Extended Abstract to obtain the Master of Science Degree in
Industrial Engineering and Management

Sustainable Supply Chain Design and Planning: a Case in the Cork Industry

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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 cork supply chain is based on the 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.

1. Introduction

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 and transforms 70% of the world's cork into final products (APCOR 2020).

Corticeira Amorim (CA) is created in this environment of growth of the cork industry. 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 (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. 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).

As mentioned, CA has a great responsibility due to its presence in the industry. It is essential that its SC minimizes social and environmental negative impacts and 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. These solutions should also take into consideration the uncertainty in the SC regarding.

In this line of thinking, the following questions are addressed in this work: **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 CA? **RQ6** How to evaluate the trade-off between the SC 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 to the collection of end-of-life products.

The remainder of this paper is structured as follows: section 2 proceeds with the presentation of the cork sector. Section 3 contains the literature review on the methodologies to follow. Section 4 presents the methodology followed. Section 5 presents an overview over the main components of the case study. Section 6 presents the main results. Section 7 concludes the paper and gives some future recommendations.

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

2.1 Characterization of Corticeira Amorim

Corticeira Amorim, S.G.P.S., S.A. is currently valued at 1.3 billion euros, listed in Euronext Lisbon (Euronext Lisbon 2019). CA leads its sector as a role model to the economy and innovation of the cork industry.

CA's operational activity level is structured into five business units: (1) Raw Materials, (2) Cork Stoppers (the focus in this work), (3) Composite Cork, (4) Cork Insulation and (5) Floor and Wall Coverings.

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 2018). The *Amorim Cork Research* is a support branch of the company that helps it to keep a leading position in the market. It is responsible for investing heavily in R&D, creating new innovative products (Corticeira Amorim 2018).

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. 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.

2.2 Corticeira Amorim: the sustainability approach

CA achieves a lead position in the market through differentiation and innovation with a sustainable approach (Corticeira Amorim 2018).

In CA's *Sustainability Report* (Corticeira Amorim 2018) it is possible to spot subjects that are important for the company and its stakeholders such as circular economy, energy efficiency, environmental impact of the product, R&D need of investment and economic performance. This issues are those who will be featured in future initiatives, investment or strategic decisions from the company (Corticeira Amorim 2018):

- ***Circular Economy*** - The company has a range of products that come directly from harvested cork and another that is originated from by-products, generated during production stages. In the context of cork stoppers, they are natural and technical cork stoppers, respectively. These by-products are mainly cork dust that will be treated as biomass or regranulates, which can be used in the other BUs;
- ***Energy Efficiency*** - CA applies continuous improvement to its energy efficiency. The company uses an indicator to assess its energetic standings (*Energy Intensity*) and another regards to carbon emissions (*Carbon Intensity*). These indicators reveal that the main energy source is biomass and electricity 95%, being the latter the main responsible for the carbon intensity (91%) (Corticeira Amorim 2018). This represent that CA is mainly powered by an internally created energy source (biomass);
- ***Impact of the product*** - Despite being a natural material, the environmental impact of cork products 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.

PwC conducted a study to assess the carbon footprint of a given cork stopper. The conclusion was that the footprint is negative, -1,8g CO_2 per stopper (Corticeira Amorim 2018). The system's boundary was not specified, so the results, although positive, may be biased. The system boundary should include for the integrity of the SC, so that the impact accounts the integrity of the SC.

Although CA has demonstrated serious concerns about the sustainability of its business, these concerns need to be addressed from an integrated SC perspective.

2.3 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 1 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, Dias, and Arroja 2013; Rives et al. 2012).

In Figure 1, the elements that are in blue are accounted in the environmental study of this work, while the ones in red are not.

