UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

FACULTAD DE INGENIERÍA MECÁNICA Y ELÉCTRICA

DESIGN OF A REVERSE LOGISTICS NETWORK FOR RECYCLING ACTIVITIES USING MAXIMAL COVERING FACILITY LOCATION PROBLEM

POR

XIMENA DORELY MEDRANO GÓMEZ

COMO REQUISITO PARCIAL PARA OBTENER EL GRADO DE MAESTRÍA EN LOGÍSTICA Y CADENA DE SUMINISTRO

DICIEMBRE, 2018

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Subdirección de Estudios de Posgrado

Los miembros del Comité de Tesis recomendamos que la Tesis "Design of a reverse logistics network for recycling activities using maximal covering facility location problem", realizada por el alumno Ximena Dorely Medrano Gómez, con número de matrícula 1353979, sea aceptada para su defensa como requisito parcial para obtener el grado de Maestría en Logística y Cadena de Suministro.

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Contents

List of Figures

List of Tables

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Aquí puedes poner tus agradecimientos. (No olvides agradecer a tu comité de tesis, a tus profesores, a la facultad y a CONACyT en caso de que hallas sido beneficiado con una beca).

Resumen

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Título del estudio: Design of a reverse logistics network for recycling activities using maximal covering facility location problem.

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Objetivos y método de estudio: Aquí debes poner tus objetivos y métodos de estudio. (Este es el formato).

Contribuciones y conlusiones: Y aquí tus contribuciones y conclusiones. (También es parte del formato).

Firma del asesor: ______________________________

Dr. Omar Jorge Ibarra Rojas

Chapter 1

Introduction

The waste generation is increasing every day worldwide. According to the report *"'What a waste 2.0 - A Global Snapshot of Solid Waste Management to 2050"'* published by World Bank Group (2018), in 2016 the solid waste generated around the world reached the amount of 2.01 billion tonnes. With the urbanization and population increasing day-to-day is spectated that the levels of solid waste generated will increase by 70 percent in 2050. The figure 1.1 shown the Waste Generation Per Capita of all the countries of the world.

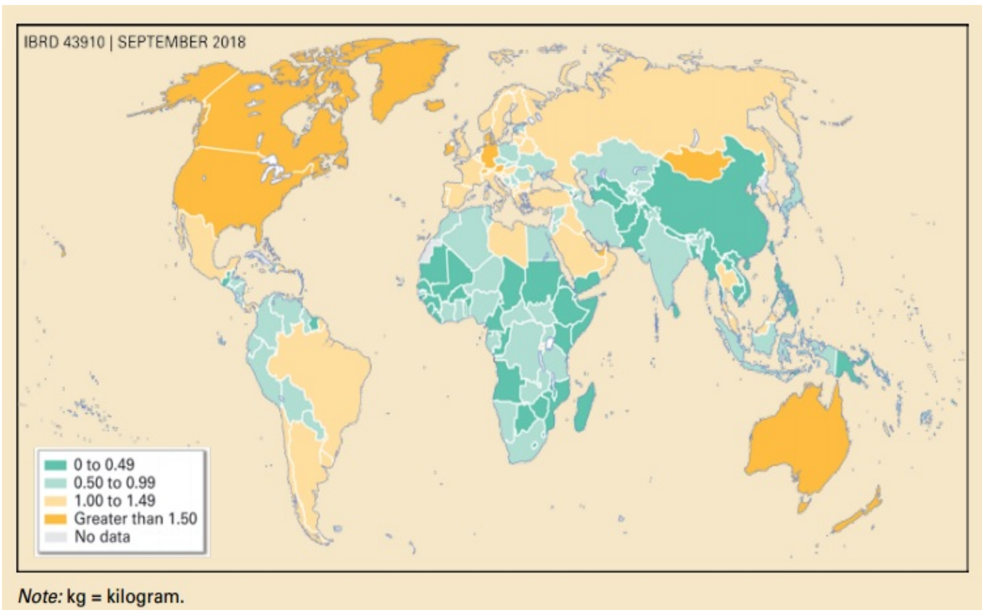

Figure 1.1: Waste Generation Per Capita taken from World Bank Group

In contrast with developed countries, the inhabitants in developing countries are mostly affected by the negative impacts of an improperly stable waste management. Poorly waste management contributes to the contamination of oceans, increase respiratory problems, provoke health problems, poor living conditions, clogging drains and causing flooding. Unfortunately, the activities related to the waste management represent the municipalities and government highest cost, actually; it can represent almost 20 percent of their budgets, on average.

Commonly, the management of waste is handling by the local authorities. Which face with the limitations of capacity for planning, scarce resources, contract management, and operational activities. These features become the waste management a difficult task, even more to the developing countries. When seen in different income dimensions, the waste management activity can represent the 20% percent of the municipal budget for the low-income countries, while to middle-income countries mean more than 10%. Even the high-income countries get affected by the cost that this activity represents, generating for them about 4% (World Bank Group). Thus, the decision makers must select the best choices when it comes to the activities related to the end of life products (waste). Nevertheless, make the best decisions about infrastructure, operational and logistics may represent a hard duty, even worst, when there are related to uncertain future events such as environmental factors change, population growth and market trends.

For it is part, the activities of recycling and reuse of EOF products may represent economic, environmental, social and ecological advantages (**?**). Giving the benefits of waste reduction, use of less energy in the process of the plants, reduce cost, obtain profits and conservation of natural resources.

As a result, was developed extensive literature involved with the reverse logistics (RL) discipline and operational research (OR) in meeting these activities. The context of this study is the strategic planning to create a functional collection network of EOL products involved the activities of recycling and reuse of this solid waste through the selection of Facility Locations for collection. However, different problems of Facility Location problem (FLP) in RL can be found through literature to represent a wide range of scenarios.

Therefore, in the next section, we punctuate the details and problem description of our recycling network, in order to differentiate our study.

1.1 Problem statement

Commonly, the EOF product management in developing countries are regulated from the government or even by the socially responsible companies. In these systems, the organization, financial resources and planning are their main challenges (??). The activities as an improper collection system management, incorrect route of planning, and poor infrastructure have been reported as the principal affectations of a good performance of collection, transfer and transport practices into the system (??). Additionally, an insufficient supply of waste collection facilities or long distance locations growth the inadequate decisions about waste disposal selection by the consumers, producing waste dumping in open areas. The Figure 1.2 shown an example of the way of a reverse logistics network works .

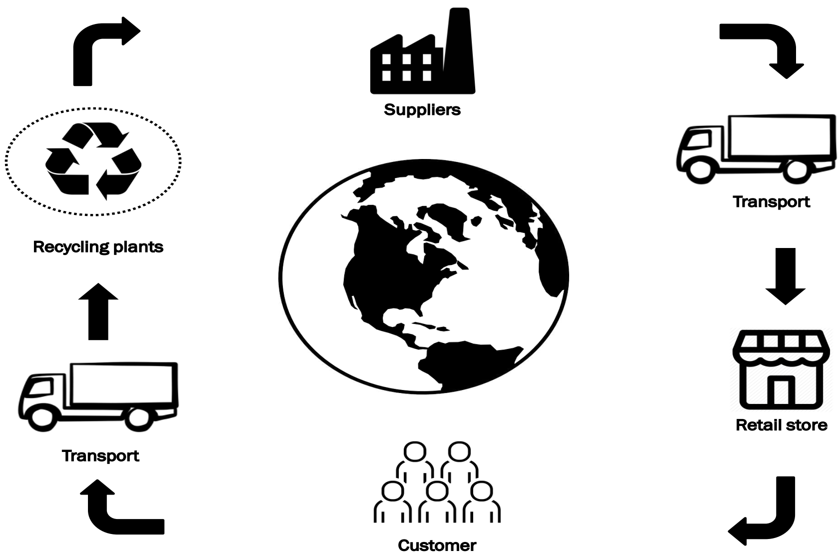

Figure 1.2: Reverse Logistics Network configuration

With the purpose of overcome the main Reverse logistics challenges, our study seeks to optimize the strategic decisions into a collection network of EOL products. In particular, by defining the quantity and location of collection centers have to be installed within a recycling network. A financial budget with the purpose to increase the number of wastes collected is established, taking into account the constraints of capacity per collection center and recycling plant of the network. As we know, in many practical cases the allocated resources are not enough to cover all of the existing demand (e.g., facilities or customers) within the desired service distance. Therefore, we allow to the problem a service coverage radius, to provide the collection services as many people as possible. To the extent of our knowledge, the characteristic of service distance level applied in Reverse Logistics area is relatively new in literature since the coverage has been considered only by a few studies.

As shown in Chapter 2 previous studies have been developed with equal characteristics as a support in the strategic decisions. Nevertheless, proficient methodologies focus on environmental characteristics are needed since the main objective is often led to the minimization of the system costs.

1.2 Objectives

The general objective of this study is provide an optimal recycling network design handled through logistics reverse and modeled by mean of a maximal covering location problem. In order to increase the quantity of waste collected by the network, with the support of an investment budget established and the profits obtained from the sale of the waste.

The specific objectives include:

- Define a representative optimization problem.
- Design a mathematical model so that it is possible to take strategic decisions about the quantity and location of collection centers to be installed. As well as to support in decisions as the capacity of each collecting center, the coverage radius of service and the financial budget to invest.

- Analyze and compare the different scenarios of experimentation with the purpose of support the network planning decisions. In an effort to get insights into the practical problem, as the most important characteristics that influence in the decision process.

1.3 Justification

The companies, governments and societies around the world are commonly motivated or obligated to apply the reverse logistics (RL) for three principls forces. These forces are categorized under the following qualification:

Within the literature, there are three forces commonly founded that either motivate or obligate to the companies to apply the logistics reverse (LR) within an organization. These forces are categorized under the following qualification:

1. Economics
2. Legislation
3. Environmental and social consciousness

Economics and Legislation forces are pretty related to companies and governments. The first one provides to the institutions' gains and reductions by the implementation of reverse logistics programs, which include the activities of reuse, recycling or from reducing disposal cost. Differently, the legislation force does not have the motivation as its principal characteristic; this one is more focused to coerce to the companies and organizations to incorporate the RL activities through their supply chain by the applications of penalties for non-compliance. Finally, environmental and social consciousness force, as its name would suggest, seeks the caring of the environment by getting concerne to the organizations and societies about to become engaged with reverse logistics.

