the problem make it necessary to divide $\boldsymbol{M_{fp}}$ into subsets, being $\boldsymbol{M_{fp}} = \boldsymbol{M_{RN}} \cup \boldsymbol{M_{Twin}} \cup \boldsymbol{M_{Aglo}} \cup \boldsymbol{M_{oCork}}$.

Let $\boldsymbol{SC}$ be the set of the possible scenarios to run in the model and $\boldsymbol{sc} = (1,2, \dots, n)$ be the index that defines them.

Let $\boldsymbol{D}$ be the set of possible investments to undertake in the model and $\boldsymbol{d} = (1,2, \dots, n)$ be the index that defines them.

Let $\boldsymbol{U}$ be the set of possible end-of-life options to choose and $\boldsymbol{u} = (1,2, \dots, n)$ be the index that defines them.

4.2.3 Decision variables

The considered decision variables are displayed in Table 13.

Table 13 - Decision variables

Continuous variables	
$S_{m,i,t,sc}$	Stock of product m at location i in period t in scenario sc
YK_i	Capacity of location i
$YKT_{i,t,sc}$	Necessary capacity of location i in time period t in scenario sc
$P_{m,g,i,t,sc}$	Amount of product m produced with technology g at location i in period t in scenario sc
$R_{m,g,i,t,sc}$	Amount of product m remanufactured with technology g at location i in period t in scenario sc
$B_{m,i,t,sc}$	Amount of biomass created from recovered products m at location i in period t in scenario sc
$W_{m,i,t,sc}$	Amount of waste products m created at location i in period t in scenario sc
$E_{i,t,sc}$	Amount of electricity consumed at location i in period t in scenario sc
$X_{m,a,i,j,t,sc}$	Flow of product m with transportation mode a from location i to j in period t in scenario sc
$X_{m,a,j,i,t,sc}$	Flow of product m with transportation mode a from location j to i in period t in scenario sc
Binary variable	
υ_i	1, if entity in location i is open; 0, otherwise
$\zeta_{g,m,i}$	1, if technology g is used to produce/remanufacture product m at location i; 0, otherwise

4.2.4 General constraints

The present subsection presents the general constraints that are common to all analyzed cases. The constraints were divided in the following categories: Technical Cork Stoppers Facility, Balance Constraints, Demand and Product Return constraints, Entity Capacity Constraints, Transportation Constraints and Technology Constraints. Constraints that are specific to a given sustainability objective function are defined in Appendix A.

1. *Technical Cork Stoppers Facility – Material Balance, Production/Remanufacturing, Biomass*

This subsection includes the constraints that relate to the *Grinding unit* (balance, production and remanufacturing constraints), *Productions Units* (balance and production constraints), *Distribution Unit* (balance constraints), *Electric Consumption*, and *Biomass production*.

1.1 Grinding Unit

For each unit inside a technical cork stoppers facility, there is always two equations that regard to materials balance – one for the first time period and another to the remaining time periods. Equations 4.1 and 4.2 show how material balance is defined in the *Grinding Unit*.

$$pSini_{m,i} + \sum_{g \in G_{pr}} P_{m,g,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in \left(F_{IN_{dist,fp}} \cup F_{IN_{prod,ip}}\right) \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc}\right), \quad \forall m \in \left(M_{RN} \cup M_{oCork} \cup M_{ip}\right), i \in I_{grind}, t \in T_{first}, sc \in SC \tag{4.1}$$

The differences between the two equations are due to the presence of parameter $pSini_{m,i}$ in equation 4.1 that concerns to the initial inventory, in this case, at the *Grinding Unit* and due to the fact that equation 4.1 is only related to the first time period.

$$S_{m,i,(t-1),sc} + \sum_{g \in G_{pr}} P_{m,g,i,t,sc} + \sum_{g \in G_{rem}} R_{m,g,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in \left(F_{IN_{dist,fp}} \cup F_{IN_{prod,ip}}\right) \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc}\right), \quad \forall m \in \left(M_{RN} \cup M_{oCork} \cup M_{ip}\right), i \in I_{grind}, t \in (T_{other} \cup T_{last}), sc \in SC \qquad 4.2$$

Generally speaking, the two equations define that the **inventory** of product m from the last period $S_{m,(t-1)}$ plus the **production** P_m and/or **remanufacturing** R_m of product m **must be equal** to the **final inventory** of the current period $S_{m,t}$ plus the **outflow** X_m of product m. The parameter $pBOMF_{m,mm}$ works as a yield from the products leaving the *Grinding Unit.* For example, 100% of *RN* produced in the *Grinding Unit* is shipped to the *Distribution Unit*, being $pBOMF_{RN,RN}$ equal to 1 – this parameter is relevant to build distinct scenarios with different yields for different products.

Equation 4.3 defines the production of intermediate products and some final products at the *Grinding Unit*.

$$\sum_{\substack{a \in F_{NET} \\ j \in I_{sup}}} X_{m,a,j,i,t,sc} = \sum_{\substack{mm \in \left(M_{ip} \cup M_{RN}\right) \\ g \in G_{pr}}} \left(P_{mm,g,i,t,sc} * pBOMGrinding_{m,mm,g}\right), \quad \forall m \in M_{rm}, i \in I_{grind}, t \in T, sc \in SC \qquad 4.3$$

Generally speaking, the previous equation defines that the sum of **inflows of raw material** m **must be equal** to the sum of **product** mm **produced** P_{mm} at the *Grinding Unit*. The parameter $pBOMGrinding_{m,mm,g}$ establishes the relation between raw material and, in this case, intermediate products and a final product (*RN*).

The *Grinding Unit* is the unit where it is processed the recovered products and can be either transformed into a new final product or incinerated to produce energy from biomass. Equation 4.4 depicts this.

$$\sum_{\substack{a \in F_{NET} \\ j \in F_{IN_{Equipar,rp}}}} X_{m,a,j,i,t,sc} + S_{m,i,(t-1),sc} = \sum_{\substack{mm \in \left(M_{oCork}\right) \\ g \in G_{rem}}} \left(R_{mm,g,i,t,sc} * pBOMRemanuf_{m,mm,g}\right) + B_{m,i,t,sc} + S_{m,i,t,sc}, \quad \forall m \in M_{rp}, i \in I_{grind}, t \in (T_{other} \cup T_{last}), sc \in SC \qquad 4.4$$

Generally speaking, equation 4.4 states that the **inflows of recovered products** X_m plus the **inventory of recovered products** from the last time period $S_{m,t-1}$ **must be equal** to the **remanufacturing** R_{mm} **of final products** mm plus the amount of **recovered products** m **sent for incineration** B_m plus the **final inventory** of recovered products $S_{m,t}$ at the *Grinding Unit*. The parameter $pBOMRemanuf_{m,mm,g}$, like the parameter in equation 4.3, establishes the relation between recovered products and, in this case, a specific final product *oCork*.

From the equation, it can be highlighted the different options for the inflow of recovered products. They can be either used to produce the final product *oCork*, sent into incineration to produce bioenergy or stay at the *Grinding Unit* storage.

1.2 Production Units

In relation to the *Production Units*, as in the previous unit, there are two balance constraints – one for the first time period and the other for the remaining time periods (see equations 4.5 and 4.6).

$$pSini_{m,i} + \sum_{g \in G_{pr}} P_{m,g,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{IN_{dist,fp}} \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc} \right), \quad \forall m \in \left(M_{Aglo} \cup M_{Twin} \right), i \in I_{prod}, t \in T_{first}, sc \in SC \tag{4.5}$$

Again, the differences between the two equations are due to the presence of parameter $pSini_{m,i}$ in equation 4.5 that concerns to the initial inventory, in this case, at the *Production Units* and due to the fact that equation 4.5 is only related to the first time period.

$$S_{m,i,(t-1),sc} + \sum_{g \in G_{pr}} P_{m,g,i,t,sc} + \sum_{g \in G_{rem}} R_{m,g,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{IN_{dist,fp}} \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc} \right), \quad \forall m \in \left(M_{Aglo} \cup M_{Twin} \right), i \in I_{prod}, t \in \left(T_{other} \cup T_{last} \right), sc \in SC \tag{4.6}$$

Generally speaking, the two equations define that the **inventory** of final product m from the last period $S_{m,(t-1)}$ plus the **production** P_m and/or **remanufacturing** R_m of product m **must be equal** to the **final inventory** of the current period $S_{m,t}$ plus the **outflow** X_m of product m. The parameter $pBOMF_{m,mm}$ works as a yield from the products leaving the *Production Units* (same line of thought as in equations 4.1 and 4.2).

Equation 4.7 defines the production of the final products *Aglo* and *Twin*.

$$\sum_{\substack{a \in F_{NET} \\ j \in I_{grind}}} X_{m,a,j,i,t,sc} = \sum_{\substack{mm \in \left(M_{Aglo} \cup M_{Twin} \right) \\ g \in G_{pr}}} \left(P_{mm,g,i,t,sc} * pBOMProduction_{m,mm,g} \right), \quad \forall m \in M_{ip}, i \in I_{grind}, t \in T, sc \in SC \tag{4.7}$$

As in equation 4.3, the previous equation defines that the sum of **inflows of intermediate product** m **must be equal** to the sum of **final product** mm **produced** P_{mm} at the *Production Units*. The parameter $pBOMProduction_{m,mm,g}$ establishes the relation between intermediate products and, in this case, final products *Aglo* and *Twin*.

1.3 Distribution Unit

Regarding the *Distribution Unit* there are two balance constraints, one for the first time period and the other for the remaining time periods. Equations 4.8 and 4.9 show how the balance constraints are defined at the *Distribution Unit*.

$$pSini_{m,i} + \sum_{\substack{(j,mm) \in F_{IN_{dist,fp}} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{OUT_{dist,fp}} \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc} \right), \quad \forall m \in M_{fp}, i \in I_{dist}, sc \in SC, t \in T_{first} \tag{4.8}$$

Between both equations, the difference is the usage of the parameter $pSini_{m,i}$.

$$S_{m,i,(t-1),sc} + \sum_{\substack{(j,mm) \in F_{IN_{dist,fp}} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{OUT_{dist,fp}} \\ a \in F_{NET}}} \left(pBOMF_{m,mm} * X_{m,a,i,j,t,sc} \right), \quad \forall m \in M_{fp}, i \in I_{dist}, sc \in SC, t \in \left(T_{other} \cup T_{last} \right) \tag{4.9}$$

Generally speaking, the two equations define that the **inventory** of final product m from the last period $S_{m,(t-1)}$ plus the **production** P_m and/or **remanufacturing** R_m of product m **must be equal** to the **final inventory** of the current period $S_{m,t}$ plus the **outflow** X_m of product m. The parameter $pBOMF_{m,mm}$ works as a yield from the products leaving the *Distribution Unit* (same line of thought as in equations 4.1, 4.2, 4.5 and 4.6).

1.4 Electric Consumption and Needs

The electrical component of the IU is defined with two equations: equation 4.10 depicts the electric supply needed to keep the production stages running; equation 4.11 defines the maximum electrical needs that can be safeguarded with biomass energy.

$$E_{i,t,sc} = \left(\sum_{\substack{m \in (M_{fp} \cup M_{ip}) \\ g \in (G_{rem} \cup G_{pr})}} (P_{m,g,i,t,sc} + R_{m,g,i,t,sc}) * pUniElectriNeeds_{m,i,t,sc} \right) + pMinElectricNeeds_i \,, \quad \forall i \in I_{Equipar}, t \in T, sc \in SC \tag{4.10}$$

Equation 4.10 defines that the **electric consumption** E_i of **each unit** i of the IU is **equal to** the **total materials** m **produced** in the production and remanufacturing stages **times** the **electric need per unit material produced** or remanufactured, **plus** the **minimum electric need of each unit *i*** of the facility. The parameters $pUniElectriNeeds_{m,i,t,sc}$ and $pMinElectricNeeds_i$ are respectively the energy needed to produce or remanufacture a unit of material and the minimum electric demand of a given unit.

Then, equation 4.11 will expose how much energy from biomass can be derived from biomass.

$$\sum_{\substack{m \in M_{rp} \\ i \in I_{grind}}} (B_{m,i,t,sc} * pEnerRec_m) \leq \sum_{i \in I_{Equipar}} E_{i,t,sc} - \sum_{\substack{m \in M_{wp} \\ i \in (I_{grind} \cup I_{prod})}} (W_{m,i,t,sc} * pEnerRec_m) \,, \quad \forall t \in T, sc \in SC \tag{4.11}$$

Equation 4.11 defines that the **energy derived from biomass** $(B_m * pEnerRec_m)$ is **less or equal to** the total **energy that the IU consumes** E_i minus the **energy recovered from the incineration of by-products**/waste $(W_m * pEnerRec_m)$. The parameter $pEnerRec_m$ converts quantities of incinerated products in kg to energy kWh.

1.5 Biomass Production

Biomass energy is gathered from the incineration of recovered (from clients) and waste products (originated from the production and remanufacturing processes). For both subsets of products there are two equations that define how these products are sent for incineration.

Equation 4.12 defines the recovered products that are sent for incineration.

$$B_{m,i,t,sc} \leq \sum_{\substack{j \in F_{IN\,j,rp} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} \,, \forall m \in M_{rp}, i \in I_{grind}, t \in T, sc \in SC \tag{4.12}$$

The previous equation defines that the **amount of recovered products sent for incineration** B_m are **less or equal to** the **amount of recovered products that arrives at the *Grinding Unit*** from the reverse supply chain. The model will optimize the quantity sent for incineration, since some can be remanufactured (*oCork*) and then sent to the IU's clients. In addition, this quantity is also constrained by equation 4.11 that defines the energetic demand of the IU.

Equation 4.13 defines how waste products are originated at the IU.

$$W_{m,i,t,sc} = \sum_{\substack{mm \in (M_{ip} \cup M_{fp}) \\ g \in (G_{pr} \cup G_{rem})}} \left((P_{mm,g,i,t,sc} + R_{mm,g,i,t,sc}) * pWasteProducts_{mm,m} \right), \quad \forall m \in M_{wp}, i \in (I_{grind} \cup I_{prod}), t \in T, sc \in SC \qquad 4.13$$

Equation 4.13 defines that the **amount of waste products sent for incineration** W_m are **equal to** the **quantity of waste products originated from the production and remanufacturing processes**. The parameter $pWasteProducts_{mm,m}$ defines the amount of waste product m that is originated per unit of final product mm produced or recovered product mm remanufactured.

2. *Balance Constraints*

The present subsection has equations related to the material balance at the *Warehouses* and *Seaports*.

2.1 Warehouse – Material Balance

The *Warehouse – Material Balance* is defined similarly to the balance constraints shown in the previous subsection (e.g., equations 4.1 and 4.2).

Equation 4.14 defines the material balance in the first time period.

$$pSini_{m,i} + \sum_{\substack{(j,mm) \in F_{IN_{w,fp}} \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,j,i,t,sc}) = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{OUT_{w,fp}} \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,i,j,t,sc}), \quad \forall m \in (M_{RN} \cup M_{Twin} \cup M_{Aglo}), i \in I_w, t \in T_{first}, sc \in SC \qquad 4.14$$

The difference from the previous equation to equation X is the presence of the parameter $pSini_{m,i}$, which is the initial inventory, in this case, at the warehouse.

Equation 4.15 defines the material balance for the remaining time periods.

$$S_{m,i,(t-1),sc} + \sum_{\substack{(j,mm) \in F_{IN_{w,fp}} \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,j,i,t,sc}) = S_{m,i,t,sc} + \sum_{\substack{(j,mm) \in F_{OUT_{w,fp}} \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,i,j,t,sc}), \quad \forall m \in (M_{fp} \cup M_{rp}), i \in I_w, t \in (T_{other} \cup T_{last}), sc \in SC \qquad 4.15$$

The parameter $pBOMT_{m,mm}$ has the same function as the $pBOMF_{m,mm}$ from the *technical cork stoppers facility* equations. In the case of SC entities with exception of the IU it is used that yield parameter (it is an assumption taken). In other words, it is assumed that material handling in SC entities other than the IU is riskier (i.e. $pBOMF_{m,mm} \geq pBOMT_{m,mm} * pBOMT_{m,mm}$).

2.2 Cross-Docking Seaports

The material balance at seaports must always be **inflows equal to outflows**. Equation 4.16 defines the material balance at seaports.

$$\sum_{\substack{(j,mm) \in (F_{IN_{port,fp}} \cup F_{IN_{port,rp}}) \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,j,i,t,sc}) = \sum_{\substack{(j,mm) \in (F_{OUT_{port,fp}} \cup F_{OUT_{port,rp}}) \\ a \in F_{NET}}} (pBOMT_{m,mm} * X_{m,a,i,j,t,sc}), \qquad 4.16$$

$$\forall m \in \left(M_{fp} \cup M_{rp}\right), i \in I_{port}, t \in T, sc \in SC$$

There are not two equations, because cross-docking implies that no stock of materials is accumulated between time periods, hence equation 4.16 is sufficient to define the material balance at the seaports. The same of thinking of the usage of the parameter $pBOMT_{m,mm}$ is the same as in *Warehouse – Material Balance*.

3. *Demand and Product Return*

The current subsection exposes the equations that define the *Demand* and *Product Return* constraints.

3.1 Demand

There are two equations that define the *Demand*. Equation 4.17 is related to the demand of final products given a service level (*RN*, *Twin* and *Aglo*) and equation 4.18 constrains the maximum flow of materials to send to the client given the demand of them.

$$\sum_{\substack{j \in F_{IN_{c,fp}} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} \geq pSerivceLvl_m * Demand_{m,i,t,sc} \,,$$
$$\forall m \in \left(M_{RN} \cup M_{Twin} \cup M_{Aglo}\right), i \in I_c, t \in T, sc \in SC \qquad 4.17$$

Equation 4.17 defines that the **flow of material m sent to clients $X_{m,i}$** has to be **greater or equal than** the **demand of that material m given** its minimum **service level $pSerivceLvl_m$**. The parameter $pSerivceLvl_m$, as stated, is the service level of a given material m (the parameter is dependent of the material m to maximize SC decisions and scenario diversity).

$$\sum_{\substack{j \in F_{IN_{c,fp}} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} \leq Demand_{m,i,t,sc} \,, \forall m \in M_{fp}, i \in I_c, t \in T, sc \in SC \qquad 4.18$$

Equation 4.18 defines that the **flow of any final product m sent to clients $X_{m,i}$** has to be **less or equal than** the **demand of that final product m**. One has to bear in mind that the recycled product *oCork* is the only final product that is not constrained by the minimum service level ($pSerivceLvl_m$), because in the Equipar's point-of-view, and in the context of the present work, the demand of that product is like a bonus business that the IU can do to maximize its NPV.

