Optimisation of a collection and recovery network of used tyres

Valorpneu case-study

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Abstract
The number of used tyres reaching their end of life is increasing every year which demonstrates the importance of an efficient and sustainable system that guarantees the correct collection and recovery of this waste flow. The implementation and management of such systems is a challenging task involving both the management of complex network's flows between the different operators and the design and planning of the network itself.

The problem addressed in the present study is concerned with this last issue where the goal is to determine the correct location and number of the collection centres in order to ensure the collection of used tyres from its sources. Additionally, these decisions must consider the economic, environmental and social sustainability of the network considering different and potentially opposing objectives. To solve this problem, a decision supporting tool for the design and planning of this network was developed considering the three dimensions of sustainability. This tool is based on a multi-objective mixed integer linear programming model, which intends to minimize the network's logistics costs and environmental impact and maximize its social benefit.

The model developed is tested under a real set considering the Valorpneu's network. The results obtained serve as baseline to compare and evaluate possible improvements concerning the three dimensions of sustainability. Different scenarios are tested revealing that the districts of Oporto, Aveiro, Santarém and Lisbon are promising districts for opening collection centres. The critical parameters are subject to sensibility analysis to test the robustness of the results obtained.

Keywords: Used tyres, Reverse Logistics, Network Design and Planning, Optimisation, Sustainability

Resumo

O número de pneus em fim de vida tem vindo a aumentar a nível mundial nos últimos anos revelando a importância de um sistema que gere este fluxo de maneira eficiente e sustentável garantindo a sua recolha e valorização. A implementação destes sistemas é complexa envolvendo não só a gestão dos fluxos entre as diferentes entidades da rede como também o projeto e planeamento da própria rede.

O problema tratado neste estudo prende-se com este último ponto, onde se pretende determinar a correta localização e número dos centros de recolha garantindo que os pneus usados são eficientemente recolhidos. Para além disso, estas decisões devem ser tomadas tendo em conta a sustentabilidade económica, ambiental e social da rede, tratando-se assim de um problema com objetivos distintos e potencialmente contrastantes. Para a resolução deste problema, uma ferramenta de apoio à decisão para a definição e planeamento desta rede, considerando aspetos económicos, ambientais e sociais foi desenvolvida. Esta ferramenta baseia-se num modelo de programação linear inteira mista, multi-objetivo, e pretende minimizar os custos logísticos e impacto ambiental e maximizar o benefício social da rede.

Na validação, o modelo desenvolvido foi aplicado à rede atual. Este resultado serviu de base de comparação para avaliação das melhorias obtidas nos pilares da sustentabilidade. Diferentes cenários foram também estudados revelando como principais pontos de interesse para a abertura de novos centros de receção os distritos do Porto, Aveiro, Santarém e Lisboa. Uma análise de sensibilidade foi feita aos parâmetros críticos para testar a robustez dos resultados obtidos.

Palavras-chave: Pneus Usados, Logística Inversa, Definição e Planeamento de Rede, Otimização, Sustentabilidade

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List of Abbreviations

ACAP: Associação do Comércio Automóvel de Portugal

ANIRP: Associação Nacional dos Industriais de Recauchutagem de Pneus

APIB: Associação Portuguesa de Industriais de Borracha

ELV: End-of-Life Vehicles

EPR: Extended Producer Responsibility

EU: European Union

GA: Genetic Algorithm

GDP: Gross Domestic Product

GRI: Global Report Initiative

ILCD: International Reference Life Cycle Data

LCA: Life-Cycle Assessment

LCC: Life-Cycle Costing

LCI: Life-Cycle Inventory

LCIA: Life-Cycle Impact Assessment

MILP: Mixed Integer Linear Programming

MINLP: Mixed Integer Nonlinear Programming

MOMP: Multiple Objective Mathematical Programming

NPV: Net Present Value

PEF: Product Environmental Footprint

PROs: Producer Responsibility Organizations

PSO: Particle Swam Optimisation

RL: Reverse Logistics

SC: Supply Chain

SCM: Supply Chain Management

SDGs: Sustainable Development Goals

SGPU: Sistema Integrado de Gestão de Pneus Usados

SLCA: Social Life-Cycle Assessment

SSC: Sustainable Supply Chain

SSCM: Sustainable Supply Chain Management

TBL: Triple Bottom Line

WEEE: Waste Electrical and Electronic Equipment

1 Introduction

1.1 Contextualisation

1.1.1 Sustainable Development and Circular Economy

Sustainable development was defined in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987) and still represents a global challenge today. The three fundamental dimensions of sustainable development: economic growth, environmental protection and social equity are addressed in the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development adopted by the international community in 2015. The European Union (EU) is fully committed on working towards the achievement of these goals which are in agreement with many of the EU's priorities for sustainable development (European Commission, 2017). Specifically, initiatives such as the 7th Environment Action programme and the Circular Economy Package target the 12th goal, aiming to ensure sustainable consumption and production patterns, through a more resource-efficient and low-carbon economy (European Commission, 2016). It is then necessary to move from the currently followed take-make-consume-dispose linear economic model to a circular model where consumption of raw materials is reduced, and waste generation minimised. A circular economy promotes the efficient management of products' life cycles and supply chains followed by the principles of eco-design, repair, reuse, refurbishment, remanufacture, product sharing, waste prevention and recycling (EEA, 2016).

Extended Producer Responsibility (EPR) schemes where producers hold responsibility for the products' end-of-life are known as important drivers for circular economy as they intend to reduce waste generation and raw materials consumption by promoting products' eco-design, recycling and reuse (Lifset & Lindhqvist, 2008). In the EU, EPR systems have been applied to some specific product's waste streams such as Waste Electrical and Electronic Equipment (WEEE), End-of-Life Vehicles (ELV), batteries, packaging, oils, medical waste, tyres among others (Monier et al., 2014). In the next subsection this concept applied to the particular case of used tyres in Portugal is addressed.

1.1.2 The Used Tyre's Context

Used tyres are defined as any type of tyre the respective owner discards or has the intention to discard and, therefore, are considered waste (MAOT, 2001).

Every year, around 17 million tonnes of tyres reach their end of life worldwide (WBCSD, 2010). Regarding the EU, in 2016, 3,5 million of tonnes of used tyres were generated (ETRMA, 2018). These numbers reinforce the importance of an efficient and sustainable management of the tyres' supply chain, particularly its reverse logistics, which includes the implementation of a used tyres management system.

The uncontrolled disposal of used tyres in landfills represents a threat for both the public health and environment and it is a prohibited practice in most Member States due to the European Directive

1999/31/EC dated 26th of April 1999. Therefore, each country is required to have a management system responsible for the collection and recovery with value creation of used tyres. In Europe, used tyres management systems are divided into three models: Extended Producer Responsibility (EPR), Liberal System and Tax System. As illustrated in Figure 1 the majority of the Member States follow the EPR system which means the producers are responsible for the collection, recovery and recycling of used tyres. This system induces the minimization of waste generated by encouraging the products' eco-design, recycling and end-of-life management (Ferrão et al., 2008). In the Liberal System, the government defines the legal targets but does not nominate a responsible entity and the operators involved in the tyres' life cycle act freely to comply with the legislation. Under the tax system, the government is the entity responsible for managing the end-of-life of used tyres (Scott, 2015).

Figure 1 - Used tyres management system's models in Europe (Scott, 2015)

In Portugal, the Decree-Law nr 11/2001 established the principles and norms applied to the tyres' and used tyres' management which propose the prevention of waste generation, the encouragement of retreading, recycling and energy recovery, and the improvement of the stakeholders' environmental performance through the tyres' life-cycle. The Decree-Law nr 11/2001 also defined the legal framework for the implementation of the EPR system for used tyres and incited the establishment of a licensed non-profit organization responsible for the management of this system (MAOT, 2001). Accordingly, to meet the terms described, Valorpneu was formed in 2002.

Valorpneu is a non-profit private company licensed by the Portuguese Ministry as the entity responsible for the Used Tyres Management Integrated System (SGPU, in Portuguese *Sistema Integrado de Gestão de Pneus Usados)*. The SGPU guarantees the correct disposal of end-of-life tyres by eliminating the disposal in landfills and by promoting the collection, separation and recovery of used tyres. Thus, Valorpneu is in charge of the network responsible for the collection, transportation and recovery of used tyres which comprehends four possible recovery alternatives depending on the tyre's condition and category: reuse, retread, recycling and energy recovery.

1.1.3 Problem Description

As previously mentioned, used tyres are an increasing waste flow and its incorrect disposal, namely in landfills, endangers the environment and the Human's health therefore, there is a strong motivation for efficiently managing this specific waste stream. Managing used tyres' reverse logistics is however a challenging task since the routing of these products comprehends different destinations that highly depend on the used tyres' type, quality and quantity, parameters subject to a high level of uncertainty. Thus, the importance of having a decision tool that supports the design and planning of the network responsible for the collection, transport and recovery of used tyres and considers its associated uncertainty, is recognised. Additionally, decisions related with the design and planning of such networks must take into account its economic, environmental and social sustainability in order to promote a circular economy for this product's life cycle (Barbosa-Póvoa et. al, 2018).

In this context, the research problem introduced in this project concerns the design and planning of a network responsible for the collection, transport and recovery of used tyres considering the three pillars of sustainability and it is applied to the Valorpneu case-study.

1.2 Objectives

This work aims to develop a decision support tool for the design and planning of Valorpneu's network considering the three dimensions of sustainability through the following objectives:

- Contextualise the research problem and characterise Valorpneu's network;
- Describe the research problem and clarify the respective objectives;
- Perform a literature review on relevant subjects such as supply chain, reverse logistics, sustainability and optimisation models for the design and planning of supply chains to provide a theoretical framework for the problem;
- Develop the decision support tool and validate the resulting model against Valorpneu's network As-Is;
- Evaluate the model results for different relevant scenarios and perform a sensitivity analysis to the critical parameters to test the robustness and feasibility of the results obtained

1.3 Structure

The present work comprehends seven chapters structured in the following way:

The first chapter is the project's introduction. First a general context to the problem in hand is provided revealing its relevance nowadays as motivation for the study. Then the specific case of used tyres and the Portuguese scenario for the problem are contextualised. Lastly, the project's objectives are defined.

During the second chapter the case-study is depicted. A brief introduction about Valorpneu is given and then Valorpneu's collection, transportation and recovery network of used tyres, the SGPU, is detailed. This includes the characterisation of network's agents and their respective role inside SGPU. Throughout this chapter the research problem which is going to be addressed in the dissertation is also described.

In the third chapter a literature review covering the relevant studies related to the research problem is presented. Accordingly, studies about supply chains, reverse logistics, sustainable supply chains and mathematical models for supply chain design and planning are analysed and compared in order to provide guidelines for the future work and to identify possible gaps in the literature to be explored.

Chapter four characterizes the mathematical model and respective formulation which is subsequently implemented in a proper software for mathematical optimization.

The fifth chapter the procedures used to collect and treat the model's input data and the assumptions considered in its absence are described.

In the sixth chapter first, model developed is validated against the current Valorpneu's network then, the scenarios considered are tested for each objective function and the respective results are presented and analysed. The critical parameters are posteriorly subject to a sensitivity analysis to test the results' robustness. In this chapter Oporto region is also further analysed.

In the last chapter the study's conclusions are drawn and future work directions discussed.

1.4 Methodology

In the context of the research problem of this study the methodology to address it can be divided into six steps as illustrated in Figure 2: characterization of Valorpneu's network; literature review; data collection; development of the decision support tool; model validation; and analysis of the results.

These steps are detailed as follows:

1 **Characterization of Valorpneu's network**: In the first phase the network of collection and valorisation of Valorpneu is characterized which includes the description of the operators involved and respective role and how they interact inside the network.

2 **Literature Review**: During the second step a literature review on the relevant topics on supply chain, reverse logistics, sustainability and optimizations models for the design and planning of supply chain is performed in order to provide a theoretical framework to address the research problem and identify possible research gaps.

3 **Data Collection**: The third step involves the collection and treatment of the data needed for implementing the model regarding the network's operation and flows. Most of this data is provided by Valorpneu. The metrics to evaluate the costs and environmental and social impacts, the assumptions considered due to absence of data and the procedures used to estimate and tackle data are also defined during this step.

4 **Development of the Decision Support Tool**: In the fourth phase the decision tool to support the design and planning of Valorpneu's network is developed based on the literature review performed on the existing optimization models.

5 **Model Validation:** The fifth step comprises the model validation. In this phase the model developed is applied to the case-study in its current status. The results obtained also serve as baseline to compare and evaluate improvements obtained concerning the three dimensions of sustainability.

6 **Analysis of the Results:** During the final phase, different scenarios are tested in order to find a solution that better satisfies the study objectives. The critical parameters are also subject to sensibility analysis to test the robustness and feasibility of the results obtained.

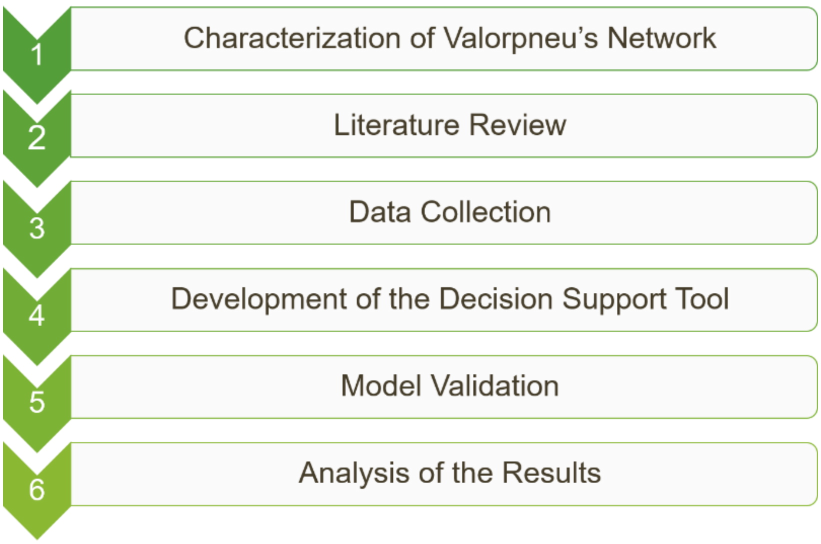

Figure 2 - Research Methodology

2 The Case-study

2.1 Valorpneu

Valorpneu – Sociedade de Gestão de Pneus, Lda. was formed on the 27th of February 2002 by the associations of tyre producers (ACAP), tyre retread manufactures (ANIRP) and rubber manufacturers (APIB) in response to the requirements defined by the Decree-Law nr 11/2001 which are based on the EPR system. Valorpneu was first licensed on the 7th of November 2002 by the Ministries of Economy, Cities, Land Management and Environment and began its operation on the 1st February 2003.

According to the Decree-Law nr 11/2001 Valorpneu's responsibilities as the entity responsible for the management of the integrated system of used tyres include:

- The coordination of the collection and transportation network of used tyres which comprises the celebration of contracts with the entities involved;
- The decision about the destination of each batch of used tyres respecting the priorities and objectives defined;
- The celebration of contracts with the retread manufacturers, recycling operators and energy recovery operators to regulate the physical and monetary flows associated with the used tyres' final routing.

Thus, Valorpneu became the organization responsible for designing, implementing and managing an integrated system that ensured the correct routing of used tyres which led to the creation of the Used Tyres Management Integrated System (SGPU).

Valorpneu has sixteen years of operation and it is up to date the only operator responsible for the collection and recovery of used tyres in Portugal.

2.2 Used Tyres Management Integrated System

The Used Tyres Management System (SGPU) is an integrated network created by Valorpneu responsible for all processes and entities which ensure the correct destination for used tyres in order to eliminate the disposal of these products in landfills and promote their reuse, retread, recycling and energy recovery.

When a tyre enters the national market, the importer must pay an Eco-value to Valorpneu. Later, once the tyre is sold this amount is charged to the buyer together with the tyre's price. This means that every tyre's importer must celebrate a contract with Valorpneu in order to charge this value. The collection of this Eco-value is how Valorpneu finances all SGPU's operations. Table 1 shows the Eco-value charged by tyre's category in euros per tyre since the 1st of January 2019. Table 1 also lists all tyre's different categories presently collected by the SGPU.

Table 1 - Eco-value Table 2019 adapted from Valorpneu (2019d)

Code	Category	€/tyre
T	Passenger/tourism vehicle	1,05
4x4	4x4 "on/off road"	1,8
C	Commercial vehicle	1,56
P	Truck	7,44
A1	Agricultural vehicle (various)	2,75
A2	Agricultural vehicle (motor wheels)	9,05
E1	Industrial (8" to 15")	1,55
E2	Solid tyres (<= 15")	3,58
G1	Civil Engineering (< 24") and Solid tyres (16" a 23")	7,99
G2	Civil Engineering (>= 24") and Solid tyres (>= 24")	38,02
M1	Motorcycles (>50cc.)	0,65
M2	Motorcycles (until 50cc.)	0,2
F	Aircraft	1,05
B	Bicycles	0,07

The structure of SGPU's network is represented in Figure 3 together with the entities which are part or influence directly SGPU's operations and the used tyres' flows. As illustrated by Figure 3, used tyres are introduced in the system by the **Holders.** These entities can either send the used tyres to the **Retread Manufacturers** if these operators are willingly to accept them or to the **Collection Centres** without any restriction or additional costs. In the **Collection Centres,** used tyres are sorted and sent to a **Retread Manufacturer** if the tyres are suitable for retreading or reuse, to a **Recycling Operator** or to an **Energy Recovery Operator.** Used tyres might have to be sent first to a **Shredder Operator** and then to the **Energy Recovery Operator** in the case this operator only accepts previously shredded tyres**.** End-of-life tyres and shredded tyres are transported to their destination by **Carriers,** which are not represented in Figure 3 but also integrate SGPU's network.

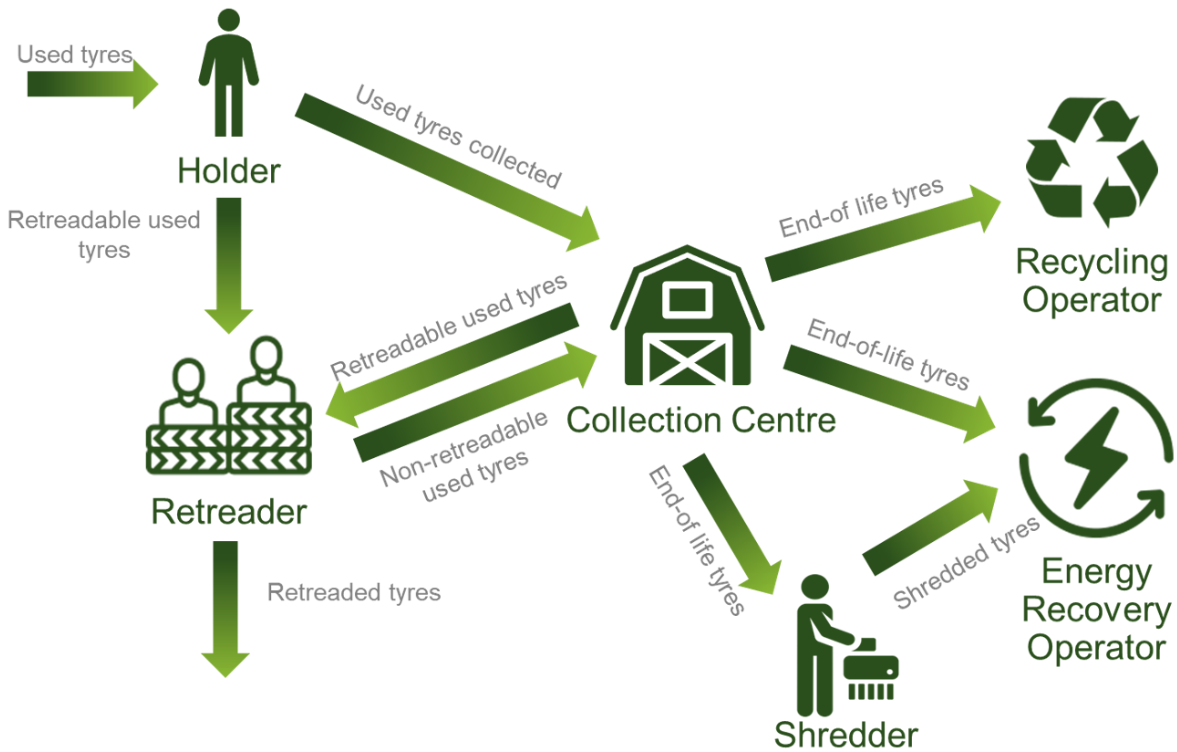

Figure 3 - SGPU network adapted from Valorpneu (2017)

In sum, SGPU's operation begins at the collection centres with the collection of used tyres from the holders, then these used tyres are transported by carriers to one of the existing recovery operators: recycling operator and energy recovery operator or alternatively, to a retread manufacturer, where SGPU's responsibility ceases. Each one of these entities are described in detail in the next subsections.

In 2017 the used tyres processed by SGPU reached a total of 81 292 tons against the 76 657 tons of used tyres introduced in the system during the same year as some existing inventory from previous years was also processed, which resulted in a processing rate of 106% (Valorpneu, 2017).

All the information related to the network flows is managed by Valorpneu through an online platform: the SGPU on-line. This information system promotes the interaction between the network's operators and supports Valorpneu's operational decisions such as:

- Which collection centres need to dispatch used tyres, how many tons should be dispatched and when?
- Which recovery operator should the used tyres be sent to?
- Which carrier should be used?

Every network's operator has access to its account and is responsible for introducing the information concerning its operation.

2.2.1 Producers

The Decree-Law nr 11/2001 defined "producer" as the entity that introduces new or second-hand tyres into the Portuguese market. This includes manufactures or importers of tyres or of any another equipment containing tyres (MAOT, 2001).

According to this legislation and based on the ERP system, the producers are responsible for the collection, transportation and destination of used tyres. These responsibilities are only transferred to Valorpneu when a contract between Valorpneu and the producer is celebrated and under the payment of the Eco-value for each tyre introduced in the national market. The producers which have a signed contract with Valorpneu are SGPU member producers (Valorpneu, 2019b).

In the end of 2017 SGPU had 2 156 member producers which represented an increase of 2,4% comparing with 2016. SGPU member producers introduced 88 462 tons of tyres into the national market in 2017, 0,7% less than in 2016 (Valorpneu, 2017).

2.2.2 Holders

Holders are the entities such as tyre's distributors, car repair shops, gas stations, dismantlers and private individuals which hold used tyres. Holders can either hand the used tyres to the collection centres at no cost or to the retread manufacturers if the tyres present the required conditions. (Valorpneu, 2019a)

These entities are important players in SGPU since they are who introduce used tyres into the system, i.e., they are the origins of SGPU's network. In 2017, as mentioned before, 76 657 tons of used tyres were introduced in the SGPU by 4 861 Holders and 74% of these used tyres was introduced by either tyre and vehicle distributors or car repair shops. The majority of used tyres introduced in SGPU in 2017 was generated in Lisbon, followed by Oporto, Braga and Leiria districts (Valorpneu, 2017). Figure 4 shows the distribution of the number of Holders who introduced used tyres into the SGPU per district in 2018.

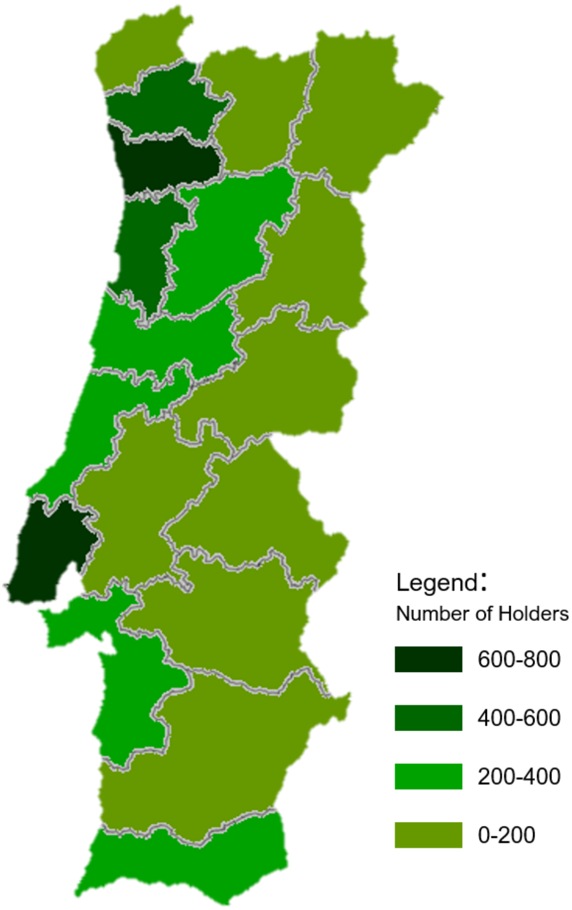

Figure 4 – Number of Holders per district in 2018 adapted from Tavares (2006) with data from Valorpneu

2.2.3 Collection Centres

Collection centres are licensed operators responsible for receiving the used tyres from the holders and storing them before they are sent to their destination which comprehends four possible alternatives: reuse, retread, recycling or energy recovery. Reuse involves tyres which, are suitable to enter the tyre market or are used for other ends without being processed. Retread is the operation that allows used tyres to be restored and used again. Recycling is the operation involving the processing of used tyres so these can be used for other purposes different from the original one. Energy Recovery is the combustion of used tyres with exploitation of energy (Valorpneu, 2019e).