Nowadays, a great number of developing countries are obligated through the economics and legislation forces to implement the RL. However, few are the studies applying the Environmental and social consciousness as the main motivation. Therefore, a well-defined methodology focus in Environmental and social consciousness is quite useful to complement and support the literature. Since our methodology has its focus in an environmental panorama by the activities of collection and recycling, it may represent an academic contribution.

1.4 Hypothesis

Through the implementation of the logistics reverse and the modeling of the study by mean of a maximal covering location problem is possible to design a recycling sustainable system that allows us to increase the number of waste collected coming from the end of life products.

1.5 Methodology

Our methodology comprises of a theoretical part (literature study about operational research) and an applied method of different phases (maximizing the amount of waste collected by the network using an optimization model). We focus mainly on the context of collection and recycling as part of RL discipline, where some issues, as well as challenges and opportunities, were found. Our endeavor is to develop a more formal framework in RL for analyzing and highlight the importance of a collection network design. To achieve this, we develop an optimization model including the parameters of "‘coverage"’ and "‘budget"’; conduct an experimental of random instances and finally use real data to conduct various practicals scenarios by working in a case of study of tires recycling.

1.6 Dissertation structure

In the next section, we present a summarizes and review of relevant papers on reverse logistics and facility location problems to relate our study to the existing literature. Section 3, introduces the methodological process implemented in order to describe and develop the problem quoted. In an effort to present a clear panorama of the different phases employed and their tools. Hereafter, Section 4 analyzes the study case results and compare the computational findings of simulated scenarios, whereas conclusions and future research are provided in Section 5 of the thesis.

Chapter 2

State of the art

In the present chapter, we expose the existing interaction between reverse logistics and operational research, which is carried out through the application of mathematical methods for the resolution of environmental concerns. A general theoretical framework focus on the different quantitative methods employed in reverse logistics discipline is introduced. Nonetheless, we make a special emphasis in Facility Location Problems (FLP), specifically in the variant in which its coverage is optimized (MCLP – Maximal Covering Location Problem).

To get the most related articles the combination of the keywords as “Reverse Logistics”, “Facility Location Problem”, “Maximal covering location problem”, “Collecting” and “Recycling” were employed in editorials such as Elsevier, Science Direct, Springer and the database of Google Scholar. A set of 52 articles were found of which only 13 of them were selected.

2.1 Contextualization of the study

Within the literature, the concept of Reverse Logistics (RL) has been defined in different ways by many authors. While some authors relate the definition with the return of product from the customer to the company, others connect the concept with the reuse and recycling activities. According to the Rogers and Tibben-Lembke (1999), reverse logistics (RL) is defined 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"'.* While, authors as **?** link the concept with a more environmental perspective.

Occasionally, the concept of reverse logistics is confused with other green practices relate with the Green supply chain management (GSCM). Some of these practices are Green transport (GT)

Nowadays the Reverse Logistics is taking more importance, and this can be seen in the growing amount of companies that are adopting it as a strategic tool (in order to get economic benefits), and create a corporate social image (**?**), (**?**). Three are the principal reasons that motivate to the companies and society to get involved with Reverse Logistics. These factors are categorize under the following headings (**?**):

- Economics: By the implementation of logistics reverse programs, the companies are able to obtain gains through the use of raw material, recycling or from reducing disposal cost. The electronics industry is a clear example of this due to the potential value which can be recovered from the end of life (EOL) products. Likewise, other benefits can be obtained as market protection, a green image, an improved customer or supplier relation and the anticipating the future legislation.

- Legislation: This factor refers to the jurisdiction impose on the companies by the Government in order to recover their products or accept them back. The recycling quotas, monetary penalties, packing regulations, and manufacturing take-back responsibility are some of the rules impose by the environmental legislation in different countries around the world.

- Corporate citizenship: Different to environmental legislation, the corporate citizenship is the environmental awareness that impels a company or an organization to become engaged with RL. Nowadays, many companies have created RL programs where both social and environmental issues are important. At the same time, this new green image may help to attract customers, bringing potential benefits to the company.

As it is stated by **?**, the process of RL network begins when the used or returned product are collected from the product acquisition, and then is inspected and sorted in different categories. After that, the product is sent to its repair, reuse, remanufacturing, recycling or their final disposal. Therefore, the product acquisition, collection, inspection/sorting, and disposition are identified into the RL process as the key steps. The figure 2.1 is shown the complete logistics process describe above, where the continuous flow from raw material to consumers represents the forward logistics, while the dashed line flow represents the reverse logistics.

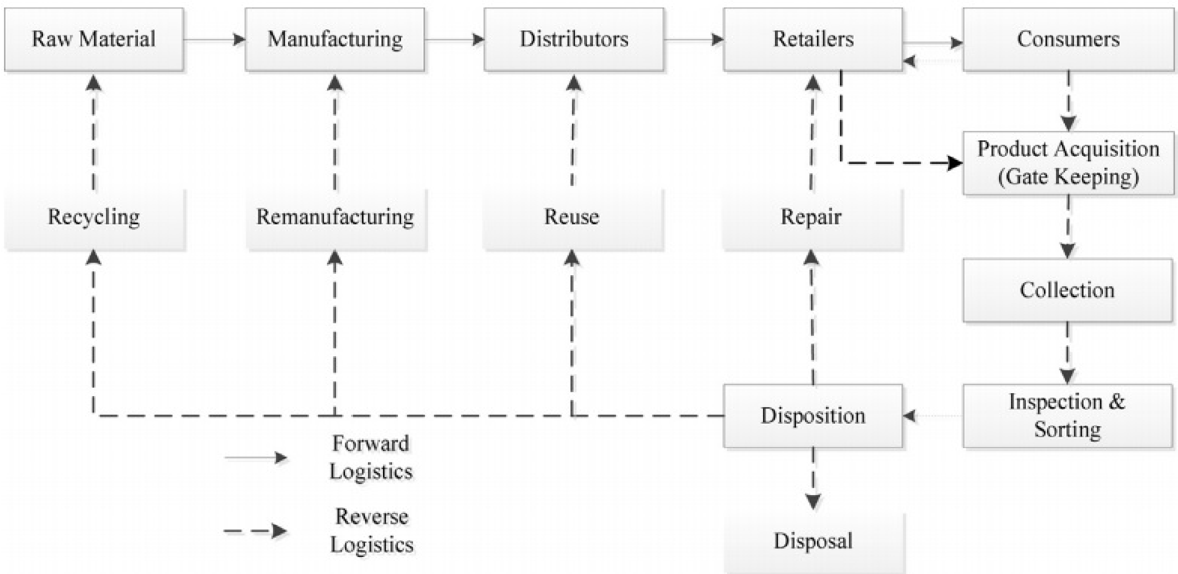

Figure 2.1: Basic flow of forward and RL processes taken from Agrawal, Singh e Murtaza (2015)

To put it in another way, the forward logistics does not apply any responsibility through its flow for end-of-life products. While the reverse logistics (also called reverse supply chain) takes this responsibility for EOL products in the most environmentally friendly way possible (**?**). The classic supply chain is not able to carry out the reverse movements, due to the costs are usually higher, and the manner to handle the goods to be recycling cannot be the same as in the direct channel (?).

? assures that RL has its focus on the management of waste, material recovery (through recycling), parts recovery or product recovery (through manufacturing). Unfortunately, as mentioned before the costs related to these activities are usually high to the investors, and even more when the recovery products as seen as a competition front to the new products, becoming a risky investment venture. However, through an optimal location and allocation of facilities in RL, the costs related to the recovered product process can be reduced.

A vast literature in optimization problems for reverse logistics network design has developed out of the broadly interest in meeting this challenge. Specifically, the Facility Location models, which are described in a general way as a given of potential set locations for facilities and a set of clients, with the objective to locate facilities in such a way that total cost for allocating facilities and fulfilling the demand of customers is minimized (?). For a detailed overview of facility location models, we refer to the works (?), (?).

2.1.1 Facility Location Problem in Reverse logistics

The decisions related to facilities location are an important element of strategic planning for a wide group of private and public organizations. The consequences based on the location of facilities are widely established in long-term decisions, generating an impact on numerous operational and logistical aspects (?). The idea that the mathematical location model can recognize optimal localization patterns is supported by the fact that some realistic objective can be identified and, in a certain way, quantified.

A large portion of quantitative models in Reverse Logistics act with the areas of facility location, production planning, inventory management in remanufacturing, and resource allocation and flows (??). ? supply a broad review in quantitative models for Reverse Logistics in three main areas, called them distribution planning (including facility location decisions), inventory control, and production planning. In addition, **?** provide a wide overview of the Interaction between operational research and environmental management comprehending locations for waste disposal. Gradually, the facility location model has been considered within the supply chain context, and as a consequence within the reverse logistics area as well (**?**).

The use of location models in reverse logistics is described in a number of studies, some related to cases. **?** address a problem of designing optimal recycling collection networks for unrecoverable tires with the objective to determinate: (i) the number of receiving centers, (ii) the location of these receiving center and (iii) the incentive price to be paid by the recycler to collecting agents per recyclable product delivered. **?** handle a case study for recycling sand by building a two-level network finding out which facilities should be built and how the sand should be classified, stored, cleaned and the delivered to the projects. On the other hand, **?** present a facility location allocation model for the collection and preprocessing of carpet waste to decide the locations of Regional Preprocessing centers. The model is applied in two practical cases, one in Europe and the other one in USA, respectively.

Furthermore, some papers conduct optimization models for reverse logistics network design with environmental issues. **?** propose a mathematical model to find the location choices for collecting the used products and for implementing recovery options, with and additional objective function to minimize the climate change (specifically, the CO2 footprint). **?** developed a model that seeks to determinate the number and location of collection centers, repairs plants, recycling plants, as well as the transportation strategy having as an extra goals the minimization of carbon emissions related to the transportation and processing of used products, and also the minimization the waste of resources in landfill.