3.2 Product Return

Regarding product return there are three equations that define it. Equation 4.19 defines that in the first time period t the product return is null; equation 4.20 models the minimum quantity that has to return from the final client and equation 4.21 defines the maximum quantity that can return from the final client.

$$\sum_{\substack{j \in F_{OUT_{c,rp}} \\ a \in F_{NET}}} X_{m,a,i,j,t,sc} = 0 \,,$$
$$\forall m \in M_{rp}, i \in I_c, t \in T_{first}, sc \in SC \qquad 4.19$$

Equation 4.19 states that the **flow of recovered products m** from the **final client $X_{m,i}$ must be equal** to **zero**. This is due to the recovered products in period t are based on the previous period $(t-1)$.

$$\sum_{\substack{j \in F_{OUT_{c,rp}} \\ a \in F_{NET}}} X_{m,a,i,j,t,sc} \geq pMinReturn_m * \sum_{\substack{(j,mm) \in F_{IN_{c,fp}} \\ a \in F_{NET}}} \left(pBOMRecovery_{m,mm} * X_{mm,a,j,i,(t-1),sc}\right) \,,$$
$$\forall m \in M_{rp}, i \in I_c, t \in \left(T_{other} \cup T_{last}\right), sc \in SC \qquad 4.20$$

Equation 4.20 defines that the **flow of recovered products m** from the **final clients $X_{m,i,t}$ must be greater or equal** to the **minimum returnable products mm** that **were shipped in the previous time period $X_{mm,i,(t-1)}$**. The parameter $pMinReturn_m$ sets the minimum level (it is a percentage) of recovered products to be retrieved from the client. The parameter $pBOMRecovery_{m,mm}$ is the relation between final product mm and recovered product m.

$$\sum_{\substack{j\in F_{OUT_{c,rp}} \\ a\in F_{NET}}} X_{m,a,i,j,t,sc} \leq \sum_{\substack{(j,mm)\in F_{IN_{c,fp}} \\ a\in F_{NET}}} \left(pBOMRecovery_{m,mm} * X_{mm,a,j,i,(t-1),sc}\right), \quad \forall m \in M_{rp}, i \in I_c, t \in (T_{other} \cup T_{last}), sc \in SC \tag{4.21}$$

Equation 4.21 defines that the **flow of recovered products** m from the **final clients** $X_{m,i,t}$ has to be **less or equal** to the **returnable products** mm that **were shipped in the previous time period** $X_{mm,i,(t-1)}$. The parameter $pBOMRecovery_{m,mm}$ has the same function as in the equation 4.20.

After result analysis, it was observed that the maximum amount of recoverable product is delimited by two factors, which are **(1)** Equipar's incineration capacity and **(2)** Estimated *oCork* demand. In the present work, this maximum amount is resumed in the **Circular Volume** concept.

Circular Volume concerns the <u>amount of final product that can be recovered at the client</u> in order to be remanufactured or revalued (either transformed into *oCork* or used to create energy from biomass). This value is from the start limited by two factors:

- <u>Equipar's incineration capacity</u>: as explained in Chapter 5, Equipar has electrical needs that can be fulfilled by the public energy network and/or through incineration of waste and recovered cork products. The model does not consider that excess energy could, for instance, be sold back to the public energy network. Table 14 provides an example to the concept. In the table, *Electric Needs* represent the amount of product that need to be incinerated (in kg). *Waste Products* are the amount of waste created and is incinerated (in kg). *Demand* represents the amount of product that could be recovered, since in this work the 1 kg of final product can be recovered into 1 kg of recovered product (see Table 16). *Circular Volume* represents the amount of **<u>amount of final product that can be recovered at the client</u>**.

Table 14 - Circular Volume example (if the demand of oCork were to be zero)

Electric Needs (in kg)	Waste Products (in kg)	Demand (in kg)	Circular Volume
5,000	**1,000**	**10,000**	**(5,000-1,000)/10,000=40%**

- <u>Estimated *oCork* demand</u>: as shown in Figure 10 in section 4.1, *oCork* can be supplied to other BUs of CA. Through company public information, the main industrial units of CA were identified. The demand for *oCork* on these locations was estimated while taking into account the total demand of final products in these locations (e.g., (1) there is an industrial unit of CA in location A; (2) there can be demand for *oCork* in location A; (3) the demand for *oCork* is proportional to the total demand of final products of that location).

4. Entity Capacity

There are four groups of constraints in the present subsections *Supply*, *Flow*, *Stock* and *Entity Capacity*.

4.1 Supply Capacity

The supply capacity of the suppliers is defined by two equations. Equation 4.22 constrains the minimum supply capacity and equation 4.23 the maximum supply capacity.

$$\sum_{\substack{j\in F_{OUT_{sup,rm}} \\ a\in F_{NET}}} X_{m,a,i,j,t,sc} \leq v_i * pMxcSup_{m,i}, \forall m \in M_{rm}, i \in I_{grind}, t \in T, sc \in SC \tag{4.22}$$

The previous equation determines the total sum of **raw material** m leaving the supplier $X_{m,i}$ has to be **less or equal** to its **maximum supply capacity**, if that supplier is actually open. If it is not, then the outflow of raw material from that supplier will be zero. This condition is defined by binary variable υ_i. The parameter $pMxcSup_{m,i}$ establishes the maximum supply capacity of supplier i of raw material m.

$$\sum_{\substack{j \in F_{OUT_{sup,rm}} \\ a \in F_{NET}}} X_{m,a,i,j,t,sc} \geq \upsilon_i * pMncSup_{m,i} \text{ ,} \forall m \in M_{rm}, i \in I_{grind}, t \in T, sc \in SC \tag{4.23}$$

Equation 4.23 has the same line of thinking as 4.22. The difference is that this equation determines that if a supplier is in fact open ($\upsilon_i = 1$), then there is a minimum level of outflow of raw material, which is equal to the parameter $pMncSup_{m,i}$.

4.2 Flow Capacity

There are two equations that define the flow capacity in the SC entities. Equation 4.24 defines the maximum flow at destination and equation 4.25 at the origin.

$$\sum_{\substack{(j,mm) \in F_{NET} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} \leq \upsilon_i * pMxf_i \text{ ,} \forall i \in I, t \in T, sc \in SC \tag{4.24}$$

Equation 4.24 defines that the total sum of **flow of material** m at destination i has to be **less or equal** to the **maximum flow capacity** of that destination i, if that entity is in fact open ($\upsilon_i = 1$). The parameter $pMxf_i$ is the maximum flow capacity at entity i.

$$\sum_{\substack{(j,mm) \in F_{NET} \\ a \in F_{NET}}} X_{m,a,i,j,t,sc} \leq \upsilon_i * pMxf_i \text{ ,} \forall i \in \left(I_{Equipar} \cup I_w \cup I_{port} \cup I_c\right), t \in T, sc \in SC \tag{4.25}$$

Similarly, to equation 4.24, the previous equation establishes the maximum flow that depart from origin i, if that entity is in fact open ($\upsilon_i = 1$).

4.3 Stock Capacity

Related to stock capacity there are two equations. Equation 4.26 defines the maximum stock capacity at a given entity and equation 4.27 the minimum.

$$S_{m,i,t,sc} \leq pMxs_{m,i} * \upsilon_i \text{ ,} \forall m \in \left(M_{fp} \cup M_{rp}\right), i \in \left(I_{Equipar} \cup I_w\right), t \in T, sc \in SC \tag{4.26}$$

Equation 4.26 establishes that the **stock of material** m in entity i has to be **less or equal** to the **maximum stock** of material m in that entity i, if it is open ($\upsilon_i = 1$). The parameter $pMxs_{m,i}$ is the maximum stock of material m at entity i.

$$S_{m,i,t,sc} \geq pMns_{m,i} * \upsilon_i \text{ ,} \forall m \in \left(M_{fp} \cup M_{rp}\right), i \in \left(I_{Equipar} \cup I_w\right), t \in T, sc \in SC \tag{4.27}$$

Equation 4.27 establishes that the **stock of material** m in entity i has to be **greater or equal** to the **minimum stock** of material m in that entity i, if it is open ($\upsilon_i = 1$).

4.4 Entity Capacity

In the present subsection there are four equations. These are relevant to calculate the necessary capacity to handle the amounts of materials in the SC.

$$YKT_{i,t,sc} = \frac{\sum_{\substack{(j,mm) \in F_{NET} \\ a \in F_{NET}}} \left(pAreaUnit_{mm} * X_{mm,a,j,i,t,sc}\right)}{4.5} + \sum_{\substack{mm \in \left(M_{fp} \cup M_{rp}\right) \\ j \in I_w}} \left(pAreaUnit_{mm} * S_{mm,j,t,sc}\right) \text{ ,} \forall i \in \left(I_{Equipar} \cup I_w\right), t \in T, sc \in SC \tag{4.28}$$

Equation 4.28 calculates the necessary capacity (in area) to accommodate materials mm at the IU and warehouses for a given period in time t. The constant 4,5 is due to inventory rotation, it is an assumption adopted from Mota et. al (2018). The parameter $pAreaUnit_m$ is the area that a unit of material m occupies.

$$YK_i \geq YKT_{i,t,sc}, \forall i \in (I_{Equipar} \cup I_w), t \in T, sc \in SC \quad (4.29)$$

Equation 4.29 defines that the **material capacity** of an industrial unit or a warehouse YK_i has to be **greater or equal** than the **necessary capacity** $YKT_{i,t,sc}$ in each time period t.

$$YK_i \leq pea_i * v_i, \forall i \in (I_{Equipar} \cup I_w) \quad (4.30)$$

Equation 4.30 establishes that the **capacity** of an industrial unit or a warehouse YK_i has to be **less or equal** to the **maximum installation area** for each of those entities pea_i, if they are open ($v_i = 1$). The parameter pea_i is the maximum installation area.

$$YK_i \geq peamin_i * v_i, \forall i \in (I_{Equipar} \cup I_w) \quad (4.31)$$

Equation 4.31 establishes that the **capacity** of an industrial unit or a warehouse YK_i has to be **greater or equal** to the **minimum installation area** for each of those entities $peamin_i$, if they are open ($v_i = 1$). The parameter $peamin_i$ is the minimum installation area.

5. *Transportation Constraints*

In the present subsection the *Physical Limitations* of transportation are presented.

5.1 Physical Limitations

The transportation of products and materials by sea, can only be made between seaports and by using specifically the boat transportation mode.

$$\sum_{\substack{j \in (I_{Equipar} \cup I_w \cup I_c) \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} = \sum_{\substack{j \in I_{port} \\ a \in A_{boat}}} X_{m,a,i,j,t,sc}, \forall i \in I_{port}, t \in T, sc \in SC \quad (4.32)$$

Equation 4.32 defines that the sum of **material flow** X_m **from entities** j except the suppliers and seaports to a given seaport i **must be equal** to the **same material flow** X_m **from a given seaport** i **to another seaport** j using a boat as the transportation mode.

6. *Technology Constraints*

In the current subsection it is depicted the *Technology Capacity* and *Technology 1-Option*.

6.1 Technology Capacity

Regarding *Technology Capacity* there are two types of equations. The first ones are related to the maximum technology capacity and the latter to the minimum technology capacity.

$$P_{m,i,t,sc} \leq pTechCap_g * \zeta_{g,m,i}, \forall m \in (M_{RN} \cup M_{Twin} \cup M_{Aglo}), g \in G_{pr}, i \in I_{Equipar}, t \in T, sc \in SC \quad (4.33)$$

$$R_{m,i,t,sc} \leq pTechCap_g * \zeta_{g,m,i}, \forall m \in M_{oCork}, g \in G_{rem}, i \in I_{Equipar}, t \in T, sc \in SC \quad (4.34)$$

Equations 4.33 and 4.34 define that the **production and remanufacturing of materials** m (respectively) have to be **less or equal** to the **maximum defined technology capacity**, if that technology g is indeed chosen $(\zeta_{g,m,i} = 1)$. The parameter $pTechCap_g$ defines the maximum capacity of technology g.

$$P_{m,i,t,sc} \geq pTechCapMin_g * \zeta_{g,m,i}, \quad \forall m \in (M_{RN} \cup M_{Twin} \cup M_{Aglo}), g \in G_{pr}, i \in I_{Equipar}, t \in T, sc \in SC \quad (4.35)$$

$$R_{m,i,t,sc} \geq pTechCapMin_g * \zeta_{g,m,i}, \forall m \in M_{oCork}, g \in G_{rem}, i \in I_{Equipar}, t \in T, sc \in SC \quad (4.36)$$

Equations 4.35 and 4.36 follow the same line of thinking as the two previous equations. The **production and remanufacturing of materials** m (respectively) have to be **greater or equal** to the **minimum defined technology capacity**, if that technology g is indeed chosen $(\zeta_{g,m,i} = 1)$. The $pTechCapMin_g$ defines the minimum technology capacity of technology g.

6.2 Technology 1-Option

The equations below that only one technology from either production or remanufacturing stages can be chosen.

$$\sum_{g \in G_{pr}} \zeta_{g,m,i} \leq v_i \text{ , } \forall m \in (M_{RN} \cup M_{Twin} \cup M_{Aglo}), i \in I_{Equipar}, t \in T, sc \in SC \quad (4.37)$$

$$\sum_{g \in G_{rem}} \zeta_{g,m,i} \leq v_i \text{ , } \forall m \in M_{oCork}, i \in I_{Equipar}, t \in T, sc \in SC \quad (4.38)$$

Respectively, equations 4.37 and 4.38 establish that the **number of chosen technologies** must be **less or equal** to **1**, if location i is open, or **0**, otherwise.

4.2.5 Objective functions

In this subsection it is introduced the different objective functions and auxiliary variables to help define them.

Economic Objective

The *Economic Objective* is defined by a single objective function with several auxiliary variables.

The initial investments are represented by auxiliary variable FCI_d. There are two types of investments that can be performed: $d = 1$, corresponds to the investment in constructing a warehouse; $d = 2$, corresponds to the investment in technologies. Equation 4.39 depicts these two options.

$$FCI_d = \sum_{g \in (G_{pr} \cup G_{rem})} \sum_{m \in (M_{ip} \cup M_{fp})} \sum_{i \in I_{Equipar}} (pTechCost_g * \zeta_{g,m,i}) \text{ , } \forall d \in D \quad (4.39)$$

In Equation 4.39 the parameter $pTechCost_g$ is the investment needed to make use of technology g (either production or remanufacturing technologies).

Next, Equation 4.40 presents how the amount of cash inflow from selling products is calculated.

$$Sold_{t,sc} = (1 - TaxR) * \sum_{\substack{(i,j,m) \in F_{IN_{c,fp}} \\ a \in F_{NET}}} (pUnitSoldPrice_m * X_{m,a,i,j,t,sc}) \text{ , } \forall t \in T, sc \in SC \quad (4.40)$$

Equation 4.40 establishes that the **products shipped** X_m to the final client **discounted of the tax rate** $(1 - TaxR)$ is **equal** to **cash inflow** derived from selling products. The parameter $pUnitSoldPrice_m$ defines the price per unit of product m sold.

Having the cash inflows defined, Equation 4.41 exposes the net earnings.

$$
\begin{aligned}
NE_{t,sc} = {} & Sold_{t,sc} + pTaxR * DP_t \\
& - \left(\sum_{i \in I_{Equipar}} E_{i,t,sc} - \left(\sum_{\substack{m \in M_{rp} \\ i \in I_{grind}}} B_{m,i,t,sc} - \sum_{\substack{m \in M_{rp} \\ i \in (I_{grind} \cup I_{prod})}} W_{m,i,t,sc} \right) * pEnerRec_m \right) \\
& * pElectPrice - \sum_{\substack{(i,j,m) \in F_{OUT_{sup,rm}} \\ a \in F_{NET}}} \left(pUnitRawCost_{m,i} * X_{m,a,i,j,t,sc} \right) \\
& - \sum_{g \in G_{pr}} \sum_{m \in (M_{fp} \cup M_{ip})} \sum_{i \in I_{Equipar}} \left(pOperatingCost_g * P_{m,i,j,t,sc} \right) \\
& - \sum_{\substack{(i,j,m) \in F_{OUT_{c,rp}} \\ a \in F_{NET}}} \left(pRecovCost_m * X_{m,a,i,j,t,sc} \right) \\
& - \sum_{g \in G_{rem}} \sum_{m \in M_{oCork}} \sum_{i \in I_{Equipar}} \left(pOperatingCost_g * R_{m,i,j,t,sc} \right) \\
& - \sum_{(i,j,m,a) \in F_{NET}} \left(pVarTranspCost_a * pProductWeight_m * dst_{i,j} * X_{m,a,i,j,t,sc} \right) \\
& - \sum_{\substack{(j,m,a) \in (F_{NET} \cap I_{port}) \\ (i \in F_{NET} \cap i \notin I_{port})}} \left(pHubVarCost_j * X_{m,a,i,j,t,sc} \right) \\
& - \sum_{(i,m) \in N_{NET}} \left(pStockCost_m * S_{m,i,t,sc} \right) - \sum_{i \in I_{port}} \left(pHubFixedCost_i * v_i \right) \\
& - \sum_{g \in (G_{rem} \cup G_{pr})} \sum_{m \in (M_{fp} \cup M_{ip})} \sum_{i \in I_{Equipar}} \left(pNrWorkerTech_g * pLaborCost_i \right. \\
& \left. * pWeeklyWorkingHr * pWeeksPerPeriod * \zeta_{g,m,i} \right) \\
& - \sum_{i \in (I_{Equipar} \cup I_W)} \left(pNrWorkerEnt_i * pLaborCost_i * pWeeklyWorkingHr \right. \\
& \left. * pWeeksPerPeriod * v_i \right) \ , \forall t \in T, sc \in SC
\end{aligned}
\qquad 4.41
$$

In equation 4.41 it is defined several terms. The first two parcels are related to the cash inflows and the rest, the cash outflows. In order, they are described below with a color code:

- The second sum parcel – What has not been lost in depreciation, on investments made, thanks to the tax rate, enters as a cash inflow;

The cash outflows are described below:

- **The 1st** parcel – **Electric infrastructure cost**. The IU's total consumption is subtracted from the energy generated from biomass and by-products generated from the production processes. The parameter $pElectPrice$ the average price of industrial electricity in the Portuguese environment;
- **The 2nd** parcel – **Raw material cost**. The inflows of raw materials from the supplier multiplied by the parameter $pUnitRawCost_{m,i}$ results in the total raw material costs. The previous parameter is the unitary cost of raw material m at supplier i;
- **The 3rd** parcel – **Production costs**. The production of final products and intermediate products multiplied by the parameter $pOperatingCost_g$ results in the total production costs. The previous parameter is the unitary cost of final/intermediate product produced with technology g;

- **The 4th** parcel – **Product recovery costs**. The outflows of recovered products from the clients multiplied by the parameter $pRecovCost_m$ results in the total product recovery costs. The previous parameter is the unitary cost of a product m recovered;
- **The 5th** parcel – **Remanufacturing costs**. The production of the final product *oCork* multiplied by the parameter $pOperatingCost_g$ results in the total remanufacturing costs;
- **The 6th** parcel – **Variable transportation costs**. The flows of products are multiplied by three parameters: $pVarTranspCost_a$ accounts for the transportation cost of transportation mode a per km traveled; $pProductWeight_m$ represents the unitary weight of product m and $dst_{i,j}$ establishes the distance between location i and j. The multiplication makes up the total transportation costs;
- **The 7th** parcel – **Hub variable costs**. The flow of products between location i and j multiplied by the parameter $pHubVarCost_j$ results in the handling costs at seaports hubs. The previous parameter is the handling cost at seaport j. Note that this cost happens only there is a flow between two seaports and the handling cost is related to the destination j;
- **The 8th** parcel – **Stock related costs**. The stock of product m at location i multiplied by the parameter $pStockCost_m$ results in the stock costs. The previous parameter is the unitary cost of product m;
- **The 9th** parcel – **Hub fixed costs**. If a seaport is open $(v_i = 1)$ there will be an added cost represented by the parameter $pHubFixedCost_i$ which is the seaport hub i fixed cost;
- **The 10th** parcel – **Labor costs (Technology scope)**. The present parcel defines the labor costs regarding the fact that a certain technology g is chosen $\left(\zeta_{g,m,i} = 1\right)$. There are four parameters associated in this parcel: $pNrWorkerTech_g$ represents the number of workers to run technology g; $pLaborCost_i$ establishes the labor cost in location i; $pWeeklyWorkingHr$ defines the number of working hours in a week; and $pWeeksPerPeriod$ represents the number of weeks in a given period;
- The last parcel – **Labor Costs (Entity Scope)**. The current parcel establishes the labor costs related to entity i which has to be open $v_i = 1$. The parameter $pNrWorkerEnt_i$ represents the fixed number of needed employees required to run entity i. The remaining three parameters are the same as those from the last parcel.