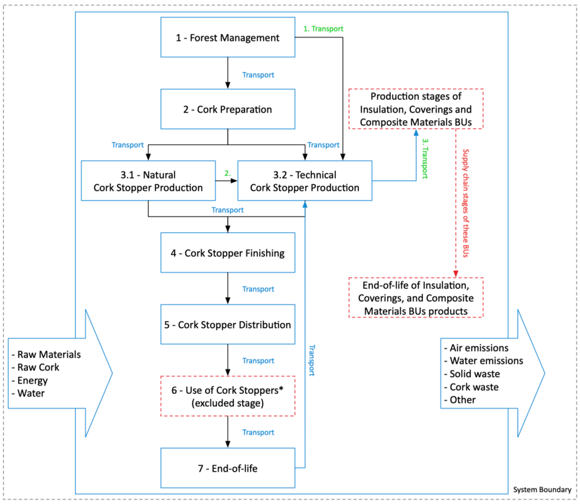

Figure 1 - Simplified Supply Chain of Cork Stoppers

Figure 1 exposes the main difference between the SC of Natural and Technical Stoppers, which is relevant since Equipar produces the latter.

All the *Transport* flows in Figure 1 are performed by third-party logistics. Regarding the three specific flows in Figure 1 (depicted in green), they are described as:

- **1. Transport** – While harvesting the cork there is a coarser visual filtration of lower quality cork. This cork is sent directly to IUs that produce technical cork stoppers;
- **2. Transport** – The cork residues that result from the cork punching (from *Stage 3.1* in **Figure 1**) are sent to IUs that produce technical cork stoppers;
- **3. Transport** – The grinding unit of IUs that produce technical cork stoppers is responsible for recycling cork. The unit shreds the used products, forming the regranulates, 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.

2.4 SC of Equipar: Amorim&Irmãos, S.A., IU Coruche

In Equipar the phase *Cork Stopper Production* is the **Stage 3.2 – Technical Cork Stopper Production** (see Figure 1). In here it is **used cork granulates to produce technical cork stoppers** **instead** of **cork planks to produce natural cork stoppers**.

Figure 2 is a strategic point of view of Equipar and provides an overview to the processes that occur there.

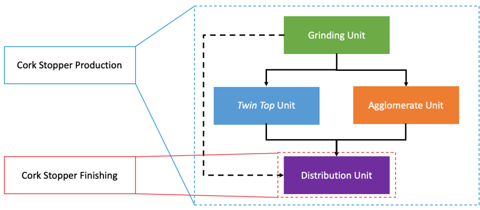

Figure 2 - Equipar Cork Production Unit: a strategic point of view

Regarding the production units within Equipar:

- **Grinding Unit** – This unit produces three types of granulates, **RCT** (used in champagne bottles cork stoppers), **RA** (used in still wines stoppers), **RN** (used in still wine bottles stoppers), in descending order of diameter;
- **Agglomerate Unit** – In this unit the granulates are glued together into rolls of cork (called *sticks*), which then are cut down to a basket;
- ***Twin Top* Unit** – 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 (*Molding*). There is an additional process called *Gluing*, where cork discs are glued to the ends of the cork bodies;

- **Distribution Unit** – In this unit the cork stoppers may be *Branded*, *Surface Treatment* (application of a lubricant and sealant to facilitate bottling, sealing and extraction of the stopper), *Coloring* and *Packaging*. From this unit, the cork stoppers/cork granulate leave Equipar to supply other IUs/clients.

The SC outside of Equipar will be covered in section 5.

From the above, 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 and promoting initiatives related to circular economy.

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 2018).

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

A literature review is performed on SC concepts, on how these have been addressed in the context of Operational Research (OR), and how sustainability. In the first section an overview of SC definitions. The second section is relative to how OR has been contributing to the decision processes within Sustainable Supply Chain. Next, it is addressed how sustainability through the Triple-Bottom-Line has been modelled in SC studies. The final section presents the section conclusions.

3.1 Sustainable Supply Chains

In 1998, SC is generally referred as "*the alignment of firms that bring products or services to market* (…)*"*. This is a simple approach to define "SC", since it does not highlight the complex interactions between the different so-called "SC" entities (Lambert, Stock e Ellram 1998).