In addition, few papers apply an investment budget constraint in the supply chain network design. **?** address an extension of the classical deterministic Capacity Facility Location Problem to create a location planning design for recycling urban solid waste, where a financial budget is considering as one of the principals constraint. For their part,

? provide a multi-objective problem that considers the environmental decision in the supply network design phase.

2.1.2 Covering Problems in Facility Location for Reverse Logistics

The Covering Problem is one of the most popular models within the Facility Location Problem. Even when these kind of problems are not new, they have been always very attractive for research, and this is in consequence of its applicability in real life (?). According to ? these model can be divided into two classes: Set Covering Problem (SCP) and Maximal Covering Location Problem (MCLP). Fundamentally, in the SCP a covering is required, while in MCLP a coverage is optimized. Some papers relate the set covering problems with the area of Reverse Logistics. ? propose a two stages location set covering and P-median integrated problem with the final purpose to implement a new location planning and assignment model to reduce the number of existing recycling centers in Taiwan. ? present a set covering problem and maximum satisfiability (MAX-SAT) formulations to establish a new selective collection system for urban waste management, where a maximum distance between users and their closest collection point is used as a measure of service. While, ? addresses a Reverse Logistics study modeled through an Uncapacitated Facility Location Problems for the collection of End-of-Life Vehicles in Mexico, with three possible scenarios, which consider 100 percent, 90 percent and 75 percent of collection coverage.

On the other hand, the MCLP seeks serve the maximum population within a fixed service distance or a time given a finite number of facilities (?). The readers who are interested in a comprehensive review of covering problems in facility location are referred to the works of (?), (?). To our knowledge, only one paper explore the maximal coverage scenario into the Reverse Logistics discipline. ? propose a maximal covering location problem in order to cover a partition service zones into sub zones by one or more collection facilities.

Authors	Enviromental objective	Monoperiodic	Capacitated	Coverage	Maximal coverage constraint	Budget allocation
Barros et al. (1998)		x	x			
Bautista and Pereira (2006)						
Cruz Rivera and Ertel (2009)				x		
Lin Ye et al. (2011)				x		
Vidovic et al. (2011)				x	x	
Wang (2011)	x		x			
Kannan et al. (2012)	x	x	x			
Toso and Alem (2014)			x			x
Yu and Solvang (2016)	x	x	x			
Jorge Burgos (2018)			x			
This study	x	x	x	x	x	x

Table 2.1: Literature review of location models for reverse logistics

Table 2.1 summarizes the literature review corresponded to location models for reverse logistics and shows the principals differences between the existing literature and the current study. The first column presents the corresponding authors and the year when the paper was published. As can be seen, the following columns used a (x) mark to point out the features applied in the other studies. On the other hand, the second column exposes the articles where the primary objective was the environmental care, either through the decrease of carbon emissions or even through the minimization of climate change. The third and fourth column presents the monoperiodic and capacitated studies, while, the column five shown the papers where the feature of coverage was applied and the sixth column difference those with the maximal coverage constraint. Finally, the last column exhibits the studies where an investment budget was implemented.

2.1.3 Conclusions

Almost all the elements that define the structure of a Facility Location Problem in Reverse Logistics are a set of potential locations, a set of clients, a demand, costs for allocating and transporting from one point to another, as well as the constraints of capacity. However, note that only a few studies consider the limitations on covering and investment budget, as well as the environmental focus of maximizing the amount of waste collected. The models found in the literature do not fit our problem definition, due to the goal of maximizing the quantity of waste collected poses a problem no usually treated in the existing literature, as well as, the feature of the investment budget that can be increased concerning the collected items. Therefore, a study and efficient model involving these features are required.

Chapter 3

Methodology

In the present chapter, our objective is to illustrate the methodological process employed to effect the description and the development of the thesis' problem. In order to introduce a clearer picture of the different phases applied.

3.1 Operational Research

The origin of the Operational Research (OR), also known as decision-making theory is attributed to the military service borrowed at the beginning of the Second World War, where was necessary the allocation of the scarce resources to the different military operations and the activities into every mission, in the more effective way. Stimulated by the success of the OR in the military field, the industrial sector beginnings to get interested in this field and it was then as it was introduced into the industry, the business, and the government.

The OR is an interdisciplinary branch of mathematics which employs algorithms and mathematical models with the aim of being used as support in the decision making. The end is finding solutions more efficient (on time, resources, benefits, etc) in comparison with the decisions making intuitively or without the support of a tool. The above is particularly true in those problems with a complex nature, which consider a hundred or even thousands of variables of decisions and constraints.

An additional feature of operations research is that it seeks to find the best solution - called commonly optimal solution- for the problem in question. **The optimization**, also known as mathematical programming is one of the principal areas of OR which count with different variants (linear, non-linear, integer, stochastic, dynamic, etc). This area can be defined as a problem of optimal allocation of limit resources, that seeks accomplish an objective given (the decision maker goal). The resources could correspond to people, materials, facilities, money, etc.

Within of the OR study, exists usual phases that serve as support for its implementation in practice, the figure 3.1 presents each one of these phases, which were applied as the methodological process in the thesis project.

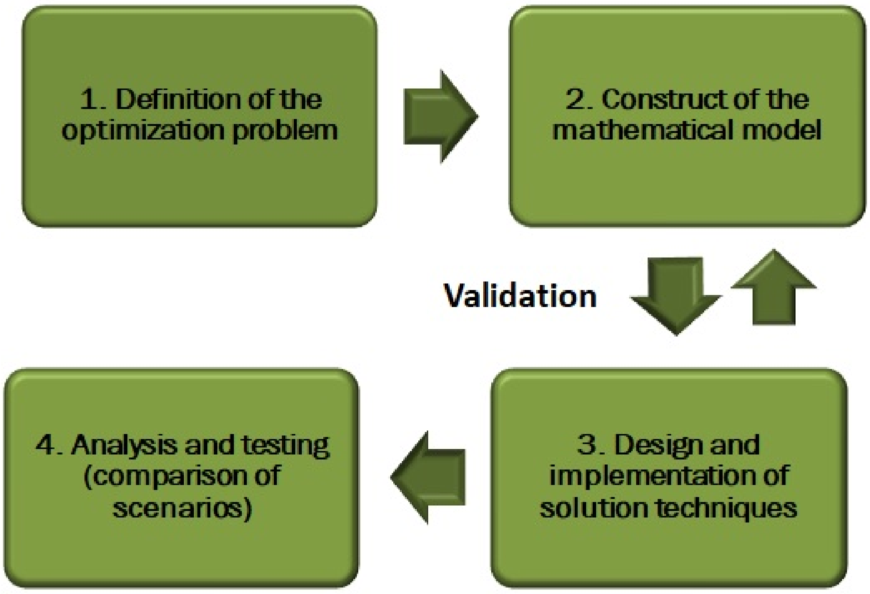

Figure 3.1: Methodological process applying the study phases of OR

Nonetheless, is important to consider that although the phases of the project usually begin in the order indicated, sometimes do not end in the same order. It happens due to the interaction that exists among them, what causes each phase to be reviewed and updated steadily until the project is completed.

3.2 Definition of the optimization problem

The phase of the definition of the optimization problem is perhaps the most delicate of the process since it supposes determining a clear and accurate definition of the problem faced. As a support, we will use the application of the optimization problems in order to solve the research problematic.

3.2.1 Application of the Facility Location Problem

One of the main activities of the human being that differentiates us from other creatures, is the decision making. There is a wide scale of decision-making problems whose information is spatial (geographic). Into the literature, this kind of decisions is called "'location decisions"'. The location of facilities is a branch of the operational research related with the positioning of new facilities to minimize or maximize at least an objective function that can be translated into cost, benefit, distance, wait for time, coverage, etc. (**?**).

In many practical applications, the allocation of existing resources (e.g. budget) is not enough to cover all the facilities (e.g. demand) with the desired level of coverage (**?**). It is then, that the maximal covering location problems are applied. As previously mentioned in the State of the art chapter, these problems seek to attend the maximum population within of a distance or a service time settle given a limit of quantity of installations.

Under these circumstances, given the features of the problematic, the available resources and the waited results, our propose is applying the use of a maximal covering location problem as a solution tool. Following below is define the Maximal Covering Location Problem for Recycling (or MCLPR, for short) corresponding to the thesis project:

Given a set of possible locations of collection centers and a set of waste generator points. The optimization problem consists in *defining the quantity and location of collection centers to be installed within a reverse logistics network, by considering the constraints of capacity, a variable investment budget which can be increased respecting* *of the collection items, a coverage radius, as well as the condition that assures the total waste collected must be sent to reuse and recycling.* The Figure 3.2 shows an illustrative example of our MCLPR exposed.

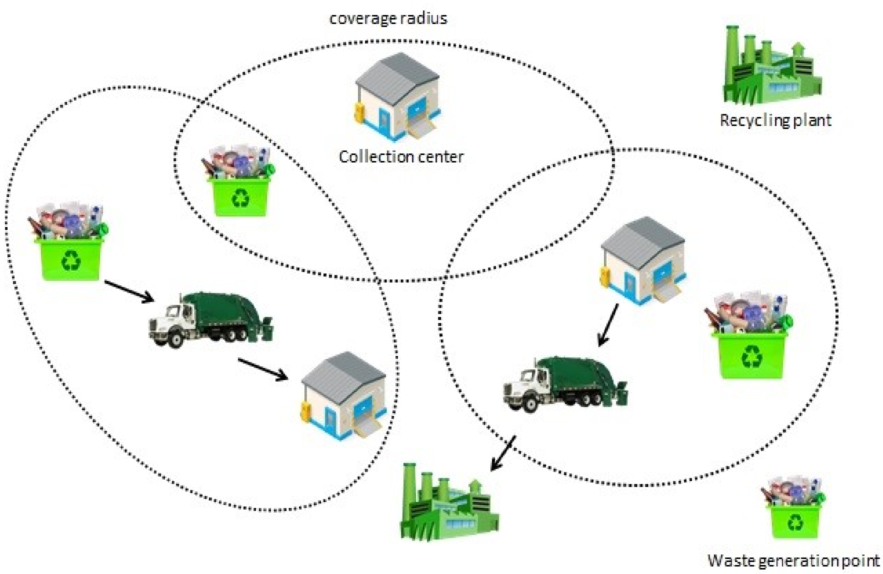

Figure 3.2: The Maximal Covering Location Problem for Recycling illustrative example

3.3 Construct of the mathematical model

Once the problem is defined, the phase of the design of the mathematical formulation is carried out, which consists in reformulating it in a convenient way for its analysis. The conventional way in which the OR obtains this objective is through the construction of a mathematical model. In order to explain in a brief way the construction of these models, we base on the four general features defined by the optimization area, which are shown below:

1. **Objective function**.- Corresponds to the quantitative measurement of the operation of the system that is desired to optimize (maximize or minimize). As an instance: the minimization of costs, the maximization of products collected, etc...