With the net earnings defined, the cash flows can be represented (see equation 4.42).

$$CF_{t,sc} = \begin{cases} NE_{t,sc}\ , t \in \left(T_{first} \cup T_{other}\ \right) \\ NE_{t,sc} + \sum_{d} pSv_d * FCI_d\ , t \in T_{last} \end{cases} \tag{4.42}$$

Equation 4.42 depicts that the cash flows are equal to net earnings except for the last time period. In this case it is considered the salvage value from the investments previously applied. The parameter pSv_d represents the fraction of the initial investment FCI_d performed that can be recovered as a salvage value.

Finally, equation 4.43 defines the NPV.

$$NPV = \sum_{sc} \left(prob_{sc} * \left(\sum_{t} \frac{CF_{t,sc}}{(1 + pInt)^t} \right) \right) - \sum_{d} FCI_d \tag{4.43}$$

The NPV equation is defined by the sum of the various cash flows from different time periods and scenarios discounted of a defined interest rate (represented by the parameter $pInt$) minus the investments performed. The parameter $prob_{sc}$ is the probability of occurrence of a given scenario sc.

Environmental Objective

As explained in Chapter 3, one has to model the SC as comprehensive as possible if it wants high standards on completeness, accuracy and preserve the reality around the problem. Thus, in the literature, the environmental aspect of the problem has been an additional focus. Moreover, Chapter 3 exposes that this aspect must be assessed by using a methodology (LCA) that is composed by several environmental indicators/metrics, in order to apply a holistic point-of-view of the problem at hand.

The present subsection introduces the environmental measures used and briefly introduces the chosen LCIA method. The previous information will be useful to develop the environmental objective function with is detailed after.

The LCA methodology has been increasingly used by the research community, as stated earlier in Chapter 3. The method of Goedkoop et al. (2009), *ReCiPe*, is used to perform the LCA and assess the environmental impacts of a given system in a given problem. As mentioned in Chapter 3, the EU considered *ReCiPe* as the most complete and suitable LCIA method to use in an LCA assessment, hence it will be the chosen method to tackle the *Environmental Objective* in the present work.

Due to information scarcity and the complexity of the problem at hand, it may be difficult to perform an exhaustive LCA assessment. To facilitate this process, a dedicated software was chosen to assess the *Environmental Objective* of the problem – SimaPro is the world's leading LCA software package (SimaPro 2020). The software allows the user to perform the LCA based on *ReCiPe*, thanks to its wide databases that are continuously updated (SimaPro 2020).

The set of midpoint environmental categories are represented by B. Let $b = (1,2,\dots,n)$ be the index to represent each one of these categories.

Equation 4.44 defines the environmental objective function. As in the work of Mota et. al (2018), the goal of using this equation is to compare different SC structures rather than perceiving the environmental impact of the SC accurately.

$$EnvImpact = \sum_{sc} prob_{sc} * \left(\sum_{b} pNormFactor_b * \left(\sum_{a \in A} \left(TranspImp_{a,b,sc}\right) + \sum_{\substack{m \in M_{fp} \\ g \in (G_{pr} \cup G_{rem})}} \left(ProdImp_{m,g,b,sc}\right) + \sum_{m \in M_{fp}} \left(FiniImp_{m,b,sc}\right) + \sum_{u \in U} \left(EOLifeImp_{u,b,sc}\right) + EntityImp_{b,sc} \right)\right), \forall sc \in SC \quad (4.44)$$

Equation 4.44 is a weighted sum of all environmental impact categories β according to the LCIA methodology normalization factors ($pNormFactor_b$), which in turn will result in a single score. The SC activities covered in this study are briefed in subsections 3.3.2 and 3.3.3: forest management, preparation and production stages

($ProdImp_{m,g,b,sc}$); finishing stage ($FiniImp_{m,b,sc}$); product distribution ($TranspImp_{a,b,sc}$); end-of-life stage ($EOLifeImp_{u,b,sc}$). In addition, the entity impact is also considered in the present work ($EntityImp_{b,sc}$).

Social Objective

Chapter 3 exposed the main metrics and methodologies used to tackle the *Social Aspect*. In addition, several papers were given as examples of how the social aspect has been modelled, with the usage of only one or two metrics being the main conclusion. Again, as in the previous objective, a more holistic approach must be used to ensure completeness and accuracy in the future results analysis.

Usually, the social indicators are chosen taking into consideration the context of the actual problem. So, in the present work the chosen social indicators are based in the Cork Industry and the reality of the SC of Corticeira Amorim. In its *Sustainability Report* (Corticeira Amorim, 2018b) CA sets the relevant social categories and indicators, based on the GRI social guidelines. The social categories are Employment (Emp.), Labor Relations (LR), Health and Safety in Work (H&S), Education and Training (E&T), Diversity and Equal Opportunities (D&EO), Local Communities (LC) and Social Evaluation of Suppliers (SEval.). Regarding the **social indicators** within each category, those are depicted in Table 15.

Table 15 - Social categories and indicators

Categories	Indicators		
[1] Emp.	**[1.1]** Employment Turnover	**[1.2]** Type of Contract	-
[2] LR	**[2.1]** Protection of Workers	**[2.2]** Monetary Compensation	-
[3] H&S	**[3.1]** Accident Frequency Ratio	**[3.2]** Occupational Disease Ratio	**[3.3]** Absenteeism Ratio
[4] E&T	**[4.1]** Training hours	-	-
[5] D&EO	**[5.1]** Salary Ratio Men vs Women	**[5.2]** Ren. Ratio Men vs Women	**[5.3]** Ratio Men vs Women
[6] LC	**[6.1]** Value Created to the Community	**[6.2]** Junior Involvement	-
[7] SEval.	**[7.1]** Certificate FSC	**[7.2]** Local Salary Ratio	-

Table 15 presents several social indicators that are described and contextualized below (Corticeira Amorim, 2018b):

- **[1.1] Employment Turnover** (Unit: %) – It measures the variation of number of employees in a given time period (e.g., +2% of employees represents a positive social impact);
- **[1.2] Type of Contract** (Unit: %) – It measures how much percentage of the total workforce have permanent effective contracts;
- **[2.1] Protection of Workers** (Unit: %) – It measures the percentage of workers covered by collective labor contracts established between APCOR and the unions in the sector;
- **[2.2] Monetary Compensation** (Unit: €/worker*time period) – How much money is invested in workers related to extra days of vacation, awarding education allowance plans and implementing programs to monitor the organizational climate and internal communication plans;
- **[3.1] Accident Frequency Ration** (Unit: 1E6*Nr accidents/Nr man-hours worked*time period) – It is defined as the number accidents occurring in a year, per million man-hours worked;
- **[3.2] Occupational Disease Ratio** (Unit: 1E4*Nr of occupational diseases/Nr of workers*time period) – It is defined as the number of new cases of work-related illnesses per 10000 workers insured by the Social Security in the year considered;
- **[3.3] Absenteeism Ratio** (Unit: %) – It is defined as the number of days missed per total workable days (not counting vacation days) in a given year;

- **[4.1] Training Hours** (Unit: Nr of training hours/worker*time period) – It measures the number of training hours per worker, sponsored by the company;
- **[5.1] Salary/Renumeration Ratio Men vs Women** (Unit: time period^{-1}) – It directly compares the men's salary/renumeration with that of women. The difference between salary and renumeration is that the latter includes other extra financial yields that the company pays the employee;
- **[5.2] Ratio of Men vs Women** (Unit: time period^{-1}) – It defines the ratio between the number of working men and women;
- **[6.1] Value Created to the Community** (Unit: €/time period) – It measures how much money, directly or indirectly, the company has contributed to the local community;
- **[6.2] Junior Involvement** (Unit: No unit) – It measures the degree of involvement with junior people (e.g. internees, researchers) by CA;
- **[7.1] Certificate FSC** (Unit: binary "Yes or No") – Does the supplier have the FSC certification or not?
- **[7.2] Local Salary Ratio** (Unit: time period^{-1}) – It is defined as the ratio between the salary of CA's employees and the minimum salary of the considered country.

In order to **validate** whether these **social indicators** are relevant or not, the social point-of-view of other four major players in the cork industry were assessed:

- **Vinventions** is a company that encompasses several brands whereby each represents a cork product (e.g., natural cork stoppers brand; technical cork stoppers brand). The company does not specify social categories/indicators but emphasizes the employee investment and protection need [(Vinventions 2017), (Vinventions, 2018) and (Vinventions 2020)]. Indirectly, it can be assumed that this social focus can be related to the <u>first five social categories</u> depicted in Table 15, because all of them are related to employee investment and protection;
- **Cork Supply** is a company that produces either natural or technical cork products. The company states that its employees (e.g., training, protection of workers and equal opportunities) and local community are important in their sustainability approach. In addition, the company shows concerns about the supply side on how to keep a sustainable resource management and health relationship with them (Cork Supply 2020). Indirectly, it can be assumed that this social focus can be related <u>all social categories</u> depicted in Table 15;
- **MaSilva** is a company that produces either natural or technical cork products. The company is clearly aligned with the FSC and other certifications, but from what is at least publicly available, the company addresses only the environmental aspect in the sustainability context (MaSilva 2020). Indirectly, it can be assumed that the company's social focus is only related to the <u>last category</u> in Table 15;
- **Lafitte** is a company that produces either natural or technical cork products. Such as MaSilva, from what is at least publicly available, the company addresses only the environmental aspect in the sustainability context (Lafitte 2020). Indirectly, it can be assumed that the company's social focus is not related to Table 15.

It can be considered that the social categories/indicators in Table 15 are relevant. Although some players recognize the social aspect important in a sustainability approach (e.g., Vinventions and Cork Supply), others still seem to have a sustainability approach, composed only of the environmental aspect (e.g., MaSilva and Lafitte).

It should be noted that CA was the company that most developed the social aspect and presented it publicly (through a Sustainability Report).

The social indicators above are deeply contextualized with the problem at hands. If one decides to apply an SLCA methodology, he has to study his problem and understand what the most pertinent social indicators are to use in his research.

As the LCA approach, the same could be done in the *Social Objective*. The SLCA methodology can be applied through Simapro, since SHDB, a social hotspots database, has been made available to use in this software (Norris, Bennema, & Norris, 2019). However, the main purpose of this work is to give recommendations about different SC decisions to follow, while considering different TBL impacts (e.g., Network A is better than B). In order to reach such conclusion, there is no need for the assessment of absolute impacts/scores. Thus, the SLCA methodology will not be applied. Instead, the same holistic reasoning in the LCA methodology will be used, but it is not expected to compute an absolute/aggregated social single score. In the present work, the social impact assessment part will be a relative **Social Impact Measurement** (SIM) will be applied. This type of assessment is relevant to compare different solution/scenarios for a given problem, which is the purpose of this work.

As stated, Figure 7 and Figure 9 summarize methodology to follow for the SIM. A normalization of each indicator is performed so that different scenarios can be compared. Figure 11 summarizes this.

To illustrate Figure 11 an example is given as follows: the Equipar's *turnover rate* is about 1.25 and in the Portuguese environment goes around 0.9. The social indicators used to assess the intended environment (in Figure 11 it is the Portuguese environment, because Equipar is located in this country), will be the points-of-comparison to perceive if Equipar is better, equal or worse than the Portuguese environment. To compute Equipar's **Relative Social Impact** for a given scenario, each indicator is normalized to a "No unit" basis (as seen in Figure 11). Each relative impact score of each indicator is represented by **x**. Being the value of **x**:

- **Greater than 1**, CA is **better** than the Portuguese environment;
- **Equal to 1**, CA has a social impact overall **equal** to the Portuguese environment;
- **Less than 1**, CA is **worse** than the Portuguese environment.

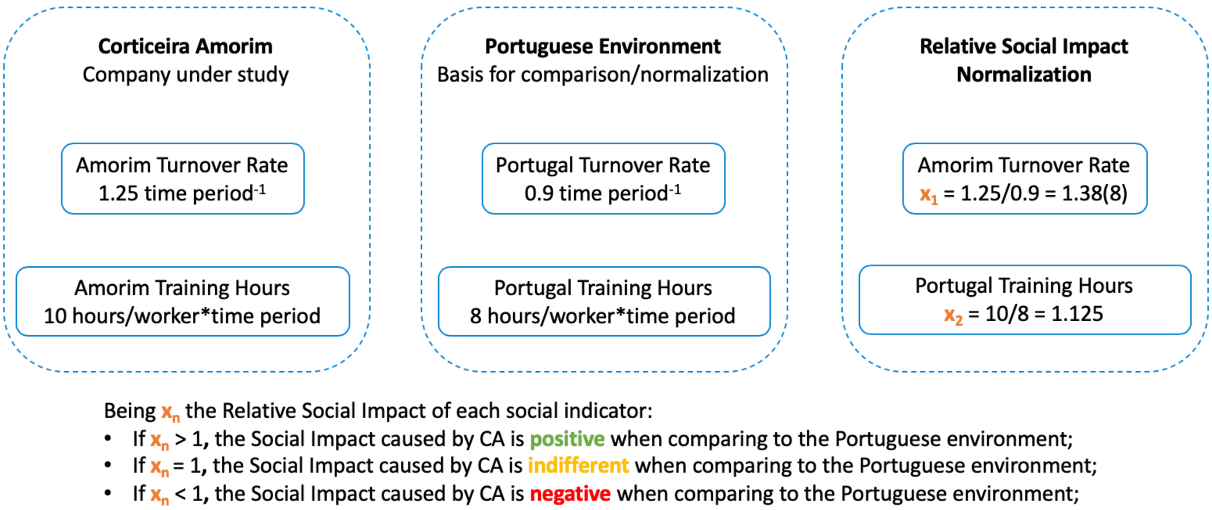

Figure 11 - Simple example of SIM

Figure 11 presents a really simple example how the SIM can be performed.

In order to this methodology to be considered holistic as an SLCA, the same method from Figure 11 has to be applied in the rest of the SC entities (suppliers, warehouses and Equipar).

The set of social categories are represented by C. Let $c = (1,2, \dots, n)$ be the index to represent each one of these categories. The set of social indicators are represented by E. Let $e = (1,2, \dots, n)$ be the index to represent each one of these indicators.

The primary focus of this work is to design different SC structures (different scenarios) and compare them. As previously stated, instead of applying the SLCIA methodology, the SIM methodology described does not imply the computation of a social single score because, in some cases, it could result in biased results (due, on the one hand, to data collection and data availability problems, and on the other hand to the problem of adding scores from different non-comparable categories). Thus, the score of each social category) will be used as the terms of comparison between different scenarios.

Equations 4.45 and 4.46 give a general example of how the score of a social category is calculated. The set of social categories are represented by C. Let $c = (1,2, \dots, n)$ be the index to represent each one of these categories. The set of social indicators are represented by E. Let $e = (1,2, \dots, n)$ be the index to represent each one of these indicators.

$$SocCat_c = \sum_{e \in E} \left(SocInd_{c,e}\right), \forall c \in C \tag{4.45}$$

$$SocInd_{c,e} = \sum_{i \in (I_{Facility} \cup I_w)} \left(\frac{v_i * pSocInd_i}{CompBasis_i}\right), \forall c \in C, e \in E \tag{4.46}$$

Equation 4.45 depicts that the score of each social category ($SocCat_c$) is equal to sum of its social indicators scores ($SocInd_{c,e}$). Equation 4.46 describes how each social indicator score is computed. The social performance ($pSocInd_i$) of each infrastructure managed by CA (facilities and warehouses) are directly compared to the environment in which they are located in ($CompBasis_i$). This operation results in a dimensionless unit that may be used for scenario comparison.

4.3 Conclusions of Chapter 4

This chapter introduces exhaustively the problem definition providing context for the development of the referred sustainable SC optimization model for the cork industry. So, **(1)** for the economic objective a generic formula of the NPV is introduced; for **(2)** the environmental objective the chosen LCIA methodology is defined and the necessary tools to implement the LCA is also introduced; for **(3)** the Social Impact Measurement methodology is introduced for the social objective.

A Mixed-Integer Programming (MIP) model is proposed to support a global SC design and planning decisions in the cork industry. The necessary modelling assumptions are provided along with a detailed explanation of the mathematical formulation and notation. In general, the model considers a **(1)** superstructure of entities and existing or potentially new geographical locations, a **(2)** transportation network, the **(3)** distance between all entities/locations, a **(4)** set of materials and products, technologies (different manufacturing processes), and respective manufacturing needs, and the **(5)** costs and social and environmental impacts related with all the decisions taken. As referenced throughout the work, this model defines an SSC which focuses on designing sustainable strategic/tactical decisions, thus maximizing economic return, and minimizing environmental and social impacts.

The following chapter introduces the case study and describes all the pertinent parameters to be used.

5 Case study

The present chapter, divided into five sections, introduces the case study on which the model is tested. The **first section** is dedicated to providing the necessary context for the case study, with the presentation of the integrated SC of CA with the focus on Equipar IU. The **second section** discusses the general assumptions that were made to overcome difficulties in data collection and SC modelling. The **third section** presents the real data of the case study, and the **fourth section** presents the data for the SC key performance measures. **Fifth section** summarizes the main contents discussed in the chapter.