Different levels of complexity exist depending on the size of the SC (Mentzer, et al. 2001). So, it is possible to deduce other concepts related to SC: <u>strategic planning</u> (e.g. warehouse allocation); <u>tactical planning</u> (e.g. flow planning); <u>operations planning</u> (e.g. daily production planning) (Mihai Felea & Irina Albăstroiu 2013).

Through time, the general attention focused on problems such as waste creation by SCs. With the increasing environmental mindset, policies such as the **Extended Producer Responsibility** (EPR) were created. It is a government policy that assigns companies the financial/physical responsibility for the post-consumer phase of their products (OECD 2019).

Eventually, the **Closed Loop Supply Chain** concept (CLSC) was originated from this growing sustainable concern. "*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, and Carvalho 2018).

The inclination towards economic and environmental concerns slowly became to encompass the social pillar as well, giving rise to the **Triple Bottom Line** (TBL) concept. 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.

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, recently published papers in OR (after 2016) are included in this review.

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 such as inventory, demand and supply management; **operational decisions** – it addresses demand fulfillment and production scheduling. 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. The operational level is less researched due to the computational effort and the decision integration of operational decisions (Barbosa-Póvoa et al. 2018).

To define and model an SSC it is necessary to integrate several decisions as decision variables. 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 (strategic/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)** and **(3)**, in the context of CLSC design (Boukherroub et al. 2015; Brandenburg et al. 2014; Eskandarpour et al. 2015; Seuring 2013; Seuring and Müller 2008; Taticchi et al. 2014); **(1)** and **(4)** have been identified as research gaps (Barbosa-Póvoa et al. 2018). Regarding **(5)**, related to cork products, only one paper have been found, but it is not related to SC design and planning (Demertzi et al. 2015).

The five decisions identified as research gaps in the literature, will be tackled in the present work.

How the TBL has been modelled

There are distinct metrics for each goal of the TBL. An overview on how these goals have been addressed in the literature using OR techniques is given, based on the work of Barbosa-Póvoa et al. (2018).

The metrics chosen to address the <u>**Economic Goal**</u> are Cost (59% of analyzed papers address this goal), profit (25%), NPV (9%) and Risk (7%). The OR models used are optimization (73%), simulation (12%) and others such as statistics, decision analysis or data analysis.

The *Economic Goal* is usually modelled with one single metric. To design different scenarios to a given SC problem, the NPV metric is the most suitable. The work from Mota et al. (2018) 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 optimize net income is vital.

The metrics chosen to address the **Environmental Goal** are CO_2 emissions (25%), GHG emissions (17%), LCA assessment (16%), and others such as Recycling, Biodiversity and Waste are the metrics chosen by authors. The OR models used are optimization (70%), simulation (9%) and others such as data analysis or decision analysis.

There is a diversity of metrics used and examples of their application such as inclusion of parameters in objective functions and the use of LCA.

The **Life Cycle Assessment** (LCA) assesses the environmental impacts from the entire lifecycle of a given product or process, using multiple impact categories (Muralikrishna e Manickam 2017). To apply the methodology, the international standards ISO 14040:2006 and 14044:2006 have to be respected (The International Standards Organisation 2006).

Usually, an LCA study follows four steps: (1) **Goal and Scope Definition** (the product's life-cycle and a definition of the boundaries of the system); (2) **Life Cycle Inventory** (LCI) (inventory of inflows and outflows); (3) **Life Cycle Impact Assessment** (LCIA) (environmental impacts are classified, evaluated and translated into impact categories); and (4) **Interpretation phase** (the results from (2) and (3) are interpreted) (The International Standards Organisation 2006).

In the context of this work and step (1), **System Boundary** is very important. The choice of elements/processes within the system depends on the criteria defined in step (1) → "*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.

According to Barbosa-Póvoa et al. (2018), *ReCiPe 2016* is the most suitable LCIA method. It has been concluded, that it is the most complete for the assessment of the potential environmental impacts of products and processes to use in the European environment (European Commission 2011; Mota et al. 2019). LCA methods are being used by authors to optimize the environmental performance/impact of a given SC of a product or process. Papers that include all the TBL are rare in the literature.