Collection centres play an essential role in SGPU's performance. They are responsible for the control and quantification of used tyres sent to the recovery operators and retread manufacturers and for the relationship between the SGPU and the holders. In order for the system to work properly, the collection centre's network must be spread across Portugal and close to the main holders (Valorpneu, 2019a).

The SGPU has a network of 48 collection centres, 39 across the Portuguese mainland, 8 in Azores and 1 in Madeira. This work will be focused on the Portuguese mainland so the collection centres in the autonomous regions Azores and Madeira will not be tackled. The network of the 39 collection centres located in continental Portugal is represented in Figure 5.

Figure 5 - Collection Centre's Network adapted from Google Maps (2019) and Valorpneu (2017)

As mentioned in subsection 2.2.2, in 2017 the collection centres accepted 76 657 tons of used tyres from the holders. The collection centres that received higher amounts of use tyres are located in Oporto, Santarem, Leiria, Braga and Lisbon districts (Valorpneu, 2017).

In the collection centres, used tyres are sorted into five different categories according to their dimensions or structure as illustrated in Table 2.

Table 2 - Used tyres' categories adapted from Valorpneu (2018)

Category	Dimensions/ Structure
Passenger vehicle	Diameter ≤ 0,70 m and width ≤ 0,35 m
Truck	Diameter ≤ 1,20 m and width ≤ 0,35 m
Industrial	Large dimensions
Damaged	Tyre with its structure considerably damaged in such a way that it is not possible put it vertically
Massive	Massive tyres including bandages

2.2.3.1 Collection Centres Selection Criteria

Aiming to guarantee the sustainability of the SGPU, ensuring a high service level of the network and the compliance of the established goals, the following criteria related to the collection centres were defined by Valorpneu (Valorpneu, 2011):

1. SGPU must have at least 40 collection centres in continental Portugal, 1 in Madeira and 2 in Azores.
2. SGPU must have at least 1 collection centre per district.
3. A municipality or neighbouring municipalities should not have more than 1 collection centre except when there are retread manufacturers in these municipalities. In this case a municipality or neighbouring municipalities should not have more than 2 collection centres.
4. The minimum distance between collection centres should be:
    - 10 km in districts with more than 1 250 thousand inhabitants;
    - 20 km in districts with more than 200 thousand and less than 1 250 thousand inhabitants;
    - 30 km in districts with less than 200 thousand inhabitants.
5. There should not exist more than:
    - 5 collection centres in districts with more than 2 000 thousand inhabitants;
    - 4 collection centres in districts with more than 1 250 thousand and less than 2 000 thousand inhabitants;
    - 3 collection centres in districts with more than 750 thousand and less than 1 250 thousand inhabitants;
    - 2 collection centres in districts with more than 200 thousand and less than 750 thousand inhabitants;
    - 1 collection centre in districts with less than 200 thousand inhabitants.

These criteria are currently being subjected to a review by Valorpneu as it was verified that they are affecting the service level of the collection network particularly in Oporto region where the distances between one of the collection centres and the holders has been restricting the quantity of used tyres collected. Thus, the results of this work should also assist the redefinition of the collection centre selection criteria.

Beyond these criteria, to become a Collection Centre an entity needs to have a license for temporary storage of used tyres and comply with several other norms that can be consulted in Valorpneu (2011).

2.2.4 Carriers

Carriers transport the used tyres from the collection centres to the recovery operators. Carriers are also responsible for the transport of used tyres first from the collection centres to the shredder operators and then to the energy recovery operators when this intermediate operation is required. They are part of SGPU's network thus their operation is controlled by Valorpneu.

In 2017 a total of 22 carriers worked in SGPU's network, 20 in continental Portugal, 1 in Azores and 1 in Madeira (Valorpneu, 2017).

2.2.5 Retread Manufacturers

Retread manufactures can be both a destination and an origin for used tyres. These entities can acquire used tyres from the collection centres or drop them off at the collection centres without additional costs when these tyres cannot be retreaded (Valorpneu, 2019a).

Retread manufactures can also be producers when they import used tyres to retread. In this case, these operators must comply with the same obligations as the producers described in subsection 2.2.1.

In 2017, Valorpneu had a contract with all the 23 retread manufacturers with operation in Portugal, 19 in continental Portugal, 2 in Azores and 2 in Madeira. From the used tyres processed by the SGPU in 2017, 11 100 tons were sent to retread and 760 tons to reuse which represents 15.5% of the total used tyres processed by SGPU. This retreading/reusing rate was lower than the rate defined in Valorpneu's previous license (prevailing in 2017) which was 27%. (Valorpneu, 2017). The current license expects that 65% of the used tyres collected are either retreaded/reused or recycled (Economia e Ambiente, 2018).

2.2.6 Shredder Operators

Some of the SGPU's recycling operators only accept used tyres previously shredded thus, some of the used tyres are sent to a shredder operator before being recycled.

Currently, SGPU works with only one shredder operator, SGR – Sociedade Gestora de Resíduos, S.A. located in Seixal.

2.2.7 Recycling and Energy Recovery Operators

SGPU's network comprehends four possible destinations for the used tyres:

- Retreading/reusing;
- Recycling;
- Processing for energy recovery;
- Reusing for a different end other than the original such as for protection of marine piers.

Although used tyres are sent annually to all the four destinations, the recycling and energy operators are the most common end point of SGPU's network since a significant number of the used tyres generated is rejected by the retread manufacturers due to their unsuitable condition for retrading/reusing or because of restrictions in the retreaded tyres' market (Valorpneu, 2017). These recycling and energy recovery operators receive and process the used tyres sent by the collection centres according with the goals established and against payment of a contribution by Valorpneu.

Valorpneu works with three recycling operators: Recipneu located in Sines, Biosafe located in Ovar and Biogoma located in Santarem. These operators receive the used tyres and convert them into granulated rubber with the separation of the incorporated metal and textile (Valorpneu, 2019c). To obtain the granulated rubber, Biosafe and Biogoma use a mechanical pulverisation process at room temperature and Recipneu uses a cryogenic treatment where the polymers from the rubber are cooled down to very low temperatures using liquid nitrogen and then the rubber is shattered by impact (Biogoma, 2019; Biosafe, 2014; Recipneu, 2019). In 2017 a total of 48 933 tons of used tyres were recycled which represents 60,2% of the used tyres processed by SGPU. The resulting granulated rubber was mainly used for production of various floors (47,3%) and for synthetic turf (42,4%). Other destinations included isolation and rubber industries, horse riding pavements and asphalt rubber mixtures. An amount of 56,1% of the granulated rubber was directly sold in the Portuguese market, 20,7% was exported to the European market and 19,5% was exported to other markets. The recycling operators are obliged to report all the information related to the sale of the used tyres' granulated rubber to Valorpneu to prove that the used tyres were effectively recycled however, the resulting profits belong to the respective operators (Valorpneu, 2017).

Regarding the energy recovery option, there are currently six energy recovery operators in SGPU's network: five concrete industrial plants, three from the Secil Group located in Maceira, Outão and Pataias and two from the Cimpor Group in Alhandra and Loulé and one cogeneration plant from Recauchutagem Nortenha in Penafiel. These operators accept the used tyres either in one piece or previously shredded and produce energy for their operation by taking advantage of the high heating value of the used tyres and avoiding the consumption of fossil fuels (Valorpneu, 2019c). During 2017, 20 499 tons of used tyres were sent to the six energy recovery operators corresponding to 25,2% of the used tyres processed by SGPU during the same year (Valorpneu, 2017).

2.3 Problem Characterization

The purpose of a used tyres management system is to ensure the correct end of these products' life cycle. This requires the promotion of used tyres' retread, reuse, recycle or valorisation with energy recovery in order to avoid other forms of disposal, harmful for both the environment and public health such as landfill disposal.

In Portugal, the specific characteristics of the tyre industry and the legal obligations, imposed by the government for the management of this specific waste stream, led to the formation of a single entity to manage the used tyres system, Valorpneu. Since its creation, Valorpneu has been working to implement and manage a network composed by multiple entities namely the holders, collection centres, carriers, retread manufacturers and recovery operators that efficiently ensures the routing of used tyres to a suitable destination according to the legal targets in terms of collection, retreading and recycling rates. The implementation and management of this network is a challenging task involving not only the management of the network's flows and interaction between the different operators but also the design and planning of the network itself.

The problem studied in the present work is concerned with this last issue. Accordingly, it is necessary to determine the correct location and number of the collection centres in order to maximize the collection of used tyres from its sources and to avoid bottlenecks along the network that keep the used tyres collected from being recovered creating unwanted stock. This is a complex problem by nature due to the uncertainty related with the quantity and quality of product collected. Additionally, these decisions must consider the economic, environmental and social sustainability of the network managed by Valorpneu resulting in a problem with different and potentially opposing objectives.

As discussed in subsection 2.2.3.1, Valorpneu defined several criteria for the selection of new collection centres that must be followed by the applying entities for these be considered as valid candidates. These criteria include among others, restrictions related with the number and distances between collection centres in the same district and/or municipality. Nevertheless, Valorpneu realized that these criteria have been compromising the service level of the network, particularly in Oporto region where the distances between one of the collection centres and the holders has been restricting the quantity of used tyres collected. Thus, this work also intends to guide the redefinition of these criteria, so the network's proposed objectives are achieved in a sustainable manner. Particularly, the collection operation's performance in Oporto region is to be improved. Furthermore, the planning of the network flows among its entities will support decisions regarding the operators' capacities, inventory levels in the collection centres and the destination given to the used tyres collected.

Lastly, the relevance of this problem also concerns its associated complexity as it deals with not only the trade-offs between the different goals but also the uncertainty related with the quantity and quality of product collected which directly influences the destination given to the used tyres and the resulting recovery rates.

3 Literature Review

In the present chapter a literature review on the relevant topics for the research problem described in the previous chapter is performed. The chapter is divided into four sections: The first section addresses the notion of supply chain covering the concepts of supply chain management, reverse logistics and sustainable supply chains as the problem concerns a reverse logistics network considering the three dimensions of sustainability. Accordingly, in the second section supply chain design and planning decisions are discussed with focus on network design of reverse logistics. The third section covers the literature on models applied to address tactical and strategic decisions of sustainable supply chain network design and planning with emphasis on reverse and closed-loop SC. Finally, in the last section conclusions are drawn and the main research gaps identified are outlined.

3.1 Supply Chain

Ever since its origin the term Supply Chain (SC) has been subject to many definitions. Ganeshan & Harrison (2002) defined SC as the network of facilities responsible for the procurement and transformation of materials and distribution of the resulting products to customers. Bhaskaran & Leung (1997) stated that SC involved more than production, distribution and transportation functions but also the coordination between its strategic, tactical and operational levels. According to Min & Zhou (2002) the key goal of a SC is to reinforce the competitiveness and operational efficiency and increase profits of a company and its business partners. Generally, a SC involves all the stakeholders: suppliers, manufacturers, warehouses, carriers, distributors and even customers, who directly or indirectly contribute to the fulfilment of an order (Bhaskaran & Leung, 1997; Chopra & Meindl, 2013; Tsiakis, Shah, & Pantelides, 2001).

3.1.1 Supply Chain Management

The concept of Supply Chain Management (SCM) emerge in the literature in the 80's when the increasing worldwide competition and resulting pressure to become more efficient, compelled manufacturers to start building strategic alliances with their suppliers and incorporate transportation and logistics functions into the value chain (Tan, 2001). Companies started to realize they can no longer work as independent players but rather as a network of organizations working together to achieve customer satisfaction (Martin, 2011; Min, 2015). Since its genesis, SCM has been a widely discussed subject. Some academics considered SCM and logistics management resembling terms (Simchi-Levi et al., 2008), others argued that SCM is a wider concept that covers the integration of more business operations than logistics management (Cooper et al., 1997; Martin, 2011). Nevertheless, all emphasised the need of an integrated SC at strategic, tactical and operational levels. Stadtler (2004) described SCM as "the task of integrating organizational units along a SC and coordinating materials, information and financial flow in order to fulfil (ultimate) customer demands with the aim of improving competitiveness of the SC as a whole" which is similar with the definition proposed by Martin (2011). Ballou et al. (2000) suggested that the SC is concerned with the activities responsible for the transformation and transport of goods and services and related information from the sources to the end users and the management is related with the internal and external integration of these activities.

3.1.2 Reverse Logistics

As previously mentioned, a SC is traditionally represented by a forward flow of materials from suppliers to customers. In the past, producers were not concerned about what happened to their products after being used but increasing environmental concerns, product returns due to customer dissatisfaction and governmental pressure have forced companies to consider and implement a reverse flow that recovers the used products in order to capture additional value or ensure a correct disposal (Beamon, 1998; Helms & Hervani, 2006; Rogers & Tibben-Lembke, 1999). Landfill and incineration for product's disposal became non-viable options in most countries resulting in high disposal costs (Thierry et al., 1995). Accordingly, Reverse Logistics (RL) started to play an important role in the companies' strategy as a mean to gain competitiveness advantage. Managing efficiently the RL network may reduce costs, increase revenues and strengthen company-customer relationship (Beamon, 1998). Moreover, the rise of environmental concerns for waste generation reduction through reuse and recycling opportunities have reinforced the importance of having a RL system (Fleischmann et al., 1997).

Following the definition given by the Council of Logistics Management for logistics, D. S. Rogers & Tibben-Lembke (1999) defined RL as "The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal". Usually RL starting points are the final users from where the products are collected and then these products are sent to different destinations including recycling, remanufacturing, repairing and disposal. The simultaneous integration of forward and reverse supply chains originates a closed-loop supply chain where returned products are introduced back into the forward supply chain (Govindan et al., 2015). In an ideal scenario companies establish a closed-loop supply chain so design and production decisions are taken considering the product's remanufacturing and recycling (Wassenhove & Guide Jr., 2002). Generally, RL systems include a set of activities such as collection, cleaning, disassembly, testing, sorting, storage and recovery operations with the purpose of recovering or properly disposing the returned products (Lu & Bostel, 2007).

3.1.2.1 Reverse Logistics Motivations

Motivations for RL arise from several reasons including reuse motivation, type of recovered items, parties involved, recovery options and return reasons (De Brito et al., 2005; Fleischmann et al., 1997; Thierry et al., 1995).

Reuse motivation can be divided into ecological and economic motivations. Ecological motivations are mainly a result of the legal requirements imposed in some countries that allocate the product life-cycle responsibility to the producer with programs such as the EPR. The growing importance of having a "green" image has also motivated companies to invest in their RL systems. Economic motivations appear when recovered products result in production savings, for example, when some valuable parts of a used product are easily recovered and incorporated into the production of the new product or when some used product's repair costs are much lower than production costs of a new product. Ideally, there is both ecological and economic motivations resulting in sustainable opportunities (Fleischmann et al., 1997).

Products are differentiated according to the return reason and time. Thus, items can be categorized into packages, spare parts and consumer goods. Reusable packages are usually returned after the goods are transported, i.e., in a short period of time while spare parts and consumer goods are returned in cases of failure/prevention or at the end of their life cycle respectively, involving longer time windows (Fleischmann et al., 1997).

As for the parties involved, they are concerned with who is responsible for the returned products and respective reuse activities, i.e., collection, cleaning, disassembly, testing, sorting, storage and recovery: the original producer or alternatively a third party firm (Fleischmann et al., 1997).

Thierry et al. (1995) distinguishes recovery options from waste management activities. Figure 6 illustrates this distinction with an integrated SC where both forward and return flows are represented. Recovery options include repair, refurbishing, remanufacturing, cannibalization and recycling and waste management activities consist in incineration and landfilling. Returned products may also be directly reused without additional processing.

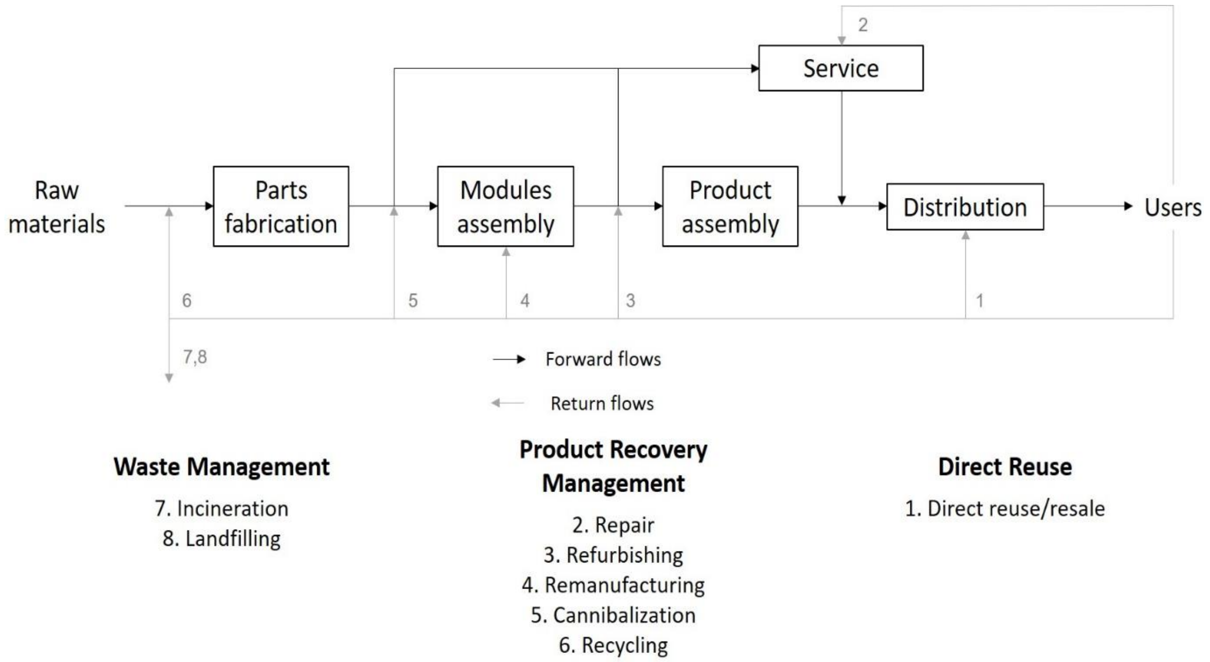

Figure 6 - Integrated SC (Thierry et al., 1995)

De Brito & Dekker (2002) considers a slightly different approach and categorizes types of recovery in product recovery where products are reused, component recovery where products are dismantled and components are used in manufacturing, material recovery, i.e. product recycling and energy recovery where energy released during incineration is recovered and used for other applications.

According to De Brito et al. (2005) the reasons behind products or materials returns may be classified as:

- Manufacturing returns like quality-control returns or raw material surplus;
- Distribution returns, i.e., returns due to the distribution of manufactured goods such as product recalls or B2B commercial returns;
- Market returns, B2C commercial returns, warranties, repair services returns, end-of-use returns and end-of-life returns.

3.1.2.2 Forward versus Reverse Logistics

Even though RL is often described as the movement of products or materials contrary to the traditional flow (Stock & Lambert, 2001), forward and reverse logistics are different concepts with distinct characteristics (Gülsün et al., 2006).

In RL supply is not determined by the system and is usually difficult to predict while in forward systems product quantity, timing and quality can be managed to meet the market needs. RL network structures are frequently more complex and include more interdependencies since the products destination highly depends on their quality. Additionally, sources of used products diverge considerably specially in number whereas the number of suppliers in traditional SC is comparably lower. This means that typically in RL the number of flows is high and the volume low. Finally, used products' markets are subject to more demand uncertainty since these types of markets are not as developed as new products' markets. This hinders the task of forecasting the demand for used products. (Fleischmann et al., 2000)

3.1.2.3 Reverse Logistics under Extended Producer Responsibility

In subsection 3.1.2.1 ecological motivations, specifically the ones originated by governmental pressure, appear as one of the reasons why RL systems are so important nowadays. Following EPR initiatives to waste management, many countries started to assign the product life-cycle responsibility to the producers including the management of the product's end-of-life. In Europe, the concept of EPR emerged in the early 1990's aiming to reduce waste generation and raw materials consumption and promote products' eco-design, recycling and reuse (Lifset & Lindhqvist, 2008; Lu & Bostel, 2007; Mayers & Butler, 2013). Accordingly, EPR initiatives induced the development of RL systems for managing waste stream flows of specific product's categories such as packaging, End-of-Life Vehicles (ELV), Waste Electrical and Electronic Equipment (WEEE), batteries, tyres, oils, medical waste among others (Monier et al., 2014). Mayers & Butler (2013) identified three phases when establishing ERP's operations: design i.e., learn the infrastructure and legislation requirements; build i.e., develop the operations of collection, treatment and recycling; and operate which involves monitoring these operations in order to ensure they work efficiently. These specific RL systems are usually managed by independent organizations responsible for the collection and processing of the returned products on behalf of the respective producers, called Producer Responsibility Organizations (PROs) (Lifset & Lindhqvist, 2008).

The implementation of EPR systems is complex involving many producers and waste collectors that need to find a way of cooperating in order to guarantee that the waste is collected at the right time and location. Thus, PROs appear to assist this task as normally, activities involved in EPR systems are not part of the producers' core business (Mayers & Butler, 2013). According to Mayers (2007) PROs are conceived to "organize pick-up of waste from designated public and retailer collection points, subsequent treatment and recycling, and reporting of results to national governments". PROs can appear as individual national structures, specific industry structures or multiple competing structures at sector, national or international levels (Mayers, 2007).

Literature on how the EPR initiatives are influencing the management of these products' waste stream is vast. Cahill et al. (2010) compare the implementation of EPR in eleven EU countries in packaging and WEEE products in order to evaluate the effect of local authorities concluding that results are more positive when local authorities are engaged in the design and implementation of EPR systems. Niza et al. (2014) evaluate the influence of EPR schemes in waste management performance in Portugal for packaging, used tyres, used mineral oils, end-of-life vehicles, WEEE, portable batteries and car and industrial batteries. In this context, Portuguese EPR policies aim to design a collection, transport and recovery network, improve the waste management ecological performance and create a competitive market for the resulting products. Milanez & Bührs (2009) analyse how EPR European policies are being implemented in Brazil for used tyres and explores the difficulties in adopting foreign policies that are context specific. Gerrard & Kandlikar (2007) assess how ELV directive in Europe is influencing vehicle design, level of ELV recovery and information provision.

In general, EPR initiatives have produced a positive impact on achieving products' recycling targets and reducing environmental impacts due to improper waste disposal but when it comes to eco-design for reuse and remanufacture their influence is still limited (Gerrard & Kandlikar, 2007; Lifset & Lindhqvist, 2008; Niza et al., 2014)

3.1.3 Sustainable Supply Chain

The concepts of sustainability and sustainable development gained a global awareness in the past few decades as society became more concerned about environmental and social issues (Hutchins & Sutherland, 2008). Accordingly, companies have been pressured to adopt more sustainable and eco-friendly practices in their operations and products (Alzawawi, 2013). Government legislation, stakeholder pressure, depletion of resources, low carbon economy, environmental standards and social responsibility are the driving forces for integrating sustainability in the companies identified by Gopalakrishnan et al. (2012).

As outlined in the beginning of this work, sustainable development was defined by the World Commission on Environment and Development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). This definition was extended to include the three pillars of sustainability explored in the concept of the Triple Bottom Line (TBL). The TBL analyses the effect of corporative decisions in the economic (profit), environmental (planet) and social (people) areas (Martin, 2011). Under the TLB context companies are compelled to bring sustainability into their business increasing its resilience through the integration of the economic, environmental and social pillars in their SC (Ahi & Searcy, 2013). Hence, the concept of Sustainable Supply Chain Management (SSCM) emerged as a challenging field attracting both researchers and practitioners (Ahi & Searcy, 2013; Barbosa-Póvoa et al., 2018; Rajeev et al., 2017; Seuring & Müller, 2008).

Ahi & Searcy (2013) defined SSCM as the integration and coordination of the economic, environmental and social aspects in every phase and process of SCM "in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term". Thus, it is important to explore sustainable opportunities during the whole product's lifecycle including the end-of-life where RL steps in. Indeed, RL is considered as fundamental to achieve sustainable development as it aims to recover the remaining value of used products and use resources efficiently (De Brito & Dekker, 2002; Dowlatshahi, 2000).

The way the literature is exploring and integrating the perspectives of the TBL concept is analysed in the next subsections.