5.1 The integrated approach SC of Equipar IU: Technical Cork Stoppers

Following what was described in sections 2.4 and 2.5, in the present section the SC of the case study is depicted with greater detail. As previously mentioned, CA has an international presence with various industrials units and other facilities across the globe. One of them is located in Coruche, which is Equipar IU that produces technical cork stoppers, shipped to several parts of the world.

Figure 5 depicts an integrated approach of the cork stoppers SC already specific to the context of CA. Regarding the present case study, Equipar IU is represented by stage 3.2 of Figure 5. All of the other entities such as warehouses, suppliers or transportation companies are not specific of the SC of Equipar IU, meaning that they store, supply or transport other IUs of CA.

In the case study there are eight suppliers (Iberian, South of France and North African), two types of transportation modes (boat and truck), twenty-six clients (European, American and Middle Eastern), twelve seaports (European, American, Middle Eastern) and eighteen warehouses (European and American). None of these entities are initially opened, hence their openness will depend solely on the SC decisions found by the optimization model. Figure 12 depicts the location of the entities.

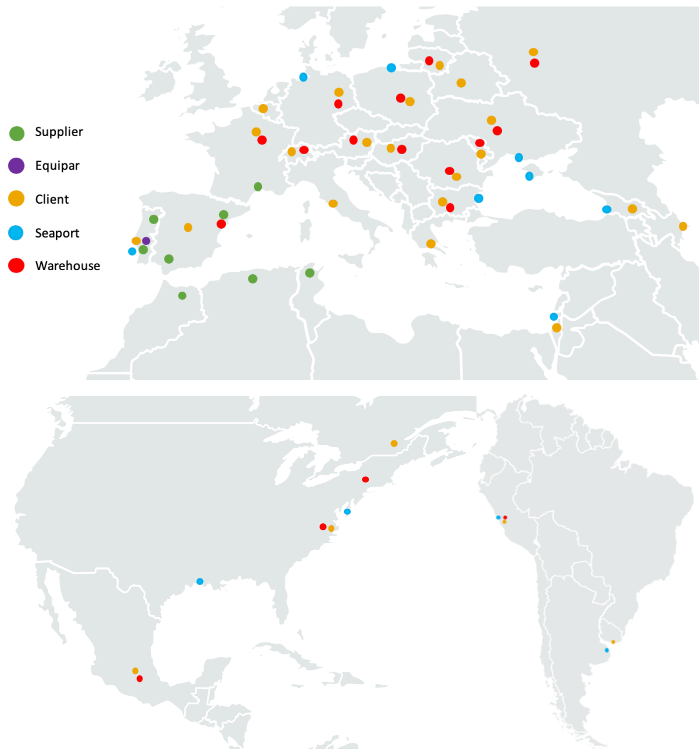

Figure 12 - Location of the SC entities

5.2 Assumptions and Simplifications

The present section depicts the necessary assumptions made in order to overcome the difficulty in estimating real-life data and SC settings. The assumptions made are in line with the reality of the SC of CA.

The assumptions and simplifications made, related with the SC, are as follows (stages depicted in Figure 5):

- **Stage 1 – Forest Management:** In fact, Equipar IU is mainly supplied by Iberian suppliers. The other suppliers only supply a residual portion of the raw materials. In the model this tendency is not implied, with the view to understand the difference between reality and the optimization results. The suppliers' location, raw materials price and availability are all estimated, based in the literature and company information;
- **Stage 2 – Cork Preparation:** It is being assumed that this stage is being performed amid the flow between suppliers and Equipar. In terms of SC decisions, this stage would not offer relevant input in the model, because it is known *a priori* that Stage 2 is not a SC bottleneck and it is performed in a CA facility also located in Coruche. The previous insights were given by SC decision-makers;
- **Stage 3.2 – Technical Cork Stopper Production:** The assumptions made are at different levels. **(1)** There are several final products that Equipar produces, but they are aggregated in three major groups (*Twin, Aglo, RN*); **(2)** There are many different combinations between intermediate and final products (as shown in Table 4), but in this work they are simplified into granulates *RA* and *RCT* being transformed into *Twin* and *Aglo* respectively (see also Table 16); **(3)** It is assumed that incineration capacity is limited by the energetic needs of Equipar; **(4)** Data related with products (ex. BOM, stock cost) and energy consumption are estimated based in the literature and company-specific information; **(5)** In Equipar, the technology alternative has never been applied at an industrial scale, but is assumed as a valid alternative to undertake (data related with the information is estimated based on the literature); **(6)** Waste products generated in the production phases are estimated on the basis of company-specific information and literature and are assumed to always be used for incineration in the time period in which they were formed; **(7)** Remanufactured products are assumed as a single (re)granulate that can be used in other BUs of CA and the information related with them are similar to that of intermediate products;
- **Stage 4 – Cork Stopper Finishing:** Customization is set to be uniform, regardless of the client (e.g., same packaging, painting, surface treatment) – the client either buy a slightly more expensive customized product or not;
- **Stage 5 – Cork Stopper Distribution:** In reality, the transportation and warehousing are all outsourced from third-party logistics companies. So, in order to diversify the SC decision making, this work assumes that the company rents the transportation capacity, but is responsible for the logistics activities such as which warehouses to rent, the needed capacity, the transportation to use, the flows between entities and all related matters related with transportation and storage;
- **Stage 7 – End-of-life:** Incineration and landfill release are assumed to be the end-of-life options. The first one includes recovering the product at the final client and incinerating them at Equipar, generating energy and avoiding use energy from the public grid (data related to product recovery costs and other information are company-specific). The products that are not recovered are assumed to be sent to a

landfill. Despite the different locations that this landfill can happen, it is assumed that the environmental impact is equal to each one of them.

The time frame of the model is set to five years to better understand what decisions are incurred in the SC. It is considered twenty time-periods, so each period represents three months of activity (quarter).

5.3 Data Collection

The present section is dedicated to the introduction of the information collected or estimated to feed the model. Starting with the characterization of the network, followed by a description of materials and products, available technologies, transportation modes being used and the demand. Other relevant parameters will be presented throughout the work when necessary.

5.3.1 Network Characterization

As previously mentioned, the focal point of the case study is Equipar IU. Figure 12 depicts the SC of CA and contextualizes the position between the IU and the rest of the SC. A cork supplier (in **green**) supplies Equipar (in **purple**), which then sends the product to either warehouses (in **red**), final clients (in **yellow**) or seaports (in **blue**) depending on the best flows to take. The reverse flow of recovered products goes in the same way.

Each supplier supplies the same cork raw material, so the decision of which supplier to choose will be between the price of the raw material, its availability and whether or not this supplier has the FSC certificate.

Production and inventory levels at Equipar depend directly on demand. Typically, Equipar IU has enough capacity to meet all the demand. However, if the demand tends to grow and exceed the installed capacity, it is expected the IU to undertake the *make to stock* production approach, so to prevent order rupture.

Instead of investing in building a warehouse, this case study considers the option of renting its capacity. The rental option offers greater flexibility in the use of warehouses, due to the fact that rental prices are much lower than those of construction. Furthermore, warehouse ownership does not necessarily improve product handling and storage (company-specific information). The warehouses are located in strategic logistics sites throughout Europe and America.

5.3.2 Materials and Products

As mentioned, for modelling purposes, cork is considered the raw material (*Cork*); there are two intermediate products that differ on granulate diameter (*RA* and *RCT*); there are three different final products (*RN*, *Twin* and *Aglo*); two types of waste products (*Cork Dust* and *Stick*); the final products are recovered at the final client as single product (*rCork*); and finally the recovered product can be remanufactured into another product (*oCork*). Respectively, these products will be represented by *rm*, *ip1*, *ip2*, *fp1*, *fp2*, *fp3*, *wp1*, *wp2*, *rp* and *rem*.

Having such different products emphasizes the need for distinct BOMs. Table 16 introduces the different BOMs considered in this case study (the first column are the inputs and the first row the outputs). For example, to produce 1 kg of *ip1* it is needed 1.618 kg of *rm*.

Table 16 - Distinct BOMs considered (based on company-specific information, Demertzi et al. (2016) *and* Rives, Fernandez-Rodriguez, Gabarrell, & Rieradevall (2012)*)*

	Grinding Unit			Production Unit		Waste creation		Remanufacturing		
	ip1	*ip2*	*fp1*	*fp2*	*fp3*	*wp1*	*wp2*	*rp*	*rem*	Unit
rm	1.618	1.618	1.618							*kg*
ip1				1.013	0	0.618	0			*kg*
ip2				0	1.013	0.618	0			*kg*
fp1						0.618	0	1	-	*kg*
fp2						0	0.013	1	-	*kg*
fp3						0	0.013	1	-	*kg*
rp						-	-	-	1.618	*kg*
rem						0.618	0	-	-	*kg*

Table 16 summarizes what happen in the production stages: the production of intermediate products from raw materials, final from intermediate products and remanufactured from recovered products result in waste products that can be valued as a biomass source. The efficiency of production and material handling is considered to be 100% due to the fact that these parameters are not as relevant for the company as others.

Another vital aspect of the model is the unitary electric consumption of each producing each product and respective technology (see Table 17). The displayed information has a basis in the literature and company-specific information.

Table 17 - Unitary energy consumption (kWh/kg)

Equipar Units	*ip1.gip*	*ip2.gip*	*fp1.gip*	*fp2.gfp1*	*fp2.gfp2*	*fp3.gfp1*	*fp3.gfp2*	*rem.frp*
Grinding Unit	0.369	0.369	0.369	0	0	0	0	0.369
TwinTop Unit	0	0	0	0.943	0.665	0	0	0
Aglo Unit	0	0	0	0	0	1.027	0.665	0
Distribution Unit	0.105	0.105	0.105	0.3278	0.3278	0.2085	0.2085	0

With this information it can be known how much energy is being consumed in a given period and compute how much of it come a biomass source or the public energy grid, for example. In addition, the unitary energy consumption difference between technologies *gfp1* and *gfp2* will dictate the different operational costs that each technology involves.

So, different scenarios will also compare the energy independence of the IU from the public energy grid, which is relevant for environmental (using a greener option) and economic reasons (the use of energy from biomass is considered, in this model, an advantage from an economic point of view).

5.3.3 Technologies

There are two technology options in the production stage of the final products *fp1* and *fp2*. Both are related with the TCA treatment introduced in section 2.5. The first technology is what is already installed, the ROSA treatment. The second is using an irradiation device such as the Cobalt-60 that eliminates the TCA, by applying 100 kGy (Técnico | Lisboa: UTR 2020) worth of ionization radiation dose [according to Pereira, Gil, & Carriço (2007), this dose has been found as the most effective]. For modelling purposes, although there are no multiple technological options, it is also considered the production stage of intermediate products *ip1* and *ip2* and final product *fp1* and remanufacture stage of *rem* as technologies. Respectively, these technologies will be represented by *gfp1*, *gfp2*, *gip* and *grp*. Table 18 summarizes the relevant information about the different technologies.

Table 18 - Information related with the technology options

Technology	Capacity (kg)	Installation Cost (€)	Workers (uni.)
gfp1	450,000	0	23
gfp2	450,000	2,000,000	10
gip	1,260,000	0	0
grp	1,260,000	0	0

5.3.4 Transportation and Warehousing

As mentioned, CA considers two options when it comes to transportation modes: truck and boat. It should be taken into account that, although the current model considers the transport capacity not to be owned by the company, logistical decisions and management are the responsibility of CA. The transportation capacity, unitary cost and maximum contracted capacity of each mode were estimated based on a match between the typical SC product flow and real-life transportation options. The transportation mode relative information is depicted in Table 19.

Table 19 - Information related with the transportation modes

Mode	Capacity (kg)	Unit Cost (€/kg*km)
Truck	25,000	6.00E-5
Boat	2,400,000	2.16E-6

It should be noted that there are no restrictions concerning the transport of different products at the same time and the storage potential of the product is considered to be 100% (e.g., a truck with a capacity of 25,000 kg carries 25,000 kg of products). The boat capacity displayed in Table 19 represents a percentage of its total capacity, because it is stipulated that CA's products would be transported alongside other cargo. Lastly, in this case study there are intra and inter-continental flows, being the latter possible with the use of two transportation modes. Intra-continental can either be performed by the two types of transportation modes or only by truck.

Table 20 - Information related with the Seaports

Continent	Seaport	Hub Cost (kg)	Unit Cost (€/kg)
Europe	Lisbon (*sea1*)	150,000	7.51E-3
	Gdansk (*sea2*)	120,000	4.89E-3
	Hamburg (*sea3*)	288,000	1.43E-5
	Nikolaev (*sea4*)	160,000	8.00E-3
	Sebastopol (*sea5*)	160,000	8.00E-3
	Varna (*sea6*)	160,000	8.14E-3
America	New York (*sea7*)	100,000	1.45E-3
	Houston (*sea8*)	100,000	4.74E-4
	Callao (*sea9*)	144,000	7.45E-3
	Buenos (*sea10*)	144,000	5.31E-2
Middle East	Batumi (*sea11*)	200,000	1.06E-2
	Haifa (*sea12*)	350,000	2.87E-2

Table 22 contains the relevant information on seaports (and their respective indexes). Handling capacity and efficiency are not considered as these two parameters are not relevant in the company perspective. The differences between fixed and variable costs of using the seaports were based on the work of Mota et al., (2018) and estimated given the region standard. Another approximation made was that the distance covered by boat to cross the Gibraltar strait was not considered due to being residual when taking into account the scale of the SC. In this case, it would have been added unnecessary computational effort.

As previously mentioned in section 5.2, the warehouses considered in this case study are located in major logistic clusters near the considered clients. In Table 21 the warehouses and their respective indexes and renting prices are presented. Respectively, the warehouses are Linz (*w1*), Berlin (*w2*), Sofia (*w3*), Barcelona (*w4*), Paris (*w5*), Budapest (*w6*), Chisinau (*w7*), Moscow (*w8*), Zurich (*w9*), Kiev (*w10*), Minsk (*w11*), Washington DC (*w12*), Albany (*w13*), Vilnius (*w14*), Mexico City (*w15*), Lima (*w16*), Warsaw (*w17*) and Bucharest (*w18*).

Table 21 - Warehouses renting prices (€/m²)

w1	*w2*	*w3*	*w4*	*w5*	*w6*	*w7*	*w8*	*w9*	*w10*	*w11*	*w12*	*w13*	*w14*	*w15*	*w16*	*w17*	*w18*
5.0	3.7	1.8	3.1	3.9	3.2	1.0	1.5	5.4	1.2	1.7	1.8	2.9	2.0	2.0	1.8	1.5	2.0

The warehouses were strategically chosen to maximize SC diversity and to assess which design will the SC take with such options. In addition, it is assumed that the minimum renting capacity is 50 m^2 and 3721 m^2. The minimum is sufficiently small to provide SC flexibility when renting warehouses (to accommodate small demand from certain clients). The maximum capacity is set to storage 1,000,000 kg worth of product (is an assumption, due to the fact that it is sufficient to store all the flows of the SC in a given time period).

The model allows for additional transportation modes, warehousing and seaports options provided that inter-continental restrictions are met.

The distance between each location is an important aspect to mention when discussing transportation. It is represented by $dst_{i,j}$. The distances used, are obtained from Ports.com and Google Maps, which return approximate values for each trip using the available modes, which can be considered as good portraits of reality. This way, it will not be necessary to adjust these values used for the distance matrix.

5.3.5 Demand

An engine was created in Microsoft Excel in order to work with existent demand and set the tone for future scenarios. The engine has multiple functionalities as follow:

- **Client Dashboard** – The user can establish how much percentage of its real demand is to be considered in the optimization model (ex. across the twenty time-periods, *c14* has 100,000 kg of total demand, but the user determines that only 40% will be considered in the model). This tool is useful for model validation and sensitivity analysis;
- **Timeline Dashboard** – The user can establish demand trends in the timeline (ex. demand growing 2% between time-periods) or simulate unexpected events (ex. in a given a time-period the demand grew 25%). This tool is useful for model validation, assess model robustness and sensitivity analysis;
- **Product Dashboard** – The user can establish the quotas of total demand for each final product (ex. in year 2020, the quotas are: 15% of *fp1*, 60% of *fp2* and 25% of *fp3*). These quotas are set yearly, so there are five different quotas. This tool is useful for model validation and sensitivity analysis;

The minimum service level for each client is set to 95%, which is line with the high standards of CA.

5.4 Objectives Data

In this section, relevant and specific data of the performance measures is briefed, detailing the parameters for each model objective: economic, environmental and social. These consider the holistic approach of the SC.

5.4.1 Economic Data

As mentioned, the economic key performance measures are all presented in Table 22 with a SC perspective.

Table 22 - Overview of the economic key performance measures

SC Stages					
Forest Manag.	**Production Stages**	**Distribution**	**Use**	**End-of-life**	**Others**
Raw Material Cost	Human Resources Operational Costs Installation Costs Stock Costs	Transportation Costs Sea Hub Costs Warehouse Costs	Selling Price	Recovery Costs	Interest Rate Salvage Rate Tax Rate Depreciation Rate

In the **Forest Management** phase, it is considered the **Raw Material Cost**, which is different, depending on the location. According to González-García et al., (2013), the typical price per kg of reproduction cork (which is the type of cork being considered in this case study) form Portuguese woodlands, is 2.07 €/kg. Due to lack of information and to improve SC diversity, the considered Raw Material Cost is considered to be 2.07€/kg in the Iberian regions, 1.035€/kg in North Africa and 1.553€/kg in South of France.

In the **Production Stages** (Preparation, Technical Cork Stopper Production and Cork Stopper Finishing stages) there are several types of costs. The **Human Resources** include parameters such as required number of workers and labor cost – the latter is based on the average income in the industry sector (Statista 2020). The **Operational Costs** include costs with electricity consumed – it is considered 0.1409€/kWh as the average electricity price in the Portuguese industry (PORDATA 2019); it is only considered the energy costs as they account for the major part of the operational costs. The technology **Installation Costs** are based on Cobalt-60 machines used for medical purposes, which have a price range between 1,275,672€ and 3,827,018€ so it will be considered 2,000,000€ (as shown in Table 18) the necessary price for installing the machine and meet all requirements (World Health Organization 2011). The **Stock Costs** were all estimated due to the company's confidentiality policy and were therefore considered to represent about 3% of its selling price.

Next, the model considers the **Distribution Stage**. The **Transportation Costs** include Variable costs for kg of product transported – both are based on the work of Mota et al., (2018) and are displayed in Table 19. The **Sea Hub Costs** include as well **(1)** Fixed costs from sea hub used and **(2)** Variable costs for kg of product transported there – both are based on the work of Mota et al., (2018) and are displayed in Table 20. The **Warehouse Costs** are related to the rent of their capacity and are depicted in Table 21 – the main source is Statista.com (Statista 2020).