The metrics chosen to address the **Social Goal** are (38%), Safety (25%), Health (16%) and other such as Poverty and Satisfaction. The OR models used are optimization (60%), decision analysis (14%) and others such as statistics or data analysis.

This aspect is often modelled with a single metric. The literature about the social aspect is recent and seems that will follow the trend of the *Environmental Pillar* by focusing solely in one or two metrics. Thus, in order to have a broader view of the social aspects, SLCA appears as a promising methodology to follow in future research (Kühnen and Hahn 2017).

Social Life Cycle Assessment (SLCA) provides a "*holistic (…) tool to understand social issues (…) in the value chains of products and services sustaining human life*" (Garrido 2017).

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.

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.

3.3 Research Gaps Cork SSC design and planning

The research gaps highlighted in this section are related to the cork SC design and planning in the context of the TBL and the use of holistic methodologies in the environmental and social aspects.

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 optimized – 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 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.

In order to expand the point of view on the evaluation of the TBL, two articles review topics similar to cork (Cambero and Sowlati 2014; Santos et al. 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.

As stated previously in this section, 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.

4. Problem Statement and Model Characterization

In this section, the model is briefly characterized.

Figure **3** 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.

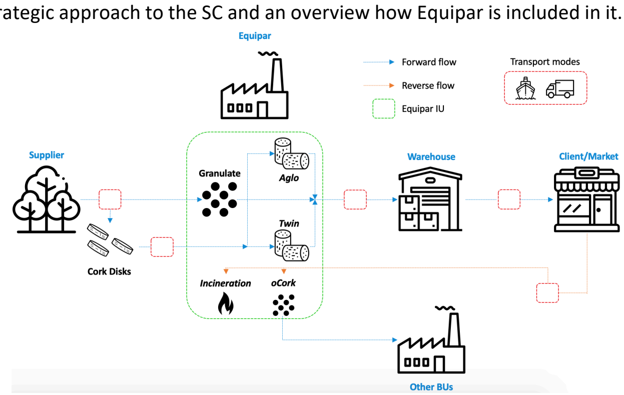

Figure 3 - Example structure of the CA's SC in the context of Equipar

The problem can be summarized as follows: **(1) Given** – Pre-determined flows and interaction between entities and existing or potentially new geographical locations; Supply and production capacities; Production and remanufacturing technologies; Bill of materials; Demand; Distance between SC entities; Transportation means available; Fixed time horizon; Economic valorization of incinerated recovered products; Initial inventory levels; **(2) The goal is to determine** - The network configuration, in terms of which warehouses to open and which suppliers to procure; The transportation network structure; 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; The TBL performance; **(3) In order to** - Maximize Net Present Value; Minimize Environmental Impact; Maximize Social Benefit.

The ***Economic Objective*** is defined by a single objective function that represents the Net Present Value (NPV). The ***Environmental Objective*** is defined by a single objective function. An LCI methodology is followed and the LCIA method used is the *ReCiPe 2016*. The ***Social Objective*** is defined through several social indicators. To apply a simpler approach than that of the SLCA, but maintain the holistic vision, an alternative methodology was applied: Social Impact Measurement (SIM). The social indicators used to assess the intended environment, 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. 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.

The model is divided into 6 main components: **(1) Technical Cork Stoppers Facility** – The structure from Figure 2 is defined mathematically (e.g., define how production stages). It is included the electric consumption and biomass production; **(2) Balance Component** – The material balance of every SC entity is defined. Important to maintain correct streamline of materials; **(3) Demand and Product Return** – The demand and material recovery are defined. *Minimum Service level* and *Minimum Recovery* are vital parameters of the model, which are included here; **(4) Entity Capacity** – The supply, entity, flow and stock capacity are defined. This component defines the installed capacity; **(5) Transportation** – The physical limitations are defined. For instance, not being able to transport material between different continents through trucks); **(6) Technology** – Technology capacity and selection restrictions are defined. In the present case only one technology could be used in the production stages.