3.1.3.1 Economic Pillar

Considering the economic dimension of sustainability, the main economic indicators addressed in the literature are cost, profit, Net Present Value (NPV) and financial risk. Other non-financial parameters are also explored like service level and product quality which are then translated into economic metrics (Barbosa-Póvoa et al., 2018).

Seuring (2013) performed a review on papers applying quantitative models on SSCM up to 2010 and concluded that the economic pillar is mainly addressed through cost related decisions. Barbosa-Póvoa et al. (2018) support this deduction in their review on operational research methods in Sustainable Supply Chain (SSC) where 59% of the analysed papers use cost as an economic measure. Furthermore, the authors also stressed that in strategic decisions such as network design location problems, NPV and financial risk should be considered as these metrics better account for investment costs and associated risks.

Life-Cycle Costing (LCC) appears as an interesting alternative to assess the economic impacts of products throughout their life cycle however it is still an option under development and there is still many discrepancies on the way LCC studies are being applied affecting the comparison of results obtained (Buyle et al., 2019; Hutchins & Sutherland, 2008).

3.1.3.2 Environmental Pillar

Regarding the environmental impact, several different approaches to model this dimension are explored in the literature (Brandenburg et al., 2014; Seuring, 2013) though the Life-Cycle Assessment (LCA) methodology is considered as the most developed and reliable method to estimate the environmental effect of a product or a process over its entire life-cycle from raw material acquisition to disposal (Commission, 2003; Ness et al., 2007). According to Wolf et al. (2012) there are five motives that make LCA such a powerful tool:

1. LCA combines several environmental problems such as climate change, toxicity and resource depletion into a common framework avoiding the increase of effects in one impact resulted from reducing another.
2. LCA is focused on a scientific and quantitative evaluation of the problems.
3. With LCA it is possible to allocate the potential environmental impacts to a specific system.
4. LCA uses an entire life-cycle approach avoiding higher impacts in one life cycle stage caused by the reduction of the impact in another.
5. Finally, with LCA is possible to evaluate the performance of different systems on a comparable ground.

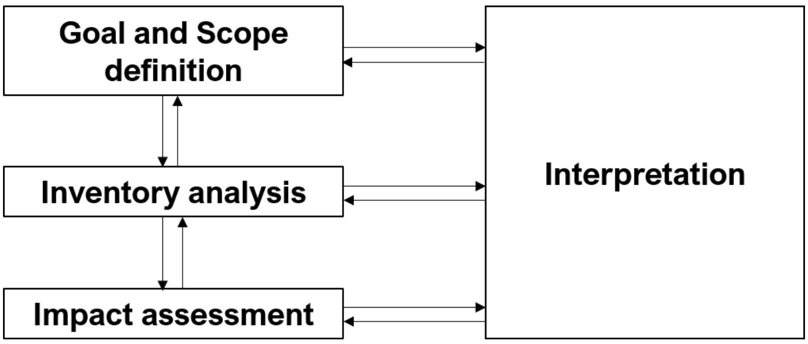

Figure 7 - LCA framework (ISO14040, 2006)

Figure 5 illustrates the four main steps of an LCA study defined by the ISO 14040 norm. The first step is the goal and scope definition where study objectives, limitations and system boundaries are defined. Then during the inventory analysis phase, the inputs and outputs of the system are quantified through the compilation of data. In the impact assessment stage, the data compiled in the inventory analysis phase is assessed against environmental impact categories or indicators. The last step involves the interpretation of the outcomes of the two previous steps. This phase should also include the conclusions and recommendations of the study related with the goal and scope defined (ISO14040, 2006).

The inventory analysis and impact assessment phases also known as Life-Cycle Inventory (LCI) and Life-Cycle Impact Assessment (LCIA) are usually present in most LCA methods and include the following steps: inventory analysis, characterization which involves the quantification of the impacts resulted from the emissions, extractions and land use and categorization of these impacts into midpoints (impact categories) and/or endpoints (damage categories), normalization followed by a weighting step and finally a single score is obtained (Eskandarpour et al., 2015; Mota et al., 2015).

A variety of different LCA methods can be found in the literature. The most frequently used are the EcoIndicator-99 and the IPCC methods (Barbosa-Póvoa et al., 2018). EcoIndicator-99 is an endpoint based method that brings together eleven impact categories into three damage categories: human health, ecosystem quality and resources (Goedkoop & Spriensma, 2001). Subulan et al. (2015) presented a network design model for a tyre CLSC considering environmental decisions and applied the EcoIndicator-99 to evaluate the environmental impact of a tyre lifecycle. In the work of Pishvaee et al. (2012) the EcoIndicator-99 was also used to support decisions on SC network configuration considering the environmental impact. IPCC is a method that evaluates only one impact category: climate change thus the results of its application are quite limited in terms of evaluating environmental influence (Barbosa-Póvoa et al., 2018). Several other methods such as IMPACT 2002+, CML92 and ReCiPe 2008 are also applied in the literature (Eskandarpour et al., 2015).

Although not commonly explored, ReCiPe 2008 is according to European Commission (2011) the most matured LCA method available. ReCiPe 2008 is based on the EcoIndicator-99 and CML 2002 methods and includes at a midpoint level eighteen impact categories: 1-climate change, 2-ozone depletion, 3-terrestrial acidification, 4-freshwater eutrophication, 5-marine eutrophication, 6-human toxicity, 7-photochemical oxidant formation, 8-particulate matter formation, 9-terrestrial ecotoxicity, 10-freshwater ecotoxicity, 11-marine ecotoxicity, 12-ionising radiation, 13-agricultural land occupation, 14-urban land occupation, 15-natural land transformation, 16-water depletion, 17-mineral resource depletion and 18-fossil fuel depletion. These impact categories are grouped in three damage categories at an endpoint level: damage to human health, damage to ecosystem diversity and damage to resource availability which are further grouped into a single score. (Goedkoop et al., 2013). The aggregation of midpoints into endpoints makes the LCIA outputs easier to understand and apply although these results are subject to a higher uncertainty level and are less comprehensive (Hutchins & Sutherland, 2008). The integration of this methodology in SC network design and planning models is found in the work of Mota et al. (2015).

The Product Environmental Footprint (PEF) is a recent LCA method developed by the European Commission which intends to present a standardized approach for evaluating a product environmental impact throughout its life-cycle (European Commission, 2012b). Nonetheless, like with ReCiPe 2008 there is an absence of works that apply this method in optimization models (Barbosa-Póvoa et al., 2018).

The International Reference Life Cycle Data System 2011 (ILCD) is a midpoint method proposed by the Joint Research Centre of the European Commission and results in a common framework used to analyse different life cycle impact assessment methodologies (European Commission, 2012a).

3.1.3.3 Social Pillar

When comparing the three dimensions of sustainability, the social pillar appears as the least explored by academics and practitioners particularly in SC (Brandenburg et al., 2014; Hutchins & Sutherland, 2008; Rajeev et al., 2017; Seuring, 2013). This is mainly due to the fact that social impact is still not defined in a clear and quantitative manner (Barbosa-Póvoa et al., 2018). Nevertheless, this is an important indicator of sustainability and efforts should be made to integrate this dimension in SC particularly in network design decisions in order to estimate the impact of SC on its stakeholders (Eskandarpour et al., 2015; Hutchins & Sutherland, 2008).

The Global Report Initiative (GRI) suggests that the social pillar of sustainability "concerns the impacts the organization has on the social systems within which it operates" and identifies four social categories: labour practices and decent work, human rights, society and product responsibility which are further detailed in several aspects (GRI, 2013).

Based on the GRI and other relevant literature found Chardine-Baumann & Botta-Genoulaz (2014) identified five social areas: work conditions; human rights; societal commitment; customer issues and business practices. Work conditions involve the sub-areas of employment; labour conditions; respect of social dialog; health and security and human resources. Human rights include child and forced labour; freedom of association and discrimination. Societal commitment is divided in involvement in local community; education, culture and technological development; job and wealth creation; healthcare and societal investment. Customer issues covers marketing and information; healthcare and security; protection of private life and access to essential services. Finally, business practices involve fight against corruption; fair-trading and corporate responsibility promotion.

Hutchins & Sutherland (2008) proposed four quantifiable indicators which can be used to support SC decisions:

- Labour equity – evaluates the income distribution among the company and can be calculated through the ratio between the average labour cost per hour and the yearly compensation of the better paid employee. The closer is the ratio to one, the better is the social performance in this indicator.
- Healthcare – measures the medical support given by the companies to their employees and families. It can be calculated through the ratio between the company's medical expenses per worker and company's market capitalization per worker.
- Safety – defines workplace safety and it is calculated through the ratio between the average of injury free days per worker with the total of days worked per worker.
- Philanthropy – describes the company's role within the community and it is calculated through the ratio between the company's contributions for the community and its market capitalization.

The authors acknowledge that the proposed indicators do not consider all aspects of the social dimension however they comprise a wide range of social issues and represent a basis to assess this pillar in SC. The major strengths of these indicators include the general availability of the required information and their calculation ease.

Several other indicators have been employed in the literature to assess social impact in supply chain design and planning. The most popularly used is job creation, others include poverty, number of working hours, discrimination, health and satisfaction. However, these indicators have been applied individually thus a more comprehensive methodology is required to evaluate the social component of sustainability (Barbosa-Póvoa et al., 2018).

Efforts have been made to integrate the social dimension into a LCA framework similar to what is done with the environmental pillar (Hutchins & Sutherland, 2008). Fontes et al. (2016) suggested a consistent and practical method to evaluate the social impact of a product's lifecycle. Their handbook provides guidelines for companies to perform Social Life-Cycle Assessment (SLCA) on their products. The method involves eight steps: goal and scope; data inventory, referencing, social topic scores, 1st level weighting, stakeholder groups scores, 2nd level weighting and total score and three stakeholders' groups: workers, consumers and local communities. Although SLCA seems a promising methodology there is still a deficit of its application in optimization models (Barbosa-Póvoa et al., 2018). Mota et al. (2015) developed a Social Benefit Indicator to support facility location decisions. This indicator favours job creation in less economically developed regions by sorting locations for the entities of the SC according with a regional factor (e.g.: unemployment rate, population density or income distribution).

3.2 Supply Chain Design and Planning

There are three type of decisions to consider while designing and planning a SC: strategic, tactical and operational decisions. The strategic level involves long-term planning decisions (2-5 years) and gives a framework for the tactical and operational levels as it defines the network design of the SC. The tactical level deals with decisions related with the flow of material and production and inventory levels which are made in an intermediate planning horizon corresponding to 6-24 months. The operational level concerns decisions made on a daily or weekly basis (Simchi-Levi et al., 2008; Wilhelm & Schmidt, 1999).

In the case of RL, as an integrating part of a SC, its design and planning also involves strategic, tactical and operational decisions although the decisions' nature might differ from the ones considered in the traditional forward chain as RL deals with different types of activities and market demand and supply characteristics.

De Brito & Dekker (2002) proposed a decision framework for RL design and planning considering the strategic, tactical and operational levels. Strategic decisions involve recovery strategy, product design, network capacity and design and strategic tools. In tactical decisions product's integration, procurement management (where forecasting methods need to be applied), redistribution channels, coordination, production and inventory management and marketing and information technologies are considered. Operational decisions denote scheduling and controlling the production and managing information.

The main focus of the present work is concerned with the strategic decisions of RL network design which deal with the number of facilities in the network, respective location and capacity and region to be served by each facility and tactical decisions such as the product's flows through the network (Agrawal et al., 2015; De Brito & Dekker, 2002).

3.1.4 Reverse Logistics Network Design

Subsection 3.1.2.2 emphasized general differences between traditional forward SC and RL. In this subsection the characteristics of RL networks are discussed in order to better understand what should be considered when designing and planning this type of networks.

The establishment of RL entails a suitable network infrastructure with physical locations, facilities and transportation links in order to manage and direct the coming flows of used products first to recovery facilities and then to possible interested markets (Fleischmann et al., 2010)

Fleischmann et al. (2000) reviewed several case studies on logistics network design for product recovery and concluded that collection, inspection/separation, re-processing, disposal and re-distribution activities are generally present in all product recovery networks. Collection concerns the activities that gather, and transport used products to the place where they are treated. During inspection/separation it is determined if the used products are suitable for reuse and, accordingly, the respective routing is established. Reprocessing involves the conversion of the used products into usable products which includes recycling, repair and remanufacturing. Disposal is the destination for non-reusable products which comprises transportation, landfilling and incineration. Finally, re-distribution denotes the activities needed to insert the reusable products in a possible market or to deliver these products to the future owners. Agrawal et al. (2015) also included product acquisition as an essential activity in RL which is considered a critical activity for the success of RL due to its related uncertainty (Fleischmann et al., 1997). The activities identified by the authors are represented in Figure 8 along with the processes of forward logistics.

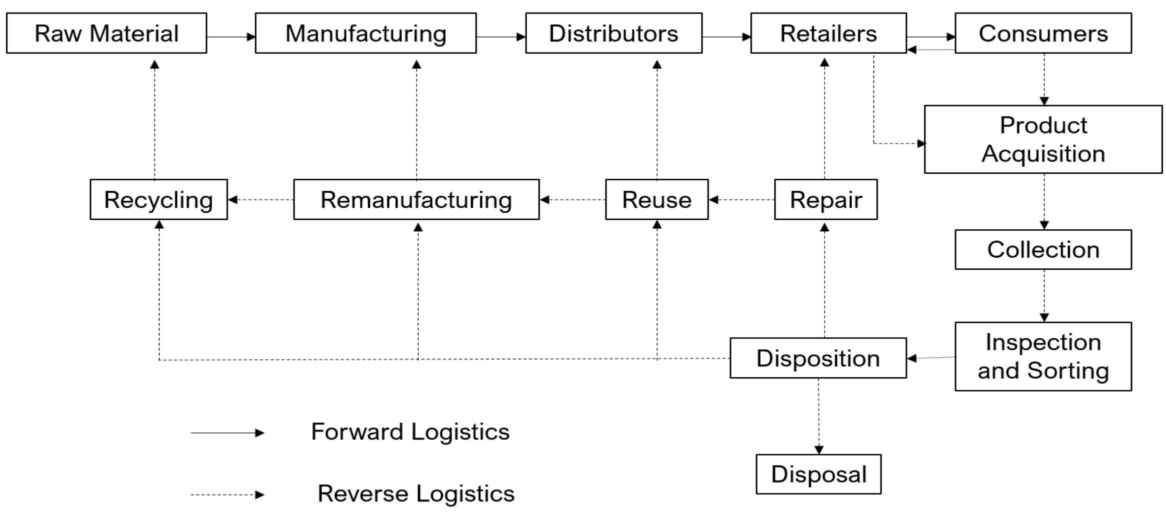

Figure 8 - Forward and RL processes and respective flows (Agrawal et al., 2015)

Wassenhove & Guide Jr. (2002) also separated the reverse supply chain into five essential activities that must be considered when making decisions about the reverse supply chain structure:

- Product acquisition i.e. return products' collection. Here is important to consider the quality, quantity and timing of returned product in order to manage efficiently the reverse supply chain;
- Reverse logistics how the RL network should be designed in order to ensure the transportation of the returned products to the recovery facilities;
- Inspection and disposition which includes all the activities needed to evaluate the condition and quality of the used products;
- Reconditioning i.e. used products remanufacturing. Reconditioning is usually more uncertain than traditional production since used products quality and timing are subject to more fluctuations;
- Distribution and sales. In this phase is also important to verify if there is demand and identify potential markets.

Hence, recovery networks can be divided into three phases: the collection phase where the flows of used products coming from different origins converge in the recovery facilities, the re-distribution phase where recovered products are sent from the recovery facilities to the different demand locations and an intermediate phase that includes the processing steps and it is usually product-specific (Fleischmann et al., 2000). The main differences among product recovery networks configuration arise precisely in this intermediate phase. Thus, Fleischmann et al. (2000) established that product recovery networks diverge in terms of:

- Degree of centralisation, in centralised networks identical operations are performed in the same facility whereas in a decentralised network, different facilities perform the same operations;
- Number of levels which refers to the network's degree of vertical integration. The higher degree of vertical integration, the fewer are the number of levels and more activities are performed by a single facility;
- Links with other networks i.e. if the network is integrated with existing networks or implemented separately;
- Open vs closed loop structure. In closed loop networks resulting products are introduced back into the forward SC closing the network while open networks Entry and exiting flow are independent;
- Degree of branch co-operation, i.e. how industry players cooperate in the implementation of these networks.

Furthermore, due to the supply uncertain characteristics, stochastic analysis for used products availability, timing, quantity and quality is vital to understand the impact of uncertainty on the RL network design (Agrawal et al., 2015).

Based on the type of returned products and recovery options described in 3.1.2.1, Lu & Bostel (2007) classified RL networks as directly reusable networks, remanufacturing networks, repair service networks and recycling networks. The design of recycling networks involves strategic decisions like facility number, location and capacity and region covered and literature applied deterministic, stochastic, simulation and heuristic models to solve these type of problems (Agrawal et al., 2015). De Brito et al. (2005) used similar network types to categorise the case studies analysed in their work about RL network structures concluding that the majority of the case studies referred to directly reusable networks.

In sum, literature identifies product acquisition, collection, processing and redistribution as the primary activities in RL. Networks for RL and traditional forward logistics are typically different mainly due to the differences discussed in subsection 3.1.2.2 such as number of suppliers and products' quality, quantity and timing uncertainty. RL can be integrated in the forward logistics network originating closed-loop structures or designed independently. When designing the network several decisions must be considered including the degree of centralisation, number of levels/echelons, links with other networks, open or closed loop structure and degree of cooperation between the actors (De Brito et al., 2005; Fleischmann et al., 2000; Srivastava, 2008).

Regarding tyres which are the products considered in the case-study addressed in this work, Sahebjamnia et al. (2018) suggested that when designing SC networks for tyres it is important to keep in mind that these products can be recycled and remanufactured and the network should have four echelons: suppliers, manufacturers/recyclers and retailers/collection centres for both forward (between supplier and customer) and RL (between collection centre to remanufacturer or recycling operator).

3.3 Models for Supply Chain Network Design and Planning

As mentioned in the previous section, this work is concerned with strategic and tactical decisions of RL network design and planning considering the three dimensions of sustainability. In this section the models used in the literature to support this kind of decisions are outlined and the particular case of product's under EPR network configuration is analysed in order to identify useful guidelines for the dissertation.

Models are seen as a simple way of representing reality and can either be conceptual involving a group of concepts that depict a situation, entity or procedure or quantitative involving a group of variables and their causal association (Meredith, 1993; Will et al., 2002). Brandenburg et al. (2014) identifies five main types of models in their review on quantitative models for SSCM: mathematical programming models, simulation models, heuristics, analytical models and hybrid models.

The design and planning of SSCM is a complex task thus, tools based on quantitative methods in particular optimisation models are very important to support such decisions (Barbosa-Póvoa et al., 2018). Indeed, literature has largely used optimisation models to solve SC problems in the strategic level sphere with focus on network design problems for forward SC. Strategic and tactical levels are commonly addressed together covering problems concerned with facility location-allocation, transportation modes and inventory management decisions (Barbosa-Póvoa, et al., 2018). Concerning network design problems generally these comprise facility location, link selection, allocation and routing decisions. Some problems that deal with these types of decisions include *p*-median, *p*-centre, incapacitated facility location, capacitated facility location maximum covering location, transportation and network flow problems among others (Contreras & Fernández, 2012). Several facility location problems involve different types of facilities that share a hierarchal flow between them. The group of a same facility type defines a level or echelon in the network (Melo et al., 2009).

Eskandarpour et al. (2015) performed a literature review on SSC network design from where the following conclusions were taken: mathematical models for SSC network design explored in the literature diverge in terms of period (single or multi), product (single or multi), number of echelons, network structure (forward, reverse, closed-loop), objective (single or multi) and type of parameters (deterministic or stochastic) and the majority of them are mixed-integer programming models with both binary variables (facility location, transportation modes, capacity) and continuous variables (product's flows). Most SSC network design models found in the literature are bi-objective linear models where the objectives considered are usually the economic together with either the environmental or the social. Multi-objective optimization models usually involve a solution of compromise between the different and often conflicting objectives specially regarding the three pillars of sustainability thus, solution methods are applied in order to solve SSC network design models. Examples of solution methods found in the literature are weighted sum of objectives, Ɛ-constraint, metaheuristics, goal programming and interactive fuzzy approaches.

Uncertainty is frequently present in SC and as already discussed, when it comes to RL network design, uncertainty plays a preponderant role. Many strategies to deal with uncertainty can be found in the literature. The more often applied are fuzzy programming, stochastic programming, fuzzy stochastic programming, robust optimization and scenario-based methods (Ebrahimi, 2018). Regarding SSC, uncertainty needs to be more addressed considering not only the economic but also the environmental and social parameters (Barbosa-Póvoa et al., 2018).

Table 3 summarizes selected works which model reverse or closed-loop SC design and planning decisions for products under EPR schemes considering some of their important characteristics like model type, network structure, objective, sustainability pillars addressed, parameters nature, recovery alternatives considered and case-study application. These works are described in more detail below.

Table 3 - Review on selected works which model reverse or closed-loop SC design and planning decisions

Articles	Model	Network Structure		Objective		Sustainability Dimension			Parameters		Recovery Alternatives			Application
		Reverse	Closed-Loop	Single	Multi	Economic	Environmental	Social	Deterministic	Stochastic	Remanufacturing	Recycling	Energy Recovery	
Dehghanian & Mansour (2009)	MINLP	X			X	X	X	X	X			X	X	Scrap tyres
Kannan et al. (2009)	MILP		X	X		X			X			X		Tyres and plastic goods
Sasikumar et al. (2010)	MINLP	X		X		X			X		X			Tyres
Bing et al. (2014)	MILP	X		X		X	X		X			X		Household plastic
Roghanian & Pazhoheshfar (2014)	MILP	X		X		X				X	X	X		N/A
Kilic et al. (2015)	MILP	X		X		X			X			X		WEEE
Mota et al. (2015)	MILP		X		X	X	X	X	X					Batteries
Subulan et al. (2015)	MILP		X		X	X	X		X		X	X	X	Tyres
Demirel et al. (2016)	MILP	X		X		X			X			X		End-of-life vehicle
Radhi & Zhang (2016)	MINLP	X			X	X				X	X			Tyres
Amin et al. (2017)	MILP		X	X		X				X	X	X		Tyres
Pedram et al. (2017)	MILP		X	X		X				X	X	X		Tyres
Banguera et al. (2018)	MILP	X		X		X			X		X	X		Tyres
Ebrahimi (2018)	MILP		X		X	X	X			X	X	X		Tyres
Mota et al. (2018)	MILP		X		X	X	X	X		X	X			Electronic components
Sahebjamnia et al. (2018)	MILP		X		X	X	X	X	X			X		Tyres

- Dehghanian & Mansour (2009) presented a Mixed Integer Nonlinear Programming (MINLP) model for the design of a sustainable recovery network using scrap tyres as case-study. Social impact of different recovery alternatives was measured through an analytical hierarchy process method and EcoIndicator-99 was used to assess relative environmental impact of the recovery options. A multi-objective Genetic Algorithm (GA) was used to obtain pareto-optimal solution for the network configuration.
- Kannan et al. (2009) illustrated and solved a closed-loop distribution inventory SC Mixed Integer Linear Programming (MILP) model using a GA and a Particle Swarm Optimisation (PSO). The model was validated with a tyre manufacturer and plastic goods manufacturer case-studies.
- Sasikumar et al. (2010) presented a MINLP model for designing a RL network of a used tyre remanufacturing system. The goal was to maximize the profit of the system and a real case of heavy vehicles tyres was used to validate the model.
- Bing et al. (2014) proposed a MILP model for the RL network design but for household plastic waste considering both transportation cost and environmental impact minimization. The transportation environmental impact is converted to a cost and calculated considering a price of carbon allowances, a carbon equivalent conversion factor and fuel efficiency. Several scenarios were tested to evaluate the best network design alternative.
- Roghanian & Pazhoheshfar (2014) also formulated a MILP model for RL network design where the facilities (disassembly and processing centres) to be opened as well as the transportation strategy were determined. However, in this case demand for returned products is considered as random and the problem was solved through a priority-based Genetic Algorithm (GA).
- Kilic et al. (2015) designed a RL network for WEEE through a MILP model. Optimal locations for storage and recycling facilities were found while meeting the minimum recycling rates of each product category defined by the EU and different collection rates were analysed through different scenarios.
- Mota et al. (2015) proposed a multi-objective MILP model for the design and planning of SSC. The three objective functions comprise: total SC costs minimization including facilities' fixed costs, price of raw material, expenses related with human resources and transportation and product recovery costs; transportation mode and facilities environmental impact minimization which is estimated with ReCiPe 2008 method and network social benefit maximization which is evaluated using the social benefit indicator mentioned in subsection 3.1.3.3. The model was validated through a case-study of a Portuguese battery provider.
- Subulan et al. (2015) developed a multi-objective MILP model for a tyre CLSC network design considering different options for recovery. The maximization of the total CLSC profit and minimization of its environmental impact were the objectives explored. The environmental impact was in this case evaluated through the EcoIndicator-99 method and an interactive fuzzy goal programming approach was used to solve the problem.