Regarding the **Use** and **End-of-life** stages it is considered the **Selling Price** and **Recovery Costs** of the products. The first is based on company-specific information whereby 1 kg worth of technical cork stoppers has a selling price of 7.5€, which can incurred from Table 23 (the remaining products are estimates). The latter are arbitrary since there is no available information about them – their purpose is to increase SC diversity.

Table 23 - Selling prices (€/kg)

fp1	*fp2*	*fp3*	*rem*	Unit
4.0	7.5	7.5	4.0	€/kg

Aside from the SC stages, it is also considered the **Interest**, **Salvage**, **Depreciation** and **Tax Rate**. The first three are related to the only investment possible, which is to install the technologic alternative. Respectively, they consist on 10%, 0% and 12.5% and are based on the work of Mota et al., (2018). The latter represents the tax rate in the Portuguese environment, which is around 30% (Deloitte 2020).

5.4.2 Environmental Data

The environmental data is mostly based on company-specific information and the literature. As in the previous subsection, the environmental data will be presented in Table 24 with a SC perspective. Bear in mind that the functional unit of the information below consists of the production of 1,000 kg of customized *fp2* (*Twin*) using, in Stage 3.2, technology *gfp1*.

Table 24 - Environmental data per SC stage (except for transportation and warehousing)

1 – Forest Management	
Inflow	***Quantity***
Chainsaw Gasol. (GJ)	7.020E-4
Tractor Gasoline (GJ)	1.530E+0
Outflow	
Raw Cork (kg)	1.888E+3

2 – Preparation Stage	
Inflow	***Quantity***
Raw Cork (kg)	1.888E+3
Electricity (kWh)	9.686E+1
Natural Gas (m^3)	8.865E+1
Water (m^3)	9.010E+0
Outflow	
Treated Cork (kg)	1.632E+3
Sludge (kg)	4.589E+1
Wastewater (m^3)	8.730E+0

3.2 – Technical Cork Stopper Production	
Inflow	***Quantity***
Treated Cork (kg)	1.233E+3
Cork Disks (kg)	3.990E+2
Electricity (kWh)	1.311E+3/1.034E+3
Glue (kg)	1.488E+2
Disk Glue (kg)	1.190E+1
Latex (kg)	1.786E+1
Water (m^3)	2.914E+1/2.000E+0
Outflow	
Twin Stopper (kg)	1.000E+3
Cork Dust (kg)	6.187E+2
Cork Stick (kg)	1.316E+1
Sludge (kg)	1.060E+1/7.300E-1
Wastewater (m^3)	4.930E+0/3.400E-1

4 – Cork Stopper Finishing	
Inflow	***Quantity***
Twin Stopper (kg)	1.000E+3
Sulfur dioxide (kg)	9.500E-1
Paint (kg)	1.200E-1
Silicone Oil (kg)	2.860E+0
Paraffin (kg)	1.786E+1
Cardboard (kg)	1.000E+1
HDPE (kg)	7.500E-3
Electricity (kWh)	3.278E+2
Outflow	
Twin Stopper (kg)	1.000E+3

7 – End-of-life (Incineration)	
Inflow	***Quantity***
Used Cork (kg)	1.632E+3
Water (m^3)	8.400E-1
Urea (kg)	6.690E+0
Electricity (kWh)	2.730E+0
Diesel (GJ)	4.900E-4
Natural Gas (m^3)	2.317E-2
Outflow	
Electricity (kWh)	1.700E+3
Carbon Dioxide (kg)	3.135E+3
Methane (kg)	2.700E-1
Carbon Monoxide (kg)	6.000E-2
Nitrogen Oxides (kg)	1.140E+0
NMVOC (kg)	4.080E+0
Nitrogen Oxide (kg)	1.700E-1
Ammonia (kg)	7.800E-9
Sulfur Dioxide (kg)	2.000E-5
Sulfur Oxides (kg)	6.500E-6
Ashes (kg)	8.160E+1

7 – End-of-life (Landfill)	
Inflow	***Quantity***
Used Cork (kg)	1.632E+3
Electricity (kWh)	1.601E+1
Diesel (GJ)	5.001E-2
Outflow	
Carbon Dioxide (kg)	3.136E+1
Methane (kg)	1.137E+1
Carbon Monoxide (kg)	1.049E-4
Nitrogen Oxides (kg)	3.215E-1
NMVOC (kg)	1.281E-1
Nitrogen Oxide (kg)	1.322E-6
Ammonia (kg)	7.833E-6
Sulfur Dioxide (kg)	1.958E-5

Regarding the information presented in Table 24, this paragraph will brief the sources used to estimate such quantities. Looking to **Stage 1**, based on the work of González-García et al. (2013) it was estimated the cork stripped per tree, the time required to strip the work, which made possible to frame the quantities of fuel needed to perform this stage. Now regarding **Stage 2**, based on Demertzi et al. (2016), Rives, Fernandez-Rodriguez, Gabarrell, & Rieradevall (2012) and company-specific information (about energy expenditures) it was estimated the given quantities for the displayed materials. For **Stage 3.2** and **Stage 4** the main sources used are company-specific information (energy expenditures and BOM) and Rives, Fernandez-Rodriguez, Gabarrell, & Rieradevall (2012) which made possible to define the needed materials and respective quantities. Both of alternatives of **Stage 7** are based on the work of Demertzi, Dias, et al. (2015).

In **Stage 3.2** there are four "*Quantity*" entries which represent the differences between technologies *gfp1* and *gfp2*. The difference is only attached to those materials because both technologies are only distinct in the process of eliminating TCA (as described in subsection 5.3.3). The distinctions are based on the type of machine considered for technology *gfp2* (Cobalt-60) and company-specific information.

Transportation is another major factor to take into account when assessing a SC environmental impact. As mentioned in subsection 4.2.5, software SimaPro will be used to assess the unit environmental impacts of each transportation mode, technology, end-of-life options and for each product.

The tables with the unit environmental impact for each transportation mode, technology, end-of-life options and for each product are presented in Appendix B.1.

5.4.3 Social Data

Based on the **Social Impact Measurement** framework described in subsection 4.2.5, here the social characterization for the actual case study is presented. Such as the last two subsections, Table 25 depicts the social indicators within a SC perspective.

Table 25 - Social indicators from Table 15 considered in this case study

SC Stages		
Forest Management	**Production Stages**	**Distribution**
[7.1] Certificate FSC **[7.2]** Local Salary Ratio	**[1.1]** Employment Turnover **[3.1]** Accident Frequency Ratio **[3.2]** Occupational Disease Ratio **[3.3]** Absenteeism Ratio **[4.1]** Training hours **[5.1]** Salary Ratio Men vs Women **[5.3]** Ratio Men vs Women	**[1.1]** Employment Turnover **[3.1]** Accident Frequency Ratio **[3.2]** Occupational Disease Ratio **[3.3]** Absenteeism Ratio **[4.1]** Training hours **[5.1]** Salary Ratio Men vs Women **[5.3]** Ratio Men vs Women

The social indicators presented are those from Table 15. Some indicators from Table 25 are not included in Table 15 and in the case study, due to complete lack of information (ex. **[2.1]** Protection of Workers, **[2.2]** Monetary Compensation or **[6.1]** Value Created to the Community).

As described in subsection 4.2.5, the SIM framework main focus is to design the SC in a way that CA maximizes its positive social impact amid the environment that the company is doing its business. For example, if the social aspect of the model is being maximized and it has to choose between two locations to rent a warehouse, the SIM framework will compute where the company has the greatest potential to make a positive social impact. In this case, it would choose the location where the social standard is the lowest.

Regarding the sources to each of the social indicators, from the perspective of the company, the 2018 Sustainability Report was used (Corticeira Amorim, 2018b). From the perspective of each environment (location), several sources were used. Starting from **Category 1** (Employment), the main source is the website TradingEconomics.com (Trading Economics 2020). Next, the main sources of the three indicators of **Category 3** (Health and Safety in Work) were the European Commission (European Commission - eurostat 2020), World Health Organization (World Health Organization 2019), *Instituto de Saúde Pública da Universidade do Porto* (Monjardino, et al. 2016), Eurofound (European Foundation for the Improvement of Living and Working Conditions 2010) and INE (Instituto Nacional de Estatística 2017). For **Category 4** (Education and Training) the main sources used were Eurofound (European Foundation for the Improvement of Living and Working Conditions 2019) and Institute for the Study of Labor (Bassanini, et al. 2005). For **Category 5** (Diversity and Equal Opportunities) the mains sources used were the European Commissions (European Commission - eurostat 2018) and CiG (Comissão para a Cidadania e Igualdade de Género 2017). Lastly, **Category 7** main source was the FSC (Forest Stewardship Council 2020).

5.5 Conclusions of Chapter 5

This chapter presents the main data points that will feed the optimization model for the given case study. The necessary assumptions and simplifications and sources are also presented, with the view to provide a basis for the validation and contextualization of the model developed.

As mentioned, the information provided are organized in a SC perspective. Besides showing the wide range of data used in the model, this type of data framing is relevant to underline how holistic the developed model is. Due to the exhaustive activity that is data collection and validation, the information diversity present in the model may be difficult to replicate in other future work. To work around this issue, for instance, the SIM framework introduced in chapter 4, facilitated the data collection process due to its simplicity and not compromising the relevance of its use in the model.

The next chapter presents the results from the application of the proposed model to the working example, by presenting different scenarios, providing a general discussion and giving several recommendations based on them.

6 Results and Discussion

The chapter includes three main sections. In the **first section**, the set of cases/scenarios to be carried out are described. The **second section** presents the results obtained in each of the defined cases/scenarios. The **third section** provides recommendations and managerial insights.

6.1 Cases definition

Different cases and scenarios were created so as to address and answer the research questions previously defined.

- **Case A:** corresponds to the solution with the optimum economic performance obtained through the maximization of the NPV;
- **Case B:** corresponds to the solution with the optimum environmental performance obtained through the minimization of the Environmental Impact indicator;
- **Case C:** corresponds to the solution with the optimum social performance obtained through the maximization of a Social Impact indicator;
- **Sensitivity analysis on the demand** corresponds to a set of different model runs. The demand parameter is defined by a random distribution, while the economic performance of the SC is being maximized;
- **Specific Scenarios, given previous results:** the conclusions taken from Case A and B are further analyzed. The model parameters are directly manipulated, in order to understand how different, the model assumptions would have to be to result in contrasting conclusions. Five specific scenarios are analyzed, corresponding to different insights or opportunities for the SC decision-makers to explore.

Cases B and C are subject to a minimum NPV level so as to remove economically unviable solutions from the search space. The minimum NPV level is defined based on SC decision-makers criterion, which was set to equal one third of the maximum NPV, obtained through Case A. This is how far the decision-makers are willing to decrease the NPV level, with the view to perceive how the environmental and social aspects are able to improve.

6.2 Results

The main results analyzed for each of the presented cases include the performance on each TBL aspect, network design decisions, overall service level, energy consumed from biomass or waste and circular volume.

The selected points were highlighted by the company as the primary results to study within each case and scenario. In addition, these are aligned with the strategic/tactical (e.g., network design) and sustainability (e.g., TBL) scope of this work. Other important results, that are case or case-specific, will also be discussed in more depth.

6.2.1 Case A

The present subsection exhibits the main results of Case A. As previously mentioned, the economic objective is translated by the NPV of the SC of CA. The overall results are displayed in Table 26.

Table 26 - Overall results for Case A

NPV Value	Environmental Impact Value	Overall Service Level	Energy from Biomass	Infrastructure Used	Circular Volume
12,969,213€	211.880	100%	50.32%	Supplier Argel Seaport Gdansk Seaport New York	12.86% out of 72.76%

Regarding the obtained network design, no warehouse is selected, supported by the fact that the production capacity accommodates the demand, and the Equipar's expedition zone stock capacity accommodates the necessary stock levels. The selected seaports are the most economically viable (see Table 20 in subsection 5.3.4). The fact that the product service level is 100% determines that, with the current SC design, the final products are highly profitable, and it is advantageous to fulfill demand even in more remote locations, such as the Middle Eastern clients, as expected.

In this Case, the maximum quantity of final product that could be recovered is 72.76%. In other words, fulfilling all of the remanufactured products demand plus transforming recovered products into energy through incineration would require 72.76% of recovered products. In this Case, the recovered products are all transformed into remanufactured product and biomass energy is only generated from waste products originated from production stages (which makes up the 12.86%). These results indicate that recovering products to incinerate them at Equipar and generate energy, is not profitable. The economic gain from not using energy from the public network does not surpass the inherent cost of transporting the recovered products. This will be further analyzed on the *Specific Scenarios* (see subsection 6.2.5), by varying the price of public electricity.

On economic terms, recovering products to incinerate them at Equipar and create energy, is not profitable. The economic gain from not using energy from the public network does not surpass the inherent cost of transport the recovered products. This will be further studied on the *Specific Scenarios*, by varying the price of public electricity.

Figure 13 depicts each environmental indicator score, by maximizing the NPV. It is immediate that Terrestrial Ecotoxicity (TEco), Marine Ecotoxity (MEco) and Human Non-Cancerous (HNC) are the most relevant environmental impact midpoint categories, when comparing the rest, due to transportation.

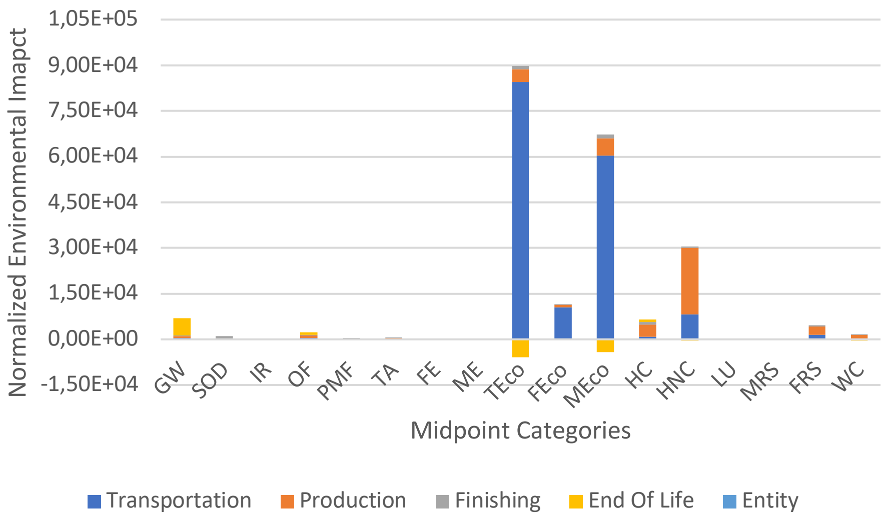

Figure 13 - Environmental impact per midpoint category and SC stage for Case A

Looking into Figure 13, transportation is the most impactful factor. This is mostly due to how wide the SC is (in terms of locations). As exposed in the previous chapter, there are clients located in three continents making for a need for transport between distanced SC entities. Here it is important to note that the model does not account for the necessary number of trips. The model focuses on optimizing the flows between SC entities regardless of how many transportation vessels are being used and with transportation impact being given by $kg * km$. So, transport utilization rates are not being accounted for, which would be interesting to approach in future work, since transportation impact is one of the major environmental factors (as exposed in Figure 13).

The production phase is also a very important factor, especially in the Human Non-Cancerous (HNC) environmental impact midpoint category. The impact is mainly due to cork stoppers using Glue (Polyurethane) as exposed in Table 24 (from subsection 5.4.2). The Glue is used to agglomerate the cork granules as well as the cork discs to the body of the corks (e.g., *Twin* has two cork discs). Here it is also important to notice that, as mentioned before, the LCI is estimated based on company-specific information as well as literature (which is not specific to the present case study). Consequently, there can be high degree of uncertainty related with these results, which should be analyzed in future work.

Regarding the social sustainability pillar, results are exposed in Figure 14.

In order to compare the various social indicators, a reference value was attributed to each indicator. The *reference* depends on the social parameters considered in this work and each social indicator has its own specific context (e.g., the *reference* for social indicator *Certificate FSC* is to choose suppliers that have the FSC certificate). The *reference* value can be defined in different ways, according to the goal and scope of the work, such as comparing the context of the cork industry and a broader context. In this case, all *reference* values were estimated in a broader context, due to data availability being scarce.

For future work to be the most inclusive and judicious, the data collection has to be based only on the cork industry and as exhaustive as possible. With this approach, it is possible to compute how far from the best or worst *reference* value a given social indicator score is. Taking the example of the *SalRatio* indicator, the best possible value for the salary ratio between men and women workers is equal to 1, a situation in which they are equal. So, in this case, being the salary ratio 1.176, the score is equal to 0.824 out of 1 [(1.176-1)/1=0.824]. Each social reference was duly analyzed taking into account the context and the elements present in this case of study.

From Figure 14 it can be perceived the high standards on the category Health and Safety **[H&S]**, Diversity and Equal Opportunities **[D&EO]** and Education and Training **[E&T]** (see Figure 14 and Table 14 from subsection 4.2.5). On the other hand, the category Social Evaluation of Suppliers **[S.Eval]** has the lowest score due to the only chosen supplier not having the FSC Certificate.

As mentioned, in this Case the infrastructure used either than suppliers and Equipar were Seaports Gdansk and New York. From Table 25 in subsection 5.4.3, the social results (expect for [S.Eval]) are driven by choosing warehouses, where CA can have its employees working. By not choosing any warehouses the social results are a direct comparison between CA and Portugal (where it operates). Despite this, there is room for improvement, because CA may rent warehousing space and spread its social benefits in others.

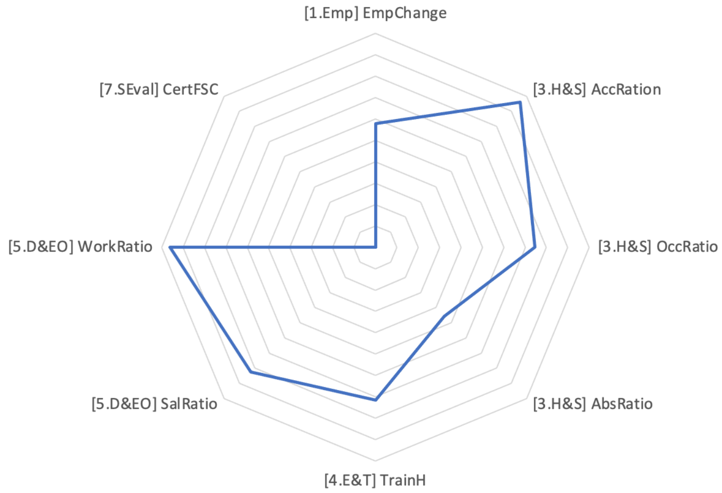

Figure 14 - Social Results for Case A

In addition, it is relevant to highlight the fact that the network only includes the one supplier that does not have the FSC certification and can practice lower prices for raw materials. By maximizing the NPV, the model optimizes the procurement to be performed at the cheapest supplier, because the trade-off *raw material price/transportation costs* is the most relevant factor that affects the NPV. This may raise the question: Does choosing a supplier that does not respect FSC standards bring any kind of added indirect cost? For instance, the market may prioritize cork products manufacturers that choose to be supplied by a vendor that respects the FSC standards, implying a loss of market share. In addition, the price of the final product is related to these decisions, that is, the product becomes more expensive (premium) if all suppliers are certified. This analysis can be included in future work.