In general, the model considers a **(1)** superstructure of entities and existing or potentially new geographical locations (see Figure 2), 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.

The following chapter introduces the case study.

5. Case Study Overview: Equipar Industrial Unit

The present section shows the main data entries of the case study. Figure 4 depicts the location of the SC entities.

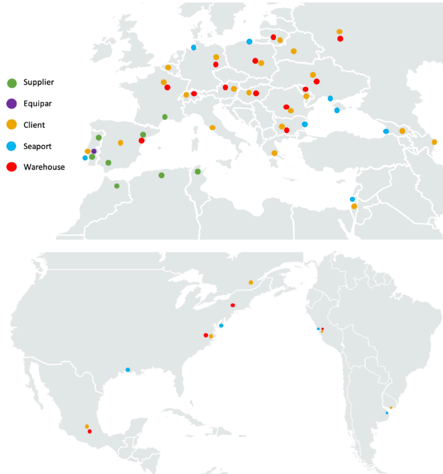

Figure 4 - Location of SC entities

The main scope of this work is that each aspect is modelled as holistically as possible. The parameters used to model each aspect are divided in SC stages depicted in Figure 1.

Regarding the ***Economic Aspect***, the parameters used are as follows: **(Stage 1)** Raw Material Cost; **(Stages 2-4)** Human Resources, Operational Costs, Installation Costs and Stock Costs; **(Stage 5)** Transportation Costs; Sea Hub Costs; Warehouse Costs; **(Stage 6)** Selling Price and **(Stage 7)** Recovery Costs. It was used other parameters such as Interest Rate, Salvage Rate, Tax Rate and Depreciation Rate.

Regarding the ***Environmental Aspect***, it was performed an entire LCI, based on company-specific information and the literature (see Table 1). In *Stage 3.2* there are four "*Quantity*" entries which represent the differences between production technologies. The alternative uses an irradiation device such as Cobalt-60 to eliminate TCA (Técnico | Lisboa: UTR 2020) (Pereira, Gil, & Carriço 2007).

Table 1 - Environmental data per SC stage

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 (m³)	8.865E+1
Water (m³)	9.010E+0
Outflow	
Treated Cork (kg)	1.632E+3
Sludge (kg)	4.589E+1
Wastewater (m³)	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 (m³)	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 (m³)	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 (m³)	8.400E-1
Urea (kg)	6.690E+0
Electricity (kWh)	2.730E+0
Diesel (GJ)	4.900E-4
Natural Gas (m³)	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 ***Social Aspect***, the parameters used are as follows: **(1)** Certificate FSC; **(Stages 2-5)** Employment Turnover, Accident Frequency Ratio; Occupational Disease Ratio; Absenteeism Ratio; Training hours; Salary Ratio Men vs Women; Ratio Men vs Women. The parameters are in the scope of CA and the industry and were validated with points-of-view from other companies.

6. Results and Discussion

The model is coded in GAMS 31.1. The tests were performed in a computer running Windows 10 with an Intel® Core™ i5-7400 CPU, four cores, processor of 3.00 GHz and 8 GB of RAM.

6.1 Cases Definition

Different cases were created to address and answer the research questions previously defined. **Case A:** solution with the optimum economic performance obtained through the maximization of the NPV; **Case B:** solution with the optimum environmental performance obtained through the minimization of the Environmental Impact indicator; **Case C-1:** solution with the optimum social performance obtained through the benefit maximization of a Social Impact indicator.

To further analyze the case study, it was performed the following: **Sensitivity analysis on the demand:** the demand is defined by a random distribution, while the economic performance of the SC is being maximized; **Specific Scenarios, given previous results:** parameters are directly manipulated, in order to understand how different, the model assumptions would have to be to result in contrasting conclusions.