2. **Decision variables**.- These decisions are made to influence directly in the objective

function. As a clear example is the case of a company, where is important to know the quantity of product produced in a period of time.

3. **Constraints**.- Correspond to the all possible limits that can be imposed on the decision variables. As an instance: The capacity production of a company or the available budget to install facilities.

4. **Parameters**.- Correspond to the known values of the system. This information may be collected or calculated in a random way.

As shown above, the problem consists of choosing the values of the decision variables so that the objective function being maximize or minimize, all subject to the constraints.

3.3.1 The Maximal Covering Location Problem for Recycling

In the present section is described the proposed model to create a reverse logistics network of recycling, which is subject to the previous problem described in the phase called construct of the mathematical model. In order to formulate the model, consider the following notation:

Sets:

$I = \{1, ..., |I|\}$: set of candidate locations.

$J = \{1, ..., |J|\}$: set of waste generators points.

$K = \{1, ..., |K|\}$: set of recycling plants.

General Parameters

d_j = Tons of waste generated in point j.

b_i = Collection center capacity per Tons in location $i \in I$.

h_k = Recycling plant capacity per Tons in location $k \in K$.

z = Investment budget allocated for maintain the reverse logistics network working.

g_k = Profit obtained per Ton of waste sent to the recycling plants.

m = Profit obtained per Ton of goods still useful sent to the secondary market.

p = Maximum fraction of goods still useful permitted to send to the secondary market.

Costs

f_i = Setup cost for installation a collection center in location i.

e_i = Operational cost of collection center in location i.

c_{ij} = Cost for collecting the waste generated from point j to collection center i.

a_{ik} = Cost for transport the waste from collection center i to recycling plant k.

Decision variables

y_i: binary variable taking the value of 1 if a collection center is opened at location i and 0 otherwise.

x_{ij}: binary variable taking the value of 1 if the collection center in $i \in I(j)$ covers to the waste generator point in j and 0 otherwise.

s_{ij}: Tons of waste transported from the point j to the center i.

w_{ik}: Tons of waste transported from the center i to the plant k.

t_i: Tons of useful goods to sell in the secondary market.

Then, our proposed mathematical formulation for the MCLPR:

$$\max \sum_{i \in I} \sum_{j \in J} s_{ij} \tag{3.1}$$

Subject to:

$$\sum_{i \in I} f_i y_i + \sum_{i \in I} \sum_{j \in J} e_i s_{ij} + \sum_{k \in K} a_{ik} w_{ik} + \sum_{i \in I} \sum_{j \in J} c_{ij} s_{ij} \leq z +$$

$$\sum_{k\in K}\sum_{i\in I} g_k w_{ik} + \sum_{i\in I} mt_i \tag{3.2}$$

$$s_{ij} \le x_{ij} d_j \qquad \forall i \in I, j \in J \tag{3.3}$$

$$\sum_{j\in J} s_{ij} \le b_i \qquad \forall i \in I \tag{3.4}$$

$$x_{ij} \le cob_{ij} y_i \qquad \forall i \in I, \forall j \in J \tag{3.5}$$

$$\sum_{i\in I} x_{ij} \le 1 \qquad \forall j \in J \tag{3.6}$$

$$\sum_{i\in I} w_{ik} \le h_k \qquad \forall k \in K \tag{3.7}$$

$$\sum_{k\in K} w_{ik} + t_i = \sum_{j\in J} s_{ij} \qquad \forall i \in I \tag{3.8}$$

$$t_i \le p \sum_{j\in J} s_{ij} \qquad \forall i \in I \tag{3.9}$$

$$y_i \in (0,1) \qquad \forall i \in I \tag{3.10}$$

$$x_{ij} \in (0,1) \qquad \forall j \in J, \forall i \in I \tag{3.11}$$

$$s_{ij} \ge 0 \qquad \forall j \in J, \forall i \in I \tag{3.12}$$

$$w_{ik} \ge 0 \qquad \forall k \in K, \forall i \in I \tag{3.13}$$

$$t_i \ge 0 \qquad \forall i \in I \tag{3.14}$$

Objective function (3.1) seeks to maximize the quantity of waste collected by collection centers. Constraints (3.3) assures the quantity of waste collected by the collection center i does not surpass the amount of waste received from points in $J(i)$. Constraints (3.4) guarantee the total quantity of waste s_{ij} collected by i does not exceed its capacity. Constraints (3.5) assure that if the waste generator in point j send their waste to the collection center i, then point i must be covered that point j and be open ($y_i = 1$). Constraints (3.6) guarantee the waste generator point j has at most one collection center allocated. Constraint (3.2) determines that the sum of open collection centers cost, operational cost and transportation costs, must not surpass the investment budget plus the total prot earn from sell the useful goods in the secondary market as well as the waste sell to the recycling plants K. Constraint (3.7) assures the capacity h_k of recycling plant k is not exceeded by the quantity of waste sent from collection centers. Constraints (3.8) guarantee the flow balance, which means that the total tons of waste sent by point i to the plant K plus the tons of useful goods sold in the secondary market, must be the same to the quantity tons transported from the waste generators point j to the collection centers i. Constraints (3.9) determines the maximal quantity of goods considered to sell in the secondary market. Lastly, the constraints (3.10)–(3.14) are the domain of the decision variables.

Due to the data limitation, the parameter of budget z was calculated through a variant of the original model. This model seeks to collect all the waste generated d_j by the network with the lowest possible cost. Noted that the constraint (3.2) of the previous model was declared now as the objective function (3.15), while the constraints (3.16) were added to the model, in order to collect all the waste generated. Finally, the constraints (3.17)–(3.27) remain in the same way. Then, the upper bound given by this model was used in order to define the reference budget to the collection of the items by the network.

$$\min \quad \sum_{i\in I} f_i y_i + \sum_{i\in I}\sum_{j\in J} e_i s_{ij} + \sum_{i\in I}\sum_{k\in K} a_{ik} w_{ik} + \sum_{i\in I}\sum_{j\in J} c_{ij} s_{ij} - \left(\sum_{k\in K}\sum_{i\in I} g_k w_{ik} + \sum_{i\in I} m t_i \right) \tag{3.15}$$

Subject to:

$$\sum_{i\in I} s_{ij} = d_j \qquad \forall j \in J \tag{3.16}$$

$$s_{ij} \leq x_{ij} d_j \qquad \forall i \in I, j \in J \tag{3.17}$$

$$x_{ij} \leq cob_{ij} y_i \qquad \forall i \in I, \forall j \in J \tag{3.18}$$

$$\sum_{i\in I} x_{ij} \leq 1 \qquad \forall j \in J \tag{3.19}$$

$$\sum_{j\in J} s_{ij} \leq b_i \qquad \forall i \in I \tag{3.20}$$

$$\sum_{i\in I} w_{ik} \leq h_k \qquad \forall k \in K \tag{3.21}$$

$$\sum_{k\in K} w_{ik} + t_i = \sum_{j\in J} s_{ij} \qquad \forall i \in I \tag{3.22}$$

$$y_i \in (0,1) \qquad \forall i \in I \tag{3.23}$$

$$x_{ij} \in (0,1) \qquad \forall j \in J, \forall i \in I \tag{3.24}$$

$$s_{ij} \geq 0 \qquad \forall j \in J, \forall i \in I \tag{3.25}$$

$$w_{ik} \geq 0 \qquad \forall k \in K, \forall i \in I \tag{3.26}$$

$$t_i \geq 0 \qquad \forall i \in I \tag{3.27}$$

3.4 Design and implementation of solution techniques

In the present phase, the model was coded in the General Algebraic Modeling System (GAMS) and solved by using the optimization system Cplex 12.6. During the coding the model was validated in several times and modified until obtain the data required.

3.5 Analysis and testing

The last phase known as "'Analysis and testing"' is widely detailed in the next chapter of Experimental Results. Through the comparative analysis we seek to obtain a feasible solution for the study problem faced.

Chapter 4

Experimental Results

In this section, we present and analyze the numerical results of implementing our mathematical model (MCLPR), in order to: (i) develop a strategic planning insight that could helps to identify appropriate facility locations for a long-term horizon; and (ii) evaluate the effectiveness of our maximal covering location model to support decisions in a solid waste management system context. To perform the experimental analysis, the model was coded in the General Algebraic Modeling System (GAMS) and solved by using the optimization solver Cplex 12.6. The computational experiment was conducted with a stopping criterion of relative gap equal "0" or the time limit of 10,800 seconds in a PC Intel (R) Core (TM) i7-2600 3.40 gigahertz, 16.0 gigabyte RAM and Windows 7 operating system.

Likewise, in order to evaluate the behavior of our model, we use a case study in the recycling of tires in the state of São Paulo in Brazil.

4.1 Case study

4.1.1 Context

Brazil is cataloged as a developing country with over 180 million inhabitants. Its most populous city is the São Paulo state in the Southeast Region with a population of 21.1 million inhabitants and a total area of 248,222.8 km^2 . According to ?, the country produces more than 60 million automobile and truck tires, of which only one-third of the amount is exported (?). Eventually, every tire reaches the end of its usage becoming either recoverable or unrecoverable. Which the real problem lies in the inadequate disposition of these objects, due to the environmental impact they can produce. Even more, if we consider the degradation period of every one of these products can reach hundreds of years. The recoverable tires are those for which some fix, such as recapping or re-treading is still possible, given the opportunity to sell them to the secondary market. While unrecoverable tires are recycling, in order to be used as raw material for the production of a certain of products. The co-processing, lamination, granulation are the different processes through which a tire is exposed to reach its recycling. As a result, Brazil developed federal resolutions to make responsible for the environmental damage to the tire producers and importers requesting them to collect their unrecoverable tires through the achievement of annual recycling or reuse goals.