These indirect costs or consequences are difficult to perceive as it is necessary to understand the clients' profile and how they react to these subjects. The market (or clients) is one of the stakeholders that the company considers as vital to its business. Thus, it is relevant to make decisions such as to procure non-compliant or more expensive raw materials.

6.2.2 Case B

The present subsection exhibits the main results obtained in Case B, where the objective is to minimize the environmental impact of the SC of CA, subject to a minimum NPV level defined by the decision-makers. In the present case study, the SC decision-makers accepted a maximum decrease on the economic objective until one third of its best performance, so 33% of 12,969,213€ which is 4,279,840€, so as to explore the potential other environmentally and socially driven solutions.

The overall results are displayed in Table 27, where it can be seen that the environmental impact decreased 70.94% and the economic value decreased 67.00%, when compared to Case A. The *Energy from Biomass* diminishes because, in this case, the production levels diminished as well, which implied fewer waste products. By analyzing Table 17 in subsection 5.4.1, the energy from incinerating 1 kg of waste products is greater than the energy needs for producing 1 kg of final product.

Table 27 - Overall results of Environmental Aspect: Environmental impact minimization

NPV Value	Environmental Impact Value	Overall Service Level	Energy from Biomass	Infrastructure Used	Circular Volume
4,279,840€	61,571	95%	45.73%	Supplier Fez Supplier Santarem Seaport Gdansk Seaport New York	0% out of 72.14%

Taking into account that transportation is the most impacting activity in case A, in case B the network reorganizes itself to minimize this impact, which results in:

- The chosen suppliers are closer to Equipar, located in Fez and Santarem. The raw materials are more expensive than those supplied from Argel. These options are the main factors for the decrease in the NPV value (raw materials prices are much higher) and the environmental impact, given that the covered distance to supply Equipar is far smaller than the NPV maximization (see Figure 15);
- No collection of end-of-life products, due to not being environmentally advantageous to recover products at the final clients and revalue or remanufacture them (because transportation impact is more relevant);
- Reducing the service level to the minimum possible in order to avoid transportation.

Despite the fact that the alternate technology has a lower impact than the current technology used, the model prioritizes to procure raw materials from more expensive suppliers, because the latter minimizes further the environmental impact. This conclusion is supported by Figure 15.

Figure 15 depicts the results obtained per environmental impact midpoint category. It is immediate that Terrestrial Ecotoxicity (TEco), Marine Ecotoxity (MEco), Human Non-Cancerous (HNC) and Human Cancerous (HC) are the most relevant indicators, due to transportation and the production stages. In addition, it can be perceived that the end-of-life stage has a relevant impact in the Global Warming (GW) indicator, given that both possible end-of-life options have relative greater characterization factors in this indicator. This may be relevant to the SC decision-makers study a less harmful option within the scope of Global Warming.

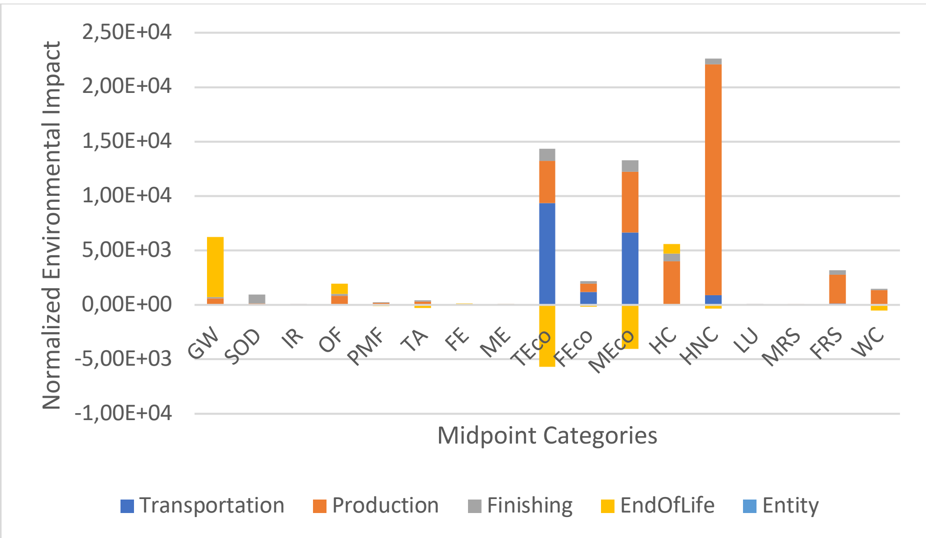

Figure 15 - Environmental impact per midpoint category and SC stage for Case B

By comparing the environmental results from Case A (Figure 14) and B (Figure 15), the decrease in the environmental impact is due to the decrease in production. Less production means less environmental from production stages and less transportation.

As mentioned in Case A, the way to influence the social results is by using warehouses. In this Case, no warehouse was opened. The single social indicator that changed was the Certificate FSC (related with the category Social Evaluation of Suppliers **[SEval.]**). Both chosen suppliers have the Certificate FSC, making this an improvement when comparing the current case with the previous one.

6.2.3 Case C

The present Case exhibits the main results obtained from maximizing the social objective. The social objective is translated by several social indicators of the SC of CA. As previously explained, the objective is to maximize the positive social impact of CA. For instance, bringing CA's business to a location where the social performance of a certain indicator is weak and the company can positively contribute towards a better work environment, such as giving more training hours for their employees in that location.

In the present Case, it was maximized the benefit from *Training Hours* to the employees. As seen in Figure 14, this indicator as *Absenteeism Ratio* have potential to improve even further. Furthermore, the scope of this Case is to maximize the benefit on one social indicator and realize what the decisions of the model are, taking into account only the NPV level.

The *Training Hours* indicator was the chosen indicator and Table 28 depicts the results obtained.

Table 28 - Overall results of Social Aspect

Objective	NPV Value	Environmental Impact Value	Overall Service Level	Energy from Biomass	Infrastructure Used	Circular Volume
Max Benefit Training Hr.	4,279,840€	637,663	98.36%	49.40%	See explanatory text below	0.66% out of 75.42%

The main outcome from the obtained results is that, as expected, the SC will be designed in a way to open every location possible where CA can impose a positive social impact. In this case, the infrastructure used were all eighteen available warehouses and suppliers in Fez and Argel (approximately 40% of raw materials are sourced from the supplier by Fez and 60% from Argel). In this case, the sole objective is to maximize the social performance, by respecting the imposed constraints, including the NPV minimum level of 4,279,840€. There is no trade-off of supply capacity (because there is enough capacity for either suppliers to solely supply Equipar), for instance. In this Case there are several optimal solutions given the imposed restrictions.

Figure 16 depicts the social performance of the other indicators rather than Training Hours.

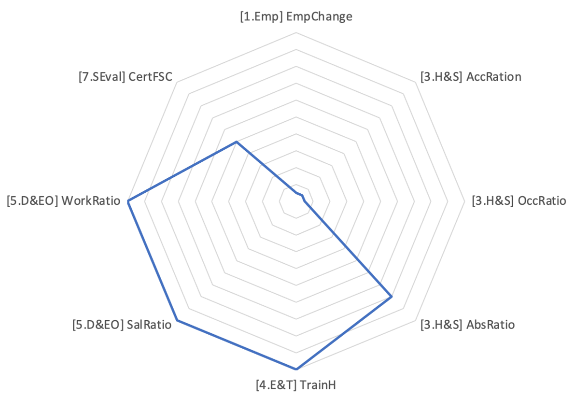

Figure 16 - Social Results for Case C

From Figure 16 immediate conclusions can be inferred: 1 out of the 2 suppliers chosen has the FSC certificate; by maximizing the benefit from *Training Hours* provided by CA, the social indicators *Salary Ratio* and *Work Ratio* are also maximized; the contrary happens with the remaining social indicators (except for *Absenteeism Ratio*).

This is due to a single fact: the indicators where social performance is close to maximum is because CA has better social parameters than the places where its business is located and vice versa.
Figure 17 depicts each environmental indicator score.

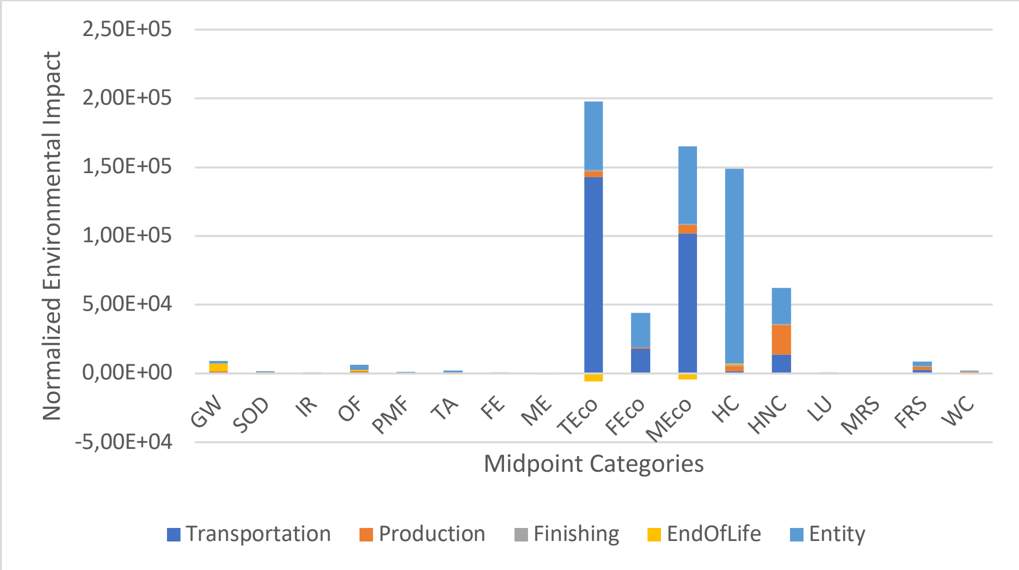

Figure 17 - Environmental impact per midpoint category and SC stage for Case C

Figure 17 indicates that entity impact has a much higher relevance. This is due to opening every possible warehouse location. The remaining environmental indicators show a similar performance as Case A, mainly due to choosing the same suppliers. By choosing the same supplier locations, the distances covered between suppliers and Equipar will be the same. Being transportation one of the major factors for the environmental performance, choosing the same suppliers in different scenarios will incur in similar environmental results.
These results are immediate to perceive, but the more diverse the SC, the more meaningful this approach gets. This statement will be further discussed in Chapter 7.

6.2.4 Sensitivity analysis on the demand

Due to data availability constraints, it was not possible to perform a formal stochastic analysis, as was the initial intention and as formulated in Chapter 4. The uncertainty on the demand was hence addressed using a different approach, which is described in this subsection.
For this analysis, it was used the *NPV maximization*. As seen in the Cases results, the service level is maximized when the NPV is being maximized. As one wants to study the uncertainty in demand, *NPV maximization* was the option taken.

Methodological Approach

The overall idea is to generate different scenarios that simulate demand volatility. Therefore, for each client and for each product, through a developed Excel engine, the average demand and respective standard deviation were calculated, based on 5 years of demand. Then, these two parameters fed the Excel function that generated a random demand parameter, based on a gaussian distribution for each client, through all considered time periods.
Equation 6.1 formulates how the demand is being generated. As shown, the generated demand of a given client *i* for a given product *m*, for a given time period *t*, is based on its demand behavior (demand and its volatility through the standard deviation) in a 5-year time span. The values for $AverageDem_{m,i,sc}$ and $StandardDev_{m,i,sc}$

are displayed in Appendix B.3.2. The parameter $Z_{m,i,t}$ is the *standard score* of the normal distribution (e.g., Z=3 means that the value is its average plus three standard deviations).

$$GeneratedDem_{m,i,t,sc} = AverageDem_{m,i,sc} + Z_{m,i,t} * StandardDev_{m,i,sc}, \forall i \in I_c, m \in M_{fp}, t \in T, sc \in SC \quad 6.1$$

After some experimentation, the total and average demand stay practically the same as for the deterministic model. As described in the **Timeline Dashboard** (see subsection 5.3.5), the average and total demand can be manipulated directly.

Obtained Results

Table 29 aggregates the results based on forty iterations of the demand, in order to understand how these results can change within each random generation of the demand. Regarding the number of iterations needed for this approach to be acceptable, it was performed 40 iterations. According to Elliott & Woodward (2007), in order to invoke the **Central Limit Theorem** (CLT) the sample size must be at least 40. This number is considered to be sufficiently "large" that safeguards the significance of statistical tests. Therefore, for the purpose of the present work 40 iterations were performed

Table 29 only shows the maximum, minimum and average values. Given different random generations of demand, this serves to understand what the main results volatility are and to understand if the SC is robust to random changes in demand given the demand behavior history.

Table 29 - Overall results of the NPV maximization case in which the demand is defined by a random distribution

Level	NPV Value	Environmental Impact Value	Overall Service Level	Energy from Biomass	Circular Volume	SC Robustness
Maximum	14,206,066€	238,963	100%	51.54%	14,38% out of 74,83%	39 out of 40
Average	12,223,403€	211,487	100%	49.63%	12.92% out of 72.30%	
Minimum	9,604,224€	192,635	100%	42.62%	11.70% out of 66.11%	

The results from Table 29 expose one of the major aspects of the present case study, which is the concentration of the major part of the demand (97.775%) on the two Iberian clients (Lisbon and Madrid). The demand behavior of these two clients will have a major impact in these results. The higher their demand standard deviation the bigger the gap between maximum and minimum levels will be.

From Table 29, it must be highlighted the fact that 39 out of 40 iterations there was a feasible solution for the problem, meaning that the SC of CA is robust to the incurred variation. Through experimentation it was concluded that the problem becomes infeasible when there is 3~4 time periods with 25%~30% of the demand higher than the installed production capacity, which is a seldom event to occur.

To conclude this subsection, the other parameters tend to be proportional to the NPV level variation. Additionally, the same conclusions from Case A can be taken: it is not economically viable revalue through incineration used products; transportation is the biggest factor in terms of environmental impact; high standards on service level.

6.2.5 Specific Scenarios and their discussion

In the present subsection, several scenarios are studied so as to explore potential opportunities within the presented case-study and obtain additional insights.

The developed scenario assumptions are summarized as follows:

- **Scenario 1:** where a sensitivity analysis on the parameter that represents the **price of public electricity** is performed, so to understand what different public electricity prices would imply in this SC, particularly in terms of making end-of-life product recovery economically advantageous;
- **Scenario 2:** where a sensitivity analysis on the parameter that represents the **energy recovered from incineration** is performed, so as to determine how much the energetic yield of this process would have to be increased for it to be environmentally beneficial to recover end-of-life products;
- **Scenario 3:** where a scenario of **market growth** is explored, to understand how the SC network would evolve if the market was to grow at a given rate;
- **Scenario 4:** where a scenario of **economic viability for the alternative production technology** is explored, which would be environmentally beneficial;
- **Scenario 5:** where a scenario of **crisis** is imposed so as to understand how the SC would adjust when facing extremely low levels of **demand**.

The obtained results and conclusions are summarized below.

Scenario 1 (NPV Maximization)

The current average price of public electricity is 0.1409€/kWh (PORDATA 2019). Through the performed analysis it was concluded that if it costed 0.20€/kWh (+42%), the energy recovered from biomass would be 88.27%, being the recovered products from the Iberian clients. This means that the trade-off between energy from biomass/transportation costs, now favors incineration for the used products recovered from Iberian clients. If it costed 0.30€/kWh (+113%) the energy from biomass would be 88.92%, being the recovered products from the Iberian and central Europe clients. The difference of 0.1€/kWh increased the radius of recovery viability from the Iberian region to Central Europe. Insight: For IUs located in energy costly countries, product recovery will be a more viable option.

Scenario 2 (Environmental Impact Minimization)

The current energy that can be recovered from incineration is 1.04166 kWh/kg. Through the performed analysis it was concluded that if it were 1.24166 kWh/kg (+20%) or even 1.54166 kWh/kg (+50%) the same result from Case A is obtained. Insight: Even if the energy gain from incineration increased 50%, it would still not be environmentally advantageous to recover products. The transportation impact of the reverse flows is bigger than the incineration or recycling gains.

Scenario 3 (NPV Maximization)

In this scenario the goal is to understand how the SC of CA would adapt in the prospect of market growth, so as to maintain its service level standards. Through the performed analysis it was concluded that if the market were to grow on a 1.50% basis per trimester for five years, the production capacity would be enough to meet the 100% service level standard. The difference from the solution obtained in Case A, is that there is a need for renting additional warehousing space. The chosen option is to rent 962m^2 of the Sofia's warehouse in the last 2 years considered in the case study, which is when the demand reaches levels 1.2 times superior to the regular demand. Insight: In a possible increase of demand the limiting factor is not the production but the storage space.

Scenario 4 (Environmental Impact Minimization)

The estimated installation cost for the alternative production technology is 2,000,000€. Through the performed analysis it was concluded that if the technology installation cost was around 750,000€ then it would be worth to install this alternative. It would be needed a 62.5% decrease, which is unlikely to happen in a predictable future. Bear in mind that this value is the breakeven point from which the model prefers to invest in the new technology while considering the minimum NPV level of 4,279,840€. To be within the required NPV level, the model (compared to Case B) chooses to lower transportation costs (by choosing more terrestrial transportation) in order to install the alternative technology. Opportunity: If CA is intending to install a new IU similar to Equipar, it should study this alternative technology and analyze the different technology installation costs.

Scenario 5 (NPV Maximization)

In this scenario the goal was to analyze how the SC of CA could react in the face of an economic crisis provoked by an unexpected event like the Covid-19 pandemic. During this pandemic period, CA stock prices suffered a 35% fall (Euronext 2020). Assuming that the demand accompanied this trend, and assuming a steady recover of 4% per trimester, the demand would be (compared to what was previously estimated), as shown in Table 30. For instance, in time period 13 (the first quarter of year 4), the demand is just 73.1% of what was initially predicted.

Table 30 - The impact of the pandemic in the demand of CA

Year	Year 3			Year 4				Year 5			
Time Period (Quarter)	10	11	12	13	14	15	16	17	18	19	20
% of expected demand	65%	67.6%	70.3%	73.1%	76%	79.1%	82.3%	85.5%	90%	92.5%	96.2%

With this demand pattern the estimated NPV decreases to 11,497,227.3€ (-11.35%), while comparing to Case A. For a 11.30% decrease of total demand there is a 11.35% decrease of the NPV, meaning that there is almost a direct relationship between NPV and demand. Regarding, the SC follows the same type decisions already studied in Case A (e.g., same network design; same chosen technology; similar circular volume).