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 was set to equal one third of the maximum NPV. 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 include the performance on each TBL aspect, network design decisions, overall service level, energy consumed from biomass or waste and circular volume (highlighted by the company).

Case A

The present subsection exhibits the main results of Case A. The overall results are displayed in **Table 2**.

Table 2 - 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%

Looking to 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.

The fact that the service level is 100% determines that, 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.

The maximum quantity of 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.

Figure 5 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 impact midpoint categories.

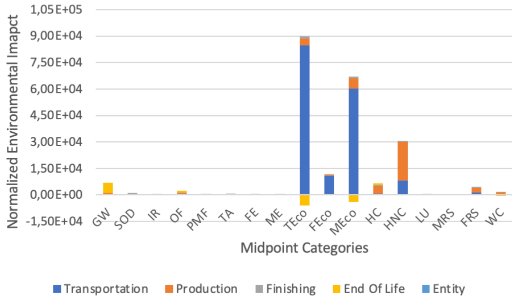

Figure 5 - Environmental impact per midpoint category and SC stage for Case A

Looking into Figure 5, 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 section, there are clients located in three continents. 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. 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.

The production phase is a very important factor, especially in the HNC environmental impact midpoint category. The impact is mainly due to cork stoppers using Glue (Polyurethane) as exposed in Table 1. The Glue is used to agglomerate the cork granules as well as the cork discs to the body of the corks. 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 aspect, results are exposed in Figure 6.

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. 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].

From Figure 6 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]**. 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.

The social results (expect for [S.Eval]) are driven by choosing warehouses, where CA is operating. By not choosing any warehouses the social results are a direct comparison between CA and Portugal (where it operates).

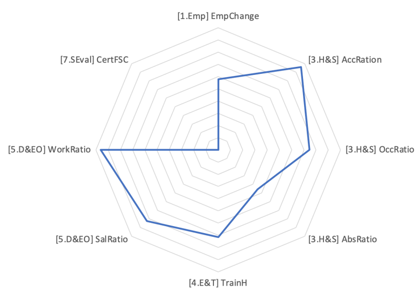

Figure 6 - Social Results for Case A

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 raises 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. Thus, it is relevant to make decisions such as to procure non-compliant or more expensive raw materials.

Case B

In Case B, the objective is to minimize the environmental impact of the SC of CA, subject to a minimum NPV level defined by the decision-makers.

The overall results are displayed in Table 3, where it can be seen that the environmental impact decreased 70.94% and the economic value decreased 67.00%. The *Energy from Biomass* diminishes because, in this case, the production levels diminished as well, which implied fewer waste products.

Table 3 - Overall results for Case B

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. The raw materials are more expensive. These options are the main factors for the decrease in the NPV value and the environmental impact, given that the covered distance to supply Equipar is far smaller;
- No collection of end-of-life products. It is not environmentally advantageous to recover products at the final clients and revalue or remanufacture them (transportation impact is more relevant);
- Service level as minimum as possible 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.

Figure 7 depicts the results obtained per impact midpoint category. It is immediate that TEco, MEco, 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.

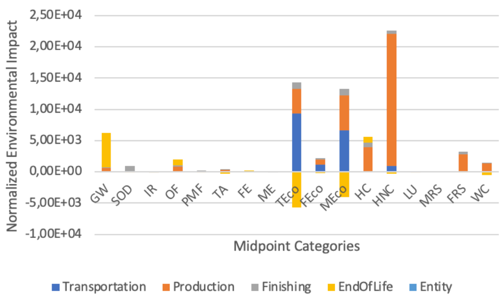

Figure 7 - Environmental impact per midpoint category and SC stage for Case B

By comparing the environmental results from Case A and B, the decrease in the environmental impact is due to the decrease in production, meaning less environmental impact 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 against Case A.

Case C-1

The social objective is translated by several social indicators of the SC of CA. The aim is to maximize the positive social impact of CA.