Nowadays, the producers and importers make the collection and recycling process by means of independent logistics reverse network systems. This means that there is not a correct planning that considers the activities developed in an integrated and coordinated way. At present, across Brazil, there are points available to receive the tires unusable dropped by the consumers. The reverse logistics begins when a specific amount of tires received is reached at these points, so their collection is requested. The responsible pick them up and transport to the recycling plants where the tires are processes to their recycling. In some cases, between these two steps exist facilities called “collection centers” which develop the activity of classification of tires. The Figure 4.1 shows the process described above.

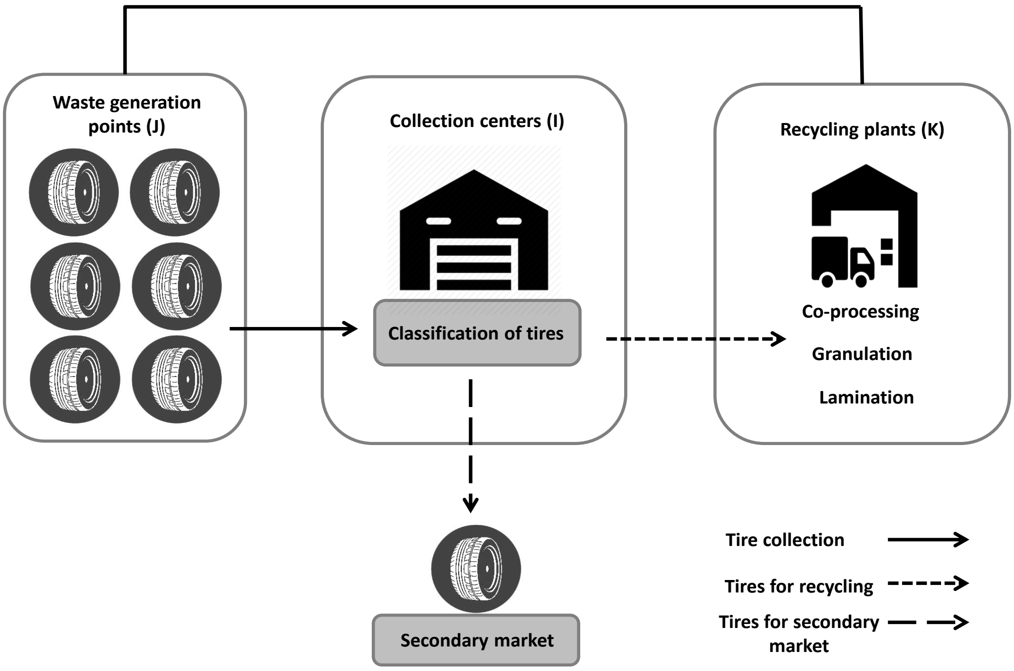

Figure 4.1: Processes of the reverse logistics network of tires in São Paulo

The installation of collection centers can greatly help to identify either recoverable or unrecoverable tires, incrementing the possibility to give a second chance to the products in a secondary market and providing extra profits, as well as, improve the organization activities through the network. Within the reverse logistics network, there are the possibilities to open facilities in a small, medium or large size, each one with different capacity and installation cost. Moreover, after the act of classification is handled within these facilities, there are two possibilities to obtain gains, trough: (1) the sale of the tires to a secondary market; and (2) the sale of the tires to the recycling plants, which provides the possibility to keep the network working.

4.1.2 Data

To perform the experimentation, the input data was taken from the study of (?). The network consists in 412 waste generators points and 20 recycling plants. Related to the set of potential locations of collection centers were considered the 41 principal cities and the metropolitan region of São Paulo state (given a total of 42 potential locations); see the tables A.1, A.2 and A.3 in appendix to get an overview of the data described above.

To calculate the quantity of waste collected d_j per each waste generator point j, we consider the amount generated in November, due to this month reports the more representative amount among of the months of a year.(see column 3 in table A.2 included in the appendix). The collection capacity b_i and the setup cost f_i depends on the size of the opened center in each location i (Table 4.1), while the operational cost e_i per collection center remain in the same rate of 12.5 BRL per ton classified (Brazilian Real) to all the centers. On the other hand, the shipping cost c_{ij} and a_{ik} generated for the activities developed of collecting and transportation among the location j, i and k per ton for different ranges of distance are shown in Table 4.2. Regarding to the profit m obtained by the selling to the secondary market of a maximum fraction (p) of 20 percent of tires, this rate corresponds to 380 BRL per ton. Finally, the capacity per tons h_k and the profit g_k generated by the recycling process developing in each k are show in column 3 of Table A.3 included in the appendix and the Table 4.3, respectively.

Size of collection center	**Capacity (Tons)**	**Fix cost (BRL)**
Small	375	125,000
Medium	750	250,000
Large	1125	375,000

Table 4.1: Collection center capacity.

Due to the data limitation, some parameters were calculated as follows. In order to calculate the investment budget z (as described in the chapter of Methodology) are used a variant of the original model, which seeks to define the monetary amount needed

Size	**Distance (Km)**	**Cost (BRL/Ton)**
Pretty short	50	72.88
Short	400	133.39
Medium	800	205.33
Large	2400	476.79
Pretty large	6000	1075.37

Table 4.2: Shipping costs.

Recycling process	**Profit (BRL/Ton)**
Granulation	120
Co-processing	50
Lamination	200

Table 4.3: Profit obtained per each recycling plant.

to collect all the d_j tons of waste generated by the set J. Through this range, we will be able to determine the budget amount required to open and cover a certain number of points and centers. Regarding the coverage radius cov, we considered a distance of 50 km and 100 km due to the broad territorial extension of São Paulo state.

4.1.3 Generated instances

The case study was solved by five types of scenarios. Each one with a combination of different features (coverage radius, investment budget and collection center size). Their features are described as follow:

- The scenarios A, B and C consider a coverage radius of 50 Km. However, the size of the collection center is different among one and other. On the one hand, the A scenario allocates only small collection centers, while the B scenario and C scenario allocates medium and large centers, respectively.

- The D scenario considers a coverage radius of 50 Km and a combination of the different sizes of collection centers (small, medium and large). The collection center size allocated in each potential location is defined by the population density of each city (see column 3 in the table included in the appendix for an overview).

- Finally, the E scenario considers a coverage radius of 5 km distance service and a combination of the different sizes of collection centers (small, medium and large). This scenario was developed in order to get an sensitivity analysis of the study.

4.2 Validating proposed approach on a small scenario

Firstly, in order to validate the mathematical model, an illustrative and small instance was designed. The instance was composed of 30 waste generator points, 5 recycling plants, and 10 potential locations to install collection centers. To this instance was consider a coverage radius of 10 Km, the allocation of small and medium type of collection centers, the maximum fraction of 20% of tires to sell in the secondary market and a investment budget of 32,000 BRL. The remain characteristics of this instance are fully described in the Figure 4.2.

The instance is solved in optimality with a gap of 0% and an execution time of 0.046 seconds. The results showed that is convenient open 3 collection centers in location i, given the possibility to cover 8 waste generators points j and collect a total amount of 116.66 tons. The Figure 4.3 shows the specific location of the collection centers opened and the waste generator points covered. Note that the squares represent the collection centers allocated, while the circles correspond to the waste generator points covered. Where the collection center in color blue corresponds to the Adamantina city which covers the

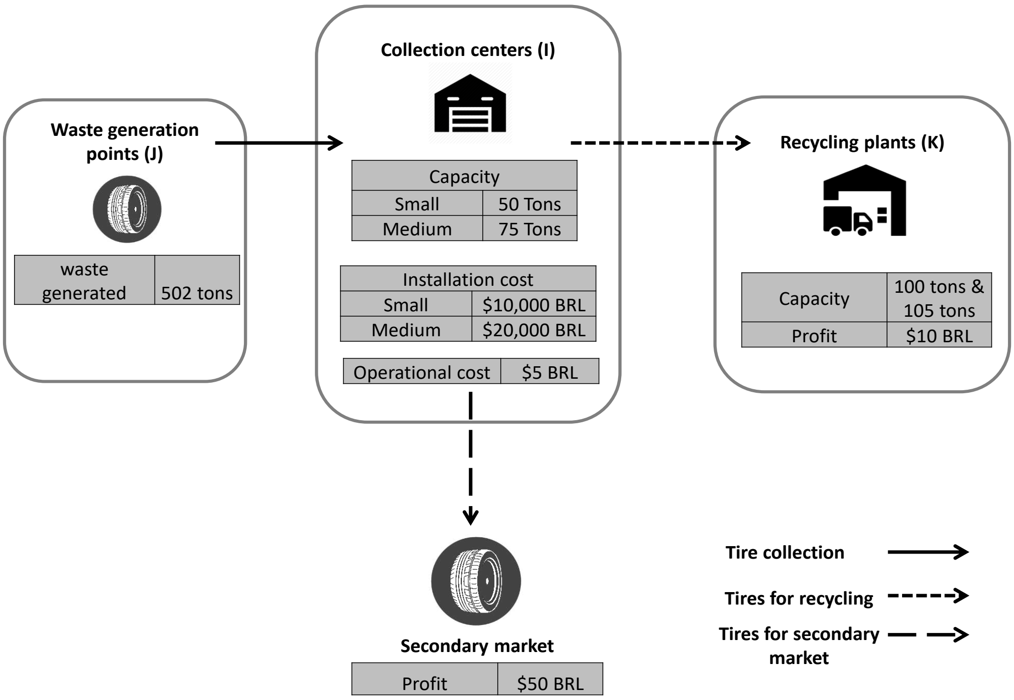

Figure 4.2: General data of the small scenario

waste generator points (shown in color blue) of Alvares Machado and Arujá. While, the collection center in color orange corresponds to the Aracatuba city which covers the waste generator points (shown in color orange) of Aracatuba and Araras, respectively. Finally, the collection center in color red is allocated in Assis city which covers the waste generators points (shown in red) of Aracatuba, Araraquara, Araras, and Avanhandava. Moreover, when talk in percentages, is seen that 23% of demand is collected with a 30% of collection centers opened generating that 27% of points were covered from the total existent and only 40% of recycling plant were used to process the waste collected. The Table 4.5 presents the specific quantity of waste transported among the different points.

