Optimisation of a collection and recovery network of used tyres

Valorpneu case-study

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Abstract The problem addressed in this paper 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. 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. 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 Valorpneu's network and the results obtained serve as baseline to compare and evaluate possible improvements. Different scenarios are also tested revealing that the districts of Oporto, Aveiro, Santarém and Lisbon are promising districts for opening more collection centres. The critical parameters are subject to a sensitivity analysis to test the robustness of the results obtained.

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

1. Introduction

Every year, around 17 million tonnes of tyres reach their end of life worldwide (WBCSD, 2010). This increasing trend reinforces the importance of an efficient and sustainable system which guarantees the correct collection and recovery of this waste flow. Such need has been imposed in Europe through the European Directive 1999/31/EC dated 26th of April 1999. In Portugal, the Decree-Law nr 11/2001 established the principles and norms applied to the tyres' and used tyres' management and defined the legal framework for the implementation of the ERP system for used tyres. The implementation and management of such systems is a challenging task involving not only the management of a complex network's flows and interaction between the different operators but also the design and planning of the network itself. Accordingly, the problem addressed in this study is concerned with the design and planning of a Portuguese recovery network for used tyres aiming to determine the number and location of the collection centres that guarantee an efficient collection of the used tyres from its sources while considering the three dimensions of sustainability.

This paper is organized as follows:

First a brief review on the literature on reverse logistics, sustainable supply chains and design and planning of recovery networks is made. In the Section 3. the case-study in analysis is presented. The mathematical model resulted from the decision support tool developed is formulated in Section 4. In Section 5. the results of the scenarios considered are outlined and discussed. Finally, in the last section conclusions are drawn and future work directions discussed.

2. Literature Review

2.1. Reverse Logistics and EPR systems

Reverse Logistics (RL) plays nowadays an essential role in the companies' strategy as a mean to gain competitive advantage. Ecological motivations, specifically the ones originated by governmental pressure, appear as one of the reasons why RL systems are so important nowadays. Following Extended Producer Responsibility (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 (Lu & Bostel, 2007). 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 and tyres (Monier et al., 2014).

2.2. Sustainable Supply Chains

The definition for sustainable development was extended to include the three pillars of sustainability explored in the concept of the Triple Bottom Line (TBL) which 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 Supply Chain (SC) (Ahi & Searcy, 2013). 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). Seuring (2013) performed a review on papers applying quantitative models on Sustainable Supply Chain Management (SSCM) 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 SSCM where 59% of the analysed papers use cost as an economic measure. Concerning the environmental pillar, 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. The most frequently used LCA methods in the literature are the EcoIndicator-99 and the IPCC methods (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. When comparing the three dimensions of sustainability, the social pillar appears as the least explored by academics and practitioners particularly in SC (Seuring, 2013). The most popularly methods used to assess the social dimension are job creation, poverty, number of working hours, discrimination, health and satisfaction. (Barbosa-Póvoa et al., 2018). Mota et al. (2015) developed a Social Benefit

Indicator to support facility location decisions which favours job creation in less economically developed regions.

2.3. Network Design and Planning

As an integrating part of a SC, the design and planning of RL also involves strategic, tactical and operational decisions although the decisions' nature differ from the ones considered in the traditional forward chain as RL deals with different types of activities, market demand and supply characteristics. 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 (De Brito & Dekker, 2002). To solve SC problems in the strategic level sphere optimisation models have been largely applied in the literature. 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). 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. From the papers reviewed concerning reverse and closed-loop SC, 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. The main research gaps identified in the papers reviewed are the lack of multi-objective models for products under EPR systems network design and planning considering the three pillars of sustainability, the uncertainty related with the returned products is 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 the tyre case-study are still limited.

3. Case-Study

As previously mentioned, the present work focus on Valorpneu's recovery network. Valorpneu is the organization responsible for designing, implementing and managing a network composed by multiple entities 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.

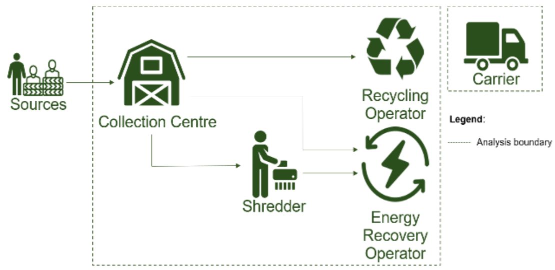

Figure 1:Valorpneu's network schematic representation

Thus, Valorpneu's network has a four-echelon structure composed by the holders which are the entities who introduce used tyres in the system, the collection centres where these used tyres are stored, the recycling and energy recovery operators and the retread manufacturers. Additionally, the shredder operator is an intermediate entity between the collection centres and the energy recovery operators in case these entities only accept previously shredded tyres. Figure 1 illustrates the schematic representation of Valorpneu's network. Accordingly, 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. Mathematical Formulation

The model developed for the current case study is based on the work of Mota et al. (2018) though some adaptations were made to better represent the case-study: only the reverse network of the tyre lifecycle was considered; location and capacity decisions are only taken for the collection centres, the remaining entities are considered fixed, different products are modelled according to the product's categories accepted by each recovery operator; transportation is outsourced and unimodal thus a single freight type is contemplated and transport capacity is not regarded as limited. The three dimensions of sustainability are also introduced as objective functions although with some alterations as further discussed.

4.1. Sets

The following general sets to characterize the network's superstructure are considered: I for all the entities, M for the products and T for time.