- Demirel et al. (2016) formulated a multi-echelon MILP problem for the network design of an end-of-life vehicle recovery system. The aim was to minimize transportation, disposal, recovery and fixed costs of the RL network and a real case of an end-of-life vehicle recovery system in Ankara was used to validate the model.
- Radhi & Zhang (2016) addressed a remanufacturing supply network configuration problem with quality of returns and demand uncertainty. They formulated a MINLP model where profit is maximized. Quality of returns and demand uncertainty is tackled through either normal or exponential distributions for the quality case and normal distribution for demand and respective effects on the system are analysed. The proposed model is applied to the tyre remanufacturing industry.
- Amin et al. (2017) designed a tyre remanufacturing CLSC using a MILP model with the objective of maximizing the total profit. The effect of different sources of uncertainty such as demand and return in the CLSC network was studied through a procedure based on decision tree and discounted cash flow.
- Pedram et al. (2017) suggested a MILP model for product recovery network considering both forward and reverse flows to support decisions on recovery options, number and locations of facilities and material flows. The objective of the model is profit maximization and uncertainty in demand and quantity and quality of returned products is addressed via scenario-based model.
- Banguera et al. (2018) developed a MILP model for RL network design considering collection targets and penalties for products under EPR. The model is employed on a used tyre case-study in Chile to exemplify its applicability.
- Ebrahimi (2018) proposed a stochastic multi-objective MILP model for the development of CLSC network for the tyre industry considering environmental impact and quantity discounts. The three objective functions include cost and emissions impact minimization and network response maximization. The model is solved through the Ɛ-constraint method and a scenario-based stochastic programming approach is applied to deal with uncertainty.
- Mota et al. (2018) further developed the previous work integrating several strategic-tactical decisions to the previous model such as SC design and production, remanufacturing, inventory, supplier, supply, transportation network and product recovery planning. The economic pillar is assessed through the Net Present Value (NPV) that as discussed in subsection 3.1.3.1 better accounts for investment costs. The environmental impact was estimated using ReCiPe 2008 as in the previous work but in this case the impact of different production and remanufacturing technologies and different transportation modes was also considered. The social impact was determined using a Gross Domestic Product (GDP) metric that favour job creation in less economic developed countries. Demand uncertainty was also addressed through a scenario-based approach.
- Sahebjamnia et al. (2018) proposed MILP model for the design of a tyre CLSC network considering both economic, environmental and social objectives. The economic dimension was

modelled through the minimization of the network total cost: fixed costs of opening a facility, variable costs, transportation costs and purchasing costs. For the environmental dimension, the environmental impacts of opening a facility, tyre processing, transportation and tyre disposal in the nature were estimated using the ReCiPe 2008 database and minimized in the objective function. The social dimension was addressed considering two factors: job opportunities (fixed and variable) and work injuries. The objective function maximizes the job opportunities and minimizes employees' lost days due to working accidents. To solve the problem four hybrid metaheuristics algorithms were developed.

A few general conclusions can be drawn from the models just described applied to a tyre case-study: complexity is added when more than one objective is considered. This requires a solution approach to solve the problem which in the models reviewed include using metaheuristics, fuzzy goal programming and the Ɛ-constraint method. Applying multi-objective models to a real case may result in large scale problems which are usually hard and time consuming to solve with some of the common solution approaches. A possible alternative to overcome these drawbacks is to develop hybrid metaheuristics algorithms like in the study of Sahebjamnia et al. (2018). Another factor that further adds complexity to these problems is uncertainty which is usually present in parameters like quantity and quality of used products and demand for the resulted processed products. To address this issue several strategies are used such as scenario-based and decision tree methods and probabilistic distributions applied to the uncertain parameters.

General recommendations provided by these works to future research comprise adding more quantitative indicators for the sustainability dimensions namely for the social pillar; contemplating uncertainty in the environmental and social parameters as well as in demand for remanufactured/recycled products and returned products quantity and quality; considering more than one type of product and different quality levels and examining the effect of cannibalization of retreaded tyres sales on new tyres sales in CLSC cases.

3.4 Chapter Conclusions

In this chapter the literature on SSC network design and planning was reviewed with special focus on RL and RL under EPR systems in order to provide insights for solving the Valorpneu case-study problem. RL network activities were identified and differences between the forward and reverse SC were clarified. The decisions that must be considered when designing this type of network were also enumerated. Finally, the characteristics of the mathematical models applied to solve SSC network design and planning problems were depicted and the works applying this type of models for the network design and planning of product's under EPR systems were analysed and summarized in Table 3 according to selected relevant features to facilitate their comparison.

One of the main research gaps identified was the lack of multi-objective models for products under EPR systems network design and planning considering the three pillars of sustainability simultaneously. The uncertainty related with timing, quantity and quality of returned products was also rarely considered despite its impact on network design and planning decisions and in most of the works reviewed only one or two recovery options were contemplated. Lastly despite of the literature on products under EPR has increased in the last decade, works applying this type of products are still limited.

Considering the characteristics of the Valorpneu case-study research problem and the review performed the model proposed by Mota et al. (2018) appears as the most suitable to address the objectives proposed in this work as it presents a SSC design and planning mathematical model which integrates both strategic and tactical decisions, addresses the three dimensions of sustainability and considers demand uncertainty.

4 Model

4.1 Problem Definition

As previously mentioned, the main goal of the present work is to develop a decision support tool for the design and planning of Valorpneu's network involving decisions related with the number, location and capacity of the collection centres, network flows and quantity of used tyres processed by the recycling and energy recovery operators while considering the three dimensions of sustainability.

In light of the case-study characterization outlined in chapter 2, Figure 9 illustrates a schematic representation of Valorpneu's network with a four echelon structure and this study's boundary. The retread manufacturers together with the holders comprise the sources of used tyres (first echelon) in this representation since the flow of used tyres from the collection centres to the retread manufacturers is negligible (less than 0.05 percent of the total amount of outbound flow of the collection centres for the years analysed) and therefore not considered in this work. Used tyres are then forwarded to the collection centres and finally to the recycling or energy recovery operators. The shredder is an intermediate entity between the collection centres and the energy recovery operators in case these entities only accept previously shredded tyres. These recovery operators are known, and this information is an input of the model.

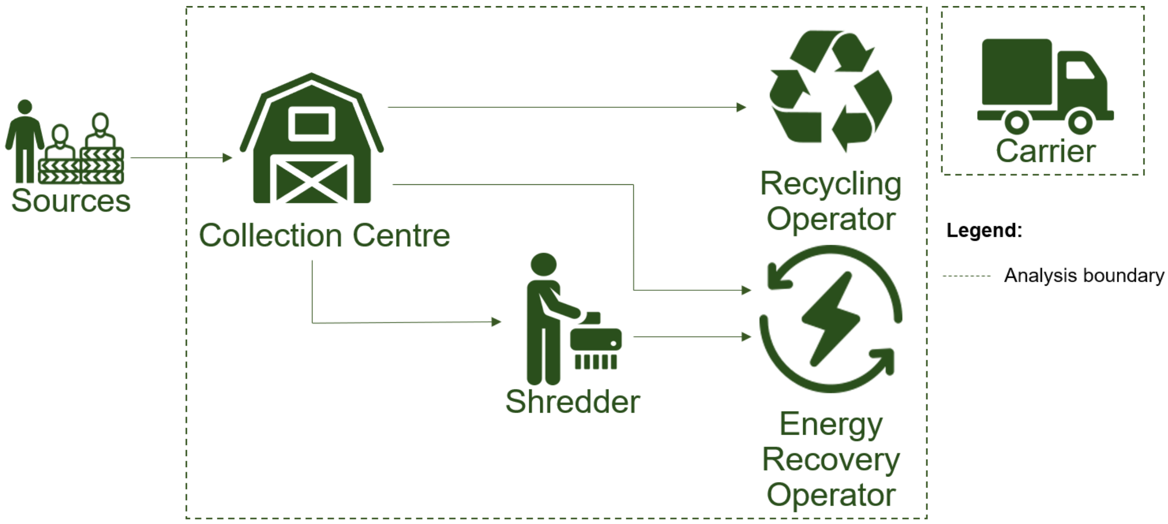

Figure 9 - Network schematic representation

The problem addressed can be stated as follows:

Given:

- A possible superstructure for the location of the network's entities;
- Amount of each product category available at each source;
- Distance between each pair of entities;
- Initial stock levels at each collection centre;
- Collection and recycling legal targets;
- The product category accepted by each recycling and energy recovery operator;

- Maximum and minimum storage capacity of the collection centres;
- Maximum processing capacity of the shredder, recycling and energy recovery operators;
- Compensation fees given to the collection centres, shredder, recycling and energy recovery operators;
- Storage costs;
- Transportation costs;
- Environmental and social impact of each entity and transportation mode.

Determine:

- Number and location of the collection centres;
- Flows amounts between entities;
- Collection centres required capacity;
- Stock levels;
- Amount of product processed by each entity.

In order to:

- Minimize the total network cost;
- Minimize the environmental impact of the network's entities and transportation;
- Maximize the social benefit of the network.

4.2 Mathematical Formulation

In this section the mathematical formulation of the multi-objective MILP model developed to address the current case-study is presented. As discussed in the previous chapter, this model is based on the work of Mota et al. (2018) though some adaptations were made to better represent the case-study. These adaptations and other assumptions made to develop the model are also depicted in this section.

4.2.1 Model Adaptations

Several modifications were made from the original model proposed by Mota et al. (2018). Starting with the network structure, the present work only concerns the reverse network of the tyre lifecycle thus, the forward network is not considered. Location and capacity decisions are only taken for the collection centres, the remaining entities are considered fixed. Instead of having demand to satisfy there is end-of-life product to be collected from the origins. This product must be entirely collected by the collection centres so direct flows from the holders to the recovery operators are not allowed. The products modelled are not related with the production phase but rather with the fact different recovery operators accept different product categories (such as passenger, industrial or shredder). The shredder category can be originally any category which is processed by the shredder operator and then sent to the energy recovery operators that only accept shredder tyres. Transportation is entirely outsourced and unimodal since only mainland Portugal is contemplated as already discussed in chapter 2 thus, a single freight type is considered and transport capacity is not regarded as limited. The three dimensions of sustainability are also introduced as objective functions although differing from Mota et al. (2018). In this study, the total network cost is to be minimized. The costs involved in Valorpneu's network are:

- Compensation fee paid to the collection centres per tonne processed;
- Recovery cost paid to the shredder, recycling and energy recovery operators per tonne processed;
- Transportation cost which depends on the distances between the entities and amount of product transported. Although the transport between the holders and the collection centres is not Valorpneu's responsibility thus not a cost for the company, this flow is also included in the transportation cost, so the model favours collection centres close to the holders.
- Storage cost per tonne kept in the collection centres.

The environmental objective function is identical to the original model, although just the impact of the transportation, collection centres opened, and recovery operators is considered. For the social objective function a simplified version which will be later detailed was applied also involving the transportation, collection centres and recovery operators.

4.2.2 Indices

- i, j Entities or locations
- m Products
- t Time periods
- c Environmental midpoint categories

4.2.3 Sets and Subsets

a) Entities

- I_h Holders
- I_c Collection centres
- I_r Recycling operators
- I_{vs} Energy recovery operators which only accept previously shredder tyres
- I_{vc} Energy recovery operators which accept not previously shredder tyres
- I_s Shredder operator

$$I = I_h \cup I_c \cup I_r \cup I_{vs} \cup I_{vc} \cup I_s$$

b) Products

- M_p Passenger
- M_{tr} Truck
- M_{ind} Industrial
- M_d Damaged
- M_{mass} Massive

- M_{sh} Shredder

$$M = M_p \cup M_{tr} \cup M_{ind} \cup M_d \cup M_{mass} \cup M_{sh}$$

c) Time periods

- T_{first} First time period
- T_{last} Last time period
- T_{other} All time periods except the first

$T = \{T_{first}, T_{other}\}$

d) Allowed entity-entity connections

- $A_{hc} = \{(i,j): i \in I_h \land j \in I_c\}$

Flow from the holders to the collection centres.

- $A_{cr} = \{(i,j): i \in I_c \land j \in I_r\}$

Flow from the collection centres to the recycling operators.

- $A_{cv} = \{(i,j): i \in I_c \land j \in I_{vc}\}$

Flow from the collection centres to the energy recovery operators.

- $A_{cs} = \{(i,j): i \in I_c \land j \in I_s\}$

Flow from the collection centres to the shredder.

- $A_{sv} = \{(i,j): i \in I_s \land j \in I_{vs}\}$

Flow from the shredder to the energy recovery operator.

$$A = A_{hc} \cup A_{cr} \cup A_{cv} \cup A_{cs} \cup A_{sv}$$

e) Allowed product-entity relations

- $N_{mh} = \{(m,i): m \in M \setminus M_{sh} \land i \in I_h\}$

Connects the product category available at the holders and the holders.

- $N_{mc} = \{(m,i): m \in M \setminus M_{sh} \land i \in I_c\}$

Connects the product category accepted by the collection centres and the collection centres.

- $N_{ms} = \{(m,i): m \in M \setminus M_{sh} \land i \in I_s\}$

Connects the product category accepted by the shredder operator and the shredder operator.

- $N_{ss} = \{(m,i): m \in M_{sh} \land i \in I_s\}$

Connects the product category available at the shredder operator and the shredder operator.

- $N_{mr} = \{(m,i): m \in M \land i \in I_r\}$

Connects the product category accepted by each recycling operator and the respective recycling operator.

- $N_{mv} = \{(m,i): m \in M \land i \in (I_{vs} \cup I_{vc})\}$

Connects the product category accepted by each the energy recovery operator and the respective energy recovery operator.

$$N = N_{mh} \cup N_{mc} \cup N_{ms} \cup N_{ss} \cup N_{mr} \cup N_{mv}$$

f) Allowed flows of materials between entities

- $F_{Outh} = \{(m,i,j):(m,i) \in N_{mh} \wedge (i,j) \in A_{hc}\}$

Flow of product leaving the holders.

- $F_{Inc} = \{(m,i,j):(m,j) \in N_{mc} \wedge (i,j) \in A_{hc}\}$

Flow of product entering the collection centres.

- $F_{Outc} = \{(m,i,j):(m,i) \in N_{mc} \wedge (i,j) \in A \backslash (A_{hc} \vee A_{sv})\}$

Flow of product leaving the collection centres.

- $F_{Inr} = \{(m,i,j):(m,j) \in N_{mr} \wedge (i,j) \in A_{cr}\}$

Flow of product entering the recycling operator.

- $F_{Ins} = \{(m,i,j):(m,j) \in N_{ms} \wedge (i,j) \in A_{cs}\}$

Flow of product entering the shredder operator.

- $F_{Outs} = \{(m,i,j):(m,i) \in N_{ss} \wedge (i,j) \in A_{sv}\}$

Flow of product leaving the shredder operator.

- $F_{Inv} = \{(m,i,j):(m,j) \in N_{mv} \wedge (i,j) \in (A_{cv} \cup A_{sv})\}$

Flow of product entering the energy recovery operator.

$$F = F_{Outh} \cup F_{Inc} \cup F_{Outc} \cup F_{Inr} \cup F_{Inv} \cup F_{Ins} \cup F_{Outs}$$

4.2.4 Parameters

a) Entities

- $maxcap_i$ Fixed maximum capacity of entity i (in tonnes)
- turnover Annual average stock turnover of the collection centre
- $dist_{ij}$ Distance between entity i and j (in kms)
- maxvol Maximum allowable capacity for the collection centres (in m^3)
- minvol Minimum allowable capacity for the collection centres (in m^3)
- cindex Capacity index of the collection centres (in ton/m^3)
- minflow Minimum outbound flow capacity from the collection centres (in tonnes)

b) Product

- $initstock_{mi}$ Amount of initial stock of product m in collection centre i (in tonnes)
- $quant_{mit}$ Amount of product m available at the holders at time period t (in tonnes)

c) Environment

- eic_{ic} Environmental impact characterization factor of collection centre i at midpoint category c (per cubic meters)
- eir_{ic} Environmental impact characterization factor of recovery operator i at midpoint category c (per tonnes)

- eit_c Environmental impact characterization factor of transportation at midpoint category c (per ton.km)
- η_c Normalization factor for midpoint category c

d) Social

- $wrecovery_i$ Number of workers required in recovery entity i (per tonnes processed)
- wc_i Number of workers required in collection centre i (per m^3)
- wtransp Number of workers required in transportation (per ton.km)

e) Costs

- ctransp Transport cost (in €/ton.km)
- cstorage Storage cost (in €/ton)
- cfee Processing compensation fee given to the collection centres (in €/ton)
- $crecovery_t$ Recovery processing cost at time period t (in €/ton)

f) Others

- α Recycling target
- β Energy recover target (β=1-α)
- γ Recovery target
- bigM Large number

4.2.5 Decision Variables

a) Non-negative continuous variables

- X_{mijt} Amount of product m transported from entity i to entity j during time period t (in tonnes)
- S_{mit} Amount of product m stored at collection centre i at time period t (in tonnes)
- YC_i Capacity of collection centre i (in tonnes)
- YCT_{it} Used capacity of entity i during time period t (in tonnes)

b) Binary variables

- Y_i =1 if entity i is opened

c) Auxiliary variables

- Tcost Total cost
- Tei Total environmental impact
- Tsb Total social benefit

4.2.6 Constraints

a) Material balances

Material balance constraints ensure the balance between each entity inbound and outbound flows for each time period, so material is conserved throughout the network.

Material balance at the collection centres:

$$\text{initstock}_{\text{mi}} + \sum_{\text{j: (m,j,i)} \in \text{F}_{\text{Inc}}} \text{X}_{\text{mjit}} = \sum_{\text{j: (m,i,j)} \in \text{F}_{\text{Outc}}} \text{X}_{\text{mijt}} + \text{S}_{\text{mit}}, \forall \text{t} \in \text{T}_{\text{first}} \land (\text{m}, \text{i}) \in \text{N}_{\text{mc}} \quad (1)$$

$$\text{S}_{\text{mit}-1} + \sum_{\text{j: (m,j,i)} \in \text{F}_{\text{Inc}}} \text{X}_{\text{mjit}} = \sum_{\text{j: (m,i,j)} \in \text{F}_{\text{Outc}}} \text{X}_{\text{mijt}} + \text{S}_{\text{mit}}, \forall \text{t} \in \text{T}_{\text{other}} \land (\text{m}, \text{i}) \in \text{N}_{\text{mc}} \quad (2)$$

In the collection centres, stock can be kept between time periods so equation (2) ensures that for each product category the inbound flow of a collection centre for a given time period plus the stock kept during the previous time period equals the outbound flow of the same collection centre plus the stock kept during that time period. No stock was kept before the first time period so the initial stock ($\text{initstock}_{\text{mi}}$) of each of each product category at each collection centre is considered instead, as described in equation (1). Thus, equation (1) is defined for $t = 1$ and equation (2) for $t > 1$.

Material balance at the shredder operator:

$$\sum_{\text{m,j:(m,j,i)} \in \text{F}_{\text{Ins}}} \text{X}_{\text{mjit}} = \sum_{\text{m,j:(m,i,j)} \in \text{F}_{\text{Outs}}} \text{X}_{\text{mijt}}, \forall \text{t} \in \text{T} \land \text{i} \in \text{I}_{\text{s}} \quad (3)$$

The shredder operator does not keep stock of any product category which means that for a given time period the shredder operator's inbound flow equals its outbound flow as described in equation (3).

Available product at the holders:

$$\text{quant}_{\text{mit}} = \sum_{\text{j:(m,i,j)} \in \text{F}_{\text{Outh}}} \text{X}_{\text{mijt}}, \forall \text{t} \in \text{T} \land (\text{m}, \text{i}) \in \text{N}_{\text{mh}} \quad (4)$$

All the products available at the holders must be collected so equation (4) ensures that for each holder the amount of each product category available in a given time period equals the outbound flow of that product category in that same time period.

b) Capacity constraints

Capacity constraints set limits to the flows and stock amounts of the entities in the network.
Collection centres capacity:

$$\text{YCT}_{\text{it}} = \frac{1}{\text{turnover}} \times \sum_{\text{m,j:(m,j,i)} \in \text{F}_{\text{Outc}}} \text{X}_{\text{mjit}} + \sum_{\text{m:(m,i)} \in \text{N}_{\text{mc}}} \text{S}_{\text{mit}}, \forall \text{t} \in \text{T} \land \text{i} \in \text{I}_{\text{c}} \quad (5)$$

$$\text{YC}_{\text{i}} \geq \text{YCT}_{\text{it}}, \forall \text{t} \in \text{T} \land \text{i} \in \text{I}_{\text{c}} \quad (6)$$

$$\text{YCT}_{\text{it}} \leq \text{cindex} \times \text{maxvolY}_{\text{i}}, \forall \text{i} \in \text{I}_{\text{c}} \quad (7)$$

$$\text{YCT}_{\text{it}} \geq \text{cindex} \times \text{minvolY}_{i}, \forall \text{i} \in \text{I}_{\text{c}} \quad (8)$$

The capacity installed in the collection centres is a decision to be taken in this problem thus, equation (5) determines the used capacity of each collection centre during a given time period to accommodate the current stock and inbound flow levels considering the product rotation. Equation (6) establishes the capacity needed for each collection centre during the time horizon considered. Equations (7) and (8) limit the installation capacity of a collection centre opened during the time horizon according to the maximum and minimum, respectively, admissible volumes of a collection centre.

Flow capacity:

$$\sum_{\mathrm{m,j}:(m,i,j)\in(F_{Inr}\cup F_{Inv}\cup F_{Ins})} \mathrm{X_{mijt}} \leq \mathrm{bigMY_i}, \forall \mathrm{t} \in \mathrm{T} \wedge \mathrm{i} \in I_c \tag{9}$$

$$\sum_{\mathrm{m,i:(m,i,j)\in F_{Outh}}} \mathrm{X_{mijt}} \leq \mathrm{bigMY_j}, \forall \mathrm{t} \in \mathrm{T} \wedge \mathrm{j} \in I_c \tag{10}$$

Equations (9) and (10) ensure that for each time period only opened collection have outcoming and incoming flows, respectively.

Capacity recovery operators

$$maxcap_i \geq \sum_{m,j:(m,j,i)\in(F_{Inr}\cup F_{Inv}\cup F_{Ins})} X_{mjit}, \forall t \in T \wedge \mathrm{i} \in (I_r \cup I_{vs} \cup I_{vc} \cup I_s) \tag{11}$$

Equations (11) establishes that the inbound flow of the recovery operators (shredder, recycling and energy recovery operators) must not exceed its capacity, for a given time period.

Entity existence constraints

$$\sum_{\mathrm{m,j:(m,j,i)\in F_{Outh}}} \mathrm{X_{mjit}} \geq \mathrm{Y_i}, \forall \mathrm{t} \in \mathrm{T} \wedge \mathrm{i} \in \mathrm{I_c} \tag{12}$$

$$\sum_{\mathrm{m,j}:(m,i,j)\in(F_{Inr}\cup F_{Inv}\cup F_{Ins})} \mathrm{X_{mijt}} \geq \mathrm{minflow} \times \mathrm{Y_i}, \forall \mathrm{t} \in \mathrm{T} \wedge \mathrm{i} \in \mathrm{I_c} \tag{13}$$

Equations (12) ensures that collection centres are only opened if product inbound flow exists through them. Equation (13) establishes a minimum outbound flow from the collection centres to avoid opening collection centres with unrealistic outbound flow amounts.

c) Target constraints

Recovery target:

$$\sum_{(m,i,j):(m,i,j)\in F_{Outc}} X_{mijt} \geq \gamma \sum_{m,i:(m,i)\in N_{mh}} quant_{mit}, \forall t \in T \tag{14}$$

Recycling target:

$$\sum_{(m,i,j):(m,i,j)\in F_{Inr}} X_{mijt} \geq \alpha \sum_{m,i,j:(m,i,j)\in F_{Outc}} X_{mijt}, \forall t \in T \tag{15}$$

Energy recovery target:

$$\sum_{(m,i,j):(m,i,j)\in F_{Inv}} X_{mijt} \geq \beta \sum_{m,i,j:(m,i,j)\in F_{Outc}} X_{mijt}\ , \forall t \in T \tag{16}$$

A recovery network usually has recovery targets that must be met. The target constraints guarantee that the recovery, recycling and energy recovery targets are complied. Equation (14) guarantees that a percentage of the total amount of product available at the holders leaves the collection centres, i.e. is not stocked. This percentage is applied to the total amount of used tyres available at the holders and not to each product category. The used tyres that remain in the collection centres are stocked for the next time period. Equations (15) and (16) force that a percentage of the amount of leaving the collection centres is sent to recycling and the rest is sent to energy recovery.