In the present Case, it was maximized the benefit from *Training Hours* to the employees. As seen in Figure 6, this indicator and *Absenteeism Ratio* have potential to improve even further. Furthermore, **(1)** this indicator is easier to tackle mathematically than, for instance, *Salary* and *Work Ratio* (because their best possible result is equal to 1; the fact that in the engine used you cannot implement conditionals, their benefit maximization is not obvious). In addition, **(2)** the scope of this Case is to maximize the benefit on one social indicator and realize what the decisions of the model are.

Table 4 depicts the results obtained.

Table 4 - Overall results for Case C

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%

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. 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 both can solely supply Equipar). The engine where the model is being executed computes by default until it reaches the objective. In this case, this procurement is enough to meet the objective and stay accordingly with the imposed model restrictions.

Figure 8 depicts the social performance of the social indicators.

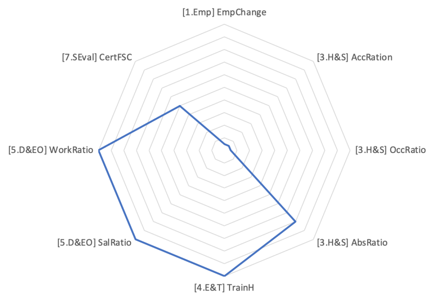

Figure 8 - Social Results for Case C

From Figure 8 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 9 depicts each environmental indicator score.

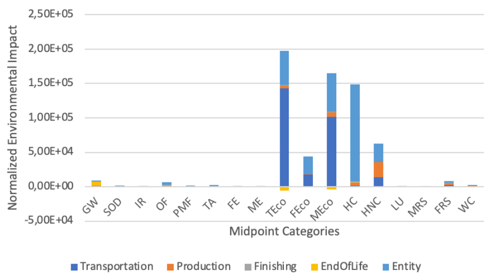

Figure 9 - Environmental impact per midpoint category and SC stage for Case C

Figure 9 indicates that entity impact has a much higher relevance, due to renting every possible warehouse. 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.

These results are immediate to perceive, but the more diverse the SC, the more meaningful this approach gets.

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. The uncertainty on the demand was hence addressed using a different approach.

For this analysis, it was used the *NPV maximization*, because service level is maximized due to the uncertainty in demand being under study.

The overall idea is to generate different scenarios that simulate demand volatility. Thus, for each client and for each product, the average demand and respective standard deviation were calculated. Then, these two generated a random demand parameter, based on a gaussian distribution for each client, through all considered time periods (in 5 years).

Figure 6 aggregates the results based on forty iterations of the demand. 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.

Figure 6 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 5 - 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 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 Figure 6, 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, the other parameters tend to be proportional to the NPV level variation. Additionally, 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.

Specific Scenarios and their discussion

Several scenarios are studied so as to explore potential opportunities within the presented case-study and obtain additional insights.

The developed scenario assumptions as follow:

- **Scenario 1:** a sensitivity analysis on the parameter **price of public electricity** is performed, to understand what different prices would imply in this SC, particularly in terms of making end-of-life product recovery economically advantageous;

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. Insight: For IUs located in energy costly countries, product recovery will be, in principle, a more viable option.

- **Scenario 2:** a sensitivity analysis on the parameter **energy recovered from incineration** is performed, 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;

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:** a scenario of **market growth** is explored, to understand how the SC network would evolve if the market was to grow;

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 Case A, is that there is a need for renting 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 first limiting factor is not the production but the storage space.

- **Scenario 4:** a scenario of **economic viability for the alternative production technology** is explored;

The estimated installation cost for the alternative production technology is 2,000,000€. Through the performed analysis, if the alternative technology installation cost was around 750,000€ then it would be worth to install it. The needed 62.5% decrease 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:** a scenario of **crisis** is imposed so as to understand how the SC would adjust when facing extremely low levels of **demand**.

During the Covid-19 pandemic, CA stock prices suffered a 35% fall (Euronext 2020). Assuming that the demand accompanied this trend, and a steady recover of 4% per trimester, the demand would be as shown in Table 6. For instance, in time period 13 the demand is 73.1% of what was initially predicted.