6.3 General Discussion and Recommendations

Having studied the three objectives and the results through experimentation in the specific scenarios, in the current subsection the main results are explained.

The main results and conclusions are highlighted as follow:

1. **Product recovery is not economically and environmentally advantageous**

With Case A, it was possible to conclude that product recovery is not economically advantageous since the transportation costs are too expensive. The same is true in Case B, where the impact of transportation is much more significant than that of remanufacturing or incineration. Recommendations: **(1)** Study, at an operational level, the routing options of the SC, which optimize the transportation costs and impact; **(2)** Study the possibility of using multiple modes of transportation, which can potentiate the trade-offs between service level/transportation costs and service level/transportation impact; **(3)** Study, for each market cluster (i.e., Western Europe or Northern Europe), what are the optimal locations to install product recovery facilities, since cork products are highly recyclable, which will diminish transportation needs and bring the company closer to its customers.

2. **The final products are highly profitable**

When maximizing the economic aspect, service level is at its maximum, meaning that with the current cost structure, it is advantageous to sell CA's products even in more remote locations. Recommendations: List, at an operational level, the cost structure to confirm this fact. If this conclusion stands, CA can either: **(1)** expand their product portfolio and sell different products for their current clients (given the fact that these products have a cost structure similar to the current final products) and fill a possible market gap; **(2)** or look for new clients in the market clusters that the company is already established (supported by the fact that production capacity is not at its maximum, with the current demand).

3. The supply chain of CA is robust

If the demand of CA is defined by a random distribution, given the demand pattern of its clients, CA meet their current high service level standards. Recommendation: Apply this methodology if the demand is not so concentrated in one market cluster, which is the case of the present case study. If the demand is more distributed, the decisions around production, inventory and, for instance, warehouses or seaports used, will not be as expected as the present case study, due to the greater possibility of demand concentration changing from iteration to iteration.

4. Poor social assessment, due to poor representativity

The SIM framework showed poor result diversity, due to poor representativity. The only source of distinct social results came from the usage of warehouses, which focused the results on an expected direction. In addition, the model has only one industrial unit (Equipar), taking away decision diversity regarding the production stages; transportation is all outsourced, taking away decision diversity regarding the transportation stage. Lastly, the fact that the demand is not high enough to promote the opening of warehouses in different locations, restricts even further the social results because no warehouse will be opened, hence altering the social performance. Recommendations: **(1)** Apply the methodology, but with an approach that permit to normalize the result, such as social performance given the number of workers involved, like Mota et al. (2018) did (i.e, the social performance depending in the number of employees and not only in the locations they are working in); **(2)** Use the same social indicators, but with regard to the cork industry and not the country where the SC entities are located in, so that it can be compared directly with CA.

5. Network design: focuses on two seaports and no warehouses

The network design focuses on using the Seaports of New York and Gdansk for a simple reason: fixed and variable costs are, in general, lower. As already briefed, the warehouses are not used due to installed production capacity being high enough, avoiding the renting warehouse space. Recommendation: If SC decision-makers want to study what are the best warehouses options, they can use the **Timeline Dashboard** that modules the amount of demand for a given time period.

6. Comparing obtained results to the data of subsection 2.3

There are many approaches from which it is possible to compare obtained results with the data of subsection 2.3. The main source of difference between them is that the data is referent to CA as a whole, not just Equipar. Looking to both data and results it is not possible to compare energy intensity because in the model it is not specified the distinct energy sources used throughout production stages; the same goes for carbon intensity. If the present work were to be at an operational level these two indicators would be more relevant for comparison reasons. One interesting result is that the model defines that biomass is responsible for approximately 50% of Equipar's electricity source, while the data states that is 65%. There is either SC synergies that the developed model is not taking into consideration or this specific IU is not able to reach such high standard. Further development needed to be performed (such as point 6 of chapter 7).

7 Conclusions and Future Work

Firstly, it will be summarized how this work answers the research questions presented in chapter 1:

- **RQ1**: The present work tackles the three aspects of the TBL as described in chapter 4 (defining the problem in the context of each pillar) and 5 (definition of the data used in the model, in the context of each pillar);
- **RQ2**: This work gathers the main economic parameters specific to the SC of CA (e.g., raw material price, transportation costs). Consequently, the decisions that will result from the optimization model have a basis on the economic background of the cork-type SCs;
- **RQ3**: This work accounts the environmental impact of all SC stages as seen in Figure 5 in section 2.4. In order to do that, the model includes environmental parameters that are based in company-specific information and on the literature. Consequently, the SC decisions will take into account several factors related to all of the SC;
- **RQ4**: This work accounts the social benefit that CA may bring to the locations where the company operates. An alternative methodology to the SLCA was implemented, the SIM framework aims to simplify the approach so that decision-makers can easily judge which set of SC decisions are best. The data is highly decentralized and scarce, and its collection is an exhaustive process;
- **RQ5**: The scope of this work includes a holistic approach to the SC. Throughout chapters 4 and 5 it is indicated that the indicators used measure different parameters and cover the integrability of the SC (see Table 22, Table 24 and Table 25 of section 5.4). The parameters used, maximize the representativity for each SC stage, so that the SC decisions take into account the whole process between cork harvest and final product recovery;
- **RQ6**: Throughout chapter 6 the results are evaluated while taking into account what are the implicit trade-offs in each decision taken. Specifically, the main trade-off in this work is transportation costs/environmental results and there is no meaningful trade-off for the social results due to non-existent inventory levels. Transportation costs and impact were identified as the most critical.

Looking to a SC in the most holistic way as possible is no simple task, even more for a SC related to cork. There are **(1)** a wide variety of products and several types of (re)manufacturing processes possible to undertake (for instance, differing in the environmental data shown in Table 24); **(2)** different types of raw materials such as cork disks, white and black cork [depending if the SC includes the preparation stage or not (Rives et al., 2011)] and other cork waste that could be considered as raw materials; **(3)** different manufacture technologies, but with minimal validation in real-life; **(4)** warehouse management differs from product to product so it is also difficult to centralize the necessary warehousing space and the number of workers needed. So, several assumptions were made to simplify the SC, which can cause the results from the model to have a high degree of (non-measurable) uncertainty, while comparing against real-life. To minimize this uncertainty, during parameter estimation, exhaustive work was carried out regarding the respect for orders of magnitude of the data.

Despite this uncertainty, the main purpose of this work is to model the entire SC in a strategic/tactical approach, which was done. By respecting the orders of magnitude, by using parameters transversal to the three aspects of the TBL, the fact that the estimated information is based on the company and on the literature related to cork, it can be affirmed that the final results will have a high degree of coherence and supported in the reality of the industry.

With a holistic approach, this dissertation has come to occupy a research gap in the literature. The model parameters are estimated based on the literature and rough approximations from SC decision-makers, but this dissertation is the groundwork to understand what the real impacts of the cork industry are, by approaching in the most holistic way as possible.

The major conclusions and subjects to bear in mind in future work will be displayed as in previous subsections 6.2.5 and 6.3. For each conclusion, a remark will be given to be taken into consideration in future work.

1. **Transportation: operationalize to assess in detail conclusions taken**

In the present work, transportation flows are optimized between SC entities. It is not accounted utilization rates or minimum capacities for transportation, which in reality are relevant. This was done because, in reality, the transport is done by third-party logistic companies. Although this is an acceptable approach, the objective of this work is also to focus on Equipar/Amorim's position and realize what the implications of transporting their products would be if the company were to detain them.

The fact that CA transportation is all outsourced and the present work focuses on a strategic/tactical point-of-view of the SC, it should be implemented minimum transportation capacities to approximate the current model to reality. For that, the model needs to compute the necessary number of trips, so that it could be defined a minimum transportation capacity per trip made. With this approach, there will be chosen options such as cross-docking that will optimize utilization rates and close the gap between the model and reality (during the development of this dissertation, this approach was actually implemented, but due the wide SC and complexity, the computational effort was too great for the timeframe available to develop the present work).

In addition to minimum transportation capacities, adding the plane transportation mode (and respective airports) and multiple options within each mode (i.e., large, medium and smaller truck) would diversify the transportation decisions in the model, which is relevant due to the complex SC that is being studied. For instance, this may originate more detailed conclusions regarding product recovery, because trucks transporting recovered products to remanufacture them at Equipar, could also transport those to produce energy from biomass.

Finally, it should be included exportation/importation fees or other transportation related costs to be as detailed as possible.

2. **Use specific locations for specific clients and not market clusters**

In the present work, the client locations represent market clusters. CA could not give more specific information due to confidential terms.

Product recovery may be being too penalized by the fact that market clusters are located too far from Equipar. For instance, 93% of the demand is Portuguese and maybe those clients are located much closer to Equipar than Lisbon itself, so product recovery would have a higher chance of being economically and environmentally advantageous. By implementing what was discussed in the previous point and specifying client locations can evade the strategic/tactical scope into a more operational approach of the problem, but, in this case, in terms of transportation would interesting to understand if it could be more optimized, since it is one of the major costs and environmental factors (as seen throughout this chapter).

3. **Include extra End-of-Life alternatives**

The current End-of-Life options were directly taken from the literature and there might be alternatives that could optimize the environmental impact in this stage. In addition, there is a major source of uncertainty because products that were not recovered at market clusters were considered to be sent to landfill. For instance, using public energy in different countries has distinct impacts (given their different energy sources, like percentage of energy from oil or coal versus solar or wind), and the same can be considered to landfill. If the environmental impact of choosing landfill in each location is studied, one might come to the conclusion that, in some locations, it is more advantageous to recover and perform incineration than send used products to a landfill site. To conclude, by diversifying the available end-of-life options, it could firmly confirm if product recovery is viable or not. In addition, it could be also considered third parties that could recover those products and are located strategically near the market clusters to which CA sells.

4. **Environmental data uncertainty**

The environmental data is mostly based on the literature and company-specific information (rough estimations of product composition).

As stated, the present work is the first of its kind in the literature. The existent research is environmental assessments of natural or technical cork stoppers. But even so, there are several possible combinations of the production stage data showed in Table 24. Therefore, the data from subsection 5.4.2 may have a high degree of uncertainty. The major remark for future work is that, to keep environmental results as unbiased and holistic as possible, the system (SC of CA) boundary has to be as inclusive as possible, in order to attain for all the stages between cork stripping into final product disposal or revaluation. Also, it is possible to confirm that, at least the order of magnitude of the data displayed in Table 24 are aligned with reality, so one can perceive the uncertainty, at least, not as extreme as one could think. For future work one has to use hard and specific data directly from the factory, the raw material collection site and the specific end-of-life options within each location (as described in the previous point).

5. **Use social data related with the cork industry, given different locations**

The social data is related with the countries where the SC entity is located (except for Equipar). This means that the data is not specific to the cork industry.

As stated in point 4 in subsection 6.3, the social data should all be related with the scope of the cork industry, so that different locations can be compared (because the basis of comparison is the same). As exhaustively as it is, with the view to be as correct as one could be, the data should be related with the cork industry of a given location. In addition, in order to diversify and give depth to the results, the social data should be normalized taking into account the number of workers involved in the SC stages, number of hours worked or something that measures the amount of human resources involved. The next point would further diversify the social assessment of the SC of CA.

6. **Populate the model with other IUs of CA**

In the present work, only Equipar is considered as the sole industrial unit.

As said throughout this work, other BUs of CA can use recycled cork (as granulates) into their production stages as raw material. If, for instance, the model includes other IUs and their respective final products, the SC decision-makers would have a greater overview of the SC and possible synergies that could happen between IUs. To do this, it would be necessary to locate where are other IUs and map their need for recycled cork, which would be used to produce final products in parallel production stages. By accounting this IU in the boundary of the analyzed system, SC decision-makers would gain an improved view of economic, environmental and social aspects of CA as a whole and not only a narrow point-of-view, such as Equipar's.

Having resumed the main conclusions and recommendations for future work, the main contributions of this work are (1) a proposed model for SC network design and planning in the context of the cork industry; (2) the model proposed as a tool for testing different scenarios and study the impact of parameters; (3) the introduction in the literature of the first environmental assessment that included all stages of the Technical Cork Stopper SC; (4) the introduction of the SIM framework, which tries to simplify and give a generalized approach to how the social aspect of the SC could be measured.

In conclusion, given the limited scope and limited space for this research, several assumptions and simplifications are required to overcome the problems of extreme lack of data and uncertainty in the estimation of parameters. Despite that, the main idea was to create the groundwork for future cork SC modelling, which, throughout the years, has been gaining an increase importance due to cork having unique properties that are useful in several situations and contexts. As studied, something being environmentally advantageous is not an obvious conclusion, since many factors have to be taken into consideration (e.g., recycling or incineration). And if anyone aspire, in the future, to create or develop a new or alternate product, it needs to do so at the light of the TBL, so that it can perceive its viability regarding the three distinct aspects of sustainability.

7.1 Acknowledgements

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A Appendix A – Environmental Equations

$$TranspImp_{a,b,sc} = \sum_{m,i,j,t} \left(pTranspImp_{a,b} * dst_{i,j} * X_{m,a,i,j,t,sc}\right) ,\forall a \in A, b \in B, sc \in SC \tag{A.1}$$

Equation A.1 – Transportation Impact

$$ProdImp_{m,g,b,sc} = \sum_{i,t} \left(pProdImp_{m,g,b} * P_{m,g,i,t,sc} * R_{m,g,i,t,sc}\right) ,\forall m \in M_{fp}, a \in A, b \in B, sc \in SC \tag{A.2}$$

Equation A.2 – Production Impact

$$FiniImp_{m,b,sc} = \sum_{i,t,g} \left(pFiniImp_{m,b} * P_{m,g,i,t,sc}\right) ,\forall m \in M_{fp}, b \in B, sc \in SC \tag{A.3}$$

Equation A.3 – Production Impact

$$\begin{aligned} EOLifeImp_{u,b,sc} = {} & \left(\sum_{i,t,m} \left(B_{m,i,t,sc} + W_{m,i,t,sc}\right)\right) * pEOLifeImp_{u,b} + \left(\sum_{t \in T_{last}} \sum_{m \in M_{rp}} \sum_{i} \left(S_{m,i,t,sc}\right)\right) * pEOLifeImp_{u,b} \\ & + \left(\sum_{\substack{(j,i) \in F_{IN_{c,fp}} \\ a \in F_{NET}}} X_{m,a,j,i,t,sc} - \sum_{\substack{(j,i) \in F_{OUT_{c,rp}} \\ a \in F_{NET}}} X_{m,a,i,j,t,sc}\right) * pEOLifeImp_{u,b} ,\forall u \in U, b \in B, sc \in SC \end{aligned} \tag{A.4}$$

Equation A.4 – Production Impact. 1st parcel represents the incineration of waste and recovered products; 2nd parcel represents the stock at the final period that is sent to a landfill; 3rd represents those products that are not recovered and are sent to a landfill

$$EntityImp_{b,sc} = \sum_{i} \left(pEntityImp_{b} * YK_{i} * {}^{20}/_{15}\right) ,\forall\, b \in B, sc \in SC \tag{A.5}$$

Equation A.5 – Entity Impact. The factor 20/15 is introduced because the warehouse space is rented over a 20-trimester period.

B Appendix B – Case Study

B.1 Environmental Data

Table B-1 - Environmental characterization and normalization factors

Environmental Indicators	Entity[1] (per sqm)	Production Stage (per kg)						Finishing Stage[2] (per kg)	
		Twin – *gfp1*	Twin – *gfp2*	Aglo – *gfp1*	Aglo – *gfp2*	RN	oCork	Twin	Aglo
Global Warming	4,24E+02	4,12E-01	4,04E-01	3,90E-01	3,83E-01	3,31E-02	9,89E-03	7,52E-02	7,00E-02
Stratospheric Ozone Depletion	1,07E-04	5,51E-07	5,37E-07	5,21E-07	5,07E-07	3,66E-08	1,81E-08	4,85E-06	4,84E-06
Ionizing Radiation	5,00E-01	2,74E-03	2,71E-03	2,57E-03	2,53E-03	1,58E-04	4,55E-05	-3,26E-05	-5,66E-05
Ozone Formation	2,54E+00	1,50E-03	1,47E-03	1,44E-03	1,40E-03	1,40E-04	4,74E-05	4,15E-04	3,91E-04
Fine Particulate Matter Formation	7,69E-01	3,56E-04	3,28E-04	3,52E-04	3,24E-04	5,93E-05	3,72E-05	1,86E-04	1,66E-04
Terrestrial Acidification	2,26E+00	1,13E-03	1,04E-03	1,12E-03	1,03E-03	1,86E-04	1,23E-04	4,30E-04	3,65E-04
Freshwater Eutrophication	1,02E-02	2,50E-06	2,49E-06	2,33E-06	2,32E-06	9,97E-08	7,91E-09	2,89E-06	2,88E-06
Marine Eutrophication	2,31E-03	9,42E-06	8,78E-06	8,83E-06	8,19E-06	2,22E-07	5,29E-09	-1,34E-07	-1,34E-07
Terrestrial Ecotoxicity	1,69E+03	3,56E-01	3,04E-01	3,66E-01	3,14E-01	9,49E-02	6,88E-02	1,27E-01	9,06E-02
Freshwater Ecotoxicity	1,01E+00	8,82E-05	8,08E-05	8,59E-05	7,85E-05	1,18E-05	4,46E-06	2,82E-05	2,58E-05
Marine Ecotoxicity	1,91E+00	5,30E-04	4,85E-04	5,20E-04	4,76E-04	7,80E-05	5,12E-05	1,18E-04	9,07E-05
Human Carcinogenic Toxicity	1,29E+01	1,01E-03	8,43E-04	9,82E-04	8,14E-04	9,45E-05	3,10E-05	1,94E-04	1,79E-04
Human Non-Carcinogenic Toxicity	1,29E+02	3,07E-01	3,06E-01	2,85E-01	2,84E-01	2,97E-03	7,09E-04	7,28E-03	6,93E-03
Land Use	5,85E+00	2,11E-02	2,09E-02	1,96E-02	1,94E-02	1,91E-04	2,82E-05	4,28E-03	4,27E-03
Mineral Resource Scarcity	4,20E+01	5,96E-04	5,96E-04	5,53E-04	5,52E-04	1,38E-06	1,39E-07	3,95E-06	3,88E-06
Fossil Resource Scarcity	9,56E+01	2,38E-01	2,37E-01	2,27E-01	2,26E-01	5,73E-02	2,10E-03	3,71E-02	3,88E-02
Water Consumption	2,48E+00	3,26E-02	1,47E-02	3,28E-02	1,49E-02	7,69E-03	1,71E-03	3,04E-03	2,20E-03

Notes:

- **Entity[1]** – Simapro® *Building, hall, steel construction, RoW*;
- **Finishing Stage[2]** – Finishing stage impact with customization.