4.2.7 Objective Functions

a) Economic objective

$$\begin{aligned} \min \text{Tcost} = & \sum_{\text{m,i,j:(m,i,j)}\in \text{F} \wedge\, \text{t}\in\text{T}} \text{ctransp} \times \text{dist}_{\text{ij}} \times \text{X}_{\text{mijt}} \\ & + \sum_{\text{m,i: (m,i)}\in \text{N}_{\text{mc}} \wedge \text{t}\in\text{T}} \text{cstorage} \times \text{S}_{\text{mit}} \\ & + \sum_{\text{m,i,j:(m,i,j)}\in \text{F}_{\text{Outc}} \wedge\, \text{t}\in\text{T}} \text{cfee} \times \text{X}_{\text{mijt}} \\ & + \sum_{\text{m,i,j:(m,i,j)}\in (\text{F}_{\text{Inr}} \cup \text{F}_{\text{Inv}} \cup \text{F}_{\text{Outs}}) \wedge\, \text{t}\in\text{T}} \text{crecovery}_{\text{t}} \times \text{X}_{\text{mijt}} \end{aligned} \tag{17}$$

The economic objective function given by equation (17) involves four different types of costs. The first term represents the transportation cost given by the sum of the amount of product transported between each pair of entities times the distance between these entities (dist_{ij}) and the unit transportation cost (transpcost). The storage costs in the second term are given by the sum of the amount of product stored in all the collection centres (S_{mit}) times the unit storage cost (stcost). The third term is concerned with the compensation fee cost which is given by the sum of the amount of product leaving the collection centres times the unit compensation fee (cfee). Finally, fourth term describes the recovery cost given by the sum of the amount of product entering the shredder, recycling and energy recovery operators times the unit recovery cost (rcost_{t}).

b) Environmental objective

$$\begin{aligned} \min \text{Tei} = \sum_{\text{c}} \eta_{\text{c}} \Bigg(& \sum_{\text{i}\in I_c} \text{eic}_{\text{ic}} \times \frac{\text{YC}_{\text{i}}}{\text{cindex}} + \sum_{\text{m,i,j}\in\text{(m,i,j)F} \wedge \text{t}\in\text{T}} \text{eit}_{\text{c}} \times \text{dist}_{\text{ij}} \times \text{X}_{\text{mijt}} \\ & + \sum_{\text{m,i,j:(m,i,j)}\in (\text{F}_{\text{Inr}} \cup \text{F}_{\text{Inv}} \cup \text{F}_{\text{Outs}}) \wedge\, \text{t}\in\text{T}} eir_{ic} \times \text{X}_{\text{mijt}} \Bigg) \end{aligned} \tag{18}$$

In the environmental objective function depicted in equation (18) the environmental impact of the collection centres and transportation is minimized. This impact is determined through the International Life Cycle Data (ILCD) system methodology where the individual environmental impacts are estimated for each midpoint category c. The first term represents the environmental impact of the network's collection centres given by the sum of each entity environmental impact characterization factor at midpoint category c ($\mathrm{eic}_{\mathrm{ic}}$) times the respective capacity in cubic meters, i.e., the capacity of collection centres i (YC_{i}) divided by the capacity index (cindex). The second term is the environmental impact of transportation given by the sum of the environmental impact characterization factor of transportation at midpoint category c ($\mathrm{eit}_{\mathrm{c}}$) times the total distance travelled, and quantity transported within the network. In the third term the environmental impact processing the used tyres in the recovery operators is given by the sum of the environmental impact characterization factor at midpoint category c ($\mathrm{eir}_{\mathrm{c}}$) times the total amount of used tyres processed. These three individual results are multiplied by the sum each midpoint category normalization factor (η_{c}) resulting in a single value.

c) Social objective

$$\max \mathrm{Tsb} = \sum_{\mathrm{m,i,j:(m,i,j)} \in (\mathrm{F_{Inr}} \cup \mathrm{F_{Inv}} \cup \mathrm{F_{Outs}}) \wedge \mathrm{t} \in \mathrm{T}} \mathrm{wrecovery_i} \times \mathrm{X_{mijt}} + \sum_{\mathrm{i} \in \mathrm{I_c}} \mathrm{wc_i} \times \frac{\mathrm{YC_i}}{\mathrm{cindex}} + \sum_{\mathrm{m,i,j} \in \mathrm{(m,i,j)F} \wedge \mathrm{t} \in \mathrm{T}} \mathrm{wtransp} \times \mathrm{dist_{ij}} \times \mathrm{X_{mijt}} \quad (19)$$

The social objective function applied in this study and represented in equation (19) is a simplified version of the Social Benefit indicator proposed by Mota et al. (2015) where only the number of workers required by each entity and transportation are contemplated. The first term illustrates workers needed per tonne of used tyres processed in the recovery entities given by the sum of the number of workers required in each entity per tonne ($\mathrm{wrecovery}_{\mathrm{i}}$) times the total quantity processed by that entity. The second term concerns the workers necessary in each collection centre according to its capacity given by the sum of the number of workers required in the collection centre i per cubic meter (wc_{i}) times the capacity of that collection centre divided by the capacity index. In the third term the workers needed in transportation are calculated through the sum of the number of workers required per kilometres travelled and tonnes transported ($\mathrm{wtransp}$) times the distance travelled, and the amount of product transported in the network.

5 Data Treatment

Throughout this chapter the methodology and assumptions made to treat and obtain the input data for the model are described. First, the network superstructure is depicted with the possible locations and other relevant characteristics of each type of entity. In the second section, the parameters of the model are defined, and the assumptions considered in this study are outlined.

5.1 Network Superstructure

5.1.1 Holders

Holders are fixed entities and account for more than 4 000 entities in each time period considered. For simplification purposes and to avoid computational difficulties the holders were aggregated by municipality resulting in a total of 278 locations corresponding to the 278 municipalities of mainland Portugal. To calculate the distances between the holders and the collection centres, the centre of each the municipality was considered.

5.1.2 Collection Centres

The location and number of collection centres are decisions of this problem. For that purpose, the possible locations considered were the locations of the existing collection centres and the remaining municipalities where currently no collection centre exists. Accordingly, there are 280 possible locations for the collection centres but, unlike the holders, a collection centre does not need to exist in every possible location.

5.1.3 Recovery Operators

The recovery operators namely the shredder, recycling and energy recovery operators are fixed entities like the holders. In the past some of these entities closed or opened during different time periods though for the present analysis it was considered that this situation does not happen in the future, i.e., all recovery operators are opened during the time horizon analysed. However, in the model validation this situation was contemplated since the objective is to compare the model results with Valorpneu's network as it is.

Table 4 - Tyre categories accepted by each recovery operator

Entity \ Category	Passenger vehicle	Industrial	Truck	Damaged	Massive	Shredder
R1	X					
R2	X		X			
R3	X		X			
V1	X					
V2						X
V3						X
V4						X
V5	X		X			
V6	X	X	X	X		

Another peculiarity of the recycling and energy recovery operators is that each of these entities accepts different tyre categories depending on the destination given to the used tyres and technologies involved. Table 4 shows the tyre category accepted by the three recycling operators (R1, R2 and R3) and the six energy recovery operators (V1, V2, V3, V4, V5 and V6). The network with the location of these entities is represented in Figure 10 .

Figure 10 - Recovery Operators network

5.2 Data Collection

5.2.1 Used Tyres Available for Collection

The quantity and category of used tyres available at each source during each time period was obtained considering the quantity sent by each holder to each collection centre during each time period provided by Valorpneu. Before being stored, the used tyres are weighted and Valorpneu keeps record of the total weight of used tyres sent by each holder annually. As previously mentioned, the holders were aggregated by municipality and so was the quantity of used tyres by adding the weight of all used tyres sent by holders belonging to the same municipality.

5.2.2 Time Horizon

As formerly explained, the present work deals with strategic and tactical decisions thus, the time horizon considered is five years with yearly increments.

5.2.3 Stock

Throughout this work, it is assumed that the only entities allowed to keep stock between two time periods are the collection centres. This represents the ideal scenario where the total amount of used tyres sent to the recovery operators is processed when in reality this may not happen due to production planning and efficiency i.e. it is only economical sustainable to process the used tyres when the quantity of product in the recovery operators achieves a certain level. No limit is imposed on the maximum stock stored in a collection centre although the recovery target (i.e. the γ parameter in the model) must be respected which assumes that 96% of the used tyres generated in a given year is sent to a recovery operator during that same year. For the initial stock, data about the quantity and category of stock kept at each collection centre in the end of the year before the first year in analysis was considered. To account for product rotation inside the collection centres, the annual average inventory turnover ratio was calculated considering historical data. The inventory turnover ratio defines the number of times the inventory is replaced in a period of time and it is given by equation (23). In this study because the monetary value of the used tyres is not considered, an adaptation was made to calculate the inventory turnover ratio as demonstrated in equation (24).

$$\text{inventory turnover} = \frac{\text{cost of goods sold (€)}}{\text{average inventory (€)}} \tag{20}$$

$$\text{inventory turnover} = \frac{\text{outbound flow (tonnes)}}{\text{average inventory (tonnes)}} \tag{21}$$

5.2.4 Capacities

In the collection centres, the capacity installed is one of the decisions of this problem though the collection centres which currently belong or belonged to the network have known capacities provided by Valorpneu which were used when validating the model. On contrary, the recovery entities have fixed known maximum and minimum installed capacities measured in tonnes processed which are established in the contract celebrated between these entities and Valorpneu. These capacities and respective recovery operator including the shredder operator (SO1) can be found in Table 5.

Table 5 – Maximum and minimum contracted capacities of the recovery entities (in tonnes)

	Capacity (tonnes)									
	R1	R2	R3	V1	V2	V3	V4	V5	V6	SO1
Maximum	14 000	25 000	15 000	12 000	7 000	7 000	7 000	6 000	2 500	20 000
Minimum	8 000	18 000	5 600	7 200	0	0	0	4 500	990	0

In order to avoid unrealistic scenarios where collection centres are installed with capacities too large or too small, minimum and maximum capacities where defined based on the capacities of the smallest and largest collection centres that are currently installed in the network. Flows between entities are measured in tonnes however, capacities in the collection centres are measured in cubic meters so the capacity index is used to calculate how many tonnes fit in a cubic meter. No information on how many tonnes of used tyres can fit in a cubic meter of a collection centre is available however, Valorpneu calculates how many tonnes fit a trailer with a given capacity for every shipment made. So, the capacity index was calculated through the average of the load capacity index of the shipments of used tyres made in 2018 from the collection centres that do not dispose of loading equipment to the recovery operators. When the collection centres dispose loading equipment, the load capacity index is much higher since the used tyres are better sorted inside the trailers which does not happen when storing the used tyres inside the collection centres so the load capacity index of these collection centres was not considered when calculating the capacity index. This parameter is subject to a sensitivity analysis to infer how it affects the results.

5.2.5 Distances between entities

The distance between entities is fundamental since this parameter highly influences the location chosen for the collection centres. The location of the recovery operators and collection centres that belong to the network is known and provided by Valorpneu, for the holders the location considered was the centre of the municipalities. To calculate the distance matrix for this problem the Bing Maps, a geospatial platform from Microsoft was used. This is procedure works exactly as using the Bing Maps web mapping service application to obtain directions from a point to another but instead of entering each pair of locations one by one, a distance matrix is calculated by linking the Bing Maps web mapping service to Excel. The steps are described as following: First an API key needs to be obtained from Bing Maps website (Microsoft Corporation, 2019). Then, in an Excel sheet, to calculate the coordinates of a location the Excel function WEBSERVICE() is employed to call the permalink[1] that provides the coordinates of a given address. This information appears in an XML format thus to retrieve the longitude and latitude the excel function FILTERXML() is used. After getting the coordinates for the pair of locations the distance between the two locations is calculated this time calling a second permalink[2] that provides the distance in kilometres between the pair of coordinates previously determined. Finally, the FILTERXML() Excel function is again employed to retrieve the distance between the two coordinates. For more information about this procedure and please refer to Chandoo (2018). Distances are given in kilometres and the shortest road distance is considered.

5.2.6 Costs

As formerly outlined the costs considered in this study are the compensation fees, the recovery cost, the transportation cost and the storage cost. The next subsections describe the approach used to estimate each of these costs.

5.2.6.1 Compensation fees and storage cost

The compensation fees are the value paid by Valorpneu to the collection centres with exception of the storage cost. The value paid to each collection centre is 26€ per tonne of used tyres sent to recovery.

[1]https://dev.virtualearth.net/REST/v1/Locations?countryRegion=$1&adminDistrict=$2&locality=$3&postalCode=$4&addressLine=$5&maxResults=1&o=xml&key=$bingmaps.key

[2]https://dev.virtualearth.net/REST/v1/Routes/DistanceMatrix?origins=$1&destinations=$2&travelMode=$3&o=xml&key=$bingmaps.key

This value is fixed for all the collection centres. At first it might seem that some collection centres are disadvantaged compared to others as they may incur in more costs (for example rents) however this is justified by Valorpneu by the fact those collection centres usually handle more outbound flows thus earning more. No information about the storage cost of each collection centre is available as this cost is included in the 26€ per tonne paid by Valorpneu. Yet, for the problem it is important to estimate this cost to avoid excessive stock creation in the collection centres so to allocate these costs, during a meeting with Valorpneu it was considered that 15% of the 26€ per tonne is the collection centres' margin and the remaining 22,1€ per tonne are costs. It was also agreed that from the 22,1€ per tonne, about 15% accounts for storage costs accordingly, the storage cost at each collection centre is 3,32€ per tonne and the compensation fee is 22,68€ per tonne.

5.2.6.2 Recovery cost

For the recovery cost the average annual recovery expenditure was considered. This information is available in Valorpneu's Annual Reports and represented in Table 6. For Valorpneu and the present study, an average value is more plausible since the destination given to the used tyres does not depend on the cost of processing used tyres at each recovery operator but on meeting the legal targets imposed which might include processing more used tyres in the most expensive recovery operators.

Table 6 - Average recovery cost of each time period considered (in € per tonnes)

Average recovery cost (€ per tonnes)				
Year 1 (2014)	Year 2 (2015)	Year 3 (2016)	Year 4 (2017)	Year 5 (2018)
54,37	57,23	57,29	60,17	61,78

5.2.6.3 Transportation cost

The transportation cost was calculated through the total transportation cost of 2018 divided by the total tonne kilometres travelled during the same year in mainland Portugal. In 2018 the total transportation cost in mainland Portugal was 1 938 501€ and the total tonne kilometres travelled was 9 324 085 tonne.km thus, the transportation cost is 0,21€/tonne.km. The cost of transportation from the sources to the collection centres was also considered as 0,21€/tonne.km although as noted earlier this cost is a dummy cost.

5.2.7 Targets

As discussed in chapter 2 the collection and recycling targets are defined in Valorpneu's license accounting for 96% and 65%, respectively. The methodology used in this study to calculate these targets is the same used by Valorpneu where the collection target (named recovery target in this work), represents the quantity of used tyres that must be recovered (i.e. must be processed either by the recycling or energy recovery operators) during a given year and it is calculated through equation (26). The used tyres collected are the used tyres received by the collection centres from the holders. The used tyres processed are the tyres sent to the recovery operators. In this study since the used tyres processed by the retread manufacturers and by the Azores and Madeira islands are not contemplated, the respective quantities are not considered in this calculation.

$$Recovery\ target\ (96\%)\ = \frac{Total\ used\ tyres\ processed}{Total\ used\ tyres\ generated} \tag{22}$$

The recycling target is obtained with equation (27) and since Valorpneu must recover all the used tyres in the network (tyres cannot be sent to landfills), the remaining tyres are sent to energy recovery as illustrated in equation (28).

$$Recycling\ target\ (65\%)\ = \frac{Total\ used\ tyres\ recycled}{Total\ used\ tyres\ processed} \tag{23}$$

$$Energy\ recovery\ target = \ 1 - Recycling\ target \tag{24}$$

5.2.8 Environmental Impact

To determine the environmental impact of the collection centres, transportation and recovery operators two approaches were used to retrieve the information required. Due to data limitations on the impacts of the recovery operators, the results obtained in 3Drivers (2013) were used to quantify the environmental impact of one tonne of used tyres processed by these entities. 3Drivers (2013) presents a report on Valorpneu's environmental, economic and social performance where the environmental impact of the network was determined through the ILCD 2011 methodology proposed by the European Commission Joint Research Centre. Although the ILCD 2011 comprises sixteen midpoint impact categories in the report only the four most affected impact categories are considered: Climate Change, Acidification, Terrestrial Eutrophication and Marine Eutrophication. To quantify these impact categories, an LCA was performed on SimaPro 7.3.3 and the LCI data was retrieved from Ecoinvent 2.2 database. The functional unit is one tonne of used tyre. The aspects included to evaluate the environmental impact of the recovery operators are described as followed: For the shredder operator it was included the impact of energy and other materials consumption to produce chips. For the recycling operators besides the impact of energy consumption and other materials to recycle used tyres, the benefits associated with recycling namely products avoided are considered. For the energy recovery operators, the main air emissions as well as the benefits of using used tyres for combustion instead of fossil fuels and products avoid are included.

The environmental impact of the collection centres and transportation were also determined through the ILCD 2011 methodology so the results can be combined with the results from the recovery operators of 3Drivers (2013). An LCA for these activities was performed on SimaPro 8.4 and the LCI was retrieved from Ecoinvent 3 databasa. With the results obtained the environmental impact of each activity for each midpoint category was gathered. The normalization factor also provided by SimaPro reduces the results of each impact category to the same unit so these can be aggregated into a single score (assuming an equal weight of 1 for each impact category). For the transportation mode the option *Transport, freight, lorry 7.5-16 metric ton, EURO5 {GLO}*| *market for* | *Conseq, S* of Ecoinvent database was considered since the majority of Valorpneu's carriers have vehicles with EURO5 European norm and an average capacity of 15 tonnes. The {GLO} and *market for* options were chosen because the data are not region specific and the supplier is unknown. The consequential (*Conseq*) option was selected since the aim is to analyse the environmental consequences of modifications made to a baseline case. The *S* stands for system process which provides a more global and simplified view of the lifecycle inventory of the activity considered compared to the unit process option which provides information about the contributions of each individual process but involves more calculation time and does not affect the significantly the results. Concerning the collection centres, although these entities are outsourced it is important to consider the environmental impact of installation since a previous construction is required to use these entities. In SimaPro, the option *Building, multi-storey {GLO}| market for* | *Conseq, S* was selected since used tyres are stored at height and capacity is measured in cubic meters. The average lifetime of a warehouse is according to Zaks (2010) 15 years thus, these impacts were uniformly amortized over that time period. The results obtained are used to compare different network designs and decisions and not to characterise the network's accurate environmental impact.

5.2.9 Social Impact

As discussed in the previous chapter, the evaluation of the social benefit is based on the jobs created by each entity and transportation i.e. the number of people employed by Valorpneu's network. The information concerning the recovery operators was provided by Valorpneu and it was obtained through surveys made to these entities. Table 7 illustrates the number of workers per tonne of used tyres processed by the recovery operators. The recycling operators require more workers than the energy recovery operators because processing used tyres is their business unlike the energy recovery operators that process tyres to obtain energy for their main activity. Only the workers assigned to activities related with the recovery of used tyres were considered.

Table 7 - Number of workers per tonne processed in the recovery operators

	R1	R2	R3	V1	V2	V3	V4	V5	V6	SO1
Total no. of workers	15	24	24	4	2	2	2	3	3	5
Capacity (tonnes)	14 000	25 000	15 000	12 000	7 000	7 000	7 000	6 000	2 500	20 000
No. of workers per tonne	0,0011	0,0010	0,0016	0,0003	0,0003	0,0003	0,0003	0,0005	0,0012	0,0003

Regarding the collection centres, information related with the workers needed for the tasks related with the used tyres was also collected by Valorpneu for some collection centres. Hence, the value of the workers required per cubic meter is an average of the workers required in each of those collection centres divided by their respective capacity (in cubic meters) corresponding to 0.00258 workers per cubic meter. The number of workers per tonne kilometre was calculated through the number of people employed in the transportation sector in Portugal in 2017 which was 203,9 thousand (PORDATA, 2019) divided by total tonne kilometre of the road freight transport in Portugal in 2017 which was 34 186 million tonne kilometre (Eurostat, 2018) giving a total of $5{,}964 \times 10^{-6}$ workers per tonne kilometre.

6 Results and Discussion

In this chapter the proposed model is implemented, and the computational experiments and results are discussed. First the model is validated using the Valorpneu's current network for comparison, considering an economic objective. Then, in section 6.2 the scenarios under analysis are outlined and the respective results obtained are discussed focusing on the three sustainability objectives. In section 6.3 a sensitivity analysis is performed on the parameters subject to higher uncertainty. Section 6.4 presents a more detailed scenario analysis just for the Oporto region since this region was identified as problematic in the problem characterization. Finally, in section 6.5 conclusions on the scenarios analysed and results obtained are drawn.

The model was implemented in GAMS 27.2 and the case study was solved using CPLEX 12.6.3 in a 1.8 GHz Intel Core i5 computer with 12 GB RAM.

6.1 Model Validation

In this section the model developed is applied to current Valorpneu's network (e.g As-Is scenario), i.e., the network's data of the time period between 2014 and 2018 is used to test the model results against the real case, considering an economic objective. The entities considered in this validation are the network's existing entities during this time horizon and the capacities of the collection centre are defined according with the real capacities provided by Valorpneu. It was concluded that the collection and recycling legal targets defined in Valorpneu's license were not followed during the period considered, i.e. Valorpneu actually collected and recycled more than the quantity defined by the targets accordingly. Then two preliminary scenarios were tested: first the model is validated against the network's real information by using the same collection and recycling rates as Valorpneu (the As-Is scenario). Then, the legal targets are followed (the Targets scenario), and the economic, environmental and social results obtained are compared with the As-Is scenario.

6.1.1 Real case versus As-Is scenario

In the As-is scenario, the model results show that the total amount of used tyres sent to the recovery operators is the same since the same recovery and recycling rates were followed: approximately 99,8% of the used tyres collected were sent to the recovery operators from which 69% was sent to recycling and the remaining 31% to energy recovery.

Concerning the network costs, as outlined in Figure 11, the model returns a total network cost 12% lower than the cost incurred by Valorpneu. This is mainly explained by the difference in the total transportation cost which is 47% lower for the model results. From the costs considered, the transportation cost is the one where the model has more influence as it decides to use the network flows between the entities that are closer (in terms of distance) to each other resulting in lower costs. Note that for the As-Is results to be comparable with the real case, the cost of transporting the used tyres from the holders to the collection centres was excluded since they do not represent a real cost incurred by Valorpneu, as discussed before. The remaining costs results are very similar since they highly dependent on the quantities collected and sent to the recovery operators, which are constrained by the rates defined. The small difference in the total collection centres' processing cost might result from the fact the storage cost was disaggregated in this study from the compensation fee paid to the collection centres while in reality Valorpneu does not consider the storage cost, only the cost of the total compensation fee paid to the collection centres per tonne sent to recovery.

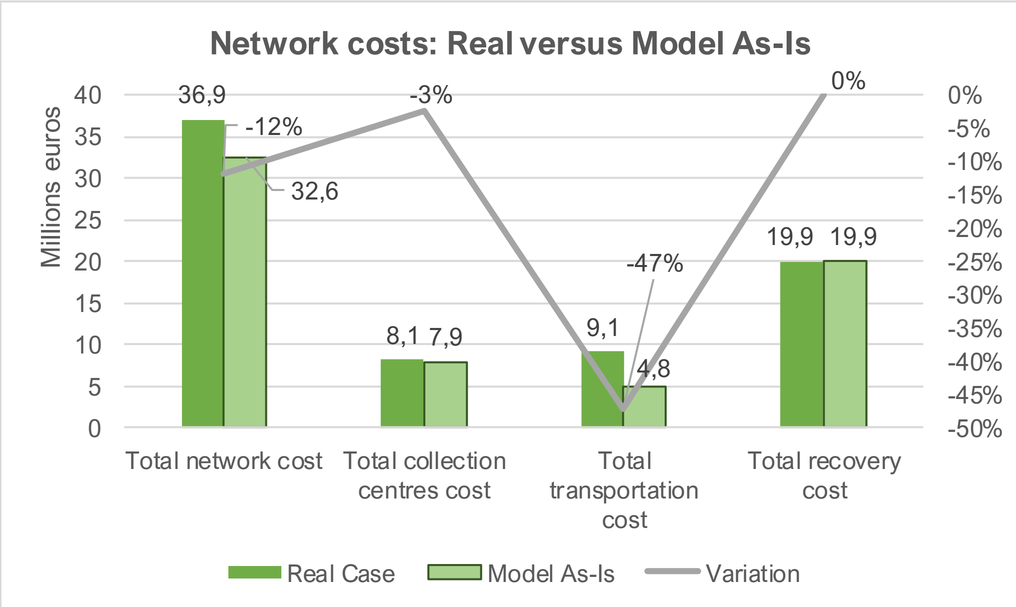

Figure 11 – Comparison of the total network costs between the real case and model As-Is scenario

6.1.2 As-Is scenario versus Targets scenario

Comparing the As-Is and the Targets scenario, as illustrated in Figure 12, the total amount sent to the recovery operators by the collection centres in the Targets scenario is close to the total amount that was sent in the As-Is and real scenarios (less 0,1%). Although when comparing the total amount sent to recycling and to energy recovery in the second scenario less 6% of used tyres were recycled and more 13% were sent to energy recovery. In the Targets scenario 99,7% of the used tyres collected were sent to the recovery operators and 65% and 35% were sent respectively to the recycling and energy recovery operators.