Table 6 - 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%

The estimated NPV decreases to 11,497,227.3€ (-11.35%) (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. In addition, the SC follows the same type of decisions already studied in Case A (e.g., same network design; same chosen technology; similar circular volume).

6.3 General Discussion and Recommendations

The main results and conclusions are discussed as follows:

i. 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 high. The same is true in Case B, where the impact of transportation is more significant than that of remanufacturing/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 leverage the trade-offs between service level/transportation costs and impact; **(3)** Study, for each market cluster, 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.

ii. The final products are highly profitable

When maximizing the economic aspect, service level is at its maximum, meaning that 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.

iii. The SC of CA is robust

If the demand of CA is defined by a random distribution, it meets high service level standards. Recommendation: Apply this methodology when the demand is not so concentrated in one market cluster. If the demand is more distributed, the decisions around production, inventory and 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.

iv. Poor social assessment, 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 this methodology, but with an approach that normalizes the result based on the number of workers involved or number of hours worked; **(2)** Use the same social indicators, but with data related to the cork industry and not the country where the SC entities are located in.

v. 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. The warehouses are not used due to installed production capacity. Recommendation: If SC decision-makers want to study what are the best warehouses options, they can apply the same approach as *Scenario 3*.

7. Conclusions and Future Work

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

- **RQ1**: The present work tackles the three aspects of the TBL as described, by defining the problem 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);
- **RQ3**: This work accounts the environmental impact of all SC stages as seen in Table 1 in section 5. So, the decisions will consider 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 judge which set of 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 sections 4 it is indicated that the indicators used measure different parameters and cover the integrability of the SC;
- **RQ6**: Throughout section 5 the results are evaluated while taking into account what are the implicit trade-offs in each decision taken. 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.

Looking to a SC in the most holistic way as possible is no simple task. There are **(1)** a wide variety of products and several types of (re)manufacturing processes possible to undertake; **(2)** different types of raw materials (Rives et al. 2011); **(3)** different manufacture technologies; **(4)** warehouse management differs from product to product. So, several assumptions were made to simplify the SC, which can cause uncertainty. To minimize it, during parameter estimation, exhaustive work was carried out regarding the respect for orders of magnitude of the data.

Despite this, the main purpose of this work is to model the entire SC in a strategic/tactical approach. By respecting the orders of magnitude and 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 work has come to occupy a research gap in the literature. It is the groundwork to understand what the real impacts of the cork industry are, by approaching in the most holistic way.

The major conclusions and future work will be displayed as follow:

i. Operationalize Transportation

In this work, transportation flows are optimized between SC entities. It is not accounted utilization rates or minimum capacities for transportation, which in reality are relevant, because the transport is outsourced. 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 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. 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 (this approach was implemented, but due the wide SC and complexity, the computational effort was too great for the timeframe available to develop this work).

In addition to minimum transportation capacities, adding the plane transportation mode (and respective airports) and multiple options within each mode (i.e., medium and smaller truck) would diversify the transportation decisions, 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.

ii. 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 specifying client locations, it would be interesting to understand if transportation flows could be further optimized, since it is one of the major costs and environmental factors.

iii. 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 addition, there is a major source of uncertainty because products that were not recovered at market clusters were considered to be sent to landfill, which is not the same in different locations. 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. By diversifying the available options, it could confirm if product recovery is viable or not. In addition, it could be considered third parties that could recover those products and are located strategically near the market.

iv. Environmental data uncertainty

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

The present work is the first of its kind in the literature. As stated, there are several possible combinations in the production stage, so the data from Table 1 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 1 is aligned with reality. 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).

v. Use social data related with the cork industry

The social data is related with the countries where the SC entity is located, meaning it is not specific to the cork industry.

As stated in point iv in section 6.3, the social data should all be related with the scope of the cork industry, so that different locations can be compared (ensure same basis of comparison). 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.

vi. Populate the model with other IUs of CA

In the present work, 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 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.

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