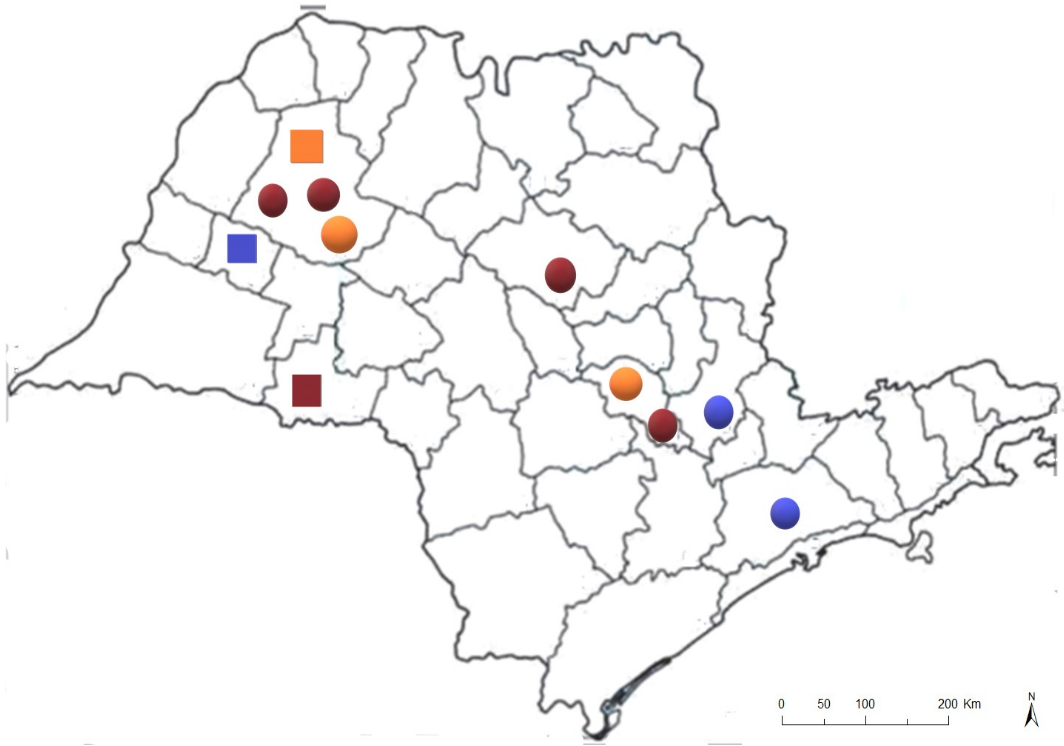

Figure 4.3: Location of Collection centers in the state of São Paulo

On the other hand, in order to guarantee the reverse logistics network is respecting the available resources, the general costs generated were examined. In this case, the setup cost f_i of \$30,000.00 BRL, the shipping cost c_{ij} and a_{ik} of \$3,516.58 BRL, and the operational cost e_i of \$583.30 BRL generated a totally amount of \$34,099.88 BRL. Proving that the available budget of \$32,000.00 BRL, the profit obtained of \$2,099.88 BRL give the exactly amount of \$34,099.88 BRL needed to keep the network working.

Tons of waste transported		
From J to I	From I to K	From I to Secondary market
116.66	93.32	23.33

Table 4.4: Quantity transported among points J, I and K

	Scenario A		**Scenario B**		**Scenario C**		**Scenario D**	
	Gap	**Time**	**Gap**	**Time**	**scenario**	**Time**	**Gap**	**Time**
1	0	8.81	0	7.59	0	9.02	0	10.36
2	0	9.06	0	6.88	0	12.41	0	12.78
3	0	17.06	0	17.05	0	14.88	0	7.91
4	0	23.77	0	7.05	0	35.44	0	7.19
5	0	49.28	0	10.11	0	127.22	0	31.82
6	2.37	10,800.00	1.69	10,800.00	8.47	10,800.17	1.69	10,800
7	2.45	10,800.00	0	605.14	1.24	10,800.00	1.93	10,800
8	0.95	10,800.00	0	934.58	2.08	10,800.00	2.13	10,800
9	1.60	10,800.00	11.35	10,800.16	0	3,535.84	1.82	10,800
10	0.07	10,800.00	44.27	10,800.16	44.27	10,800.00	0	223.69

Table 4.5: Numerical results of gap and time

4.3 Numerical results on generated instances

To show an overview of the solutions obtained by our proposed model, we will first analyze the efficiency of the solver used to generate feasible solutions for our optimization problem. The table 4.5 shows the relative gap and the execution time for all instances. Notice that the first five instances are solved to optimality. In particular, we highlight that the more significant gaps were reported in rows six, nine and ten of the B and C scenarios, respectively. However, the remain instances are easy to solve, due to them showed gaps smaller of 5%.

Regarding to the A, B, C and D scenarios, was noted that by using a budget between 4.5 to 2.5 million BRL corresponding to the instance from 1 to 5, the network is able to collect the totally of waste generated by the points (see the tables A.4, A.5, A.6 and A.7 in appendix). Under those circumstances, the analysis was made staring from the instances 6 to 10 of all scenarios. The figures 4.5, 4.7, 4.6 and 4.4 show the results in percent of opened centers, demand collected, recycling plants used and generators points covered to make a comparative among the different scenarios created.

The larger quantity of opened centers was reported in the A scenario, while the C scenario showed the smaller amount. On the other hand, when we talk about the percent of demand collected the scenario D presents good solutions in all their instances, compared with the remain scenarios (A, B and C) which only show competitive percents in some of their results. The better percentages of recycling plants used were reported in the scenarios A and D, leaving to the scenario C as the worst option. Lastly, when we refer to the percent of generators points covered, the scenario A give the best solution leaving behind the scenario D as the second best option, while scenario B and C show similar results. To summarize, the A scenario presents the better results in almost all the solutions obtained by the model, which provide us a full overview in respect of the size of collection center required when a low amount of budget is available to keep the network working. Nonetheless, the D scenario results were also positive, becoming to the scenario in a good option when the population density of each city must be consider.

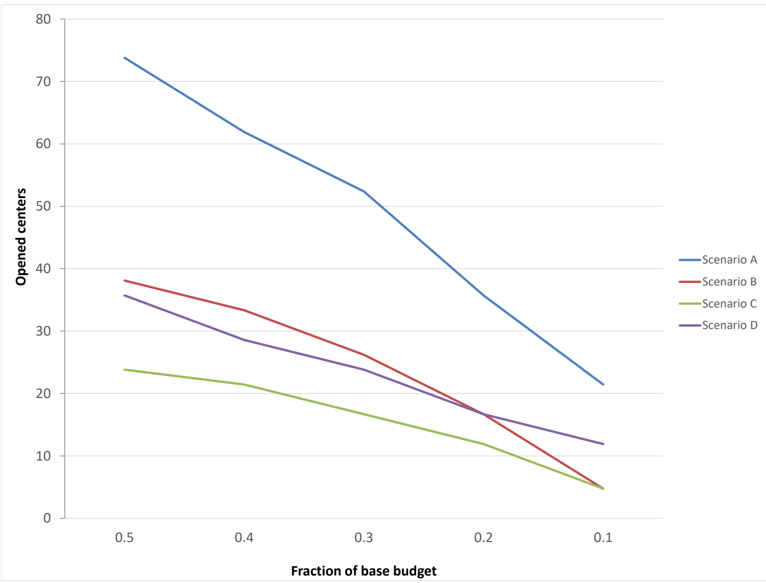

Figure 4.4: Graphic of the percent of opened centers

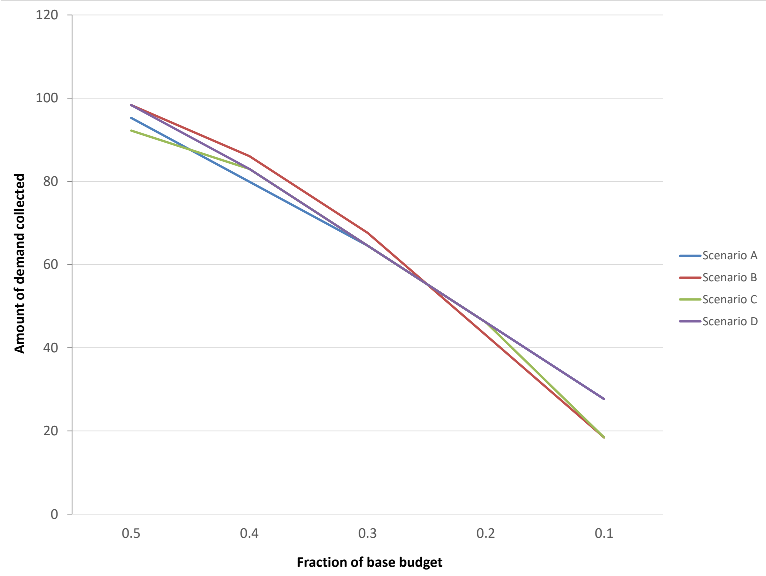

Figure 4.5: Graphic of demand percent collected

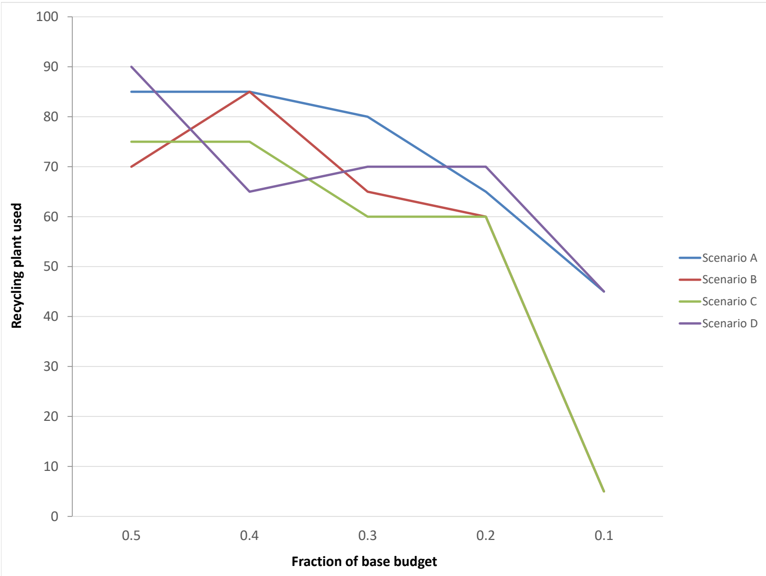

Figure 4.6: Graphic of recycling plants percent used

Finally, the results of the E scenario are shown in the table 4.6. This scenario was created in order to provide an overview of the model behavior when a 5 km of coverage radius is available and a combination of different size of collection centers are allocated. It can be seen that even with the greatest investment budget, the network is not capable of collecting or covering all the generating points and waste, this due to the limitation of distance service available. Likewise, we found that large percentage differences are