4.1.1. Entities

The network is defined by six groups of entities: the holders, the collection centres, the recycling operators, the energy reocvery operators which only accept previously shredder tyres, the remaining energy reocvery operators and the shredder operator.

4.1.2. Products

Six product categories are contemplated: passenger, truck, industrial, damaged, massive and shredder.

4.1.3. Time

For modelling reasons three types of time intervals are considered: First time interval, last time interval and all the time intervals except the first. The time horizon considered is 5 years.

4.2. Parameters

Parameters are the inputs received by the model. Concerning the network entities, maximum and minimum capacities and distances are considered. Regarding the products the initial stock at the collection centres and the quantity available for collection are the parameters contemplated. The legal collection, recycling and energy recovery targets are also defined as parameters. Additionally, the cost, environmental and social parameters used in the objective functions are also included.

4.3. Decision Variables

4.3.1. Continuous variables

Four continuous and non-negative variables, i.e., variables which may assume continuous values are used: the variable X which allows to know the flow amount between each pair of entities during a time period, the variable S which represents the amount of product stored in a given collection centre during a time period, and the two variables used to define the capacity in the collection centres: one determines the used capacity of a collection centre in a given period of time and the other determines the overall capacity of each collection centre.

4.3.2. Binary Variables

The binary variable has only two possible values, 1 if the entity is opened, 0 otherwise.

4.3.3. Auxiliary variables

As auxiliary variables, the total network cost, the total environmental impact and the total social benefit of the objective functions are considered.

4.4. Objective Functions

4.4.1. Economic Objective

The economic objective function involves four different types of costs: transportation cost given by the sum of the flow amount transported between the entities times the respective distance and cost; the storage cost given by the sum of the amount of product stored in all collection centres times the storage cost; the compensation fee cost which multiplies the total amount of product processed in the collection centre by the compensation fee and the recovery cost of the total amount of product processed at the shredder, recycling and energy recovery operators.

4.4.2. Environmental Objective

In the environmental objective function the environmental impact of the collection centres, transportation and recovery operators is minimized. To calculate these impacts for each entity the ILCD system methodology where the individual environmental impacts are estimated for each midpoint category was applied.

4.4.3. Social Objective

In the social objective function the number of workers required by each entity is maximized.

4.5. Constraints

The objective functions described are subject to a set of constraints to ensure the model complies with the real case characteristics. Thus, four types of constraints are considered: material balance constraints that ensure the balance between the entities inbound and outbound flows; capacity constraints that set limits to the flows and stock amounts of the entities in the network; and target constraints that guarantee that the recovery, recycling and energy recovery legal targets are complied.

5. Results and Discussion

In this section the model presented in the previous section is implemented. First the model was validated using the Valorpneu’s current network for comparison, considering the economic objective. Then the scenarios under analysis were tested. A sensitivity analysis was also performed on the parameters subject to higher uncertainty. Finally, a more detailed scenario analysis just for the Oporto region was conducted since this region was identified as having problems in collecting used tyres from the holders due to the high distances between these entities.

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.

5.1. Model Validation

The model developed was applied to the current Valorpneu's network, 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 model returned a total network cost 12% lower than the actual cost incurred by Valorpneu which is mainly explained by the difference in the total transportation cost which is 47% lower for the model results. Since collection centres locations and number were fixed for comparison purposes, 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.

5.2. Scenarios Analysis

For the scenario analysis nine different scenarios were defined following the hypotheses of constant flow of used tyres available at the collection centres during the time in analysis (hypothesis 1), increasing flow of 2% (hypothesis 2) and decreasing flow of 0.65% (hypothesis 3). The 2% increase is the currently observed trend thus, it is considered as the most likely and the 0.65% decrease is the tendency observed in the number of new tyres sold which might impact the generation of used tyres thus, it is also considered. Concerning the sustainable objectives defined another three cases are studied corresponding to the optimal solution of each of the three objectives thus, 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 presented. Table 1 compiles the main results obtained in each scenario. When minimizing the cost (case A scenarios), 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 (case B scenarios) 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 (case C scenarios), result in a total network cost 70% higher and an environmental impact 79% greater than in the economic optimum and environmental optimum scenarios Accordingly, 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..

Table 1: 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**

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. 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. Considering the remaining scenarios, particularly scenarios A2 and B2, 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. 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 thus 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.

5.3. Sensitivity Analysis

The input parameters used to solve the present model 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 section. Accordingly, a sensitivity analysis was performed on these critical parameters to test the robustness of the model results. 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 thus it is important to ensure the accuracy of these parameters by performing further analysis on their calculation. Regarding the cost related parameters, for a 10% variation their impact on the total network cost and structure is minimal.

5.4. Oporto Region Analysis

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. This analysis showed again that 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.

6. 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. Hence, in Portugal, Valorpneu is the entity responsible for implementing and managing a network composed by multiple entities 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, thus, 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 under different scenarios in order to find the solutions that better satisfy Valorpneu's requirements. The literature review on the optimisation models showed that the work proposed by Mota et al. (2018) was the most suitable to address the objectives proposed thus, the mathematical optimisation model developed is based on this work. 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. 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 in these two parameters result on different network configurations representing a limitation of this study. From the scenario analysis 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, 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. The social optimum scenarios return networks involving more distances travelled between the entities which is the opposite of what Valorpneu pretends thus, these scenarios are not considered as viable solutions for the present problem. On the Oporto region analysis, 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. 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. 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. 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.

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