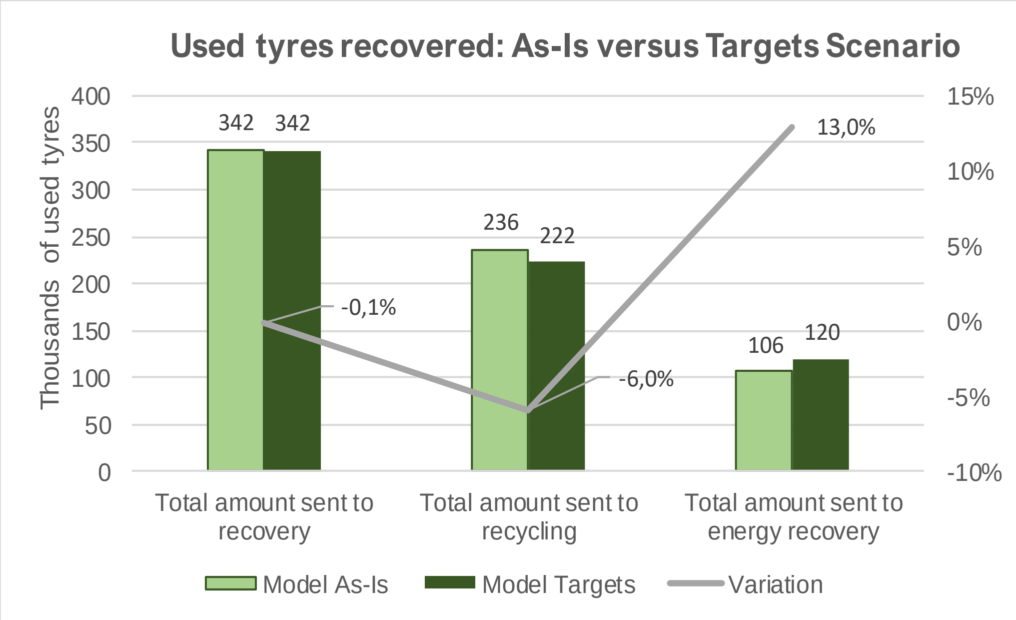

Figure 12 - Comparison of the total used tyres recovered between the As-Is and scenario 2

Regarding the network costs, Figure 13 shows that the Targets scenario returns a total network cost 0,8% lower than the As-Is scenario. This difference is explained by the variance between the amount of used tyres sent to recovery which, as mentioned earlier, is less 0,1% in the Targets scenario. The fact that more tyres are sent to energy recovery (and less to recycling) might also contribute to lower the cost of the Targets scenario, since there are more energy recovery operators than recycling operators allowing that shorter distances are travelled.

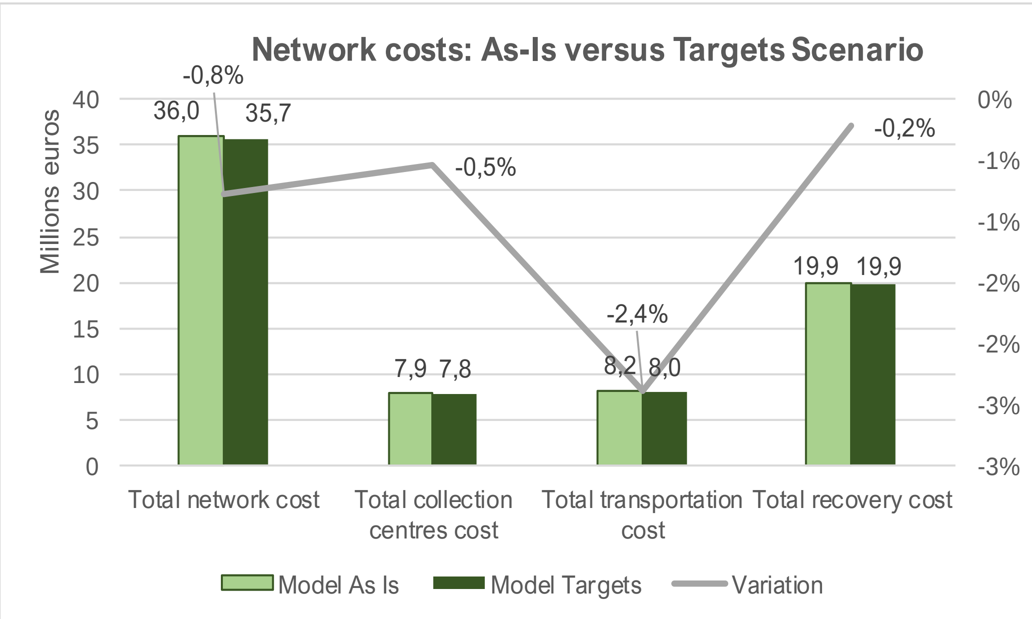

Figure 13 - Comparison of the total network costs between the As-Is and Targets scenario

Analysing the results obtained for the environmental and social values when optimizing the economic objective function are represented in Table 8, it is concluded that the Targets scenario has a worse performance in both objective functions as it has a higher value for the environmental objective function (greater environmental impact).Tthough the difference is almost neglectable and lower value for the social objective function (less workers employed). The increase of the environmental impact in the Targets scenario results from the fact that the recycling operators have a greater environmental benefit than the energy recovery operators and, in this scenario, more used tyres are sent to the energy recovery operators than in the As-Is scenario. The social benefit is lower in the Targets scenario because less used tyres are sent by the collection centres to the recovery operators so less workers are needed for transportation and at the recovery operators.

Table 8 - Environmental and Social values: As-Is and Targets scenario

	Environmental impact	Social Benefit (nr. of workers)
Targets	9 730 400	813
As Is	9 728 600	833
Variation	0,02%	-2%

Table 9 summarizes the results obtained in the Targets scenario for the network's total cost, environmental impact and social benefit for the optimal solution of each objective function. The numbers in bold are the optimal values for each objective function. It is concluded that higher social benefit involves higher costs and the environmental impact does not suffer significant differences when optimizing each of the objective functions. In this scenario the collection centres are fixed so their environmental impact remains unchanged and the impact of transportation and of the recovery operators depends on the amount of used tyres sent to recovery which is determined by the legal targets.

Table 9 - Results of the Target scenario for the optimal solution of each objective function

	Economic optimum	Environmental optimum	Social optimum
Total cost (€)	**35 672 186**	37 180 796	82 762 380
Total enviromental impact	9 730 400	**9 728 805**	9 730 206
Total social benefit (nr. of workers)	813	844	**2 143**

In light of the results presented in this section, it is considered that the model adequately represents Valorpneu's network and can be further employed to optimize it. The Targets scenario also serves as baseline to evaluate the results of the optimal case for the three dimensions of sustainability discussed in the next section.

6.2Scenario Analysis

For the scenario analysis nine different scenarios were defined as following: Valorpneu's network is designed to collect and recover the used tyres available at the holders thus, the quantity of used tyres available for collection is an important parameter to study. In a first premise it is assumed that the quantity of used tyres available for collection remains the same over time horizon analysed. From an analysis made to the past five years it was concluded that the quantity of used tyres sent to the collection has been increasing an average of 2% annually thus, a second hypothesis is to consider this 2% annually increase in the analysed time horizon. Finally, since 2017 there has been a decreasing tendency of the number of tyres sold mainly because the majority of the new cars sold ceased to have a replacement tyre. This tendency might influence the quantities of used tyres available in the holders in the same direction in the future, so the last proposition is an annual decrease of 0,65% according to the average annual decrease of new tyres sold.

Concerning the sustainable objectives defined another three cases are studied corresponding to the optimal solution of each of the three objectives. Accordingly, case A considers the optimal solution of the economic objective function (minimum network cost), case B considers the optimal solution of the environmental objective function (minimum network environmental impact) and the case C considers the optimal solution of the social objective function (maximum network social benefit). These three cases are studied considering the three hypotheses for the quantity of used tyres available for collection resulting in nine scenarios summarised in Table 10.

Table 10 - Summary of the scenarios in analysis

Scenarios	A	B	C
1	**A1**: Economic optimal solution considering the same quantity of used tyres available	**B1**: Environmental optimal solution considering the same quantity of used tyres available	**C1**: Social optimal solution considering the same quantity of used tyres available
2	**A2**: Economic optimal solution considering an annual increase of 2% in the quantity of used tyres available	**B2**: Environmental optimal solution considering an annual increase of 2% in the quantity of used tyres available	**C2**: Social optimal solution considering an annual increase of 2% in the quantity of used tyres available
3	**A3**: Economic optimal solution considering an annual decrease of 0,65% of used tyres available	**B3**: Environmental optimal solution considering an annual decrease of 0,65% of used tyres available	**C3**: Social optimal solution considering an annual decrease of 0,65% of used tyres available

Table 10 compiles the main results obtained in each scenario described above. As expected, scenarios A3, B3 and C3 present the lowest value of total cost, environmental impact and social benefit, respectively since hypothesis 3 assumes a decrease of the quantity of used tyres available for collection. Comparing the case A scenarios, scenario A2 returns a higher network cost, environmental impact and social benefit since more quantity of product is available for collection. In case B and C scenarios once again, the tendency observed in case A scenarios is followed, network cost, environmental impact and social benefit are higher in scenario B2 for case B and in scenario C2 for case C. When minimizing the cost (scenarios A1, A2, A3), the total normalized environmental impact increases around 82% and the total social benefit decreases 45% comparing to the respective environmental and social optimization. Looking at the optimization of the environmental objective function (scenarios B1, B2 and B3) the total cost suffers an 8% increase and the total social benefit an 75% decrease comparing to the economic optimal and social optimal solutions, respectively. The social benefit objective function optimization (scenarios C1, C2 and C3), result in a total network cost 70% higher and an environmental impact 79% greater than in the economic optimum and environmental optimum scenarios. Accordingly, it is deduced that the trade-offs between each sustainability optimum are as follows: Lower network costs mean higher environmental impacts, in turn, lower environmental impacts result in lower social benefits and higher social benefits imply higher total costs. Case B scenarios seem to represent more favourable solutions for the trade-offs experimented since the optimization of the environmental objective function returns a network cost only 8% higher than the economic optimum while the results of optimizing the economic objective function have an 82% higher environmental impact. Analogous, the optimization of the environmental objective function returns a social benefit 75% lower than the social optimum solution while the social optimal solution returns an environmental impact 79% higher than the environmental optimum. Nevertheless, these trade-offs should be analysed using a multi-objetivo approach so solutions of compromise are obtained for all the three objective functions.

The remaining results and findings for each scenario are detailed in the subsections below.

Table 11 - Summary of the results of each scenario

Scenarios	Total Cost (€)	Environmental Impact	Social Benefit (nr. of workers)
A1	**33 429 601**	2 630 669	2 725
A2	**35 593 048**	2 778 840	2 840
A3	**32 767 445**	2 543 125	2 689
B1	36 465 241	**472 058**	1 228
B2	38 786 426	**477 635**	1 285
B3	35 789 019	**470 199**	1 210
C1	111 313 448	2 263 893	**4 923**
C2	117 777 482	2 377 242	**5 159**
C3	109 162 143	2 244 540	**4 848**

6.2.1 Case A

6.2.1.1 Scenario A1

Scenario A1 concerns the optimization of the economic objective function considering that the quantity of used tyres available at the holders remains unchanged during the time horizon in analysis. This scenario returns a total cost of 33 429 601€ and network of 162 collection centres (more 123 collection centres than the current network) with an average capacity of 212 tonnes.

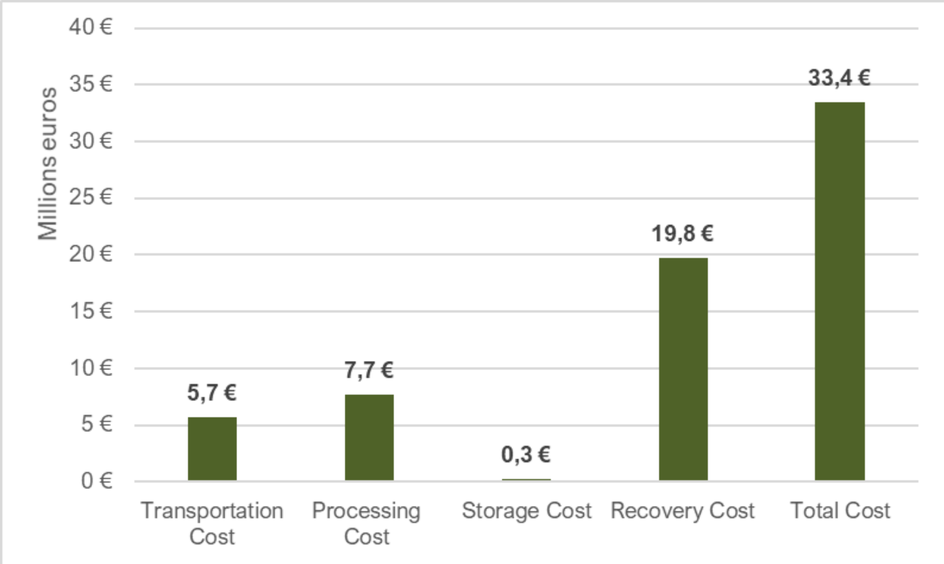

Figure 14 - Costs Scenario A1

Figure 14 outlines the distribution of the different costs in millions of euros. The recovery cost i.e., the cost of recycling or sent to energy recovery the used tyres represents the higher cost in this scenario. The cost of the tyres processed in the collection centres is the second highest and the cost of the stock kept the lowest. The fact that the cost per tonne stored in the collection centres is much lower than the recovery cost per tonne recycled or sent to energy recovery explains why the model only sends to the recovery operators the amount demanded by the legal target. Consequently, the amount of used tyres stocked in the collection centres increases over the time period as illustrated in Table 12, which summarises the amount of used tyres available for collection at the holders, sent to the recovery operators, to recycling, to energy recovery and stocked in each time period.

Table 12 - Flow amounts Scenario A1

Results A1	Time Period				
	1	2	3	4	5
Amount available (tonnes)	70 821	70 821	70 821	70 821	70 821
Amount sent to recovery (tonnes)	67 988	67 988	67 988	67 988	67 988
Amount sent to recycling (tonnes)	44 192	44 192	44 192	44 192	44 192
Amount sent to energy recovery (tonnes)	23 796	23 796	23 796	23 796	23 796
Stock (tonnes)	10 412	13 245	16 078	18 910	21 743

6.2.1.2 Scenario A2

In the scenario A2 the economic performance of the network is optimized assuming that the quantity of used tyres available for collection increases 2% annually. In this scenario the total cost is 35 593 048€ and an optimal network composed by 170 collection centres with a global average capacity of 214 tonnes. In Figure 15 the total cost of each activity in millions of euros is represented. Similar to the scenario A2, the recovery cost is the highest accounting for a total of 21 017 554€ and the storage cost the lowest totalizing 273 604€.

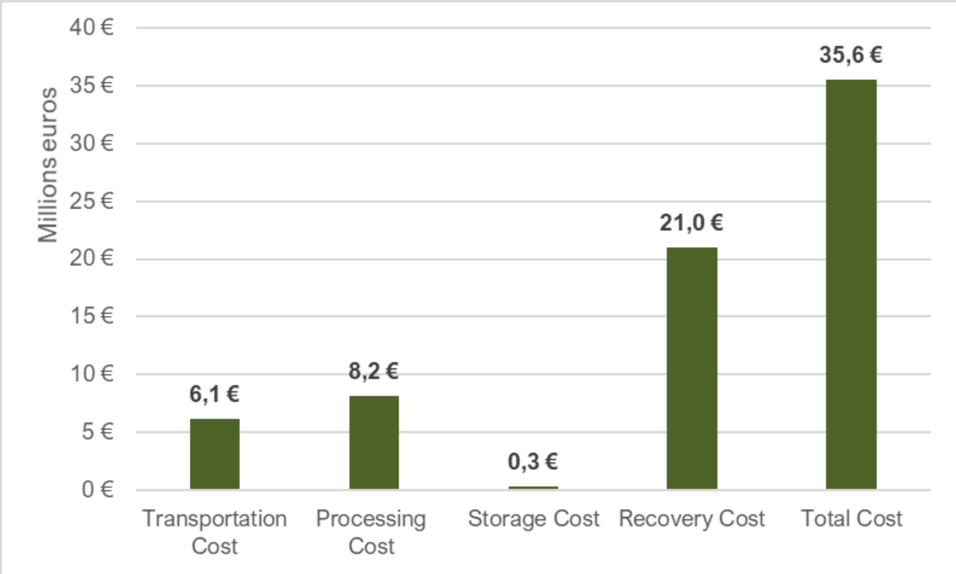

Figure 15 - Costs Scenario A2

Table **13** shows the flows amounts from the holders to the collection centres (amount available), from the collection centres to the recovery operators (amount sent to recovery), the inbound flows amounts to the recycling and energy recovery operators and the total stock kept during each time period. As expected, the quantity of used tyres sent to recovery increases as the quantity available in the holders rises. The total amount stocked also increases over the time period since this option is cheaper than sending the used tyres to recovery, as already discussed.

Table 13 - Flow amounts Scenario A2

Results	Time Period				
	1	2	3	4	5
Amount available (tonnes)	72 237	73 682	75 156	76 659	78 192
Amount sent to recovery (tonnes)	69 348	70 735	72 149	73 592	75 064
Amount sent to recycling (tonnes)	45 076	45 978	46 897	47 835	48 792
Amount sent to energy recovery (tonnes)	24 272	24 757	25 252	25 757	26 272
Stock (tonnes)	10 469	13 416	16 422	19 488	22 616

6.2.1.3 Scenario A3

Scenario A3 is the last of the optimal economic scenarios and concerns an annual decrease of 0,65% of the total quantity available at the holders. This scenario returns a total cost of 32 767 445€ and a network of 166 collection centres with a global average capacity of 200 tonnes. The cost allocation for each activity is illustrated in Figure 16 and like in the previous scenarios, recovery is the activity with a higher cost followed by processing in the collection centres and transportation.

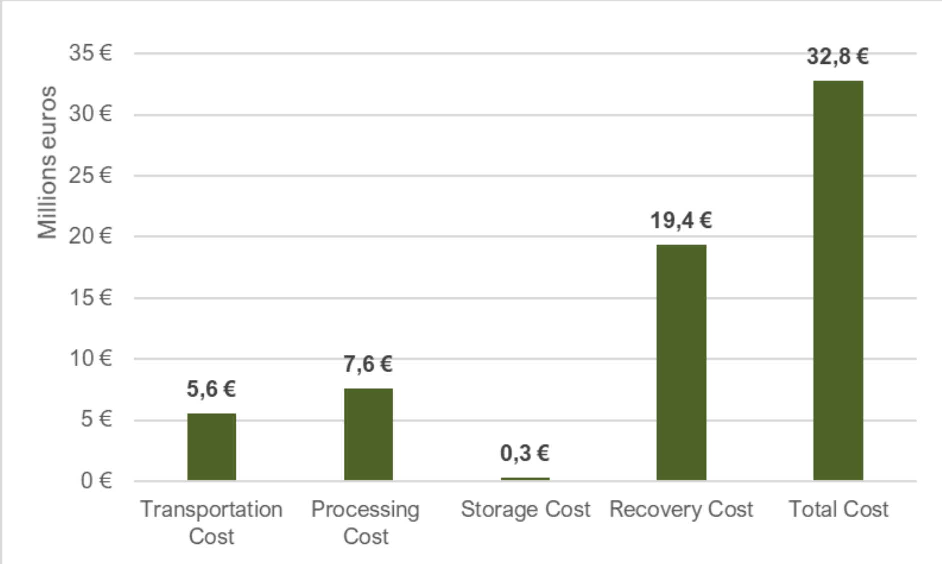

Figure 16 - Costs Scenario A3

6.2.1.4 Case A scenarios versus Targets scenario

In order to assess the economic benefit of opening so many new collection centres as implied in the results of the three economic optimal scenarios, the costs of these scenarios are compared against the current network: the Targets model. The Targets model is the version of the model with fixed collection centres corresponding to the locations of the current network for the same three hypotheses considering the quantities available at the holders (constant, 2% increase and 0,65% decrease). Table 14 outlines the differences between the costs of case A scenarios and the Targets scenarios. Except for the storage cost, Case A scenarios present lower costs especially the transportation cost from the holders to the collection centres. Although this cost is not incurred by Valorpneu, it is an important metric to evaluate Valorpneu's service level. A lower cost for the same quantity transported means that the collection centres are closer to the holders which is one of the goals of Valorpneu's network.

Table 14 - Comparison of the costs between the case A scenarios and the Targets scenario

Quantities	Scenarios	Transportation Cost from the Holders to the Collection Centres	Total Transportation Cost	Processing Cost	Storage Cost	Recovery Cost	Total Cost
Constant	Targets Scenario	3 169 471 €	7 616 494 €	8 004 631 €	76 704 €	20 496 069 €	36 193 898 €
	Scenario A1	1 358 669 €	5 679 238 €	7 709 841 €	266 888 €	19 773 635 €	33 429 601 €
	Variation	-57%	-25%	-4%	71%	-4%	-8%
+2%	Targets Scenario	3 373 043 €	8 332 282 €	8 514 247 €	59 628 €	21 823 714 €	38 729 870 €
	Scenario A2	1 428 998 €	6 116 937 €	8 184 954 €	273 604 €	21 017 554 €	35 593 048 €
	Variation	-58%	-27%	-4%	78%	-4%	-8%
-0.65%	Targets Scenario	3 100 371 €	7 415 040 €	7 844 738 €	82 810 €	20 079 919 €	35 422 507 €
	Scenario A3	1 315 309 €	5 558 234 €	7 560 796 €	264 762 €	19 383 653 €	32 767 445 €
	Variation	-58%	-25%	-4%	69%	-3%	-7%

6.2.1.5 Case A summary

Total network costs increase according with the quantity available for collection at the holders, i.e., the greater the quantity to be collected and recovered the higher is the total cost. Scenario A1, A2 and A3 optimal network consist of 162, 170 and 166 collection centres opened respectively. This represents a much higher number of collection centres than the current network which is justified by the much lower total cost when comparing each scenario with the Targets scenario (current network) with the same quantity available for collection. The cost reduction is particularly higher in the cost of transportation from the holders to the collection centres since more collection centres mean less kilometres travelled by the holders. Additionally, recycling operator R2 and energy recovery operators V4, V5 and V6 are the recovery operators preferred by the three scenarios and recycling operator R1 and recovery operator V1 the least preferred as they operate at maximum and minimum capacity, respectively, during the time periods considered. In all three scenarios Oporto, Aveiro and Santarém are the districts where more collection centres are opened which indicates that these might be interesting regions to open new collection centres. The number of collection centres opened per district in the three scenarios as well as the collection centres networks for each scenario of case A can be found in appendix B.1.

6.2.2 Case B

6.2.2.1 Scenario B1

Scenario B1 corresponds to the solution with the optimal environmental performance considering that the amount of used tyres available for collection remains constant during the time period in analysis. In this scenario, the model returns a total normalized environmental impact of 472 058 points and a network formed by 89 collection centres with a global average capacity of 78 tonnes. Figure 17 represents the normalized environmental impact for each entity. Collection centres are the entities with a greater environmental impact. The recovery operators present an environmental benefit (negative environmental impact) since the environmental impact of the recycling and energy recovery operators considers the benefits of recycling and sent to energy recovery used tyres i.e. the impacts of the alternatives for these two options. This results explain the reason why in this scenario a greater flow of amount of used tyres is sent to recovery than the defined by the legal target (in contrast to the economic scenario) and less stock is kept in the collection centres as outlined in Table 15.