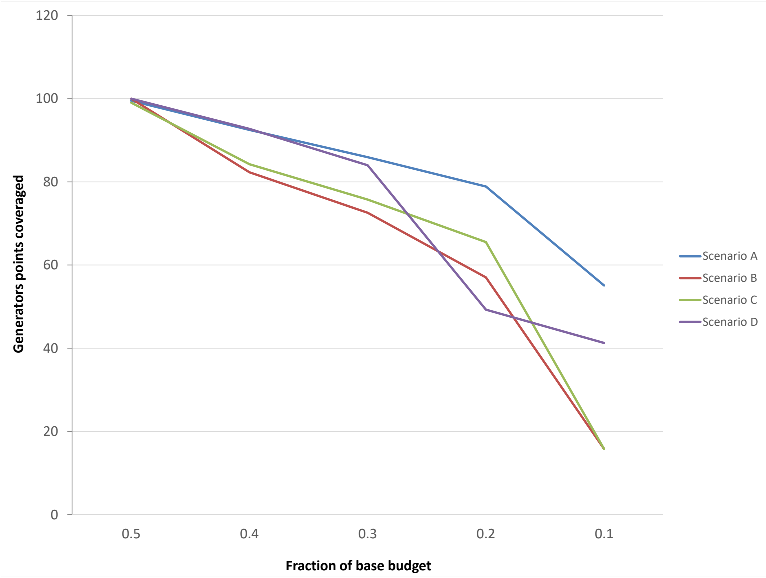

Figure 4.7: Graphic of the percent of generator points covered

reported between instances 9 and 10 of all the exposed solutions, making the 900,000 budget a good option when compared against the 400.00 budget.

Instance	Budget	(%) Opened centers	(%) Demand collected	(%) Recycling plants used	(%) Generators points coverage
1	4,508,348.17	64.29%	48.79%	75.00%	45.39%
2	4,057,513.35	59.52%	47.12%	75.00%	43.20%
3	3,606,678.54	54.76%	45.20%	85.00%	40.78%
4	3,155,843.72	50.00%	43.23%	80.00%	37.86%
5	2,705,008.90	35.71%	41.28%	75.00%	36.89%
6	2,254,174.09	42.86%	38.36%	70.00%	33.01%
7	1,803,339.27	33.33%	34.72%	60.00%	27.18%
8	1,352,504.45	28.57%	30.35%	55.00%	23.79%
9	901,669.63	21.43%	23.87%	50.00%	19.17%
10	450,834.82	14.29%	15.86%	35.00%	13.11%

Table 4.6: Results of the E scenario

Chapter 5

Conclusions

This study seeks to describe several features of establishing a reverse logistics network for the collection of end-of-life products. Our proposed Maximal Covering Location Problem for Recycling (MCLPR) has the objective to maximize the quantity of waste collected by the network. In particular, our problem provides the support to take the strategic decisions related to the number and location of allocating collection centers by considering characteristics as: budget, coverage radius, capacity per facility, general costs (setup cots, operation cost & transportation cost) and profits.

Summarizing, we design 50 instances considering the input data provided in the study of (?) about a recycling network of tires in the state of São Paulo in Brazil. The different instances were designed considering the variation related to the size per collection center, budget and coverage radius available.

5.1 Validating the objective of the study

The results show that the general objective was reached, due to our model provides the planning process of a reverse logistics network of end-of-life products appropriately, giving consistent solutions to the case of study applied. Indeed, the installation of collection centers can greatly help to identify either recoverable or unrecoverable tires, incrementing the possibility to give a second chance to the products in a secondary market and providing extra profits, as well as, improve the organization activities through the network.

Moreover, trough the analysis was possible to respond the questions related to the number and location of collection centers, size of collection centers to allocated, coverage radius, amount of waste collected and collection centers opened. Likewise, the budget needed to keep the network working.

On the other hand, when we talk about the model contributions is seen that quality results were obtained, due to the low computational time needed to resolve the problem. Moreover, in the majority of the experiments, a smaller gap of 5% was achieved, except some experiment which gap was more extensive.

5.2 Contributions

Appendix A

Apendix

A.1 Database

Table A.1: Potential locations for the collection centers

General data of collection centers		
Collection centers	*Location*	*Population density*
1	Adamantina	85.07
2	Andradina	59.37
3	Araçatuba	165.15
4	Araraquara	225.69
5	Assis	220.57
6	Avaré	72.86
7	Barretos	76.14
8	Bauru	549.65
9	Botucatu	94.08
10	Bragança Paulista	313.44
11	Campinas	1465.07
12	Caraguatatuba	233.6

Continued on the next page

Collection centers	*Location*	*Population density*
13	Catanduva	411.15
14	Cruzeiro	265.23
15	Dracena	94.01
16	Fernandópolis	123.9
17	Franca	564.84
18	Guaratinguetá	158.21
19	Itapetininga	87.75
20	Itapeva	50.76
21	Jales	132.73
22	Jaú	208.53
23	Jundiaí	932.02
24	Limeira	510.48
25	Lins	133.48
26	Marília	198.21
27	Ourinhos	372.8
28	Piracicaba	284.06
29	Presidente Prudente	396.32
30	Registro	77.93
31	Ribeirão Preto	1023.66
32	Rio Claro	401.19
33	Santos	1546.18
34	São Carlos	212.32
35	São João da Boa Vista	172.4
36	São José do Rio Preto	1024.56
37	São José dos Campos	626.33
38	Sorocaba	1431.94
39	Taubaté	483.73
40	Tupã	104.54

Continued on the next page

Collection centers	*Location*	*Population density*
41	Votuporanga	216.97
42	São Paulo	7867.82

Source: Compiled by author based on Jorge Meneses 2018 data

Table A.2: Waste generators points

General data of waste generator points		
Location	*Quantity of points*	*Quantity per Tons*
Adamantina	1	13.00
Agudos	1	9.82
Altinópolis	1	4.54
Álvares Machado	1	6.91
Americana	4	87.13
Américo Brasiliense	1	11.75
Andradina	1	21.13
Angatuba	1	5.96
Araraquara	4	87.86
Araras	3	48.3
Araçatuba	5	83.33
Arealva	1	2.00
Arujá	1	26.98
Assis	1	37.60
Atibaia	3	53.28
Avanhandava	1	2.73
Avaré	1	29.96
Bálsamo	1	2.84
Bariri	1	11.94
Barra Bonita	2	14.14

Continued on the next page

Location	*Quantity of points*	*Quantity per Tons*
Barretos	5	44.22
Barueri	6	84.85
Bastos	1	7.48
Bauru	5	137.82
Bebedouro	1	30.16
Birigui	3	47.7
Bocaina	1	3.35
Boituva	1	19.72
Borborema	1	4.85
Botucatu	2	47.21
Bragança Paulista	2	60.08
Brotas	1	7.59
Buritama	1	5.25
Cachoeira Paulista	1	7.56
Cajobi	1	2.57
Cajuru	1	6.94
Campinas	3	448.58
Capivari	1	17.02
Caraguatatuba	3	30.28
Carapicuíba	3	92.64
Catanduva	2	52.32
Cerqueira César	1	5.39
Conchal	1	8.28
Conchas	1	4.85
Cordeirópolis	1	7.81
Cosmópolis	1	19.18
Cosmorama	1	2.60
Cotia	5	67.8

Continued on the next page

Location	*Quantity of points*	*Quantity per Tons*
Cubatão	1	28.00
Diadema	2	101.3
Dracena	1	17.27
Duartina	1	3.56
Embu	3	54.92
Fernandópolis	1	28.21
Ferraz de Vasconcelos	1	33.43
Franca	4	125.11
Francisco Morato	2	22.13
Franco da Rocha	4	25.52
Garça	1	13.91
Guaíra	1	13.57
Guararapes	1	10.49
Guaratinguetá	4	34.3
Guaraçaí	1	2.66
Guareí	1	2.65
Guariba	1	9.79
Guarujá	1	66.62
Guarulhos	7	323.98
Herculândia	1	2.29
Iaras	1	0.84
Ibaté	1	8.53
Ibirá	1	3.22
Ibitinga	1	19.38
Igaraçu do Tietê	1	6.03
Ilha Solteira	1	8.79
Indaiatuba	3	88.64
Irapuru	1	1.57

Continued on the next page

Location	*Quantity of points*	*Quantity per Tons*
Itaí	1	6.21
Itajobi	1	5.35
Itapecerica da Serra	4	37.4
Itapetininga	2	46.26
Itapeva	1	28.60
Itapevi	3	45.63
Itapira	1	26.89
Itápolis	1	15.35
Itaquaquecetuba	1	55.77
Itararé	1	11.27
Itatiba	1	39.53
Itatinga	1	4.09
Itu	2	59.78
Jaboticabal	2	27.88
Jacareí	3	64.92
Jaguariúna	1	19.21
Jales	2	21.68
Jandira	3	26.66
Jaú	3	50.68
José Bonifácio	1	13.32
Jundiaí	2	158.48
Junqueirópolis	1	5.94
Leme	1	33.68
Lençóis Paulista	1	22.15
Limeira	3	104.5
Louveira	1	13.68
Lucélia	1	5.90
Macatuba	1	4.98