(Continuation) Table B-1 - Environmental characterization and normalization factors

Environmental Indicators	Finishing Stage[3] (per kg)				End-of-Life Stage (per kg)		Transportation (per kg*km)		Normalization Factor
	Twin	Aglo	RN	oCork	Incineration	Landfill	Truck[4]	Boat[5]	
Global Warming	7,50E-02	6,98E-02	4,60E-03	4,60E-03	1,89E+00	2,61E-01	1,34E-04	8,73E-06	1,25E-04
Stratospheric Ozone Depletion	4,85E-06	4,84E-06	8,40E-09	8,40E-09	-7,91E-08	1,74E-09	1,02E-10	6,34E-12	1,67E+01
Ionizing Radiation	-3,71E-05	-6,11E-05	2,12E-05	2,12E-05	-2,25E-04	3,61E-05	9,61E-07	5,67E-08	2,08E-03
Ozone Formation	4,15E-04	3,90E-04	2,21E-05	2,21E-05	8,68E-04	3,98E-05	2,49E-07	3,87E-07	4,86E-02
Fine Particulate Matter Formation	1,86E-04	1,66E-04	1,73E-05	1,73E-05	-1,64E-04	2,00E-05	8,09E-08	6,10E-08	3,91E-02
Terrestrial Acidification	4,29E-04	3,64E-04	5,72E-05	5,72E-05	-5,31E-04	1,32E-05	1,56E-07	1,91E-07	2,44E-02
Freshwater Eutrophication	2,89E-06	2,88E-06	3,66E-09	3,66E-09	-4,37E-08	5,50E-07	1,63E-10	1,01E-11	1,54E+00
Marine Eutrophication	-1,34E-07	-1,34E-07	3,50E-10	3,50E-10	2,31E-07	7,26E-09	4,22E-11	9,19E-13	2,17E-01
Terrestrial Ecotoxicity	1,27E-01	9,05E-02	3,20E-02	3,20E-02	-2,87E-01	1,15E-03	2,82E-03	1,93E-05	9,65E-04
Freshwater Ecotoxicity	2,80E-05	2,56E-05	2,06E-06	2,06E-06	-1,02E-05	4,02E-07	4,19E-07	2,45E-09	8,15E-01
Marine Ecotoxicity	1,17E-04	9,04E-05	2,38E-05	2,38E-05	-2,04E-04	1,09E-06	2,00E-06	1,43E-08	9,69E-01
Human Carcinogenic Toxicity	1,94E-04	1,79E-04	1,40E-05	1,40E-05	1,17E-04	1,16E-06	7,44E-08	2,98E-08	3,61E-01
Human Non-Carcinogenic Toxicity	7,28E-03	6,92E-03	3,13E-04	3,13E-04	-2,44E-03	8,31E-05	3,95E-05	3,14E-07	6,71E-03
Land Use	4,28E-03	4,27E-03	1,27E-05	1,27E-05	-3,41E-04	8,45E-05	3,43E-07	2,99E-08	1,62E-04
Mineral Resource Scarcity	3,95E-06	3,87E-06	6,38E-08	6,38E-08	3,57E-06	6,38E-07	1,02E-08	1,19E-10	8,33E-06
Fossil Resource Scarcity	3,69E-02	3,58E-02	9,77E-04	9,77E-04	-3,71E-03	1,71E-03	4,42E-05	2,62E-06	1,02E-03
Water Consumption	3,04E-03	2,20E-03	7,41E-04	7,41E-04	-6,37E-03	1,83E-05	1,42E-08	1,16E-09	3,75E-03

Notes:

- **Finishing Stage[3]** – Finishing stage impact without customization;
- **Truck[4]** – Simapro® *Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U*;
- **Boat[5]** – Simapro® *Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Conseq, U*.

B.2 Social Data

Table B-2 - Social indicators values for each supply chain entity

Supply Chain Entities	Social Indicators (Industrial Unit & Warehouses)							Supply Chain Entities	Social Indicator (Supplier)
	Employment Change	Accident Ratio	Occupational Diseases	Absenteeism Ratio	Training Hours	Salary Ratio	Women & Men Ratio		Certificate FSC
Equipar	-0,01	14,61	0,0304	3,70	16,93	0,97	0,88	*sGirona*	1
wLinz	-0,20	7,20	0,0020	3,80	5,60	0,80	0,80	*sGuarda*	1
wBerlin	-0,10	8,09	0,0024	3,80	4,25	0,79	0,83	*sSevilha*	1
wSofia	-0,40	0,28	0,0008	4,20	1,28	0,86	0,79	*sFez*	1
wBarcelona	0,14	9,68	0,0055	3,90	5,94	0,86	0,82	*sArgel*	0
wParis	0,30	8,12	0,0085	3,80	15,04	0,85	0,85	*sMarselha*	1
wBudapest	-0,10	2,22	0,0003	3,20	1,65	0,86	0,74	*sTunis*	1
wChisinau	0,20	7,44	0,0006	3,80	1,00	0,87	0,88	*sSantarem*	1
wMoscow	-0,10	3,42	0,0000	3,90	1,00	0,74	0,78		
wZurique	-0,10	7,44	0,0030	3,80	7,00	0,83	0,85		
wKiev	0,10	6,31	0,0016	3,30	3,00	0,79	0,74		
wMinsk	0,10	9,30	0,0001	4,50	1,00	0,75	0,81		
wWashington	-0,10	4,90	0,0007	2,80	7,74	0,81	0,82		
wAlbany	-0,10	4,90	0,0007	2,80	7,74	0,81	0,82		
wVilnius	-0,20	1,19	0,0037	3,20	1,00	0,86	0,84		
wMexicoCity	0,20	3,78	0,0342	10,00	1,50	0,72	0,56		
wLima	-0,20	7,90	0,0339	11,00	1,00	0,71	0,83		
wWarsaw	-0,30	1,83	0,0030	5,40	1,28	0,93	0,74		
wBucharest	0,30	0,43	0,0010	1,80	0,75	0,95	0,70		

Notes: See Chapter XXX for the considered units of the social indicators.

B.3 Demand Data

B.3.1 Demand – Deterministic Model

Table B-3 - Product share of the demand between the considered years

Year	Product	Product Share
1	*RN*	15,00%
	Twin	40,46%
	Aglo	44,54%
2	*RN*	15,00%
	Twin	33,86%
	Aglo	51,14%
3	*RN*	15,00%
	Twin	42,50%
	Aglo	42,50%
4	*RN*	15,00%
	Twin	60,00%
	Aglo	25,00%
5	*RN*	15,00%
	Twin	30,00%
	Aglo	55,00%

Table B-4 - Total demand of each client

Client	Demand Share	Total Demand
cBerlin	0,043%	6,193
cVienna	0,056%	8,095
cBaku	0,000%	26
cBrussels	0,022%	3,238
cMinsk	0,068%	9,838
cSofia	0,072%	10,491
cMontreal	0,024%	3,430
cMadrid	4,527%	659,350
cWashington	0,604%	87,971
cParis	0,414%	60,275
cTiblissi	0,011%	1,666
cAtenas	0,008%	1,106
cBudapest	0,024%	3,567
cJerusalem	0,023%	3,395
cRome	0,410%	59,668
cVilnius	0,007%	1,052
cMexicoCity	0,000%	39
cChisinau	0,071%	10,336
cLima	0,013%	1,953
cWarsaw	0,032%	4,712
cLisbon	93,249%	13,582,467
cBucharest	0,013%	1,842
cMoscow	0,237%	34,539
cBern	0,002%	267
cKiev	0,069%	10,109
cMontevideu	0,002%	223

Notes: The total demand, each year, is equal to 2,580,770 kg of final products. This is due to this value being the only data point available by the company. The product share was estimated based on company-specific information. Table B-4 includes the demand of remanufactured products.

B.3.2 Demand – Sensitivity Analysis

Table B-5 - The parameters used in the sensitivity analysis

Client	Product	Average Demand	Standard Deviation
cLisbon	*RN*	89,869	31,536
	Twin	247,829	109,896
	Aglo	261,426	113,709
cMadrid	*RN*	4,495	2,257
	Twin	12,396	7,160
	Aglo	13,076	7,459
cWashington	*RN*	660	364
	Twin	1,819	1,134
	Aglo	1,919	1,183

Notes: Table B-5 only shows a portion of the parameters used in the sensitivity analysis. There are parameters for all the clients and respective product demand.

C Appendix B – Results

C.1 Sensitivity Analysis Iterations

Table C-1 - Results from each iteration

Iteration	NPV Level	Env. Level	Energy from Biomass	Circular Volume	Out of	Service Level
1	12,430,033	209,101	47,30%	13,00%	73,10%	100%
2	13,812,538	233,840	51,54%	11,70%	66,11%	100%
3	12,471,509	205,097	47,18%	12,76%	72,15%	100%
4	12,663,818	222,172	47,31%	12,34%	69,75%	100%
5	13,819,547	227,880	49,55%	11,97%	73,27%	100%
6	14,206,066	238,963	49,17%	11,74%	71,84%	100%
7	14,015,310	223,987	49,39%	12,27%	73,86%	100%
8	10,425,224	192,729	50,14%	14,38%	73,41%	100%
9	11,393,546	206,833	50,01%	13,30%	73,32%	100%
10	12,655,252	209,090	50,15%	12,98%	72,10%	100%
11	9,896,673	195,766	51,10%	13,73%	70,78%	100%
12	12,048,694	208,962	50,25%	12,88%	71,51%	100%
13	12,876,464	218,133	49,40%	12,62%	73,81%	100%
14	FAILED	FAILED	FAILED	FAILED	FAILED	FAILED
15	11,109,779	203,606	49,70%	13,64%	74,07%	100%
16	13,245,465	226,968	48,82%	12,20%	74,62%	100%
17	13,033,177	213,948	50,79%	12,50%	70,99%	100%
18	12,822,467	215,905	46,30%	12,44%	70,65%	100%
19	9,604,224	192,635	50,36%	14,28%	72,81%	100%
20	13,660,066	224,817	49,83%	12,22%	73,82%	100%
21	12,273,519	213,100	50,15%	12,79%	72,65%	100%
22	10,561,448	197,572	51,06%	13,71%	71,45%	100%
23	11,936,683	201,714	50,96%	13,46%	71,64%	100%
24	11,886,885	204,234	50,14%	13,22%	71,54%	100%
25	12,058,671	214,409	50,12%	12,61%	72,00%	100%
26	12,770,513	215,891	50,16%	12,57%	72,49%	100%
27	11,507,976	202,906	50,42%	13,55%	73,09%	100%
28	9,781,509	196,460	42,62%	13,87%	74,83%	100%

Table C-2 - Results from each iteration

29	11,655,620	201,803	50,20%	13,43%	71,76%	100%
30	12,779,751	204,846	50,80%	13,11%	71,23%	100%
31	13,716,391	212,860	50,59%	12,73%	72,15%	100%
32	13,834,652	225,039	51,04%	12,22%	73,92%	100%
33	12,411,929	213,186	50,22%	12,77%	72,62%	100%
34	11,877,790	212,430	49,44%	12,93%	73,52%	100%
35	14,029,161	223,243	48,97%	12,12%	68,88%	100%
36	11,956,680	211,796	50,23%	12,83%	72,38%	100%
37	11,132,299	209,492	49,89%	13,09%	73,07%	100%
38	11,121,915	210,171	49,53%	13,18%	74,09%	100%
39	12,197,616	208,463	50,52%	12,86%	71,08%	100%
40	11,031,839	197,976	50,21%	13,94%	73,18%	100%

C.2 Environmental Results – Case A, B and C

Table C-3 - Environmental results for Case A: NPV Maximization

Indicator	Transportation	Production	Finishing	End of Life	Entity
GW	5,23E+02	5,60E+02	9,96E+01	5,69E+03	0,00E+00
SOD	5,31E+01	9,98E+01	8,87E+02	-2,73E+01	0,00E+00
IR	6,23E+01	6,13E+01	-1,02E+00	-8,30E+00	0,00E+00
OF	3,90E+02	8,01E+02	2,15E+02	9,31E+02	0,00E+00
PMF	1,00E+02	1,59E+02	7,54E+01	-1,19E+02	0,00E+00
TA	1,22E+02	3,15E+02	1,06E+02	-2,67E+02	0,00E+00
FE	7,82E+00	4,11E+01	4,87E+01	1,65E+01	0,00E+00
ME	2,85E-01	2,18E+01	-3,19E-01	1,09E+00	0,00E+00
TEco	8,46E+04	4,10E+03	1,15E+03	-5,82E+03	0,00E+00
FEco	1,06E+04	8,02E+02	2,41E+02	-1,69E+02	0,00E+00
MEco	6,03E+04	5,80E+03	1,11E+03	-4,15E+03	0,00E+00
HC	8,43E+02	4,03E+03	7,38E+02	9,01E+02	0,00E+00
HNC	8,24E+03	2,18E+04	5,23E+02	-3,34E+02	0,00E+00
LU	1,73E+00	3,62E+01	7,60E+00	-8,77E-01	0,00E+00
MRS	2,64E-03	5,25E-02	3,58E-04	7,40E-04	0,00E+00
FRS	1,40E+03	2,72E+03	4,25E+02	-4,31E+01	0,00E+00
WC	1,66E+00	1,41E+03	1,07E+02	-5,03E+02	0,00E+00

Table C-4 - Environmental results for Case B: Environmental Impact Minimization

Indicator	Transportation	Production	Finishing	End of Life	Entity
GW	5,84E+01	5,42E+02	9,67E+01	5,54E+03	0,00E+00
SOD	5,92E+00	9,64E+01	8,62E+02	-2,66E+01	0,00E+00
IR	6,95E+00	5,94E+01	-9,96E-01	-8,09E+00	0,00E+00
OF	5,49E+01	7,74E+02	2,08E+02	9,08E+02	0,00E+00
PMF	1,26E+01	1,52E+02	7,32E+01	-1,16E+02	0,00E+00
TA	1,64E+01	3,01E+02	1,03E+02	-2,60E+02	0,00E+00
FE	8,73E-01	3,99E+01	4,73E+01	1,61E+01	0,00E+00
ME	3,16E-02	2,12E+01	-3,10E-01	1,06E+00	0,00E+00
TEco	9,36E+03	3,89E+03	1,11E+03	-5,68E+03	0,00E+00
FEco	1,17E+03	7,74E+02	2,34E+02	-1,64E+02	0,00E+00
MEco	6,67E+03	5,56E+03	1,07E+03	-4,05E+03	0,00E+00
HC	9,99E+01	3,89E+03	7,16E+02	8,78E+02	0,00E+00
HNC	9,12E+02	2,12E+04	5,07E+02	-3,26E+02	0,00E+00
LU	1,94E-01	3,51E+01	7,38E+00	-8,55E-01	0,00E+00
MRS	2,92E-04	5,09E-02	3,47E-04	7,22E-04	0,00E+00
FRS	1,57E+02	2,64E+03	4,13E+02	-4,20E+01	0,00E+00
WC	1,86E-01	1,36E+03	1,04E+02	-4,90E+02	0,00E+00

Table C-5 - Environmental results for Case C: Training Hours Benefit Maximization

Indicator	Transportation	Production	Finishing	End of Life	Entity
GW	8,88E+02	5,52E+02	9,76E+01	5,80E+03	1,61E+03
SOD	9,01E+01	9,81E+01	8,70E+02	-2,78E+01	5,43E+01
IR	1,06E+02	6,03E+01	-1,00E+00	-8,46E+00	3,16E+01
OF	7,02E+02	7,89E+02	2,10E+02	9,50E+02	3,75E+03
PMF	1,75E+02	1,56E+02	7,39E+01	-1,21E+02	9,14E+02
TA	2,16E+02	3,09E+02	1,04E+02	-2,72E+02	1,68E+03
FE	1,33E+01	4,04E+01	4,78E+01	1,68E+01	4,77E+02
ME	4,83E-01	2,14E+01	-3,13E-01	1,11E+00	1,52E+01
TEco	1,43E+05	4,03E+03	1,13E+03	-5,94E+03	4,96E+04
FEco	1,80E+04	7,92E+02	2,36E+02	-1,72E+02	2,50E+04
MEco	1,02E+05	5,70E+03	1,08E+03	-4,23E+03	5,62E+04
HC	1,45E+03	3,97E+03	7,23E+02	9,18E+02	1,42E+05
HNC	1,40E+04	2,14E+04	5,12E+02	-3,40E+02	2,63E+04
LU	2,94E+00	3,55E+01	7,44E+00	-8,95E-01	2,88E+01
MRS	4,48E-03	5,14E-02	3,50E-04	7,55E-04	1,06E+01
FRS	2,38E+03	2,73E+03	4,16E+02	-4,39E+01	2,96E+03
WC	2,82E+00	1,41E+03	1,05E+02	-5,13E+02	2,83E+02

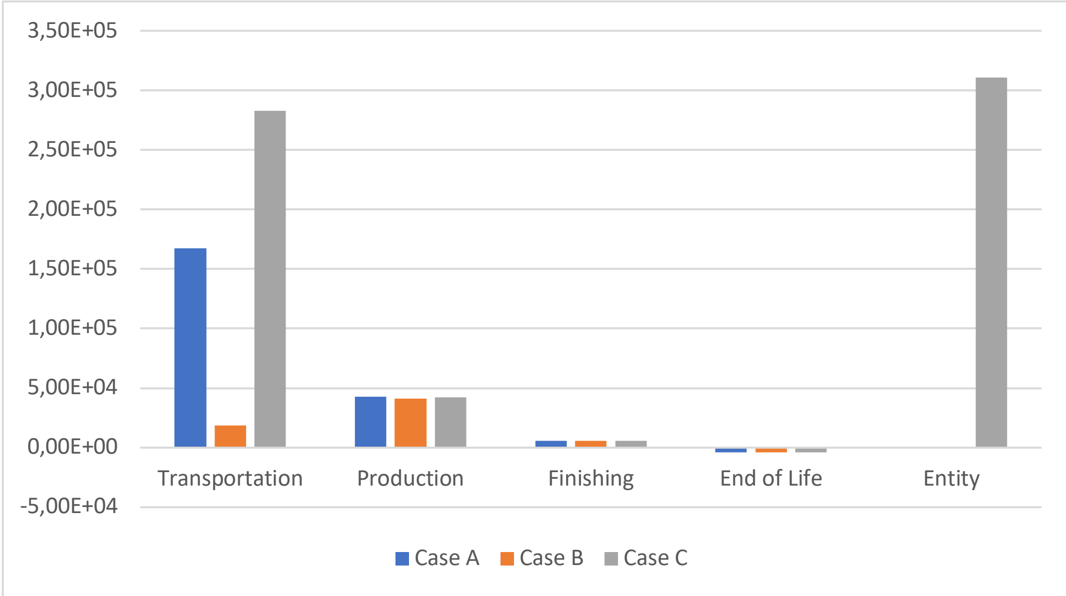

Figure C-1 - Environmental Impact comparison between the studied Cases