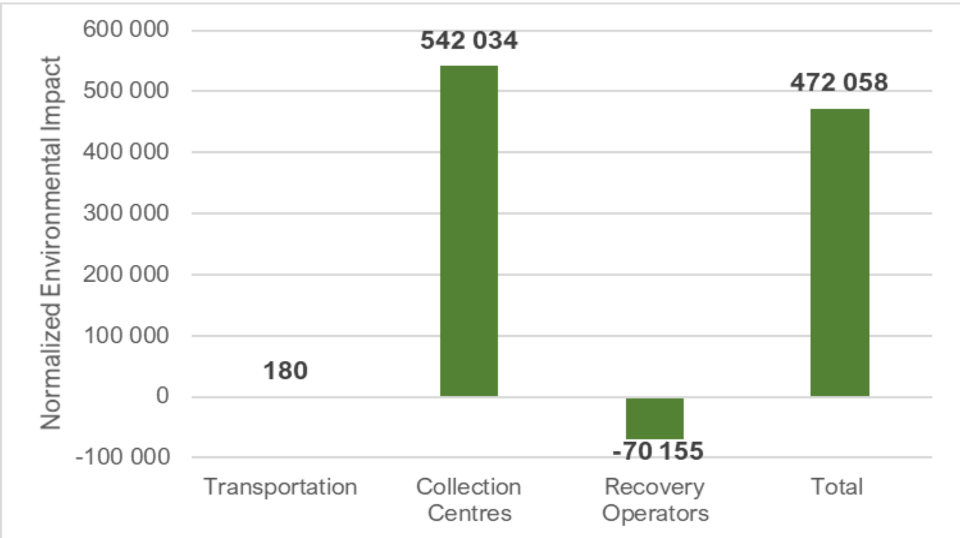

Figure 17 - Normalized Environmental Impacts Scenario B1

Table 15 - Flows amounts scenario B1

Results	Time Period				
	1	2	3	4	5
Amount available (tonnes)	70 821	70 821	70 821	70 821	70 821
Amount sent to recovery (tonnes)	78 400	70 089	70 975	70 723	71 497
Amount sent to recycling (tonnes)	50 960	45 558	46 134	45 970	46 473
Amount sent to energy recovery (tonnes)	27 440	24 531	24 841	24 753	25 024
Stock (tonnes)	0	732	578	676	0

6.2.2.2 Scenario B2

Scenario B2 optimizes the environmental objective function for an annual increase of 2% of the total quantity available at the holders. This scenario results in a total normalized environmental impact of 477 635 points and a network of 91 collection centres with a global average capacity of 77 tonnes. Like in the previous scenario, scenario B2 sends more used tyres to the recovery operators than the mandatory by the legal target as a result of the environmental benefit in the recovery operators explained in scenario B1. The normalized impacts the entities can be found in Figure **18** analogous to scenario B1, collection centres involved the highest environmental impact and the recovery operators have an environmental benefit.

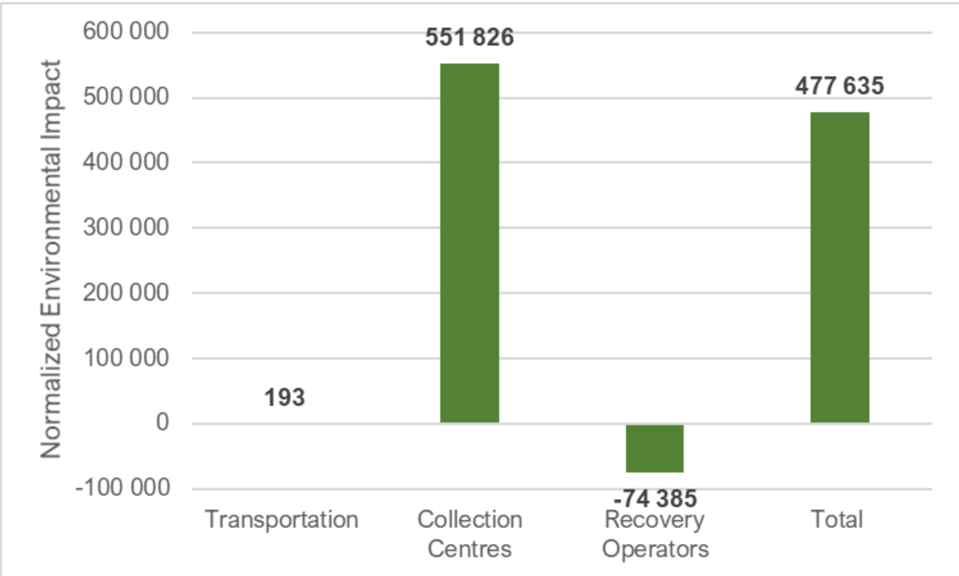

Figure 18 - Normalized Environmental Impacts Scenario B2

6.2.2.3 Scenario B3

In scenario B3 the optimal solution for the environmental objective function and an annual decrease of 0,65% of the used tyres available in the holders is considered. In this scenario a normalized total environmental of 470 199 points is achieved resulting in a network of 86 collection centres a global average capacity of 80 tonnes. Figure 19 exhibits the normalized environmental impact of the network's entities with similar conclusions as the previous two scenarios.

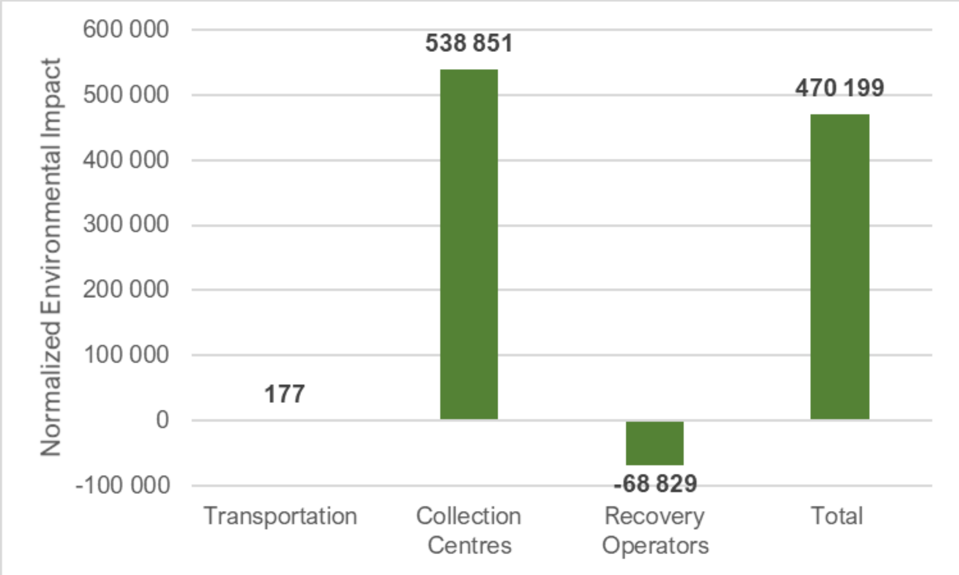

Figure 19 - Normalized Environmental Impacts Scenario B3

6.2.2.4 Case B scenarios versus Targets scenario

When comparing the results from case B scenarios with the results of the Target scenario considering the same quantity of used tyres available for collection, there is a substantial improvement in case B scenarios normalized environmental impact. Especially in the collection centres since the global average capacity of the collection centres in the case B scenarios is much smaller compared with the current capacity of the collection centres (average capacity of 78, 77 and 80 tonnes for scenarios B1, B2 and B3 respectively and 328 tonnes for Targets scenario). These results are summarised in Table 16.

Table 16 - Comparison of the normalized environmental impact between the case B scenarios and the Targets scenario

Quantities	Scenarios	Environmental Impact Transportation	Environmental Impact Collection Centres	Environmental Impact Recovery Operators	Total Environmental Impact
Constant	Targets Scenario	201	9 796 592	-70 155	9 726 638
	Scenario B1	180	542 034	-70 155	472 058
	Variation	-11%	-94%	0%	-95%
+2%	Targets Scenario	249	9 796 592	-74 385	9 722 456
	Scenario B2	193	551 826	-74 385	477 635
	Variation	-22%	-94%	0%	-95%
-0.65%	Targets Scenario	226	9 796 592	-68 829	9 727 989
	Scenario B3	177	538 851	-68 829	470 199
	Variation	-22%	-94%	0%	-95%

6.2.2.5 Case B summary

The total normalized environmental impact increases according with the quantity available for collection at the holders, i.e., the greater the quantity to be collected and recovered the higher is the total normalized environmental impact since the capacities determined for the collection centres need to be larger. Scenario B1, B2 and B3 optimal network consist of 89, 91 and 86 collection centres opened with a global average capacity of 78, 77 and 80 tonnes respectively. This represents a higher number of collection centres and lower global average capacity than the current network. This is justified by the much lower total normalized environmental impact when comparing each scenario with the Targets scenario (current network) with the same quantity available for collection. In return, this happens because the highest environmental impact is associated with the collection centres capacity which is on average smaller in case B scenarios than in the current network. Furthermore, the global average capacity of collection centres decreases with the rise of the quantity available for collection. This situation is triggered by the minimum flow constraint, more quantity available for collection means more outbound flows from more collection centres and a lower global average capacity. Recycling and energy recovery operators work close to their maximum capacity since these entities have an environmental benefit as the benefits of using these entities instead of alternative options and products avoids are considered in the environmental impact of these operators. In all three scenarios Oporto, Lisbon and Aveiro are the districts where more collection centres are opened. The number of collection centres opened per district as well as the resulting collection centres networks for the three scenarios can be found in appendix B.2.

6.2.3 Case C

6.2.3.1 Scenario C1

Scenario C1 represents the optimal social performance for a constant quantity of used tyres available for collection. In this scenario a total of 4 923 workers are employed by Valorpneu's network composed by 55 collection centres with a global average capacity of 539 tonnes. Figure 20 outlines the distribution of workers by the entities. Most of the workers are employed in transportation followed by the collection centres.

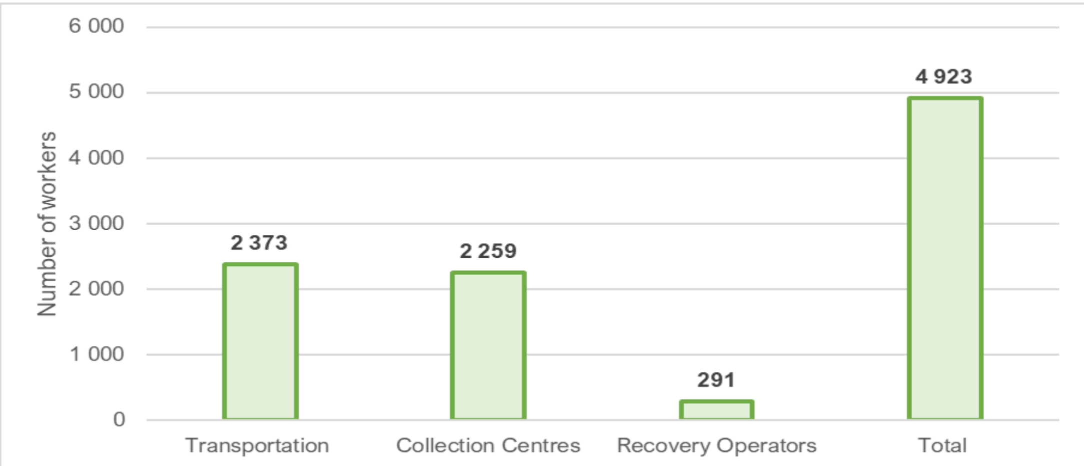

Figure 20 - Number of workers employed by each entity scenario C1

The number of workers needed in the collection centres per cubic meter is greater than the number of workers required in the recovery operators per tonne recovered as described in section 5.2.9. This explains why capacity of the collection centres in this scenario is larger than the current capacity of Valorneu's collection centres and than the global average capacity of the previous scenarios.

6.2.3.2 Scenario C2

In scenario C2 the social objective function is maximized considering an annual increase of 2% of the total used tyres available in the holders. This scenario returns a social benefit of 5 159 workers and a network of 55 collection centres with a global average capacity of 567 tonnes. The number of workers required in each entity are shown in Figure 21, similar to the previous scenario transportation and collection centres are the entities with a greater number of workers.

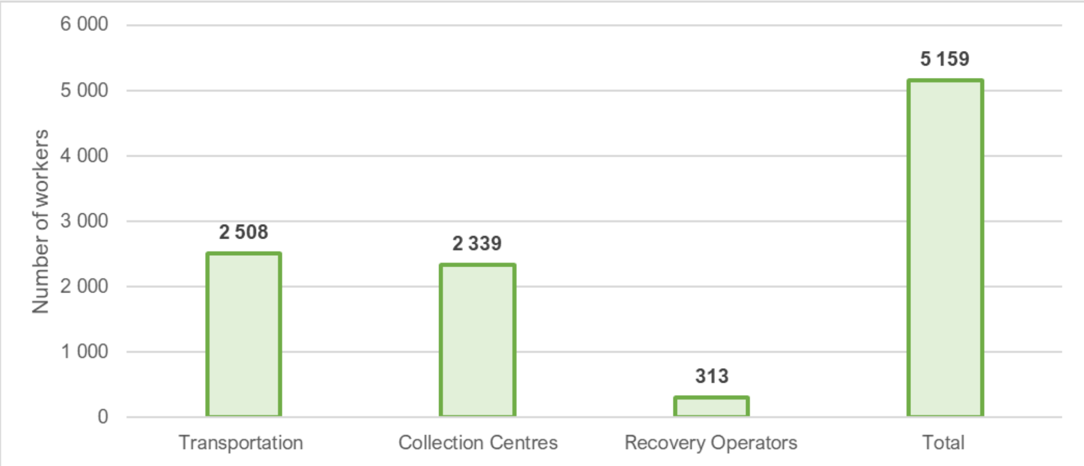

Figure 21 - Number of workers employed by each entity scenario C2

6.2.3.3 Scenario C3

Scenario C3 is the last scenario in analysis that corresponds to the optimum social performance and an annual decrease of 0,65% of the used tyres to be collected from the holders. The total social benefit obtained in this scenario is 4 848 workers, less than in the previous two scenarios as less quantity of used tyres is collected. The resulting network has 54 collection centres and a global average capacity of 544 tonnes. The distribution of the number of workers required by each entity can be found in Figure 22.

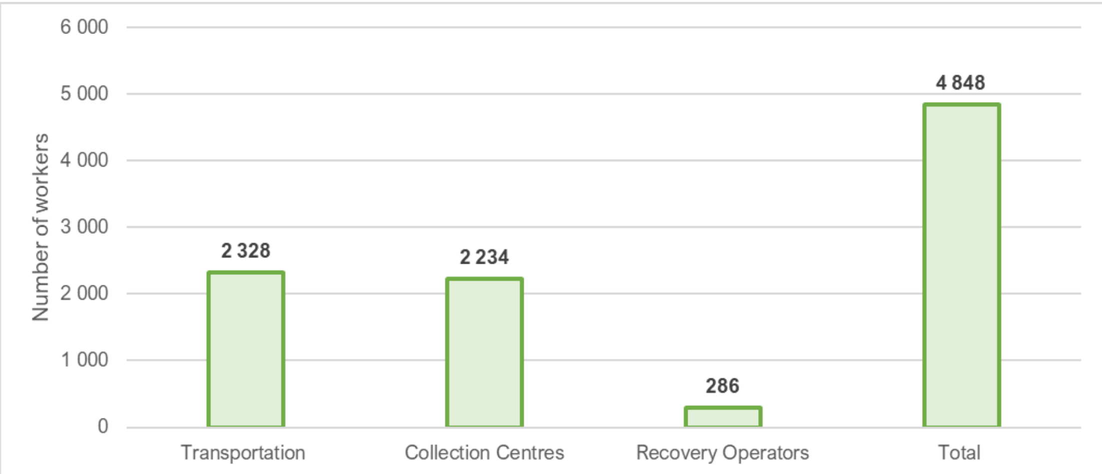

Figure 22 - Number of workers employed by each entity scenario C3

6.2.3.4 Case C scenarios versus Targets scenario

Comparing the results obtained from the case C scenarios with the Target scenarios higher social benefit is obtained in case C scenarios. All entities require a great number of workers in case C scenarios except the recovery operators. The number of workers required in the recovery operators is greater in the Target scenario since more used tyres are sent to these operators than the quantity defined by the legal target. In the case C scenarios only, the quantity defined by the legal target is sent to recovery the remaining is stocked in the collection centres since these entities have the highest social benefit. In the Targets scenarios the capacity in the collection centres are fixed. Consequently, the number of workers required in collection centres are fixed too thus, more used tyres are sent to recovery.

Table 17 - Comparison of the social benefit between the case C scenarios and the Targets scenario

Quantities	Scenarios	Social Benefit Transportation (nr.of workers)	Social Benefit Collection Centres (nr.of workers)	Social Benefit Recovery Operators (nr.of workers)	Total Social Benefit (nr.of workers)
Constant	Targets Scenario	1 608	278	323	2 208
	Scenario C1	2 373	2 259	291	4 923
	Variation	32%	88%	-10%	55%
+2%	Targets Scenario	1 691	278	341	2 309
	Scenario C2	2 508	2 339	313	5 159
	Variation	33%	88%	-8%	55%
-0.65%	Targets Scenario	1 580	278	319	2 176
	Scenario C3	2 328	2 234	286	4 848
	Variation	32%	88%	-10%	55%

6.2.3.5 Case C summary

Scenario C1, C2 and C3 optimal network consists of 55 collection centres opened for the first two and 54 for the third with a global average capacity of 539, 567 and 544 tonnes respectively. This represents a higher global average capacity than the current network which is justified by the greater number of workers required in the collection centres when comparing each scenario with the Targets scenario (current network) for the same quantity available for collection. All scenarios return a lower social benefit in the recovery operators than the Target scenario since only the quantity of used tyres set by the recovery target is sent to the recovery operators. This happens because the number of workers needed in the collection centres per cubic meter is greater than the number of workers required in the recovery operators per tonne recovered. The high number of workers needed in transportation is a consequence of greater distances travelled between the entities (holders to collection centres and collection centres to recovery operators) which is the opposite of what Valorpneu pretends: to be close to the holders improving the collection service level. In all three scenarios Faro and Bragança are the districts where more collection centres are opened. These districts differ from the ones chosen in the two previous cases because the social optimum favours the collection centres that require more kilometres travelled within the network while the opposite happens in the economic and environmental optimum. The number of collection centres opened per district in the three scenarios and the respective collection centres networks can be found in appendix B.3.

6.2.4 Scenario Analysis Conclusions

Comparing the results of each optimum scenario with the results from the Targets scenario (current network), all nine scenarios have a better performance on the respective objective function (economic, environmental and social) than the respective Targets scenario though this is achieved thanks to a greater number of collection centres opened.

Case C scenarios open the lower number of collection centres with the greatest overall average capacity which results in greater distances travelled within the network and a much higher network cost. Furthermore, in these scenarios the model opts for selecting the locations that require more kilometres travelled for opening collection centres instead of choosing the ones near the main sources of used tyres as is desirable. Thus, these scenarios are considered as unsuitable to meet Valorpneu's requirements and this study's objectives.

Considering the remaining scenarios, particularly scenarios A2 and B2 (as these scenarios represent the hypothesis of a 2% increase in the quantity available for collection at the holders which is the current observed tendency thus, the hypothesis considered to be more likely), in scenario A2 the model opens 162 collection centres with a global average capacity of 212 tonnes while in scenario B2 91 collection centres are opened with global average capacity of 77 tonnes. Thus, scenario A2 opens more collection centres with a higher average capacity but returns lower network costs (-8%) and higher social benefit (55%). Scenario B2 involves higher network costs and lower social benefit but returns a lower network environmental impact (-83%) and opens less collection centres with a lower average capacity. Nevertheless, both scenarios open more collection centres than the current network and, in both scenarios, a better performance in terms of total network costs and environmental impact is achieved than in the current case (Targets scenario). Accordingly, to achieve better economic and environmental performance namely, to be closer to the holders and improve the collection service level, Valorpneu should open more collection centres. Both A2 and B2 scenarios select the Oporto and Aveiro districts to open more collection centres, additionally in scenario A2 the district of Santarém has a high number of collection centres opened (15 collection centres) and in scenario B2 the Lisbon district is also among the preferred to open collection centres. The Oporto district will be further analysed in the next sections. Considering Aveiro, the current network has two collection centres located in this district while scenario A2 optimal network has 16 collection centres and scenario B2 10. Accodingly, opening more collection centres in Aveiro district is advisable particularly in the municipalities of Águeda, Arouca, Aveiro, Espinho, Oliveira de Azeméis, Ovar, Santa Maria da Feira and São João da Madeira where in both scenarios collection centres are opened. In the district of Santarém there are currently two collection centres while in scenario A2 15 collection centres are opened and in scenario B2 9. The municipalities of Alcanena, Alpiarça, Chamusca, Golegã, Salvaterra de Magos, Santarém and Tomar are selected in both scenarios. Finally, in Lisbon there are currently 5 collection centres whereas in scenario A2 and B2 10 and 13 collection centres respectively are opened. The municipalities of Azambuja, Lisboa, Odivelas, Oeiras and Torres Vedras are selected to open collection centres in both scenarios.

6.3 Sensitivity Analysis

The input parameters used to solve the present model and presented in chapter 5 were collected from different sources and although the majority of the information was provided by Valorpneu, due to the absence of data some parameters are based on premises. Thus, some parameters are subject a significant level of uncertainty and it is important to analyse how this uncertainty affects the results achieved in the previous sections. Accordingly, in this section a sensitivity analysis is performed on these critical parameters to test the robustness of the model results. These parameters are the capacity index, the storage and processing cost in the collection centres, the transportation cost, and the environmental impact of the collection centres. This analysis was performed for a variation of 10% on hypothesis 2: annual increase of 2% of the product available for collection since this option refers to the current observed tendency and therefore, it is considered as the most likely hypothesis.

6.3.1 Capacity Index

The capacity index defines how many tonnes fit in a cubic meter. This parameter is particularly relevant to define the capacities levels inside the collection centres. As outlined in Table 18, the variation of this parameter does not have a great impact on the total cost but affects the number of collection centres opened and their global average capacity. The increase of this parameter means that the same maximum allowable capacity in cubic meters is translated into a greater allowable capacity in tonnes. Thus, the global average capacity increases and as a result, the number of collection centres opened decreases since the more economical locations can process more tonnes of used tyres.

Table 18 – Results of Sensitivity Analysis on Capacity Index

Variation	-10%	A2	+10%
Total cost (€)	35 592 354	35 593 048	35 594 816
Nr. Collection Centres opened	177	170	164
Global average capacity (tonnes)	211	214	220

6.3.2 Compensation Fee

The compensation fee is the amount paid by Valorpneu to the collection centres per tonne processed. This fee might change when opening new collection centres thus, the impact of a 10% variation on this fee was analysed. As demonstrated in Table 19, the impact of this parameter on the collection centres is null and low on the global average capacity (less than 1%). In the total cost the impact is around 2% for both a 10% increase and decrease of the compensation fee which is also relatively low.

Table 19 - Results of Sensitivity Analysis on Compensation Fee

Variation	-10%	A2	+10%
Total cost (€)	34 825 354	35 593 048	36 440 436
Nr. Collection Centres opened	170	170	170
Global average capacity (tonnes)	212	214	215

6.3.3 Storage cost

As explained in section 5.2.6.1, the storage cost is aggregated with the compensation fee but in this study these two costs were differentiated in order to avoid the excessive stock creation in the collection centres when maximizing the economic objective. Hence, the impact of a 10% variation on the optimal network obtained in scenario A2 is also tested and exhibited in Table 20. The total cost increases with a 10% decrease of the storage cost since a decrease in the storage cost implies an increase on the remaining compensation fee cost which is paid by tonne processed and sent to the recovery operators. Since this quantity is imposed by the recovery target, it is expectable that the total cost increases although this increase is almost neglectable for a 10% variation (around 0,2%). The number of collection centres and global average capacity remain almost unchanged with a 10% variation on the storage cost.

Table 20 - Results of Sensitivity Analysis on Storage Costs

Variation	-10%	A2	+10%
Total cost (€)	35 677 098	35 593 048	35 505 011
Nr. Collection Centres opened	170	170	170
Global average capacity (tonnes)	214	214	216

6.3.4 Transportation Cost

Transportation is the activity where the model has more decision freedom thus, where it saves the greater cost. Looking at Table 21 it is noted that a variation of 10% in this parameter barely affects the results obtained for the economical optimum. The total cost suffers a variation of 2% for both a 10% increase and decrease on the transportation cost. Concerning the number and capacity of the collection centres, a 10% increase on transportation cost increases the global average capacity in 1% and as a result less one collection centre is opened. This happens since the model prefers to increase the capacity in the collection centres with better location economically wise.

Table 21 - Results of Sensitivity Analysis on Transportation Cost

Variation	-10%	A2	+10%
Total cost (€)	35 036 963	35 593 048	36 204 758
Nr. Collection Centres opened	170	170	169
Global average capacity (tonnes)	214	214	217

6.3.5 Environmental Impact Collection Centres

The environmental impact in the collection centres is the highest in all the environmental optimum scenarios highly contributing to the total environmental impact of the network. The results illustrated in Table 22 reinforce that this parameter has an high influence on the total normalized environmental impact since a 10% variation on these parameter results on a more than 10% variation on the total environmental impact. The optimal network suffers some changes: with a 10% decrease the number of collection centres decreases to 89 and the global average capacity increases 3%, with a 10% increase the optimal network has two additional collection centres and a 1% decrease on the average capacity. The environmental impact in the remaining entities remains unchanged thus, the network alterations are counter the variation on the environmental impact of the collection centres.