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Location	*Quantity of points*	*Quantity per Tons*
Mairiporã	1	25.42
Manduri	5	2.93
Marília	4	79.81
Martinópolis	1	6.46
Matão	1	32.06
Mauá	2	105.9
Mirandópolis	1	8.61
Mirante do Paranapanema	1	3.98
Mogi das Cruzes	2	114.38
Mogi Guaçu	3	54.24
Moji Mirim	3	35.07
Monte Alto	1	19.60
Monte Aprazível	2	7.93
Monte Castelo	1	1.06
Monte Mor	1	13.52
Nova Europa	1	2.52
Nova Granada	1	6.23
Nova Independência	1	0.77
Nova Luzitânia	1	0.82
Nova Odessa	1	20.77
Olímpia	1	18.23
Osasco	4	211.35
Osvaldo Cruz	1	11.40
Ourinhos	3	36.6
Ouroeste	1	2.72
Pacaembu	1	3.37
Palmeira d'Oeste	1	3.38
Palmital	1	7.07

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Location	*Quantity of points*	*Quantity per Tons*
Panorama	1	4.40
Paraguaçu Paulista	1	14.20
Paraíso	1	1.95
Parapuã	1	2.89
Paulínia	1	35.95
Pederneiras	1	15.07
Penápolis	1	24.21
Pereira Barreto	1	7.87
Piacatu	1	1.42
Piedade	1	16.16
Pindamonhangaba	2	43.56
Piracicaba	4	148.93
Piraju	1	9.37
Pirangi	1	3.62
Pirassununga	1	27.74
Pitangueiras	1	9.59
Poá	2	25.4
Pompéia	1	6.47
Pontalinda	1	0.82
Porto Feliz	1	15.62
Praia Grande	1	65.62
Pratânia	1	1.45
Presidente Epitácio	1	13.54
Presidente Prudente	4	82.1
Presidente	1	13.44
Promissão	1	11.87
Regente Feijó	1	5.72
Ribeirão dos Índios	1	0.57

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Location	*Quantity of points*	*Quantity per Tons*
Ribeirão Pires	2	33.77
Ribeirão Preto	7	260.69
Rinópolis	1	2.97
Rio Claro	3	81.4
Rosana	1	4.38
Sales Oliveira	1	3.35
Salto	2	35.5
Santa Adélia	1	5.27
Santa Bárbara d'Oeste	2	69.48
Santa Clara d'Oeste	1	0.59
Santa Cruz do Rio Pardo	1	15.96
Santa Fé do Sul	1	12.13
Santa Gertrudes	1	7.62
Santa Isabel	1	13.60
Santa Mercedes	1	0.71
Santana de Parnaíba	1	39.47
Santo Anastácio	1	6.57
Santo André	4	262.01
Santos	6	142.05
São Bernardo do Campo	4	296.87
São Caetano do Sul	6	72.79
São Carlos	4	87.73
São Joaquim da Barra	1	17.19
São José do Rio Preto	7	189.44
São José dos Campos	3	212
São Manuel	1	13.10
São Miguel Arcanjo	1	7.70
São Paulo	29	3972.79

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Location	*Quantity of points*	*Quantity per Tons*
São Pedro	1	11.73
São Roque	1	23.19
São Vicente	1	67.72
Sarapuí	1	2.77
Sertãozinho	3	43.31
Severínia	1	3.94
Sorocaba	7	230.53
Sumaré	4	77.12
Suzano	4	62.9
Tabatinga	1	4.69
Taboão da Serra	2	63.41
Tanabi	1	8.22
Taquaritinga	2	18.79
Taquarituba	1	6.85
Tatuí	2	39.94
Taubaté	2	104.66
Teodoro Sampaio	1	5.50
Tietê	1	13.36
Torrinha	1	3.47
Três Fronteiras	1	1.78
Tupã	1	26.18
Tupi Paulista	1	4.76
União Paulista	1	0.53
Urânia	1	3.20
Urupês	1	4.63
Valinhos	2	47.56
Valparaíso	1	5.60
Vargem Grande Paulista	1	13.95

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Location	*Quantity of points*	*Quantity per Tons*
Várzea Paulista	1	31.83
Vinhedo	1	30.96
Viradouro	1	5.52
Votorantim	2	32.76
Votuporanga	1	40.92

Source: Compiled by author based on Jorge Meneses 2018 data

Table A.3: Recycling plants

General data of recycling plants			
Recycling plants	*Location*	*Recycling process*	*Capacity (Tons)*
1	Utep do Brasil Ltda.	Granulation	3,987.25
2	CBL Comércio e Reciclagem de Borrachas Ltda.	Granulation	1,977.67
3	Intercement Brasil S.A.	Granulation	2,161.42
4	Policarpo & Cia. Ltda.	Co-processing	1,737.92
5	Roseli Fialho de Lana Emerich	Granulation	315.58
6	Vila Nova Energia Ltda	Granulation	1,170.58
7	Votorantim Cimentos S.A.	Co-processing	1,310.42
8	Intercement Brasil	Granulation	399.50
9	Sukako Fabricacao de Artefatos de Borracha Ltda.	Granulation	171.83

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Recycling plants	*Location*	*Recycling process*	*Capacity (Tons)*
10	CBL Comércio e Reciclagem de Borrachas Ltda.	Granulation	447.50
11	Borcol Indústria de Borracha Ltda.	Granulation	39.92
12	Laminação de Pneus Nicoletti Ltda.	Lamination	163.83
13	CBL Comércio e Reciclagem de Borrachas Ltda.	Granulation	71.92
14	Gonçalves & Bressan Ltda.	Granulation	59.92
15	Morales & Silva Recuperação de Materiais Ltda.	Granulation	35.92
16	Barão Comercio de Pneus Ltda	Lamination	35.92
17	Torre Engenharia e Pesquisa Tecnologica Ltda.	Granulation	28.00
18	Interag Reciclagem de Pneus e Comércio de Pecas EM	Lamination	1,977.58
19	Pneus Sarapuí Com. Reciclagem Borrachas Eireli Epp	Lamination	35.92
20	Pneus Sarapuí Com. Reciclagem Borrachas Eireli Epp	Lamination	35.92

Source: Compiled by author based on Jorge Meneses 2018 data

Instance	**Budget**	**(%) Opened centers**	**(%) Demand collected**	**(%) Recycling plants used**	**(%) Generators points coverage**
1	4,694,780.00	97.62%	100.00%	75.00%	100.00%
2	4,225,302.00	88.10%	100.00%	95.00%	100.00%
3	3,755,824.00	88.10%	100.00%	100.00%	100.00%
4	3,286,346.00	80.95%	100.00%	90.00%	100.00%
5	2,816,868.00	38.10%	100.00%	80.00%	100.00%
6	2,347,390.00	73.81%	95.26%	85.00%	99.51%
7	1,877,912.00	61.90%	79.90%	85.00%	92.48%
8	1,408,434.00	52.38%	64.53%	80.00%	85.92%
9	938,956.00	35.71%	46.10%	65.00%	78.88%
10	469,478.00	21.43%	27.66%	45.00%	55.10%

Table A.4: Results of the A scenario

Instance	**Budget**	**(%) Opened centers**	**(%) Demand collected**	**(%) Recycling plants used**	**(%) Generators points coverage**
1	4,635,584.00	54.76%	100.00%	90.00%	100.00%
2	4,172,025.60	50.00%	100.00%	90.00%	100.00%
3	3,708,467.20	47.62%	100.00%	95.00%	100.00%
4	3,244,908.80	45.24%	100.00%	80.00%	100.00%
5	2,781,350.40	38.10%	100.00%	80.00%	100.00%
6	2,317,792.00	38.10%	98.34%	70.00%	100.00%
7	1,854,233.60	33.33%	86.04%	85.00%	82.28%
8	1,390,675.20	26.19%	67.61%	65.00%	72.57%
9	927,116.80	16.67%	43.02%	60.00%	57.04%
10	463,558.40	4.76%	18.44%	5.00%	15.78%

Table A.5: Results of the B scenario

Instance	Budget	(%) Opened centers	(%) Demand collected	(%) Recycling plants used	(%) Generators points coverage
1	4,486,827.00	38.10%	100.00%	80.00%	100.00%
2	4,038,144.30	33.33%	100.00%	70.00%	100.00%
3	3,589,461.60	30.95%	100.00%	80.00%	100.00%
4	3,140,778.90	28.57%	100.00%	85.00%	100.00%
5	2,692,096.20	40.48%	100.00%	85.00%	100.00%
6	2,243,413.50	23.81%	92.19%	75.00%	99.03%
7	1,794,730.80	21.43%	82.97%	75.00%	84.22%
8	1,346,048.10	16.67%	64.53%	60.00%	75.73%
9	897,365.40	11.90%	46.10%	60.00%	65.53%
10	448,682.70	4.76%	18.44%	5.00%	15.78%

Table A.6: Results of the C scenario

Instance	Budget	(%) Opened centers	(%) Demand collected	(%) Recycling plants used	(%) Generators points coverage
1	4,491,813.00	59.52%	100.00%	95.00%	100.00%
2	4,042,631.70	59.52%	100.00%	85.00%	100.00%
3	3,593,450.40	54.76%	100.00%	80.00%	100.00%
4	3,144,269.10	50.00%	100.00%	85.00%	100.00%
5	2,695,087.80	38.10%	100.00%	80.00%	100.00%
6	2,245,906.50	35.71%	98.34%	90.00%	100.00%
7	1,796,725.20	28.57%	82.97%	65.00%	92.72%
8	1,347,543.90	23.81%	64.53%	70.00%	83.98%
9	898,362.60	16.67%	46.10%	70.00%	49.27%
10	449,181.30	11.90%	27.66%	45.00%	41.26%

Table A.7: Results of the D scenario