Table 22 - Results of Sensitivity Analysis on Environmental Impact Collection Centres

Variation	-10%	B2	+10%
Total Normalised Environmental impact	427 468	477 635	532 817
Nr. Collection Centres opened	89	91	93
Global average capacity (tonnes)	79	77	76

6.3.6 Sensitivity Analysis Conclusions

The sensitivity analysis performed on some parameters identified as critical due to their related uncertainty allows to draw the following conclusions: For a 10% variation the parameters with higher impact on the results obtained are the capacity index and the environmental impact of the collection centres. Particularly, concerning the network structure, alterations in these two parameters result on different number of collection centres opened and different global average capacities. Therefore, it is important to ensure the accuracy of these parameters by performing further analysis on their calculation such as measuring exactly how many tonnes fit in a cubic meter of a collection centre instead of using the load capacity index of the shipments of used tyres as reference for the capacity index case. For the environmental impact in the collection centres a more complete and specific LCA should be performed for these type of entities. Regarding the cost related parameters, for a 10% variation their impact on the total network cost and structure is minimal yet for a greater variation this might change thus it might be interesting to investigate how likely is to observe a higher variation on these costs.

6.4 Oporto Region

As discussed in chapter 2, Oporto district has been having some problems with the collection service level due to the distances between the holders and the collection centres available, thus an additional analysis is performed considering only this district and the scenarios presented above. For this study 18 holders and 18 collection centres were considered corresponding to the municipalities of Oporto district. From the 18 collection centres 5 are from the current Valorpneu's network and the remaining 13 are located in the remaining municipalities where currently no collection centre exists.

Table 23 summarises the results obtained for each objective function of each scenario. In each case the scenarios with higher network cost, environmental impact and social benefit are the ones considering the increase of the quantity of used tyres available (A2, B2, and C2) and the scenarios with lower cost, environmental impact and social benefit consider exactly the opposite, a 0,65% decrease of the quantity of product available for collection (A3, B3 and C3). Consequently, the quantity of used tyres collected from the holders has a significant impact on the objective functions studied. When the economic objective function is optimized (case A scenarios), the environmental impact is about 83% higher and a social benefit 30% lower when comparing with the respective environmental and social optimal objective functions. On the other hand, the cost of the results of optimizing the environmental objective function are about 8% higher and the social benefit 70% lower than the respective economic and social optimal solutions. Social optimal solutions have a cost penalty of 56% and an environmental impact 84% higher when comparing with the economic and environmental optimal objective function results respectively. Thus, once again case B scenarios offer interesting trade-off solutions since the optimization of the environmental objective function returns a network cost only 8% higher than the economic optimum while the optimization of the economic objective function results in an 83% higher environmental impact. Furthermore, the optimization of the environmental objective function returns a social benefit 70% lower than the social optimum solution while the social optimal solution returns an environmental impact 84% higher than the environmental optimum.

Table 23 - Summary of the results of each scenario for Oporto region

Scenarios	Total Cost (€)	Environmental Impact	Social Benefit (nr. of workers)
A1	**4 556 521**	396 528	380
A2	**4 839 763**	415 543	395
A3	**4 467 702**	389 599	375
B1	4 956 256	**69 176**	164
B2	5 277 716	**69 997**	171
B3	4 923 217	**68 903**	162
C1	10 396 863	436 939	**546**
C2	11 039 932	455 236	**571**
C3	10 195 161	428 641	**538**

In the scenarios A1, A2 and A3 the 18 collection centres are opened with global average capacities of 288, 302 and 283 tonnes respectively. Figure 23 illustrates the map of the economic optimum scenario. The collection centres 1, 2, 3, 4 and 5 are already part of the current network. The municipalities of Matosinhos and Maia (represented by the numbers 17 and 18) are particularly interesting locations to open collection centres as they receive a greater number and amount of flows of used tyres from the holders (five holders sent used tyres to these locations).

Figure 23 – Scenarios A1, A2 and A3 map of the opened collection centres in Oporto district

Comparing these results with the ones obtained from the Targets scenario (in this case the scenario with collection centres 1, 2 ,3 ,4 and 5 and fixed capacities of respectively 460, 710, 205, 460 and 490 tonnes) just for the Oporto region, significantly improvements are obtained in the cost and social objectives: Network costs are 6% lower and the social benefit between 21% and 24% depending on the quantity available at the holders as outlined in Table 24. On the downside, the total normalized environmental impact is between 56% and 59% higher in the case A scenarios.

Table 24 - Comparison of the economical optimum results of case A and Targets scenarios in Oporto

Quantities	Scenarios	Total Cost (€)	Environmental Impact	Social Benefit (nr. of workers)
Constant	Targets Scenario	4 826 233	172 723	298
	Scenario A1	4 556 521	396 528	380
	Variation	-6%	56%	22%
+2%	Targets Scenario	5 140 124	172 082	302
	Scenario A2	4 839 763	415 543	395
	Variation	-6%	59%	24%
-0.65%	Targets Scenario	4 728 222	172 925	296
	Scenario A3	4 467 702	389 599	375
	Variation	-6%	56%	21%

In the scenarios B1, B2 and B3 9, 8 and 7 collection centres with a global average capacity of 113, 129 and 144 tonnes respectively are opened. Figure 24 demonstrates the environmental optimum network: in scenario B1 all 9 collection centres are opened, scenario B2 does not open collection centre number 13 and scenario B3 does not open collection centres number 13 and 15. From the current network only 4 collection centres are opened and like in the economic optimum scenarios the collection centres located in Matosinhos and Maia are chosen (collection centres number 17 and 18).

Figure 24 - Scenarios B1, B2 and B3 map of the opened collection centres in Oporto district

When analysing the results of scenarios B1, B2 and B3 and the respective Targets scenarios as illustrated in Table 25, in terms of environmental performance, case B scenarios have a total normalized environmental impact around 60% lower than the Targets scenarios. In terms of social performance case B scenarios are in disadvantage having a social benefit about 46% lower than the Targets scenarios. The total network cost is similar for both scenarios (1% lower for scenarios B1 and B2 and 0,3% higher in scenario B3).

Table 25 - Comparison of the environmental optimum results of case B and Targets scenarios in Oporto

Quantities	Scenarios	Total Cost (€)	Environmental Impact	Social Benefit (nr. of workers)
Constant	Targets Scenario	5 006 316	172 445	301
	Scenario B1	4 956 256	69 176	164
	Variation	-1%	-60%	-46%
+2%	Targets Scenario	5 315 397	171 821	305
	Scenario B2	5 277 716	69 997	171
	Variation	-1%	-59%	-44%
-0.65%	Targets Scenario	4 907 952	172 641	300
	Scenario B3	4 923 217	68 903	162
	Variation	0,3%	-60%	-46%

The social optimum (scenarios C1, C2 and C3) returns a network with 6 collection centres and global average capacities of 948, 988 and 930 tonnes respectively. As illustrated in Figure 25, scenarios C1, C2 and C3 return the same network as the current Valorpneu's network with exception of collection centre number 10 located in the municipality of Felgueiras which is additionally opened.

Figure 25 - Scenarios C1, C2 and C3 map of the opened collection centres in Oporto district

Examining the results of case C and Targets scenarios, C1 and C3 scenarios return a social benefit 15% higher than the respective Targets scenarios and in scenario C2 this social benefit is 17% higher. In terms of costs, again scenarios C have a better performance having a total network cost 3% lower than the Targets scenarios though when considering the impact of these solutions on the environment this situation is reversed. Accordingly, the environmental impact in the Targets scenarios is 60% lower than in the case C scenarios.

Table 26 - Comparison of the social optimum results of case C and Targets scenarios in Oporto

Quantities	Scenarios	Total Cost (€)	Environmental Impact	Social Benefit (nr. of workers)
Constant	Targets Scenario	10 702 860	172 596	463
	Scenario C1	10 396 863	436 939	546
	Variation	-3%	60%	15%
+2%	Targets Scenario	11 334 150	171 981	476
	Scenario C2	11 039 932	455 236	571
	Variation	-3%	62%	17%
-0.65%	Targets Scenario	10 503 450	172 789	459
	Scenario C3	10 195 161	428 641	538
	Variation	-3%	60%	15%

Additionally, the kilometres made by the holders to the collection centres in each scenario were calculated and can be found in Table 27. As expected, scenarios C1, C2 and C3 involve more kilometres travelled by the holders since more kilometres travelled mean more workers required in transportation thus, these scenarios are not a solution for Valorpneu's current problem. In both the economic and environmental optimum, the collection centres located in Matosinhos and Maia are opened and represent interesting candidates as they receive used tyres from five different holders (including the three with usually the highest amount of used tyres available for collection). Furthermore, the network provided by the solution of scenario B2 presents a good trade-off between the number of collection centres opened, the total network cost and environmental impact. Comparing the results of scenario B2 with scenario A2 (the corresponding scenario for the economic optimum) scenario B2 opens less 10 collection centres, has a total cost 8% higher and an total normalized environmental impact 70% lower. Therefore, the municipalities of Valongo and Porto (locations number 15 and 16 also opened in scenario B2) are also promising locations to open collection centres apart from the municipalities of Matosinhos and Maia. Concerning the outbound flows from the collection centres, as expected, in the economic and environmental optimum cases, the recovery operators chosen are the recycling operator R1 and the energy recovery operator V5 as these entities are the closer entities of Oporto district available. The social optimum choses the recycling operator R1 and energy recovery operator V3, the further recovery operators.

Table 27 - Total kilometres travelled by the holders in each scenario

Scenarios	A1	A2	A3	B1	B2	B3	C1	C2	C3
Total distance travelled by the holders	31 km	32 km	31 km	69 km	80 km	90 km	331 km	340 km	329 km

6.5Chapter Conclusions

Considering the scenario analysis for the entire network, the optimal network for each scenario represented a better performance in the respective objective when comparing to the current network (Targets scenario) though for all scenarios, this means more collection centres opened than the presently opened. Additionally, scenarios A2 and B2 represent interesting solutions in particular the districts of Oporto, Aveiro, Santarém and Lisbon where more collection centres were opened in both scenarios. The hypothesis of the quantity of used tyres available at the holders will increase 2% was selected as the most reasonable as this is the tendency currently observed and more likely to be observed in the future. The results of the social optimum scenarios select the locations that involve more distances travelled for opening the collection centres in order to increase the number of workers required. This situation is the opposite of what Valorpneu's pretends: to decrease the distances between the network's entities namely between the holders and the collection centres thus these results were discarded as possible solutions for the current problem.

From the sensitivity analysis the parameters capacity index and environmental impact of the collection centres were identified as having the highest impact on the results obtained for a 10% variation particularly in the network structure. This means that these parameters must be calculated with the maximum accuracy as alterations in these two parameters result on different number of collection centres opened and different global average capacities dimensioned for the collection centres representing a limitation of this study.

The analysis made to the Oporto region showed again that the significant improvements in the sustainable dimensions are obtained in each optimal network compared with the current network. In both the economic and environmental optimum the municipalities of Matosinhos, Maia, Valongo and Porto represent good candidates to open collection centres as these municipalities receive a high amount of used tyres from the several different holders which means that opening collection centres in these locations is likely to improve the collection service level of Oporto region. The social optimum scenarios are again discarded as these scenarios involve more kilometres travelled by the holders to the collection centres thus a poorer collection service level.

7 Conclusions and Future Work

The importance of a sustainable development is globally acknowledged and a crucial step to achieve this goal is to make the current economy more resource efficient. In the EU efforts to move from a linear to a circular economic model have been put into practice through several initiatives and directives such as the implementation of ERP schemes for specific products' waste streams like tyres. Altogether, the number of used tyres generated has been increasing yearly and environmental and health problems arise when this waste flow is disposed in landfills uncontrollably. This reinforces the importance of having management systems responsible for the collection and recovery with value creation of used tyres which are often implemented under EPR schemes.

In Portugal, Valorpneu is the entity responsible for managing this used tyres' collection and recovery system. Thus, Valorpneu's purpose is to implement and manage a network composed by multiple entities namely the holders, collection centres, carriers, retread manufacturers and recovery operators that efficiently ensures the routing of used tyres to a suitable destination according to the legal targets in terms of collection, retreading and recycling rates. The implementation and management of such network is a challenging task. Hence, the present dissertation has the main objective of developing a support decision tool for the design and planning of Valorpneu's network that minimizes the total network costs and environmental impact and maximizes the social benefit by determining the number, location and capacity of the collection centres that enables the collection of used tyres from its sources. Accordingly, a mathematical optimisation model was developed to address this problem and tested for different scenarios in order to find the solutions that better satisfy this study objectives and Valorpneu's requirements.

The literature review showed that optimisation models have been largely employed to solve this kind of problems where often the three pillars of sustainability are translated into different objectives in a multi-objective model. Though, just a few works were found where multi-objective models considering the three dimensions of sustainability are applied to the network design and planning of products under EPR schemes. Moreover, energy recovery is not considered as a recovery option in most studies analysed. Considering the type of products under EPR schemes studied it was concluded that the number of works employing the tyre case-study is still limited. From the optimisation models reviewed, the work proposed by Mota et al. (2018) was identified as the most suitable to address the objectives proposed. Thus, the mathematical optimisation model developed is based on this work though some adaptations were made to better represent the case-study namely, in the present study only the reverse network of the tyre lifecycle is considered and the objective functions were modified to better address the problem in hand and for simplification purposes.

Concerning the collection of the model's input data, although most of the information was provided by Valorpneu, due to the lack of information assumptions and simplifications were required to estimate some of the parameters resulting on a higher related uncertainty. Furthermore, given the limited time and scope of this research, parameters related with environmental and social impact were obtained from external sources. From the sensitivity analysis the parameters with the highest impact on the results are the capacity index and the collection centres environmental impact since variations on these two parameters result on different network configurations representing a limitation of this study.

From the scenario analysis presented, in the previous chapter, it is concluded that the resulting networks from all the scenarios considered show significant improvements in the respective objective function compared with the current network. This is possible thanks to a greater number of collection centres opened in all scenarios thus, in order to achieve a better performance in the three dimensions of sustainability and improve the collection service level by being closer to the holders, Valorpneu needs to open more collection centres. The districts of Oporto, Aveiro, Santarém and Lisbon were identified as primarily action areas to open collection centres as these districts are the ones where a greater number of collection centres are opened in the economic and environmental optimal solutions and where the difference between the existing collection centres and the opened by the model is higher. Namely Valorpneu should consider the locations in the municipalities of Águeda, Arouca, Aveiro, Espinho, Oliveira de Azeméis, Ovar, Santa Maria da Feira and São João da Madeira in Aveiro district; Alcanena, Alpiarça, Chamusca, Golegã, Salvaterra de Magos, Santarém and Tomar in Santarém district and Azambuja, Lisboa, Odivelas, Oeiras and Torres Vedras in Lisbon district to open new collection centres. The social optimum scenarios return networks involving more distances travelled between the entities which is the opposite of what is pretended and therefore, these scenarios are not considered as viable solutions for the present problem.

On the Oporto region analysis, it is reinforced the need of opening more collection centres than the ones currently opened. In both the economic and environmental optimal scenarios opening collection centres in the municipalities of Matosinhos, Maia, Valongo and Porto represent a promising solution to improve the collection service level of Oporto region and eliminate the existing problem as these municipalities receive a high amount of used tyres from the several different holders. Hence, new collection centres should additionally be opened in these locations. Once again, in this case the social optimal scenarios were not considered since they choose to open the further collection centres resulting in more kilometres travelled within the network.

Finally, suggestions for future developments include: the integration of the three dimensions of sustainability in a unique solution of compromise which establishes the trade-offs between the three sustainable objectives through a Multiple Objective Mathematical Programming (MOMP) approach. Several attempts to run this bi-objective optimisation were performed using the augmented ε-constraint method but no efficient solutions were obtained due to the very large computational time. A more extensive and accurate characterisation of the social dimension should be also done with the possible inclusion of a social indicator as proposed by Mota et al. (2015) so meaningful results for this objective in terms of actual social benefits and not just number of workers required in the network are obtained.

In addition, a complete and case specific LCA that considers more impact categories especially for the collection centres and recovery operators should be performed using the ReCiPe methodology. The uncertainty related with the tyre category available for collection should also be studied since this parameter highly influences the destination of the used tyres according to the category accepted at the different recovery operators, as formerly discussed.

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A Appendix A – Environmental Impact

Table 28 - Environmental Impact Collection Centres

Midpoint Impact Categories	Units	Total	Normalized Total
Climate change	kg CO2 eq	5,15E+02	2,87E+01
Acidification	molc H+ eq	5,69E+00	6,85E-01
Terrestrial eutrophication	molc N eq	6,40E+00	2,32E-01
Marine eutrophication	kg N eq	5,10E-01	1,54E-02

Table 29 - Environmental Impact Transportation

Midpoint Impact Categories	Units	Total	Normalized Total
Climate change	kg CO2 eq	2,18E-01	5,15E-06
Acidification	molc H+ eq	9,74E-04	2,00E-08
Terrestrial eutrophication	molc N eq	2,74E-03	4,26E-08
Marine eutrophication	kg N eq	2,45E-04	3,55E-09

Table 30 - Environmental Impact Shredder Operator

Midpoint Impact Categories	Units	Total	Normalized Total
Climate change	kg CO2 eq	2,00E+00	2,17E-04
Acidification	molc H+ eq	1,00E-02	2,11E-04
Terrestrial eutrophication	molc N eq	2,00E-02	1,14E-04
Marine eutrophication	kg N eq	0,00E+00	0,00E+00

Table 31 - Environmental Impact Recycling Operators

Midpoint Impact Categories	Units	Total	Normalized Total
Climate change	kg CO2 eq	-7,41E+02	-8,04E-02
Acidification	molc H+ eq	-4,16E+00	-8,79E-02
Terrestrial eutrophication	molc N eq	-6,69E+00	-3,80E-02
Marine eutrophication	kg N eq	-5,30E-01	-3,14E-02

Table 32 - Environmental Impact Energy Recovery Operators

Midpoint Impact Categories	Units	Total	Normalized Total
Climate change	kg CO2 eq	-3,44E+02	-3,73E-02
Acidification	molc H+ eq	-2,49E+00	-5,26E-02
Terrestrial eutrophication	molc N eq	-2,16E+00	-1,23E-02
Marine eutrophication	kg N eq	-1,80E-01	-1,07E-02

B Appendix B – Results

B.1 Case A

Table 33 - Computational Results Case A

	A1	A2	A3
Variables	1 980 528	1 980 528	1 980 528
Discrete Variables	280	280	280
Iterations	140 988	153 781	149 232
Relative Gap	6,10E-05	2,00E-06	5,00E-06
Time to solve algorithm (sec)	299	284	410

Table 34 - Number of collection centres opened scenarios A1, A2 and A3 per district

District	Nr. Collection Centres Opened			
	A1	A2	A3	Current
Aveiro	16	16	16	2
Beja	8	8	9	2
Braga	10	10	10	2
Bragança	8	8	8	1
Castelo Branco	12	12	11	1
Coimbra	2	2	2	1
Évora	4	3	5	1
Faro	8	9	9	2
Guarda	8	9	7	1
Leiria	10	10	10	3
Lisboa	9	10	11	5
Portalegre	4	4	5	1
Porto	17	17	17	4
Santarém	14	15	14	2
Setúbal	10	11	10	5
Viana do Castelo	6	7	6	2
Vila Real	8	11	8	2
Viseu	8	8	8	2
Total	162	170	166	39

Figure 26 - Collection Centres Network scenario A1

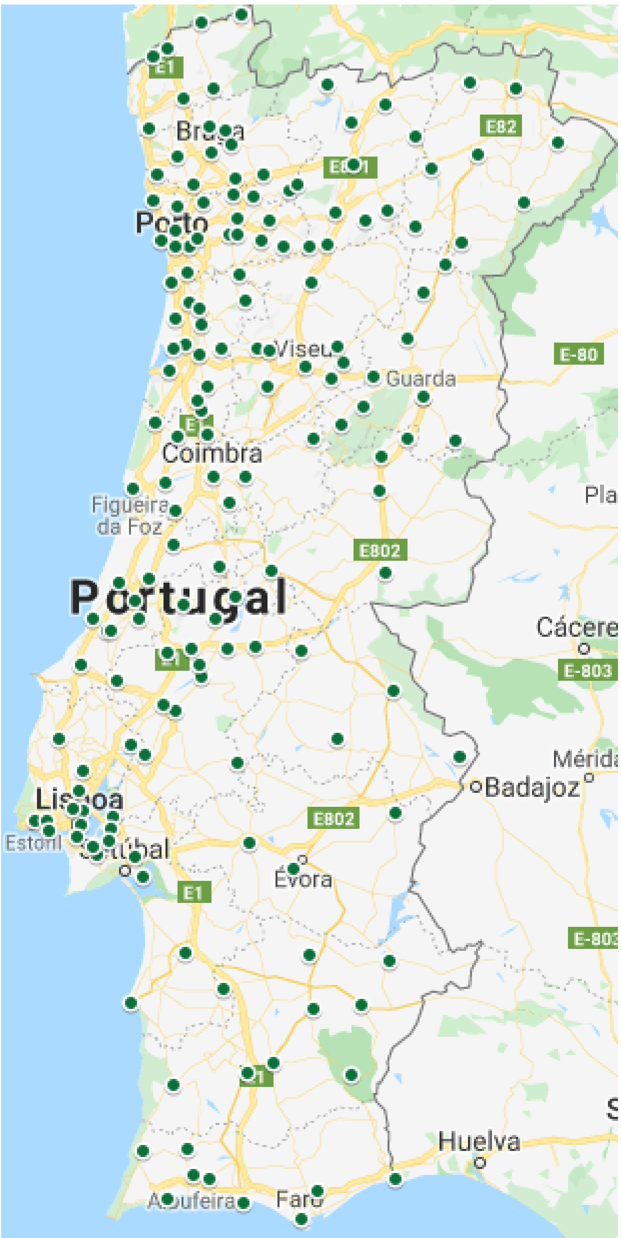

Figure 27 - Collection Centres Network scenario A2

Figure 28 -Collection Centres Network scenario A3

B.2 Case B

Table 35 - Computational Results Case B

	B1	B2	B3
Variables	1 980 528	1 980 528	1 980 528
Discrete Variables	280	280	280
Iterations	552 945	632 797	533 383
Relative Gap	0,00E+00	0,00E+00	1,00E-06
Time to solve algorithm (sec)	1 716	2 018	2 246

Table 36 - Number of collection centres opened scenarios B1, B2 and B3 per district

District	Nr. Collection Centres Opened			
	B1	B2	B3	Current
Aveiro	10	10	9	2
Beja	3	3	3	2
Braga	5	5	5	2
Bragança	1	1	1	1
Castelo Branco	3	3	2	1
Coimbra	2	2	2	1
Évora	1	1	1	1
Faro	2	2	2	2
Guarda	2	2	2	1
Leiria	8	8	8	3
Lisboa	12	13	11	5
Portalegre	1	1	1	1
Porto	13	13	13	4
Santarém	8	9	8	2
Setúbal	9	9	9	5
Viana do Castelo	2	2	2	2
Vila Real	3	3	3	2
Viseu	4	4	4	2
Total	89	91	86	39

Figure 29 - Collection Centres Network scenario B1

Figure 30 - Collection Centres Network scenario B2

Figure 31 - Collection Centres Network scenario B3

B.3 Case C

Table 37 - Computational Results Case C

	C1	C2	C3
Variables	1 980 528	1 980 528	1 980 528
Discrete Variables	280	280	280
Iterations	429 019	552 643	410 513
Relative Gap	7,00E-06	4,00E-06	7,00E-06
Time to solve algorithm (sec)	637	759	350

Table 38 - Number of collection centres opened scenarios C1, C2 and C3 per district

District	Nr. Collection Centres Opened			
	C1	C2	C3	Current
Aveiro	2	2	2	2
Beja	2	2	2	2
Braga	2	2	2	2
Bragança	6	5	6	1
Castelo Branco	1	1	1	1
Coimbra	2	2	2	1
Évora	1	1	1	1
Faro	10	11	9	2
Guarda	1	1	1	1
Leiria	3	3	3	3
Lisboa	5	5	5	5
Portalegre	1	1	1	1
Porto	4	4	4	4
Santarém	2	2	2	2
Setúbal	5	5	5	5
Viana do Castelo	3	3	3	2
Vila Real	3	3	3	2
Viseu	2	2	2	2
Total	55	55	54	39

Figure 32 - Collection Centres Network scenario C1

Figure 33 - Collection Centres Network Scenario C2

Figure 34 - Collection Centres Network Scenario C3